The Soft X-Ray Performance of CCD Detectors

by

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Declaration

I hereby declare that no part of this thesis has been previously submitted to this or any other University as part of the requirements for a higher degree. Work described here was conducted by the undersigned except for the contribution of colleagues indicated in the text.

C. Castelli
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September 1991
Dedication

To Mum and Dad and all my family and friends
for their endless encouragement.

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List of Publications

Some of the experimental results reported in this thesis have been incorporated in the following papers. The chapters to which these papers refer are given in brackets.

1. 'Further developments of CCD X-ray detectors for Astronomy',
   A.D.Holland, D.H.Lumb and C.M.Castelli,
   Proc.SPIE 1159,113,1989 (Chapter 6)

2. 'Soft X-ray Performance of Back-Illuminated EEV CCDs',
   P.C.Bailey, C.M.Castelli, M.Cross, P.Van Essen, A.D.Holland,
   F.Jansen, P.de Korte, P.Pool and P.Verhoeve,
   Proc.SPIE, 1344,1990 (Chapter 6)

3. 'Soft X-Ray response of EEV Charge Coupled Devices',
   C.Castelli, A.Wells,K.McCarthy and A.Holland,
   submitted to Nuclear Instruments and Methods, 1991 (Chapter 6)

4. 'The CCD Focal Plane Imaging Detector for the JET-X Instrument on Spectrum R-G',
   A.Wells,C.Castelli,A.Holland,K.McCarthy,J.Spragg,C.Whitford,
   Proc SPIE,1549,1991 (Chapter 6)
Abstract

The Charge Coupled Device (CCD) is useful as an imaging detector in the x-ray waveband, and, when used to detect single photon events can simultaneously provide spatial imaging and energy resolution. This capability is important in the field of x-ray astronomy and the CCD has become the detector of choice for a number of future space x-ray imaging telescopes.

With radiation focussed onto the front electrodes, the CCD suffers from reduced response below 1 keV due to absorption in the electrode structure; the same process that limits the blue response in the optical band. This thesis covers work performed to develop CCDs with an enhanced soft x-ray detection efficiency.

Experimental results from two alternative techniques to improve the CCDs low energy response are reported. The first technique enables the CCD to be illuminated on its rear face and good detection efficiency at low energy can be achieved by removing the inert substrate of the device.

The second technique studied involves fabricating an optimised front electrode structure to minimise absorption loss in the electrodes.

A Monte-Carlo simulation is used to predict the response of the back illuminated CCD and compared with experimental data. The model is then used to suggest improvements to increase the charge collection efficiency of the CCD and therefore the energy resolution and detection efficiency.

Results from both types of experimental devices are reported and the factors that effect the energy resolution and detection efficiency are fully investigated. In the case of back-illumination, the effects of charge loss in the rear passivating implant of the CCD and thinning position within the epitaxial layer on the detector's response are investigated.

The back illuminated CCD is currently being developed for the Reflection grating Spectrometer on the XMM space mission and also the EPIC cameras. The front illuminated CCD with the optimised electrode structure is being developed for the imaging cameras for JET-X the instrument to be flown on the Russian SPECTRUM-XG mission.

Through further developments in CCD technology embodied in the modelling work and experimental results of this thesis, the CCD response is shown to be able to extend down into the EUV region (100 - 10 eV) opening up a new area of EUV instrumentation. Possible future EUV space missions are described in which the EUV enhanced CCD may form the focal plane detector.
Contents

1 Introduction 5
   1.1 CCDs for X-ray Astronomy 5
   1.2 Thesis Structure 8

2 The Charge Coupled Device 10
   2.1 Introduction 10
   2.2 Two-dimensional Imaging CCDs 10
      2.2.1 Device Structure and Operation 11
      2.2.2 Buried Channel Devices 14
      2.2.3 Charge Confinement 16
   2.3 Charge Transfer in a CCD 16
      2.3.1 Charge Transfer Efficiency 16
      2.3.2 Charge Measurement 18
   2.4 Noise in CCDs 19
      2.4.1 Signal Shot Noise 19
      2.4.2 Dark Current Noise 19
      2.4.3 Noise in the Charge Sensing Amplifier 21
   2.5 Photo-ionisation in Silicon 22
      2.5.1 Photon Absorption in Silicon 22
      2.5.2 Optical Photons 23
      2.5.3 X-ray Interaction with Silicon 24

3 Methods of Enhancing the Soft X-ray Response of CCD Imagers 30
   3.1 Introduction 30
   3.2 Back Illumination 31
      3.2.1 The Rear Surface Potential 31
   3.3 Accumulation of the Rear Surface 37
      3.3.1 Backside Charging by UV radiation 37
      3.3.2 Flash-gate and Biased Flash-gate 38
      3.3.3 Ion-implantation 40
3.4 Thin Electrode CCDs .............................................. 43
    3.4.1 Open Pinned Phase CCD ................................... 44
3.5 Conclusion ......................................................... 46

4 The Low Energy CCD Test Facility 47
4.1 Introduction ...................................................... 47
4.2 Crystal Monochromator ........................................... 49
4.3 X-ray source ...................................................... 50
    4.3.1 Methods of Generating Soft X-rays ....................... 50
    4.3.2 Description of the Source ................................ 53
4.4 Monitor Detector .................................................. 57
4.5 Bragg Crystals .................................................... 61
    4.5.1 Crystal Calibration ....................................... 64
    4.5.2 Modulation of the Beam Intensity ....................... 66
4.6 CCD Electronics and Data Processing .......................... 68
    4.6.1 Overall Description ...................................... 68
    4.6.2 The CCD Sequencer ....................................... 69
4.7 Data Analysis Techniques ...................................... 71
    4.7.1 Pulse Height Spectral Analysis ........................... 71
    4.7.2 Charge Transfer Efficiency Measurement ................ 73
4.8 Conclusion ........................................................ 75

5 Simulation of the CCD's X-ray Performance 76
5.1 Introduction ...................................................... 76
5.2 Charge Collection from the p+ Implant ........................ 78
    5.2.1 CCE from a region having an arbitrary dopant profile 79
    5.2.2 Results of the Quasi-Transparent Approximation ........ 81
    5.2.3 CCE for Uniformly Doped Silicon ....................... 83
5.3 Theory of Charge Diffusion .................................... 84
    5.3.1 Initial Charge Cloud Diameter ........................... 84
    5.3.2 Charge Diffusion in a Field Free Layer ................ 85
5.4 Radial Diffusion in the Depletion Layer ....................... 86
5.5 Summary .......................................................... 88
5.6 Monte-Carlo Simulation of the CCDs Pulse Height Spectra .... 88
    5.6.1 Introduction .............................................. 88
    5.6.2 Schematic Description of the Computer Program ........ 88
    5.6.3 Simulation Results ...................................... 89
5.7 Discussion ....................................................... 94
5.8 Back Illuminated Quantum Efficiency ........................... 96
5.9 Conclusion .................................................. 97

6 Results from CCDs with Enhanced Soft X-ray Quantum Efficiency .......................... 98
6.1 Introduction .................................................. 98
6.2 Under-thinned Back Illuminated CCDs .................................. 99
   6.2.1 Device Description .................................. 99
   6.2.2 Quantum Efficiency Measurements ..................... 101
   6.2.3 Pulse height Spectrum ................................ 102
   6.2.4 Effect of Varying the Depletion Edge Position ....... 104
   6.2.5 Discussion of the Results ............................. 105
   6.2.6 The Effect of Pixel Binning .......................... 109
   6.2.7 Summary of Under-thinned Back Illuminated CCDs .... 111
6.3 Fully Depleted Back Illuminated CCDs ................................ 111
   6.3.1 Device Description .................................. 111
   6.3.2 Quantum Efficiency ................................ 111
   6.3.3 Pulse Height Spectra ................................ 112
   6.3.4 Origin of the Partial Events ........................ 116
6.4 Dark Current in Back Illuminated CCDs ................................ 116
6.5 Conclusion .................................................. 118
6.6 Thin Electrode CCDs ......................................... 120
   6.6.1 Introduction ....................................... 120
   6.6.2 Device Architecture ................................ 120
   6.6.3 Quantum Efficiency ................................ 121
   6.6.4 Soft X-ray Pulse Height Spectra ................. 122
6.7 Charge Transfer Efficiency on Energy Resolution ....................... 123
   6.7.1 Energy Dependance of CTE .......................... 126
   6.7.2 Serial CTE and Temperature ......................... 126
   6.7.3 Methods of Reducing Dark Current .................... 127
   6.7.4 Narrow Buried Channel CCDs .......................... 129
   6.7.5 Inverted Mode ...................................... 130
6.8 Low Noise Amplifiers ......................................... 131
6.9 Conclusion .................................................. 132

7 CCD Optical Filter ............................................ 134
7.1 Introduction .................................................. 134
7.2 Filter Optical Constants .................................... 134
7.3 The Optical Point Source Sensitivity of the JET-X Telescope ............... 138
   7.3.1 Introduction ....................................... 138
   7.3.2 Calculations ...................................... 139

3
8 Conclusion and Future Work 141
Chapter 1

Introduction

1.1 CCDs for X-ray Astronomy

The Charge Coupled Device or CCD has found wide use in many areas of optical imaging. In particular, the CCD is well suited to astronomical imaging of faint objects because of its increased sensitivity over photographic film, linear response and low noise. Furthermore, improvements in the manufacturing process of these devices have reached the stage where CCDs can be routinely fabricated with excellent cosmetic image quality and with a high efficiency at transferring out the signal charge (> 99.99 % per pixel). More recently CCD manufacturers now offer a range of array sizes. An example is the Ford Laboratories CCD which has 4096 x 4096 pixels covering an area of 3.5 cm², thereby offering improved image resolution. Consequently, the CCD is now being employed at all the major ground based observatories in the world and forms one of the prime focus detectors for the Hubble Space Telescope.

It was realised by the x-ray astronomy community that the energy resolution obtainable with a silicon detector could be combined with the imaging capability of the CCD to provide both spatial and energy resolution (Wells et al. 1985). The energy resolution offered by a silicon detector is substantially better than other x-ray detectors that have been flown using conventional gas or gas scintillation proportional counters. These detectors typically have a resolution of ~ 8% at 6keV which is a factor of four times worse than the resolution attainable with a silicon detector (~ 2%) at the same energy (Holt 1976). This increased resolution mainly arises from the more efficient use of the x-ray photons energy in generating the signal charge. For a gas counter the average energy to create an electron hole-pair is around 26 eV for Argon and 21 eV for Xenon (Fraser 1989). In silicon, however, this value is around 3.68 eV at room temperature giving better signal to noise per photon. The CCD has therefore been proposed as the main focal plane detector for a number of future space missions in x-ray astronomy (Wells et al. 1989). These telescopes will employ grazing incidence optics to focus the x-rays and produce a 2-D x-ray image. Figure 1.1 shows a schematic diagram of an X-ray telescope which uses small grazing angles to reflect parallel X-rays.
Figure 1.1: Schematic diagram of a Wolter 1 x-ray focussing telescope

off paraboloidal and hyperboloidal mirror sections to a focus. This optical configuration shown is called a Wolter 1 mirror. The high throughput, necessary to detect faint objects, is achieved by nesting several mirror shells. The mirrors are coated with a thin layer of gold to give a high reflectivity in the x-ray band. The resulting mirror response extends from around 15 keV down into visible wavelengths.

CCD cameras are being developed at Leicester University for two future missions in X-ray astronomy. These missions are:

- ESA’s X-ray Multi-Mirror Mission (XMM) project and is due for launch in 1998 (Briel et al.).
- The Joint European X-ray Telescope which is part of the Russian Spectrum-X satellite and is due for launch in 1994 (Wells et al. 1991).

The Spectrum-X mission with the JET-X instrument will have a nest of 12 mirrors to give an effective collecting area of 360 cm$^2$ at 1.5 keV reducing to 140 cm$^2$ at 8 keV. There will be two such telescopes, co-aligned, with a 3.5 meter focal length and cooled CCDs at the focal plane. The design criterion is for an image resolution of better than 30 arcseconds (Half Energy Width). This mission will provide the first opportunity to use an imaging CCD spectrometer at the focus of a Wolter-1 imaging telescope. Figure 1.2 shows an artists impression of the final JET-X instrument. The two co-aligned mirror modules can be seen at the top of the telescope, along with the door assembly, which is deployed after launch. The CCDs are located at the rear end of the instrument and the external passively cooled radiators and CCDs electronic box can be seen at the base of the instrument.

The second mission, XMM, will fly the European Photon Imaging Camera (EPIC) and is essentially a scaled up version of JET-X with similar angular resolution but having a greater through-put. This is provided by 3 co-aligned Wolter 1 mirror modules each with around 60
mirror nests giving a total collecting area of 6000 cm$^2$ at 1.5 keV and 4000 cm$^2$ at 8 keV. The unprecedented through-put of the XMM instrument and long 10 year duration of the mission will enable many millions of sources to be examined spectroscopically ranging from distant quasars to nearby stars.

These instruments will enable astronomers to apply the diagnostic tool of spectroscopy to energetic astrophysical plasmas, enabling for the first time, the physical properties and states of the object to be measured. A new era in astrophysics can therefore be foreseen, where many important astrophysical questions can be addressed. For example, the physical evolution and structure of many classes of x-ray sources will be able to be studied down to large red shifts because of the high throughput offered by the optics. In the inner regions of Active Galaxies the continuum slope of the x-ray spectra from these objects can be studied for a range of luminosities and red shifts. The detailed study of many x-ray emitting objects coupled with the serendipitous discovery of many others resolved in the field of view will enable the discrete component of the x-ray background to be determined. This may answer a fundamental question in x-ray astronomy as to the origin of the diffuse x-ray background. Finally, the question of the dark matter distribution in the Universe can be addressed by studying the large scale structure of hot objects. Imaging and spectroscopy will enable the temperature and density profile of x-ray emitting gas to be measured out to large radii, where it is believed most of the dark matter resides. Thus the mass distribution of many classes of objects can be traced and used to refine estimates of the total matter in the Universe. This is of great cosmological importance to the origin and evolution of the Universe.

In the thesis work of Lumb (1983) the feasibility of the CCD to detect X-rays was demonstrated on conventional CCDs for video cameras. When used to detect single X-ray photons the CCD showed that it was capable of a limited energy resolution which fell short of that predicted for a silicon detector due to the effects of charge diffusion and noise. In the thesis work of Chowaniets
(1986), improvement of the energy resolution and the high energy detection efficiency of the CCO was achieved by fabricating CCOs on high resistivity silicon. Further developments of the CCO for space applications and an investigation into the effects of the space radiation environment on the CCO performance was carried out in the thesis work of Holland (1989). The work of this thesis continues the development of the CCO as an x-ray imaging detector for future space born telescopes by investigating methods of improving the x-ray detection efficiency at low energies (< 2 keV) so that the detection efficiency of the CCO is optimised within the response band of x-ray focussing optics.

1.2 Thesis Structure

Chapter 2 describes the physics of CCOs with particular emphasis on the operation of the CCO as an x-ray detector and the factors that affect the low energy quantum efficiency. Chapter 3 reviews the technique of back illumination for improving the low energy quantum efficiency of the CCO. Several methods of treating the back surface, necessary to attain the best device performance are also reviewed. The factors affecting the choice of rear surface passivation technique used for the CCO's fabricated for this thesis work are discussed. Chapter 4 describes the physics of signal charge transport in p-type silicon. A set of expressions that describe this process for the various regions of the CCO are presented and used in a Monte-Carlo simulation programme of the CCO's pulse height output. The simulation results are compared to x-ray measurements made on back illuminated CCOs to demonstrate the validity of the modelling. The programme is then used to predict the effects of varying the different parameters of the CCO on the x-ray detection efficiency and energy resolution. An optimised set of CCO parameters for the detector is presented, based on the results of the simulation and the resulting improvement in performance predicted. Chapter 5 describes a new low energy x-ray test facility commissioned during this programme to provide a source of low energy monochromatic x-rays to enable the quantum efficiency and pulse height response of the CCO to be investigated. Particular attention is paid to the experimental techniques used for measuring CCO's detection efficiency at low energies. Chapter 6 presents the results obtained from the back illuminated CCOs. The factors that affect the quantum efficiency and energy resolution of the detector are investigated. This is achieved by illuminating the CCO with x-rays in the energy range 0.28 keV to 2.15 keV, covering absorption lengths from 0.1 to 14 µm in silicon, thus enabling the effects of charge recombination in the rear surface of the CCO, charge diffusion in the field free and depletion layers and the effects of signal to noise on the x-ray detection process to be investigated. The results from a CCO with a thin, experimental electrode structure, designed to improve the x-ray detection efficiency of a front illuminated CCO, are also presented and compared with those from a back illuminated device. Finally, the results of further developments of the CCO for space applications obtained during the period of the thesis are presented in this Chapter. These developments are concerned with the reduction in the CCO noise and dark current levels.
In Chapter 7, the degrading effects of optical light from astronomical sources on the performance of a CCD camera at the focus of an x-ray imaging telescope are described. A trade-off between different filter materials is made to suggest the best design of a light block filter for the CCD that gives the highest optical attenuation with the least impact on the transmission at low x-ray energies. Finally, in chapter 8, the main results from the thesis are summarised and the aims of further research are outlined.
Chapter 2

The Charge Coupled Device

2.1 Introduction

The Charge Coupled Device (CCD) was first conceived at the Bell Telephone Laboratories in the early 70's by Boyle and Smith (Boyle et al. 1970). The device could store charge packets in potential wells created in a semiconductor by overlying electrodes which are insulated from the silicon by an oxide layer. By applying different potentials to the electrodes, charge could be shifted from under one electrode to another. This is the process that forms the principle behind the CCD's operation.

The early devices found application in analogue signal processing systems that include delay lines and temporary storage of analogue information. The more important developments have been as 1-D or 2-D image sensors with applications in optical and x-ray imaging by virtue of the absorption properties of silicon. This Chapter reviews the physics of the operation of the CCD with particular reference to detector applications at x-ray and visible wavelengths.

2.2 Two-dimensional Imaging CCDs

The 2-dimensional imaging CCD is formed from an array of small metal-oxide-semiconductor (MOS) capacitors fabricated on the surface of a silicon crystal. When a potential is applied to these capacitors, an array of potential wells is created within the silicon that can store charge. When the silicon is illuminated, signal charge generated by photo-ionisation collects in the nearest potential well. These discrete MOS capacitors form the imaging elements or pixels of the CCD so that when an image is focussed onto the array, each pixel builds up a signal charge which is proportional to the intensity of the illumination at that point. Thus a distribution of charge is created within the CCD to form an electronic image. The signal charge can then transferred out of the array, one pixel at a time, and sensed by an amplifier to generate an output voltage signal. Figure 2.1 shows the schematic diagram of the CCD array in a frame transfer mode of operation.
The top section is illuminated for a suitable length of time to accumulate a signal charge. This is shifted into the store section by the appropriate potentials applied to the electrodes. Each line of CCD pixels is then transferred to the serial read out register. The signal charges in this register can then be transferred to the output node amplifier serially, where they are amplified to provide an analogue output signal.

2.2.1 Device Structure and Operation

The principle element of the CCD is the MOS capacitor. Figure 2.2 shows a metal oxide semiconductor structure on p-type silicon which represents a single pixel element in a CCD. When a positive bias is applied to the electrode, the p-type silicon is depleted of free charge carriers (holes and electrons); holes are repelled from the electrode whilst electrons are attracted towards it, leaving fixed ionized acceptor atoms. The resulting charge separation creates an electric field analogous to the charge separation that occurs in the dielectric of parallel plate capacitor when a bias is applied. Charge separation also occurs when electron-hole pairs are generated within the silicon by photoionisation, and separation is sufficiently rapid not to allow recombination to occur.

The one dimensional potential profile within uniformly doped p-type silicon can be obtained by solving Poissons equation, which in the depleted region is given by

$$\frac{d^2\phi}{dx^2} = -\frac{eN_a(x)}{\varepsilon_{si}}$$ \hspace{1cm} (2.1)

where $N_a$ is the dopant concentration, $\varepsilon_{si}$ is the permittivity of silicon and $e$ is the electronic charge. The silicon resistivity is determined by the dopant concentration and is shown in Figure 2.3 for both an n-type (Phosphorous) and a p-type (Boron) doped silicon at 300 K (Sze 1981). As the dopant concentration increases the resistivity of the silicon decreases. An empirical relationship
that fits the curve is given by (Damerell 1984)

\[ N_a = 10^{14} \left( \frac{150}{\rho} \right) \]  

(2.2)

where \( \rho \) is the silicon resistivity in \( \Omega \text{- cm} \). The typical dopant concentration used in a standard EEV CCD is around \( 10^{15} \text{cm}^{-3} \) corresponding to a resistivity of \( \sim 15\Omega \text{- cm} \).

Integrating equation 2.1, with the boundary condition that the electric field and potential is zero at the depletion layer boundary yields

\[ V(x) = \frac{eN_a(x - D)^2}{2\epsilon_s} \]  

(2.3)

where \( D \) is the depletion depth and \( x \) is the distance in the p-type silicon measured from the surface. At the silicon surface, \( V(x = 0) = V_s \), where \( V_s \) is the surface potential, leading to the relationship between the depletion depth and the surface potential given by equation 2.4

\[ D = \sqrt{\frac{2e_sV_s}{eN_a}} \]  

(2.4)

The potential minimum for electrons in the MOS capacitor occurs at the surface of the device. CCDs fabricated with this structure are called surface channel devices since the electron storage channel occurs near the silicon surface. The depletion depth varies inversely with \( \sqrt{N_a} \) and is proportional to \( \sqrt{V_s} \). With the typical silicon resistivity used in standard CCDs of around \( 20\Omega \text{- cm} \) the extent of the depletion depth, from equation 2.4, is \( 3.5 \mu \text{m} \). Through the use of higher resistivity silicon this depth can in principle be greatly extended. A silicon resistivity of around \( 3000 \Omega \text{- cm} \) will produce a depletion depth of around \( 41 \mu \text{m} \). The use of high resistivity silicon for CCD’s in x-ray applications is discussed in section 2.5.3.
So far, the treatment of the physics of the MOS capacitor has been assumed that there is no voltage associated with the CCD’s SiO$_2$ layer. In typical oxides there is a fixed residual positive charge due to interface states which results in the accumulation of a high electron charge density at the surface when no bias is applied (Howes et al. 1979). The voltage required to bring the bands out of depletion and into a flat band condition is called the flat band voltage $V_{fb}$. The effective gate voltage is therefore, $V_{gate} - V_{fb}$, and results in a potential across the oxide and the semiconductor. The effective gate voltage is giving by

$$V_{gate} - V_{fb} = V_s + V_{ox}$$

where $V_{gate}$ is the gate voltage and $V_{ox}$ is the potential across the oxide. The charge density at the oxide interface comprises the fixed depletion layer charge and any mobile signal charge. The depletion charge density is fixed and is given by $-\sqrt{2eN_a\varepsilon_{st}V_s}$. For silicon at room temperature with $N_a = 10^{15}$cm$^{-3}$ and $\varepsilon_{st} = 1.06 \times 10^{-12}$F/cm, this term is small and so the oxide voltage can be written as

$$V_{ox} \approx \frac{Q_s}{C_i}$$

where $Q_s$ is the signal charge and $C_i$ is the capacitance of the combined depletion oxide layer. Thus, the surface potential can now be given by

$$V_s = V'_{gate} - \frac{Q_s}{C_i}$$

where $V'_{gate}$ is the effective gate voltage as defined above.

It can be seen that for a given effective gate voltage applied to the capacitor, the surface potential of the system is proportional to the signal charge. The linear relationship therefore...
Figure 2.4: Diagram showing the band structure of the MOS capacitor with and without signal charge stored at the oxide surface. The effect on the surface potential of the system is shown.

provides a simple model for the charge storage mechanism in this device. Accumulating signal charge within the depletion layer causes the surface potential to decrease in a linear fashion in the same way that filling a well with water causes the water surface to rise. The hydraulic model is useful in explaining the charge transfer mechanism of the CCD in section 2.3. Figure 2.4 shows the energy band diagrams in the capacitor when no signal charge is present and when a signal charge $Q_{\text{signal}}$ is stored in the surface potential minimum. The surface potential without signal charge present, $\phi_{\text{sp}}$, and with signal charge present, $\phi_s$, is shown in the diagram along with the corresponding relationship of the surface potential.

However, CCDs fabricated with a surface channel storage structure are found to suffer from charge transfer problems (Barbe 1975). This is due to the oxide-semiconductor interface which have a high surface density and are a result of the interruption of the lattice periodicity (Sze 1981). The signal electrons are stored near this surface and can therefore be trapped by these interface states giving rise to charge transfer losses.

2.2.2 Buried Channel Devices

To overcome the problem of charge trapping at the oxide interface, the potential minimum for the electrons needs to be located away from this region. This can be achieved by fabricating a shallow, highly doped $n^+$ layer within the $p$-type silicon to form a $p$-$n$ junction. In this structure a potential can be applied to the $n$-type layer to cause a depletion layer to form within the $n^+$ region. This is termed the field induced depletion layer. A depletion layer also exists at the boundary between $n$ and $p$ type layer of the reverse biased $p$-$n$ junction which grows as the applied potential to the gate increases. Eventually the two depletion layers meet. At this point further increase in the bias to
Figure 2.5: Potential profile in the depletion layer of a pn junction for several bias voltages

The n-type layer has no effect on the potential profile and the depletion depth within the silicon. This condition is termed pinch-off. A potential minimum for the electrons now exists just below the depth of the pn junction in which signal electrons can be stored within a narrow region away from the silicon oxide interface states. Further increases of the gate bias deplete more of the p-type silicon, but the position of the potential minimum remains the same.

Figure 2.5 shows the potential profile calculated for uniformly doped n-type and p-type silicon layers with a suitable bias to deplete the n-type layer and achieve the pinch-off condition. For uniformly doped n and p type layers, Poisson’s equation can be solved numerically for the oxide, n-type and p-type layers of the CCD to give the potential profile through the depletion layer (Howes 1979). The profiles of figure 2.5 were derived for the typical dopant concentrations used in the manufacture of the CCDs. An n-type layer 0.2 μm wide with a dopant concentration of \( \sim 5 \times 10^{17} \text{cm}^{-3} \) was used and a p-type concentration of \( N_a = 1 \times 10^{15} \text{cm}^{-3} \). The substrate is assumed to be at ground potential and the Figure shows the resulting potential profiles for gate voltages of 0, 4, 7 and 10 volts. The first point to note is that the depletion depth extends only slightly as the gate voltage increases. The greatest effect is on the value of the potential at the buried channel which increase rapidly with gate voltage. Thus the storage potential of the signal charge can be influenced by the gate voltage. Signal electrons will move to the electrode with the lowest electron potential and can be confined underneath individual electrodes by appropriate bias voltages.

The pn junction is not in equilibrium so thermally generated carriers will accumulate in the potential well to drive the device out of depletion. Under normal operation the CCD needs to be continually read out to remove the thermally generated signal from the potential wells. The origin of this signal is discussed further in section 2.4.2.
2.2.3 Charge Confinement

For the device to be used as a 2-D imaging detector, confinement of the signal charges in the horizontal and vertical directions is necessary to provide a pixel structure. Firstly charge confinement in the vertical (parallel) direction is provided by a series of vertical p⁺ implants along the pixel boundaries. These implants typically have a width of 1μm and a dopant concentration of around $10^{18}$ cm⁻³. Under depletion by the overlying gates, these strips become highly negatively charged and create a correspondingly high electric field which repels any signal electrons away. The signal charge is therefore confined in the buried channel within the p⁺ strip boundaries.

Confinement in the horizontal (serial) direction is achieved in the CCD by fabricating a polysilicon gate structure with three electrodes per pixel. As described above, biasing the electrodes positively creates a depletion well below the electrode and by alternately biasing electrodes a series of discrete potentials across the array in the vertical can be produced.

2.3 Charge Transfer in a CCD

The main characteristic of the CCD, as its name suggests, is the ability to transfer signal charge from one electrode to the next by the technique of charge coupling. This technique is illustrated in Figure 2.6 which shows how charge is transferred between electrodes. In the first figure, the silicon is depleted below the gate by the application of a 10 V potential. The adjacent electrodes have no applied potential and so the 'on' electrode can accumulate a signal charge. At the next stage the second electrode has its potential increased to 10 volts and the electrons will diffuse into the common potential minimum formed below both 'on' electrodes because of differences in electron concentration. At the third stage, the first electrode potential is reduced and this process creates a strong electric field in the direction of the charge transfer because of the difference in potential. This field drives the electrons under the second electrode, and is essential for high-transfer rate imaging for which signals need to be transferred quickly out of the array. The sequence can be repeated such that charge can be transferred out of the device in either left or right direction.

2.3.1 Charge Transfer Efficiency

In an ideal CCD charge would be transferred between electrodes at any rate without any signal being left behind. However in a real CCD the quality of the silicon plays an important role in the ability of the device to transfer charge from pixel to pixel without loss. This is due to the presence of defect states that occur within the bulk of the CCD or at the silicon/silicon oxide interface. Early CCDs that were of a surface channel type had poor charge transfer efficiency (CTE) due to the high density of charge trapping sites through which the signal charge was transferred. The fabrication of buried channel devices has resulted in a vast improvement of the CTE but is still
Figure 2.6: Diagram showing how charge is transferred between electrodes

less than 100% due to the bulk defects and the metallic impurities in the silicon (Collet 1976).

The change in the number of electrons that are trapped, \( n_{ss} \), can be found by the difference in the capture and emission rates from Shockley-Read-Hall theory as

\[
d\frac{dn_{ss}}{dt} = \sigma v_{th} n_e (N_{ss} - n_{ss}) - \sigma v_{th} N_e n_{ss} \exp \left( \frac{-E}{kT} \right)
\]  

(2.8)

where \( N_{ss} \) is the density of bulk traps located at an energy \( E \) below the conduction band, \( N_e \) is the density of states in the conduction band, \( n_e \) is the density of electrons in the conduction band, \( v_{th} \) is the thermal speed and \( \sigma \) is the electron capture cross section (Shockley et al. 1952).

The first term is the electron capture rate and is proportional to the number of states available to trap the electrons and the second term is the electron emission rate and is proportional to the available density of states in the conduction band for the electron. In this equation hole capture is ignored because the charge storage layer is within the n-type buried channel. Hole emission from the valence band is also ignored because of the long emission time constant. Integration of the above terms yields the electron capture and emission time constants \( \tau_c \) and \( \tau_e \) as

\[
\tau_c = (\sigma v_{th} n_e)^{-1} \quad \tau_e = \frac{e^{E/kT}}{\sigma v_{th} N_c}
\]  

(2.9)

The time constant for electron capture is independent on the number of signal electrons in the packet whereas the release time is dominated by the energy level of the trap. The capture time constant is of the order of \( \mu s \) and the release time constant is much longer ~milli-seconds. Thus for a slow scan CCD system used for reducing the read-out noise, the pixel read out frequency is around 20 \( \mu s \) per pixel and so electrons may be trapped within the pixel transfer time. The signal electrons are then subsequently releases into the next pixels along the row because of the longer release time constant. In this way charge is smeared out during transfer. Parallel transfers
in the CCD show CTE values of near unity because the parallel clock cycles are longer (~ few milliseconds) and so charge trapped has a greater probability of being re-emitted into the same pixel of the transfer.

2.3.2 Charge Measurement

Once the signal is collected in the potential minimum of the CCD it can be transferred out of the CCD array to be measured. A number of schemes exist which enable small signal levels to be amplified and enable a detectable voltage to be output from the CCD. Sensing amplifiers are therefore constructed on the chip and Figure 2.7 shows a schematic diagram of a typical output amplifier.

The serial output register is connected to the input gate of an output FET. A reset transistor circuit is also present to reset the output node circuit to a given bias level after each signal charge packet has been measured. Charge is transferred to the output node when the reset transistor is turned off by lowering potential on the \( R_{\phi_3} \) electrode. The node is an n-type diffusion in the silicon which is biased so that it forms a sink for the signal charge packets. When a signal charge of \( Q \) electrons is transferred to the node the voltage on the gate of the output FET circuit changes by an amount

\[
\Delta V = \frac{Q}{C_{\text{node}}} \tag{2.10}
\]

where \( C_{\text{node}} \) is the node capacitance. The node capacitance is a combination of the sum of all the capacitances associated with the source follower gate. Typically this has a value of 0.1pF. The resulting voltage change reduces the current flowing in the output FET circuit and thereby reduces the potential drop across the load resistor. The voltage gain for this circuit can be expressed as
\[ \frac{\Delta V_{\text{source}}}{\Delta V_{\text{gate}}} = \frac{g_m}{1 + g_m} \]  

(2.11)

where \( g_m \) is the transconductance of the FET. For a given drain voltage the transconductance is given by the ratio of the change in the drain current through the FET as a result in a small change in the gate voltage (Sze 1981). The gradient of the FET output characteristic curve at the drain voltage is given by

\[ g_m = \frac{\Delta I_d}{\Delta V_{\text{gate}}} \]  

(2.12)

Typically the gain is around 0.7 and for the amplifier geometries produce around 1 to 2 \( \mu V \) per electron of signal and a low noise value.

### 2.4 Noise in CCDs

#### 2.4.1 Signal Shot Noise

Charge levels or signal generated within the CCD by photoionisation are subject to statistical fluctuations. When an x-ray interacts with the silicon lattice many electron hole pairs are created and this process is described later in section 2.5. For \( n \) signal electrons therefore, the expected noise variance is \( \sqrt{n} \) rms electrons. However, because little of the electron energy is transferred to the lattice in this process in the form of heat, Fano (1947) has suggested that the creation of secondary ion pairs are not mutually independent events. The expected variance is characterised by the Fano factor \( F \) and is given by

\[ \sigma_{\text{photons}} = \sqrt{Fn} \text{ rms electrons} \]  

(2.13)

where \( F \) has been measured to be 0.115 (Alig et al. 1980) in silicon.

#### 2.4.2 Dark Current Noise

Dark current signal in the CCD is created by the promotion of electrons from the valence band to the conduction band. Photo-generated signals therefore reside on this dark signal 'background'. The dark signal shot noise in each pixel will result in a noise component to the image signal which requires the detector to be cooled when in use. Within the CCD, dark current can be generated by surface states, states within the depleted bulk of the device and finally from states within the undepleted or field free layer.

The contribution to the dark current from the surface states can be written as

\[ I_s = e\sigma_{\text{th}} N_{\text{et}} \frac{pn - n_i^2}{p + n + 2n_i} \]  

(2.14)
where \( n_i \) is the intrinsic carrier concentration, \( v_{th} \) is the thermal velocity, \( \sigma \) is the cross section, \( N_{st} \) is the surface state density, \( n \) is the electron density and \( p \) is the hole density in the silicon (Grove 1967). Under conditions of depletion, \( p n < n_i \) and the above equation reduces to

\[
I_e = e S_0 \frac{n_i}{2}
\]

(2.15)

where \( S_0 = \sigma v_{th} N_{st} \) is the surface recombination velocity and depends on the number of surface states and therefore the manufacturing process. At room temperature (300 K), \( n_i \approx 1 \times 10^{10} \) and \( S_0 \) for a good surface is around 10, giving the dark current is about 8nA/cm\(^2\) or for a 22\(\mu\)m square pixel size around 240,000 electrons per pixel per second.

The dark current component due to the depleted bulk silicon can be written as

\[
I_b = \frac{e n_i A d}{2\tau}
\]

(2.16)

where \( A \) is the area, \( d \) is the depletion depth and \( \tau \) is the effective lifetime in the region for the minority carriers. The value of \( \tau \) depends on the capture cross section and number density of silicon traps and is therefore dependant on the manufacturing process. Typical values for a CCD is around 15 ms so that \( I_b \approx 100 \) pA cm\(^2\). Thus the contribution from the bulk silicon is around 80 times lower than that from the front surface states.

The final contribution is from the undepleted silicon volume. This signal is expressed in the equation

\[
I_\sigma = \frac{e D n_i^2}{N_a L}
\]

(2.17)

where \( L \) is the diffusion length of electrons, \( D \) is the diffusion coefficient and \( N_a \) is the dopant concentration. For low resistivity silicon \( N_a \approx 10^{14} \), \( L \) is around 0.4 cm and \( D \) has a value of 40cm\(^2\)s\(^{-1}\). The dark current has a value of around a few thousand electrons per pixel per second at room temperature.

Clearly the dark current contribution from the surface states dominates the dark signal in the CCD and this will be shown experimentally in Chapter 6. At room temperature then, the shot noise due to the random fluctuations on the dark current signal is around 300 electrons rms in total. This is an order of magnitude greater than the x-ray signal noise and therefore will seriously degrade the spectroscopic performance of the CCD. However the intrinsic carrier concentration is dependant on the temperature of the silicon and is given by the equation

\[
n_i = \sqrt{N_v N_c e^{-\frac{E_g}{kT}}}
\]

(2.18)

where \( N_v, N_c \) is the effective density of states in the conduction and valence band, \( E_g \) is the silicon band gap energy, \( T \) the temperature and \( k \) Boltzmanns constant (Sze 1981). Thus reducing the temperature of the CCD from 300 to 173 K will result in a reduction of the intrinsic carrier concentration by several orders of magnitude and thereby reduce the dark signal by the same...
amount. Cooling the CCD is found to give this expected reduction in dark current and the CCD noise is then no longer limited by the dark current signal.

2.4.3 Noise in the Charge Sensing Amplifier

Reset Noise

The processes of resetting the output diode to the reference voltage $V_{rd}$ after the signal charge has been measured is subject to Johnson or thermal noise because of the channel resistance of the reset transistor. For a given temperature, the noise variance is given by

$$n_{\text{reset}} = \sqrt{\frac{kT}{C_0}} \text{ volts} \quad (2.19)$$

where $C_0$ is the capacitance of the output node, $T$ is the temperature and $k$ Boltzmann's constant. Cooling the device to 173 K will still result in a noise of around 140 electrons for a typical value of the node capacitance of 0.2 pF. This signal is far greater than any x-ray generated charge and would render the device insensitive to x-rays. The reset noise is, however, effectively eliminated by the processes of correlated double sampling. This technique removes the pixel to pixel variation in the reset level by measuring the signal level before and after the charge has been dumped onto the output node. The reset level is removed by subtracting the two signals. By this technique the fluctuations in the reset level are effectively removed.

Transistor Noise

The primary noise component in the transistor circuits is thought to arise from fluctuations in the number of signal charge carriers because of trapping and emission of charge which occurs in the conductive drain to the source channel of the FET (Sze 1981). This is termed flicker noise or $1/f$ noise and dominates at low frequencies $< 100$ kHz. It has been shown that flicker noise is effectively reduced by the technique of double sampling in the CCD output processing stages which is necessary to remove the reset noise (Hopkinson et al. 1982). Figure 2.8 shows the effect of increasing the sample time of the correlated double sampling processor on the system noise. Below 100 kHz the noise is dominated by the flicker component and decreases as the sample time increases. The 'corner' frequency for the FET, around 100 kHz is the point at which the flicker noise has the same magnitude as the white noise component. Above this frequency the noise is dominated by the white noise component. For this particular CCD low noise performance is achieved for integrator sample times of 10-20 μseconds.

The other noise component in the FET is white noise and results from random thermal fluctuations of electrons in the conducting channel and has a flat frequency distribution. The bandwidth of processor reduces this component of noise. In a well designed system the FET noise is the only dominant noise component of the CCD.
Particularly for low light level imaging and soft x-ray spectroscopy where the signals are small, a low noise is desirable. One technique which has been studied to achieve this is by increasing the output node gain on the on-chip amplifier. This can be realised by reducing the node capacitance, (equation 2.10), which increases the voltage change to the output FET follower whilst leaving the intrinsic flicker noise of the FET unchanged since this arises in the FET source drain channel. The simplest way of achieving this is by minimising the output FET circuit geometry and smaller FETs have been fabricated with a output node capacitance of $0.06 \text{pF}$ compared to $0.12 \text{pF}$ for a conventional device. These have decreased the CCD noise from an rms noise level of 10 electrons to around 3 electrons.

A second method of noise reduction involves non-destructive measurement of the signal charge to repeatedly measure the charge packet and therefore improve the noise by a factor of $\sqrt{N}$ where $N$ is the number of samples. This has been implemented on some CCDs using a floating gate amplifier to sense the signal charges. In this case, the signal charge is not passed to an output node but into the vicinity of a sense electrode. This induces a voltage change on the gate and a source follower circuit as described above may then be used to translate this charge into an output voltage. Since this charge signal is not destructively measured, repeated measurement of the signal charge and reset level reduces the noise. This type of amplifier has found use in optical applications where sub-electron rms noise levels have been measured (Jansick 1990).

2.5 Photo-ionisation in Silicon

2.5.1 Photon Absorption in Silicon

The attenuation of electromagnetic radiation in a material is described by the equation
Figure 2.9: Absorption lengths of electromagnetic radiation in silicon

\[ I(x) = I_0e^{(-\mu(E)x)} \]  

(2.20)

where \( I(x) \) is the intensity after passage through a material of absorption coefficient \( \mu \) of thickness \( x \) and \( I_0 \) is the initial photon intensity. The absorption length in a given material \( (1/\mu) \) is a complex function of the photon energy. Figure 2.9 shows the absorption lengths for silicon extending from the visible through to the XUV and X-Ray band. For an electrode dead layer approximately 1.5 \( \mu \)m thick and an epitaxial thickness of around 15 \( \mu \)m, two regions exist in the CCD where the photon interaction occurs within the electrically active epitaxial layer of the device. In the visible this region extends from 4000 \( \AA \) to 10000 \( \AA \) and the corresponding sensitivity in the x-ray band ranges from 1 keV to 5 keV in energy. The factors that effect the detection efficiency of the device in the two bands is discussed fully in the next sections.

2.5.2 Optical Photons

When an optical photon is absorbed in silicon a photo-electron is produced through the photoelectric effect. The electron is excited from the valence band to the conduction band where it can collected in the potential wells of the CCD leaving a hole in the valence band. If an image is focussed onto the array, a pattern of signal charges is produced in the potential wells that corresponds to the intensity distribution of the image. The electronic signals can be read out to provide a video signal from the CCD.

The CCD used for imaging applications has a depletion layer of around 5\( \mu \)m and a 15\( \mu \)m wide field free region. The epitaxial layer is formed on a highly doped p\(^+\) layer which is around 500 \( \mu \)m thick and has a typical dopant concentration of \( 10^{18} \)cm\(^{-3}\). In the depletion layer the electron charges experience an accelerating potential which sweeps them towards the buried channel.
Figure 2.10: Quantum efficiency of the CCO to optical photons Courtesy of EEV

The fringes are due to interference effects caused by the regular electrode structure of the CCO. for collection. In the field free region, photogenerated charge diffuses randomly and can either recombine with holes or on reaching the depletion edge, be collected in the buried channel. A potential barrier exists between the epitaxial silicon layer and the substrate that directs any charge reaching it back into the epitaxial layer. Thus, electrons that reach this boundary are reflected back into the epitaxial region for collection. In the p-type substrate the electron life time is short (10^-7s) and signal charge generated within a few mean path lengths from the substrate/epi-layer boundary (few µm) will be collected. The optically active region of the device is therefore well defined by the epitaxial layer depth which is around 15 µm for a typical CCO.

The optical quantum efficiency is given by the equation

\[
QE = T_{\text{dead}} \left( \frac{1 - e^{-\mu X_d}}{1 + \mu L} \right)
\]

(2.21)

where \(T_{\text{dead}}\) is the transmission of the electrode layer, \(L\) is the diffusion length in the substrate, \(\mu\) is the optical absorption coefficient and \(X_d\) is the depletion depth (courtesy EEV).

Figure 2.10 shows the predicted quantum efficiency for the CCO. The 'blue' sensitivity of the device is limited by the transmission of the electrode layer. This is because at shorter wavelengths the absorption length of the photons decreases. The overlying electrode layer, therefore, becomes increasingly absorbing and limits the device sensitivity to around 5000 Å. At lower photon energies, decreased absorption in the epitaxial layer limits the sensitivity to around 10000 Å.

2.5.3 X-ray Interaction with Silicon

When an x-ray photon is absorbed in silicon a cloud of electron hole pairs is created by ionisation of the silicon atom. The number of electrons produced is proportional to the x-ray energy, and offers the possibility of using the CCD for non-dispersive x-ray spectroscopy.
The x-ray interaction with a silicon atom creates a photo-electron which is expelled from the K shell of the atom. The fluorescent yield for silicon is low (< 4%) and the probability of producing the photo-electron is high (Bertin 1975). The photo-electron is expelled with an energy given by

\[ E_{\text{electron}} = E_{\gamma} - E_k \]  

(2.22)

where \( E_{\gamma} \) is the photon energy of the x-ray and \( E_k \) is the K-shell binding energy of the silicon with a value of 1.85 keV. A fluorescent x-ray photon with an energy of 1.7 keV has a short absorption length in silicon of around 10 \( \mu \text{m} \) and is therefore likely to be reabsorbed within a single pixel, so escape peak features are generally less prominent in CCDs than in gas counters. The photoelectron has sufficient energy to cause further ionisation and a cascade of electrons is produced until there is insufficient energy to excite valence electrons to the conduction band. The excited atom then de-excites by a combination of fluorescence and Auger processes. In each ionisation event, some energy is imparted to the crystal lattice rather than in ionising the atom so the mean energy needed to create the signal electrons is rather larger than the band gap energy of silicon (1.1 eV). The value for this process is around 3.68 eV and is weakly temperature dependant, having a value of around 3.62 eV at room temperature to 3.7 eV near to absolute zero (Bertolini \textit{et al.} 1968). The statistical fluctuations associated with the process of energy partition between electron generation and phonon process is smaller than would be expected for Poissonian statistics. If all the electron hole pairs created along the ionisation track were independent (the Poissonian case), the variance is simply given by \( \sqrt{E/\omega} \) where \( \omega \) is the ionisation value for the silicon. However, as already discussed in Chapter 1, the Fano factor is introduced to relate the observed variance with the Possionian predicted value and for silicon this has been experimentally determined to be about 0.115. Unfortunately there is considerable variation in the reported values and the factors that govern the value of the Fano factor are not fully understood. The above value that fits the experimental energy resolution is still about three times less than the figure of merit for a gas counter and coupled with the higher number of charge carriers created per kilovolt energy silicon based detectors are capable of much better energy resolution. The X-ray energy resolution, assuming no charge loss mechanism and no external noise can be given by

\[ \frac{\delta E}{E} = 2.335\omega \sqrt{\frac{F \times E}{\omega}} \]  

(2.23)

and at 6 keV this gives a value of about 2% or 120 eV. This equation describes is the intrinsic resolution for a silicon x-ray detector. To achieve the ultimate spectroscopic performance, any other noise contributions, when added in quadrature, must be negligible. In this case the resolution may be termed 'Fano limited'. The energy resolution for a silicon detector with a system noise component is given by

\[ \text{FWHM} = 2.355 \times \omega \sqrt{n^2 + \frac{F \times E}{\omega}} \]  

(2.24)
Figure 2.11: Effect of noise on the energy resolution of the CCD for x-ray energies below 5 keV

where $n$ is the system noise variance in rms electrons. Figure 2.11 plots the FWHM energy resolution given by equation 2.24 as a function of x-ray energy below 1 keV. The corresponding curves for system noise components of 1, 3 and 6 electrons rms are shown to illustrate the effect of noise on the intrinsic resolution of the CCD. At low x-ray energies ($< 1$ keV) the resolution is increasingly more sensitive to noise and dominates the detector resolution at the point where the curve deviates from a straight line. At 500 eV the intrinsic FWHM is around 35 eV, but with a system noise component of 6 ele rms the resulting width is 60 eV, around a factor of two worse. At higher energies, where the signal to noise ratio is higher, the energy resolution is dominated by the intrinsic resolution of silicon. Thus for a 5 keV photon, the intrinsic resolution is about 2.2% and increases to 2.4% for a 6 ele rms noise. For soft x-ray spectroscopy, the system noise requirements are particularly stringent if the energy resolution of the device is to be fully exploited.

The X-ray quantum efficiency of the CCD is given by

$$QE_{x-ray}(E) = T_{ele}(1 - e^{-\mu x})$$  \hspace{1cm} (2.25)

where $\mu$ is the absorption coefficient at energy $E$, $T_{ele}$ is the transmission of the electrode structure and $x$ is the epitaxial layer of the device. Charge generated within the depletion layer of the device is rapidly collected in the potential minimum of the buried channel. This results in the total signal charge being collected within the pixel of photogeneration and the best energy resolution results. Photons absorbed in the field free layer diffuse over several pixels before encountering the depletion layer boundary. Reconstruction of the total signal charge from such an event results in the summation of noise from each pixel. Furthermore, if charge levels in peripheral pixels is less than the noise level, the signal will be lost. The combined effect is a degradation in resolution for spread events.

The spectroscopic detector efficiency can therefore by determined from equation 2.25 with $x$
equal to the depletion layer thickness. Figure 2.13 shows the predicted spectroscopic and total
quantum efficiency of the CCD for the whole epi-layer thickness of the CCO. The diamonds
represent efficiency measurements made on a standard CCD and show good agreement with the
model (Chowanietz 1986). The useful spectroscopic efficiency, bounded by the 10 % efficiency
points, is therefore limited to photons with energy between 1 and 4 keV.

The high energy spectroscopic efficiency can be improved by increasing the depletion depth of
the CCD. This can be achieved by fabricating the device on higher resistivity silicon. Currently the
manufacturing limit to the silicon resistivity is around 3000Ω·cm which corresponds to a dopant
concentration of \( \sim 10^{13} \text{cm}^{-3} \) or an impurity level of only 1 part in \( 10^9 \) atoms of silicon. This level
of purity is around the limit that can be achieved by state of the art of epitaxial silicon growth.
The depletion depth resulting from this resistivity given by equation 2.4 is about 35 μm. Devices
fabricated on high resistivity silicon have shown the expected increase in spectroscopic quantum
efficiency at high energies. An increase in the spectroscopic QE at 5 keV from 15% for a standard
CCD, to 85% 15000-Ω·cm high resistivity device has been measured (Chowanietz et al. 1985).

Finally, the reduction in the soft x-ray quantum efficiency, below 2 keV, of the device results
from absorption in the overlying electrode structure of the CCD. This is also illustrated in Figure
2.13 which shows the transmission of the electrode structure for a three phase CCD. For the
electrode structure employed, the 10 % transmission point occurs at a photon energy of around
700 eV. To achieve the best x-ray efficiency below 1 keV, the CCD needs to be illuminated through
a thin dead layer. An indication of the thickness of the required dead layer can be given by
the expected sensitivity of the optics for future x-ray telescopes. Figure 2.14 shows the effective
collecting area of a telescope mirror module for XMM (Briel et al.). The mirrors have a response
that extends from 15 keV down into the UV and visible part of the spectrum. At soft x-ray
energies, below 2 keV, the effective collecting area of the mirror is about 80 % of the geometric

Figure 2.12: Cross section of a CCD showing various regions of the device
Figure 2.13: Spectroscopic and total quantum efficiency for a standard CCD. Efficiency measurements are given by the data points. Also shown is the transmission of the electrode structure collecting area and this rapidly increases to 100% in the UV and visible bands. To make efficient use of this mirror response at soft x-ray energies, the detection efficiency of the CCD needs to be extended down to around 200 eV. The absorption length in silicon at this energy is 0.06 μm and this implies that a dead layer of around 0.15 μm is required for a (10 % point).

Dead layer structures of this dimension can be realised using the technique of back illumination. In this technique the inert silicon substrate upon which the CCD is fabricated is removed to expose the epitaxial layer of the CCD. The improved efficiency is then achieved by imaging onto this rear surface. In principle the only dead layer arises from the formation of a thin native oxide on the etched rear surface and because this is typically only 10 Å thick absorption is minimal. The back illuminated CCD can therefore realise the highest detection efficiency to soft x-ray and UV wavelengths. Figure 2.15 illustrates the technique of back illumination. The ~ 500μm of silicon substrate is removed to leave a sensitive imaging area at the rear of the device.
Figure 2.14: Effective collecting area for the XMM mirror module

Figure 2.15: Technique of back illumination
Chapter 3

Methods of Enhancing the Soft X-ray Response of CCD Imagers

3.1 Introduction

In this Chapter, several techniques for improving the soft x-ray quantum efficiency of the CCD are reviewed. These techniques are

- Back Illumination
- Thin electrode layers
- Open phase electrodes

Of the three, the thinnest dead layer structure results for back illumination. However, it will be shown that the etched silicon surface has a dramatic effect on the quantum efficiency and stability of the device. If left untreated the response of the CCD may be severely reduced and no improvement over front illumination detection efficiencies will be achieved. Three methods for passivating the rear surface by bringing the band structure into accumulation are discussed. These methods are

- UV charging
- Flash-gate
- Ion implantation

The reasons for the choice of ion-implantation as a method of accumulating the rear surface for the CCDs fabricated in this thesis are presented.

Two other techniques to improving the low energy response of the front illuminated CCD are also discussed. These are concerned with minimising the x-ray absorption in the electrode layer by producing thinner electrode structures. Although these methods offer intrinsically lower detection

30
Conduction Band

Band gap 1.15 eV

Valence band

Figure 3.1: Energy Band diagram at the rear face of the thinned CCD surface

efficiencies than the back illuminated technique, better spectral performance can be achieved. The advantages and disadvantages of each technique will be discussed.

3.2 Back Illumination

3.2.1 The Rear Surface Potential

The silicon substrate of a CCD can be removed by chemical etching and acid selective etches can be used to thin the CCD down to the substrate/epitaxial layer. Non-selective etches can be used that etch the silicon at a rate of around 4 μm per minute independent of the resistivity. However, with selective etches the etch rate is dependant on silicon resistivity. For a substrate \( \sim 10^{-3} \Omega \cdot cm \), the etch rate is around 1 μm per minute and is virtually zero for a resistivity of \( 10^{-1} \Omega \cdot cm \) (EEV 1987). Use of this technique enables the substrate to be etched away to the epi-boundary, where the etching stops as the high resistivity material is encountered.

At the etch boundary, a thin (< 10 Å), native oxide forms on the silicon surface. The surface states density of the resulting oxide/semiconductor interface can be as high as \( 3 \times 10^{-13} \text{cm}^{-2} \) (Cowely et al. 1965). These interface states act as donors which are positively charged when empty or neutral when filled by an electron. The position of the Fermi level at the back surface therefore determines the number of states occupied and thus the (positive) interface charge density. The interface charge will create a depletion or space charge layer at the rear surface of the CCD. Any signal charge that diffuses towards this region will be swept by the depletion field towards the rear interface states and recombine. In this way, the rear depletion layer creates a surface dead layer that reduces the quantum efficiency of the CCD.

The energy band diagram at the rear surface of the CCD is shown in Figure 3.1. The available
surface states are assumed to be uniformly distributed in energy throughout the band gap. The surface potential $V_s$ can be used to calculate the extent of the depletion layer using the expression

$$X_d = \sqrt{\frac{2k\epsilon V_s}{eN_a}}$$

(3.1)

where $k$ is the dielectric constant, $\epsilon$ the permittivity of silicon. The value of the surface potential in equation 3.1 can be found from the energy band diagram. Assuming an interface state density of $D_{it}$ states cm$^{-1}$ eV$^{-1}$ the oxide charge is equal to the depletion charge density in the space charge region. Thus, from Figure 3.1,

$$(\phi_0 - E_t - eV_s)D_{it} = eN_a\sqrt{\frac{2k\epsilon V_s}{N_a}}$$

(3.2)

where the right hand term is the depletion charge density and the left hand term is the charge density due to the charged interface traps above the Fermi level. The potential, $\phi_0$, is the level at the surface below which the interface states are filled for charge neutrality. Typically this ranges from 0.4 to 0.6 eV. Re-arranging the equation yields a quadratic equation for the surface potential given by

$$V_s = \frac{2(\phi_0 - E_t)}{4} \pm \sqrt{\left(\frac{2(\phi_0 - E_t)}{4}\right)^2 - 4(\phi_0 - E_t)^2}$$

(3.3)

where

$$A = \frac{k\epsilon N_a}{qD_{it}}$$

(3.4)

The position of the Fermi level can be calculated from

$$E_t = \frac{E_g}{2} - kT \ln \frac{N_a}{n_i}$$

(3.5)

where $E_g$ is the silicon band gap (1.14 eV at $T=173$ K) and $n_i$ is the intrinsic carrier concentration.

Figure 3.2 plots the surface potential as a function of dopant concentration over the range $10^{15}$ to $10^{20}$ cm$^{-3}$ assuming a value of the interface state densities of $10^{14}$ cm$^{-3}$, $\phi_0=0.5$ eV and a temperature of $T=173$ K. For real solutions to equation 3.2, in which values of $V_s$ are less than the silicon band gap energy, the resulting values of the surface potential lies in the range 0.15 to 0.3 volts.

At high dopant concentrations, the surface potential falls. This is because the Fermi level moves towards the valence band edge, depopulating a decreasing number of interface states, whereas the depletion charge density increases proportionality as $N_a^{1/2}$. Thus to maintain the charge equality between the interface and depletion charges the surface potential reduces. In this region therefore, the surface potential is dominated by the substrate. Also shown in the Figure 3.2 is the depletion layer width calculated from the surface potential values. Below $10^{17}$ cm$^{-3}$, the depletion depth increases rapidly and reaches a value of around 1.2 $\mu$ for a typical epitaxial layer dopant concentration of $\sim 10^{14}$ cm$^{-3}$. This is comparable to the width of the electrode dead layers in the CCD and so a CCD thinned into the epilayer will have little improvement in quantum efficiency.
Figure 3.2: The surface potential as a function of dopant concentration of silicon and interface state density.

Figure 3.3: Image of a thinned CCD under UV illumination showing large changes in sensitivity across the area (Janesicket et al. 1985)
The response of thinned CCDs typically shows large variations in sensitivity over the etched region. Figure 3.3 shows an image obtained for UV illumination of wavelength 4000 Å which has an absorption length of about 0.07 μm. The central portion shows a QE around 5% rising to about 20% at the edges. This non-uniform response can be attributed to the varying amount of p+ substrate that remains after etching the CCD. The reason for this is that the substrate/epitaxial layer boundary in the CCD is not well defined because of diffusion of the boron ions into the epitaxial region. Figure 3.4 shows the change in dopant concentration at the substrate epitaxial layer boundary for the EEV CCDs. The substrate has a concentration of around $10^{19}$ cm$^{-3}$ and falls to the epitaxial level of $10^{14}$ cm$^{-3}$ over a distance of ~ 5 μm. Thus the thinning depth into the epitaxial layer can vary by a few microns because of the dopant concentration gradient.

Figure 3.5 illustrates the effect of the thinning position on device sensitivity. In Figure 3.5a, a thick p+ layer is left and has a dopant concentration of ~ $10^{18}$ cm$^{-3}$. The thickness of the layer is comparable to the mean path length of electrons which is ~ 10 μm. Although the depletion layer is narrow (< 0.01 μm), recombination of the signal charge results a poor sensitivity. Regions with this sensitivity corresponds to the central portion of Figure 3.3.

The second type of region is shown in 3.5b. In this case more of the p+ substrate has been removed so that a dopant concentration gradient exists. The extent of the depletion layer will vary greatly depending on the dopant concentration of the surface and large changes in device sensitivity will result. Also, the dopant gradient in this region also creates an electric field that will sweep signal charge out of the substrate and therefore decrease the probability of charge recombination occurring. An optimum point will exist where sufficient substrate is left to provide a drift field whilst minimising the depletion layer depth. At this point the quantum efficiency is at its highest value for the thinned CCD.

Finally, Figure 3.5c shows a rear surface where all the substrate is removed. The rear depletion layer has its largest value for this point and the CCD quantum efficiency may be less than by front illumination. If the depletion edge reaches the rear surface, however, the sensitivity begins to increase again because the Fermi level rises. This is also accompanied by an increase in dark current because of the increased probability of an electron transition to the conduction band via the rear surface interface states. Also charge confinement by the rear well is reduced because of the lower value of the surface potential. These factors account for the rapid increase in dark current as the depletion layer reaches the rear surface.

As well as large variations in device sensitivity because of non-uniformities in the etching process, the quantum efficiency of a thinned CCD is also dependant on temperature and the levels of UV illumination. Sensitivity changes with temperature arise from the variation of the Fermi level with temperature (see equation 3.5). Figure 3.6 shows the response of a thinned CCD fabricated by Thompson CSF, in the optical band measured at a range of temperatures (Tassin et al. 1986). Sensitivity is found to increase with temperature because the Fermi level moves towards the conduction band, reducing the value of the surface potential and therefore the extent of the
The rear depletion layer. To illustrate this, the value of the surface potential has been evaluated at two different temperatures, 175 and 300 K using equation 3.5, for the case of an over-thinned CCD ($N_a \sim 10^{14} \text{cm}^{-3}$). At 175 K the surface potential is calculated to be 0.32 eV and decreases to 0.17 eV at 300 K. This causes the rear depletion depth to decrease from 2.1 μm to 1.5 μm. For a 1 keV x-rays photon (absorption coefficient $0.36 \mu^{-1}$), the quantum efficiency will increase from 46% to 60%.

Variations in sensitivity can also arise from the trapping of signal charge at the oxide/silicon interface. It has been found that illuminating the CCD with U.V. light causes a change in the population of the interface states and thereby changes in the surface potential. This process can be described by the capture and emission of electrons by interface traps given by

$$\tau_c = n_0 \tau_{\text{th}}^{-1} \quad (3.7)$$

$$t_e = \sigma_n v_t n \exp \left( \frac{E}{kT} \right) \quad (3.8)$$

where $v_t$ is the thermal velocity of electrons ($\sim 10^7 \text{cm s}^{-1}$), $\sigma_n$ is the trap cross section ($10^{-15} \text{cm}^{-1}$), $n$ is the number of signal electrons and $E$ is the position of the trap below the conduction band (Howes 1979). When illuminated with UV radiation the signal electrons generated in the conduction band immediately populate the interface states because of the very short capture time ($< 1 \mu s$). Device sensitivity will then increase as more of the interface states are filled. However, the sensitivity will also change as the traps de-populate and for this process, the emission time constant is highly dependant on the temperature. For example, at $-140^\circ$C the time constant for a trap located at an energy of 0.1 eV is around $10^9$ seconds and at $-100^\circ$C this reduces to around 200 seconds. Thus if operated below -100 C, an increased level of sensitivity almost indefinitely but as the operating temperature is raised, sensitivity will vary over time periods comparable to

Figure 3.4: Change in $N_a$ across the substrate/epitaxial layer boundary courtesy EEV Ltd.
Figure 3.5: The effects of various thinning positions within the substrate on the rear band structure of the CCD
the discharge time constant. Particularly at temperature in excess of $-90^\circ$, changes in sensitivity from image to image with CCDs illuminated by UV light have been observed (Janesick et al. 1985).

3.3 Accumulation of the Rear Surface

To overcome the problems associated with the rear oxide/semiconductor interface the rear band structure needs to be brought out of depletion and into an accumulated state. This will suppress the dark current generation from the interface states and also create an electric field at the back surface that will sweep signal charge away from the back surface and into the epitaxial layer. Accumulation of the rear surface will therefore permit complete collection of the signal charge, greatly improving the device sensitivity. Several methods of accumulating the back surface will be discussed in the following sections.

3.3.1 Backside Charging by UV radiation

One technique that may be used to accumulate the rear surface is through an intense exposure to UV photons which induce a negative charge on the oxide. This negative surface charge brings the bands into accumulation by counteracting the positive surface potential of the rear face and attracting valence holes to the surface. The energy of the UV radiation to charge up the surface has to provide sufficient energy to excite electrons from the valence band of the semiconductor into the conduction band of the silicon oxide layer. The energy required to do this is 4.25 eV so the photon wavelength has to be $< 2900\text{Å}$ (Janesick et al. 1985).

Charging by UV can only be achieved in the presence of oxygen. Oxygen is necessary to produce negatively charged $O_2^-$ ions that adsorb to the oxygen deficit sites on the surface (Morrison 1977). In this reaction the photoelectrons migrate through the thin oxide ($< 10\text{Å}$) and induce
oxygen adsorption on the surface by the following reaction

\[ e^- + O_2 \rightarrow O_2^- \]  \hspace{0.5cm} (3.9)

Thus charging is usually done in an ambient atmosphere and the CCD cannot be charged by UV when under vacuum or in a dry nitrogen environment.

Once the CCD has been UV flooded the conditions must ensure that the back side charge remains stable. The silicon oxide charge can be discharged by a number of means, the simplest of which is by contact with water vapour. Water molecules are readily absorbed onto the surface oxide and donate an electron to the semiconductor to create a positively charged \( H_2O^+ \) species. This will counteract the effects of the negative oxide ions and bring the surface back into depletion.

The ease with which the thinned sensors can be UV charged has been found to depend significantly on the amount of p+ material left after etching. Since the distribution of this material is very non-uniform, this causes a corresponding non-uniform response to UV charging (Leach et al. 1986). The reason for this is due to the reduced electron lifetime in the substrate. Excessive amounts of p+ material reduce the quantum efficiency that can be achieved by UV charging because of signal recombination. Any improvements in sensitivity are found to arise from the increased drift velocities of the electrons caused by the accumulation field rather than the diminished effect of the depletion well.

Periodic re-charging of the sensors is necessary in order to maintain sensitivity. The reason for this is because some desorption of the O\(^-\) species occurs over time. Furthermore, if the sensor is operated above \(-50^\circ\) the oxide charge is found to dissipate resulting in a loss sensitivity. Thus the CCD must be kept cool to maintain the UV charged state and not subject to temperature cycling.

### 3.3.2 Flash-gate and Biased Flash-gate

The problem of instability inherent with the method of UV charging to create the accumulation layer can in principle be overcome by fabricating a metal-oxide-structure on the rear surface. Early devices were fabricated with a rear gate or flash gate comprising of a thin film of high work function metal deposited on the rear oxide. The contact potential between the silicon and metal is created by the work function difference. If this is negative then the work function of the metal is greater than silicon and the oxide/semiconductor surface may be brought into accumulation. High work function metals used for the flash gate are are Platinum (\( \phi = 5.6 \text{ eV} \)) and gold (\( \phi = 5.2\text{eV} \)) since they are larger than the work function of silicon (\( \phi = 4.9\text{eV} \)). The contact potential produced is then dropped across both the oxide and the CCD such that

\[ \phi_{ms} = V_{oxide} + V_{oq} + V_s \]  \hspace{0.5cm} (3.10)

where \( V_{oxide} \) is the potential dropped across the oxide, \( V_s \) is the potential dropped across the CCD and \( V_{oq} \) is the flat band voltage (Janesick et al. 1987). This equation shows that the quality of the oxide will have an effect on the value of the surface potential at the oxide/semiconductor interface.
and therefore determine whether or not the CCD can be accumulated. As described in section 3.2, the oxide has a positive charge. This will neutralise a proportion of the negative charge on the oxide induced by the contact potential of the flash gate, thereby weakening the accumulation layer. If the positive oxide charge is sufficiently great, $V_{eq}$, will compensate for the flash gate potential. In this case, the effect of the flash gate will be lost and little change in the band structure will result. Experimentally, this is found to be the case. CCDs fabricated with a newly thinned surface cannot be accumulated by the flash gate. This is believed to be due to the high interface trap density of $>10^{15}$ cm$^{-3}$ for these oxides and the thickness of the oxide ($<10\AA$) which results in tunneling of the negative charge into the silicon. (Janesick et al. 1986).

The best type of oxides are produced thermally at temperatures of around 1000°C but producing a thermal oxide on the thinned CCD would cause damage to the front aluminium electrode connections. Low temperature oxides, however, can be grown using water vapour and the resulting oxide has a better quality that a native one but is still not as good as a thermally grown oxide (Ghandhi 1983). This technique has been successfully applied to the thinned CCDs (Janesick et al. 1986). The oxide layer is grown in a steam bath at a controlled rate. The resulting oxides have exhibited excellent charging characteristics and are able to hold UV charge at room temperature and bring fully into accumulation thinned CCDs without the need for a metal layer. The negative charge associated with the steam oxide needed is believed to arise from the creation of OH$^-$ species that are formed as the oxide grows.

CCDs fabricated with a flash gate on either an aged native oxide or a steam oxide have been able to accumulate the rear band structure and thus improve the sensitivity of the CCD. As in the case of UV charging, the sensitivity is dependant on the amount of p$^+$ material left on the surface and the best performance is achieved for sensors thinned into the epitaxial layer. Unfortunately, the flash gate is unstable in a high vacuum environment. The quantum efficiency of the CCD slowly degrades implying that the work function difference between the flash gate and CCD decreases, reducing the strength of the accumulation layer. This is thought to be due to the removal of water and oxygen from the oxide layer which play an important role in determining the number of dangling bonds at the oxide interface (Morisson 1977).

To overcome this problem, the bias flash gate was produced (Janesick et al. 1989). Flat band voltage changes can be compensated for by applying a small negative bias to the gate. The bias flash gate is similar in structure to the flash gate except that the metal layer is thicker ($\approx 5\AA$ metal). This simple MOS structure has been found to overcome the problems of instability with the flash gate. However it is very difficult to fabricate devices in this way and if the bias voltage is too great some CCD pixels exhibit large leakage currents due to the oxide breakdown. Also for x-ray spectroscopy, a fully depleted CCD structure is required to minimise radial charge diffusion which degrades energy resolution. If the depletion edge were to reach the rear oxide, large leakage currents may also occur from breakdown of the oxide, rendering the device unusable.
3.3.3 Ion-implantation

The previous techniques discussed use a negative charge that resides on the surface of the silicon oxide layer to accumulate the silicon beneath. In the technique of ion-implantation, the rear surface is accumulated by implanting p-type Boron ions into a thin layer below the oxide surface. The high p⁺ dopant concentration ensures that the rear depletion layer depth is minimised and also prevents the depletion layer of the CCD reaching the back surface which would cause the dark current to rapidly increase. The energy of the implanted ions provides a means of controlling the implant width and the concentration is determined by the ion beam current and duration. The implant profiles are Gaussian with a density given by

\[ N(x) = \frac{\phi}{\sqrt{2\pi}} \exp\left(-\frac{x-R_p}{2\delta R}\right)^2 \]  

(3.11)

where \( \phi \) is the ion dose concentration, \( R_p \) is the projected range parameter and \( \delta R \) is a range straggle parameter (Till et al. 1982). Both these parameters are functions of the implant energy and ion species. For the rear accumulation layer produced in the EEV CCDs, the ion dose is \( 1 \times 10^{14} \) atoms per cm\(^2\) at an energy is 25 kV. The corresponding range and straggle parameters at this energy for Boron ions are 0.07 μm and 0.03 μm respectively (Lee et al. 1974). Figure 3.7 shows the spread in dopant concentration after ion implantation calculated by the above equation.

The peak concentration occurs 0.07 μm below the surface with the concentration reverting to the epitaxial level 0.18 μm from the surface. The dopant concentration gradient will create an electric field within the implant layer that will determine the fraction of the total signal charge that is collected from this region. The electric field is given by

\[ E(x) = \frac{kT}{q} \frac{dN_a}{dx} \]  

(3.12)

where \( k \) is Boltzmann's constant, \( T \) is the temperature, \( q \) is the electric charge and \( x \) is the depth into the implant (cm) (Sze 1981). Figure 3.8 shows the resulting electric field calculated using equation 3.12.

The effect of this field is two fold. First charge generated in the negative region will be swept back towards the surface where it recombines. Secondly, charge generated in the positive field region, will experience a field directed towards the implant. However as the signal charge diffuses radially, some charge may reach the negative region and be lost if the electric field value is not sufficiently large to oppose the diffusion of charge towards the negative electric field region.

These combined effects will impair the charge collection efficiency and the spectral resolution of the back illuminated CCD. Further etching of the implant to leave just the positive electric field portion of the implant could be carried out but in practice would be very difficult difficult to achieve because of the limited control of the etching process and would lead to non-uniformities. However, the final implant profile will be modified by annealing using the laser after implantation. Annealing is required to activate the Boron ions since after implantation the ions do not come to rest in the substitutional lattice sites of the silicon, but create a trail of displacement damage.
Figure 3.7: Implanted dopant concentration of Boron ions for an implant energy of 25 keV

Figure 3.8: Electric field induced by the dopant concentration of figure 3.7
Melting the silicon lattice during annealing enables the ions to migrate into the silicon lattice during recrystallisation where they then act as donor sites.

The EEV annealing process is carried out using a pulsed ruby laser ($\lambda = 694\text{nm}$). This allows localised melting of the rear silicon implant thus avoiding damage to the front electrode structure. Doping profiles obtained from spreading resistance measurements for increasing numbers of pulses are shown in Figure 3.9. The width of the p$^+$ region increases with successive pulses as the Boron diffuses to the edge of the molten zone. The implant profile has a “top hat” profile with an average dopant concentration of around $6 \times 10^{18}\text{cm}^{-3}$. This then rapidly reduces towards the residual epitaxial level near the implant limit. This type of profile is consistent with the creation of a well defined solid-liquid interface during the laser annealing as observed in blue-sensitive silicon solar cells (Young et al. 1982). Where the implant concentration is uniform a weak field region will exist and charge transported in this region is dominated by diffusion. However, where charge reaches the implant limit the rapid change in dopant concentration creates a high electric field ($10^4\text{V/cm}$) and field induced drift sweeps charge out rapidly. Within the implant, the mean path length before recombination is around $6\mu\text{m}$. Since this is larger than the implant width, bulk recombination of signal charge will not be significant. Furthermore the high dopant concentration means that the rear depletion well has a depth of $< 0.01\mu\text{m}$. The CCD’s depletion layer is also prevented from reaching the rear interface states and dark current generation is effectively suppressed by the rear potential well. However, surface recombination of charge that diffuses towards the rear surface will affect the fraction of charge collected from this layer and influence the device quantum efficiency and energy resolution. This is discussed fully in Chapter 5 where a model for charge collection is presented. For the reasons of stability, ease of fabrication and leak tight nature of the implant, this method of accumulating the rear surface of the CCD is preferred to the bias flash gate method.
3.4 Thin Electrode CCDs

The low energy efficiency of a front illuminated CCO can also be improved by minimising absorption in the electrode dead layer structure. Although front illumination will offer an intrinsically lower quantum efficiency than the back illumination technique, device yields are higher because of the simpler processing required and the energy resolution will be better. This arises because there is no p+ layer in the front illumination CCO and minimal radial diffusion of signal charge occurs because events are absorbed in the depletion layer. In the back illumination CCO significant radial diffusion will occur if the epitaxial layer is not thinned to the depletion edge and as is shown in Chapter 6, this is the dominant cause of signal loss in back illumination CCDs.

The electrode structure of a standard three phase EEV CCD is shown in cross section in Figure 3.10. The three phase structure is formed of overlapping polysilicon electrodes (poly 1, 2 and 3) typically 0.5 μm thick, which are insulated from each other by an oxide 0.2μm thick. The silicon epitaxial layer is separated from the overlying electrodes by an oxide and nitride layer both 0.07μm thick. A protective oxide (Vapox) 0.6 μm thick is then deposited to protect them from particle contamination.

To reduce electrode absorption, the polysilicon electrodes and oxide layers should be made as thin as possible with most to be gained by reducing the Poly 3 thickness because it is not overlapped by the other electrodes in the three phase structure. Further gains are possible by
removing the protective vapox layer but again this is only feasible for the one electrode (Poly 3) because the device still needs the oxides to prevent inter-electrode shorts. Detection efficiency can be further improved by increasing the width of the Poly 3 electrode relative to the Poly 1 and 2 electrodes whilst keeping the pixel size fixed. This type of electrode structure is shown in Figure 3.10. Figure 3.11 shows the transmission of the thin electrode CCD structure compared to the transmission of a standard electrode structure for x-rays below 1 keV. The thin electrode layer has a higher transmission with a value of around 30% at 500 eV compared to 10% for a standard structure.

3.4.1 Open Pinned Phase CCD

Finally, a novel CCD structure that combines the very thin dead layer structures that can be achieved by back illumination technology, with the advantages of front illumination is shown in Figure 3.12. In this case, the thin Poly 3 phase of the CCD electrode structure is omitted to produce a CCD pixel with an open phase. The open Poly 3 phase requires an additional level shifting n+ implant of phosphorus to ensure charge can be clocked out of the array. Figure 3.13 shows the potential profiles calculated for the high and low clock phases of the CCD and the open phase electrode in a non-inverted mode. The dopant concentration of the open phase buried channel has an increased level of $1 \times 10^{17} \text{cm}^{-3}$ so that the resulting potential minimum for the buried channel is around 10 volts and therefore lies between the values for the high and low clock phases. Thus, signal charge residing in the potential minima can be transferred out of the array by a simple two phase clocking scheme.

Figure 3.14 shows the predicted x-ray quantum efficiency of the open phase CCD and a front illuminated CCD fabricated with a standard electrode structure. Both devices have a depletion
**Figure 3.12:** Cross section of an open phase CCD electrode structure

**Figure 3.13:** Potential profiles in buried channel CCD for the High, low and virtual electrode phases
3.5 Conclusion

In this Chapter, several techniques have been described that can increase the low energy quantum efficiency of the CCO. In the case of the back illumination technique, the positive surface potential of the oxide/semiconductor interface depletes the back of the device creating a dead layer. To realise the ultimate detection efficiencies offered by the technique, the rear surface has to be brought out of depletion and into accumulation. Methods of accumulating the rear surface were described and ion implantation was chosen for the CCOs fabricated for this thesis because of stability, ease of fabrication and the leak tight nature of a highly doped accumulation layer.

Methods of improving the efficiency of the front illuminated CCO have been concerned with minimising absorption losses in the front electrode structure. The best efficiencies in the soft x-ray band will be realised by the virtual phase CCO where up to 70% of the pixel can have a very thin dead layer comprising of a native oxide. The front illumination option offers an intrinsically lower quantum efficiency than back illumination. However, better energy resolution is expected. The reasons for this arises from the more efficient collection of the signal charge generated by an x-ray photon. In the back illumination device charge diffusion and recombination in the implant layer degrade the energy resolution. Thus although an event may be detected, the energy information may be lost.
Chapter 4

The Low Energy CCD Test Facility

4.1 Introduction

A new facility has been designed and developed for the investigation of the CCD's response to low energy x-ray photons. The facility is able to generate monochromatic x-ray energies from 2 keV down to 0.1 keV and is designed to measure the detection efficiency, energy resolution and the charge collection parameters of CCD's. Figure 4.1 shows a schematic diagram of the CCD test facility. The facility uses Bragg diffraction from a flat crystal monochromator to select out x-ray emission lines or narrow band continuum from the emission spectrum of an electron bombardment x-ray source. A gas counter and CCD detector are mounted on a common movable table which can be rotated about the crystal axis by a stepper motor to place either detector in the diffracted x-ray beam. The gas counter is used to calibrate the beam flux, thus enabling the detection efficiency of the CDD to be determined. A separate stepper motor controls the crystal rotation to select the appropriate Bragg angle for the emission line. The crystal monochromator is mounted at one end of a vacuum tank with the soft x-ray source at the other. An aluminium filter is placed in front of the source to attenuate optical light from the filament to a negligible level. The whole facility is evacuated using a large diffusion pump. The CCD is mounted onto a copper block which can be cooled by liquid nitrogen down to temperatures of -130°C. The CCD is controlled by external electronic drive circuits and signal processing controlled from an Archimedes microcomputer which is also used for data collection and storage. A detailed description of the various elements that comprise the spectrometer are given in this chapter.
Figure 4.1: Schematic diagram of the low energy test facility

Figure 4.2: Schematic diagram of the Monochromator Dewar
4.2 Crystal Monochromator

The crystal monochromator contains the x-ray detector table and the crystal holder inside a stainless steel vacuum chamber which can be mounted onto any suitable vacuum system. Figure 4.2 shows a schematic diagram of the monochromator showing the relationship between the crystal and the x-ray detectors. In the figure, the crystal is at a Bragg angle of \( \theta \) degrees to select the required x-ray emission line from the source input spectrum. The required Bragg angle for each line energy, can be found from the Bragg equation

\[
2d \sin(\theta) = n \left( \frac{hc}{E_x} \right) \tag{4.1}
\]

where \( d \) is the interatomic spacing of the crystal lattice, \( E_x \) is the x-ray line energy in eV, \( e \) is the electronic charge and \( h \) is Plank's constant. The selected x-ray line emerges from the crystal at an angle of \( 2\theta \). The CCD or gas counter can be moved into this position to intercept the x-ray beam.

The monochromator chamber was provided with a gate valve at the x-ray beam entrance to allow it to be isolated and separately pumped from the rest of the vacuum system thereby minimising the pump down time after changing crystals or CCDs. A rotary pump provides initial vacuum level inside the chamber down to around \( 1 \times 10^{-3} \) Torr. Separate vacuum gauges for both high vacuum and backing vacuum pressures are mounted on the chamber to provide pressure indication over all possible operating pressures. The monochromator was mounted onto an existing vacuum facility which could achieve a pressure of around \( 10^{-6} \)Torr.

The monochromator crystals were mounted on a holder to allow them to be interchanged easily for the required energy range. Movement of the crystal holder and the detector table was achieved through the use of separate, independently driven stepper motors. These motors were mounted externally on either side of the monochromator chamber to maintain a clean vacuum system, free from oil contaminants that may originate from the motor mechanisms. Vacuum rotary feeds connect the stepper motors to the internal drive shafts of the crystal and detector table. Reduction gearing was employed on both motors to produce .01 degree of movement per step. This positional resolution is necessary to accurately set the crystal Bragg angles and thereby optimise the x-ray line to background intensity. Calibration of the crystal and detector angles is discussed later in section 4.5. The stepper motor drives are interfaced to a computer by an external electronics unit for computer control of stepper motor positions. The unit also provides the correct DC voltages for the motors.

Under normal operation, the CCD needs to be cooled to around \(-100^\circ C\) to minimise the dark current signal within the device. Cooling of the CCD is achieved through the use of a copper cold finger. A copper pipe allows liquid nitrogen to cool a copper block inside the vacuum chamber. A reservoir for the liquid nitrogen is provided by an insulated bucket mounted above the monochromator chamber. This cold block is attached, by a set of flexible braids to allow movement of the CCD, to another copper cold finger assembly to which the CCD is clamped. This cooling arrangement was designed to minimise the length of the cold finger so that the CCD's...
temperature could be reduced efficiently.

A high vacuum within the test facility is necessary for three reasons; to eliminate absorption of the x-rays by the atmosphere, to ensure that the CCD detector when operated cold does not become covered with a surface layer of ice or other contaminants which may affect the detection efficiency measurements and finally to minimise heat transfer to the cold finger from the ambient environment by conduction.

To provide a convenient source of monochromatic x-rays for energy calibration of the CCD and to allow the performance of the gas counter to be checked, a low flux Fe$^{55}$ x-ray source was installed inside the chamber which emits a known x-ray line energy at 5898 eV. The source was mounted below the crystal holder so that it would not contaminate the monochromatic beam from the crystal but could be rotated to illuminate either the CCD or gas counter.

The detector table and crystal holder are mounted on a single aluminium flange so that they can be removed from the dewar when required. The flange also carries separate connectors for the CCD bias and clock voltages and a high voltage connector for the gas counter anode supply. The photograph in Figure 4.3 shows the flange with the detector table and crystal holder. The associated wiring for the CCD drive voltages and signals is visible in the photograph. The CCD electronics card which has a first stage preamplifier circuit can also be seen.

4.3 X-ray source

4.3.1 Methods of Generating Soft X-rays

Characteristic x-ray emission lines can be generated be either bombardment of target atoms with electrons or x-rays. In either case, the electron or x-ray photon ejects an electron from the inner K, L or M shells of a target atom. The excited atom then de-excites, filling the shell vacancy, with the excess energy transferred to an x-ray photon giving rise to characteristic x-ray line emission, or by Auger emission of an electron (Bertin 1975). For materials with atomic numbers of 40 or less, the fluorescent yield for the material decreases rapidly with atomic number, with increasing dominance of the Auger process in atomic de-excitation. Equally important to the fluorescent efficiency of the source is the absorption depth of the incident radiation in the target material. If this is too deep, the line radiation generated is heavily attenuated as it emerges from the target material. Characteristic line emission therefore occurs from a progressively thinner surface layer of the material as the x-ray line energy decreases. For the highest efficiency all of the incident energy needs to be absorbed within this surface layer and it is this reason that gives the different efficiency between the two methods.

Excitation by electron bombardment, called primary fluorescence, was favoured rather than x-ray or secondary fluorescence because of its greater fluorescent efficiency. As the electron penetrates the material, it imparts some of its energy to the target atoms by scattering or excitation until all its energy has been lost. The path length in matter depends on the electron energy and density of
Figure 4.3: Photograph of the monochromator assembly showing the detector table and crystal holder.
the material. The energy/range curve for electrons has been found to follow the form

$$\frac{R}{K} = a \eta^{1.75}$$  (4.2)

where $R$ is the electron range in the material, $K$ is a constant depending on the material and $\eta$ is related to the electron energy (Hoff et al. 1971). For an electron energy $\sim 3$ keV, the range curve in copper, used as the anode material for the x-ray source, gives electron penetration depths of $< 0.1 \mu m$. In this case, x-ray fluorescence of the 0.96 keV Cu-L line will occur within this surface layer and because of its thickness is essentially transparent to the emission line ($> 80\%$ transmission). The line intensity, $I$, follows the expression (Bertin 1975)

$$I \propto i(V - V_k)^{-1.7}$$  (4.3)

where $i$ is the tube current, $V$ is the tube potential and $V_k$ is the x-ray line excitation potential.

In secondary fluorescence the photons excite x-ray lines throughout their penetration depth provided the photon energy is greater than the absorption edge energy for the characteristic emission line. The efficiency of the secondary fluorescence process from a material is given by the equation

$$\frac{I_1}{I_0, E_l} = C \frac{\mu_{A,E_{pri}}}{\mu_{M,E_{pri}} + \mu_{M,E_l}}$$  (4.4)

where $C$ is a constant for a given system that depends on the fluorescent yield, detector solid angle and concentration of the analyte element, $\mu_{A,E_{pri}}$ is the value of the absorption coefficient for the analyte at the incident beam energy, $E_{pri}$, $\mu_{M,E_{pri}}$ is the value of the absorption coefficient for the material at the beam energy and finally, $\mu_{M,E_l}$ is the absorption coefficient at the emission line energy $E_l$ (Bertin 1975). In the simple case of a single target element and a monochromatic x-ray beam, the above equation reduces to

$$\frac{I_1}{I_0} = C \left( \frac{1}{1 + \frac{\mu_{E_{pri}}}{\mu_{E_{pri}}}} \right)$$  (4.5)

The term in brackets accounts for the fraction of atoms stimulated by the incident beam that emerge from the target material. The best fluorescent efficiency occurs when the incident beam energy is slightly higher than the emission line energy. In this case, $\mu_{pri} = r \mu_l$ where $r$ is ratio between the absorption coefficient at either side of the absorption edge for the line concerned. Typical values of $r$ for light elements range from 15 to 30 giving a value near 1 for the term in the brackets. However, as the incident x-ray energy increases, the decreasing value of $\mu_{E_{pri}}$ causes this term to tend towards zero, reducing the fluorescent efficiency of the source. Figure 4.4 plots out the term in the brackets for the same case as above where the Cu-L (930 eV) emission line is being generated from a copper anode as a function of the incident x-ray energy. Absorption coefficient data from Henke (1982) was used to evaluate the expression. Initially, the source efficiency is at an optimum where the incident radiation is slightly higher than the emission line energy. As the
incident beam energy increases the source efficiency decreases rapidly. At an input x-ray energy of 6 keV, the source efficiency has fallen to around 3.5 % of its optimum value illustrating the poor fluorescent efficiency of this method unless the incident x-ray energy can be arranged to be slightly higher than the emission line energy.

In practice this is difficult to achieve and the input x-ray spectrum from a typical Bremsstrahlung source has only a narrow range of energies above the absorption edge energy where the line fluorescence is efficient.

In general, comparison between the two methods of x-ray generation by various workers has shown that for a given x-ray tube power, the x-ray line intensity is around 100 times more intense with primary excitation than obtained by secondary fluorescence (Bertin 1975). Secondary fluorescence does have the advantage that the lines are generated on a much lower back-ground because no continuum radiation is generated. However, because spectral lines from other contaminant elements will always be present, eg C-K (278 eV), some form of monochromation is still necessary by either a crystal or careful choice of transmission filters.

4.3.2 Description of the Source

The x-ray source was based around an electron impact type and consists of an electron emitting thermionic cathode and a target anode that can be held at a high positive potential relative to the cathode. Electrons produced by the cathode are accelerated by the electric field towards the anode to generate characteristic and continuum x-ray emission. The x-ray source is shown in cross section in figure 4.5.

The anode is constructed using a 15 mm diameter electrical vacuum feed-through made from high purity copper (99.99 %). A tungsten filament positioned above the anode is heated to
incandescence to generate thermionic emission. Power dissipated in the electron impact spot on the anode is conducted away via an oil reservoir on the outer body of the source. No additional cooling is necessary because the source power is low, <30 Watts. Within the oil reservoir an expansion volume filled with inert nitrogen gas was provided to allow for the expansion of the oil when heated. Limited focussing of the electron beam is accomplished by a ground ring between the anode and filament and by localising the filament height above this ring. In this way the electrons can be focussed easily onto the anode. The anode is insulated from the source casing by a ceramic washer. A PET connector mounted on the end of the oil reservoir is used to connect the high voltage supply to the anode. The required x-ray emission lines can be generated by coating the anode with a suitable compound. This is best done by forming a suspension of the compound in isopropyl-alcohol, and painting it onto the anode surface.

The x-ray tube is housed in a stainless steel enclosure and mounted about 3.5 m away from the crystal. A gate valve between the source and the main vacuum chamber allows the source to be pumped separately. This allows filaments to be changed and new anode coatings to be applied without having to release the vacuum in the main tank, thus reducing the pump down time. The filament and anode voltages are fed from stabilised power supply units. Safety features incorporated in the design ensure that the source can only be switched on when it is enclosed in the system under vacuum.

Source Light Filter

When the x-ray source was first used, it was discovered that the CCD output signal saturated due to the light emitted from the x-ray source filament. Two methods of overcoming the problem were considered.
1. The use of alternative low light emitting cathodes.

2. The use of a light blocking filter.

The first method was initially considered because of the attenuation that a filter would cause on the soft x-ray flux. Shielding of the filament behind the anode, in a source design used by Henke (Henke et al. 1973) to overcome the problem of tungsten contamination of the anode from the cathode, would still produce scattered light which would be detected by the CCO. It was therefore decided to investigate the use of 'cold cathodes' as a source of electrons. The principle of these cathodes rely on a low work function material which requires little heat to produce electrons (Knoll 1967). The cathode material is usually a tungsten-molybdenum alloy containing powdered barium aluminate which is pressed into a dense flat disk. This disk is mounted at one end of a cylindrical holder encasing the cathode heater element. These cathodes developed for mass production applications ie TV tubes, can deliver typically around 60mA of emission current and have an operating temperature of around 750°C. It was hoped that the enclosed heater design and lower operating temperature would enable these filaments to be operated in the source without generating a significant optical signal in the CCO.

Several cathodes were obtained from Philips to assess their performance in the test facilities x-ray source. When operated in the x-ray source, the emission current from the cathodes was found to drop rapidly off from an initial value set at around 10 mA to virtually no measurable current after several hours of use. On inspection, the cathode surface was found to be pitted and slightly discoloured. This occurred for all the test cathodes used at various levels of emission current. The damage of the coating was attributed the effects of ionization (Knoll 1967) which occurs when ions created in the high field region of the x-ray anode bombard the cathode surface. Since these cathodes are normally used at pressures of around 10^-8Torr, the ion density around the cathode was much higher than the design specifications and is believed to cause the shorter than expected cathode life-time.

The other option was to use a suitable light block filter. A typical filter to attenuate the optical flux comprises a plastic substrate onto which is coated a thin layer of highly reflective metal to attenuate the light. Plastic substrates are used because they are made from low atomic number materials, e.g. carbon and hydrogen, so that they have a low absorption coefficient in the x-ray band. A commonly used material that can be obtained as thin film is Lexan C₁₅H₁₄O₄. First a thin film of Lexan coated with a layer of Aluminium was tried in the test facility. Lexan, obtained from a commercial manufacturer, had a thickness of around 2 μm with 0.2 μm thick coating of aluminium. The aluminium layer was found to be opaque when held against a strong light source. To check the light leakage, a section of the material was mounted in the entrance port to the monochromator. With the CCO in the straight-through position, viewing the source directly, no optical signal above the noise level for the CCO was observed. However, the soft x-ray count rates from the source were severely attenuated by the filter. This is due to the thickness of the Lexan
film since the 0.2 \( \mu \) aluminium layer is transparent to x-rays (70 \% at 500 eV). For a material with absorption coefficient \( \mu \text{cm}^{-1} \) and thickness \( x \) (cm), the transmission is given by

\[
T = e^{-\mu x}
\]  

Figure 4.6 shows the transmission of the Lexan calculated using equation 4.6, for values the absorption coefficient from Barstow et al. (1985). It can be seen that as the x-ray energy decreases below 1 keV, the filter becomes increasingly opaque to the x-rays. The absorption edges for carbon and oxygen at 0.28 KeV and 0.52 keV respectively, can be seen in the Figure. A filter was therefore obtained for the test facility comprising a similar aluminium layer thickness of around 2500 \( \AA \) on a thinner Lexan film which had a thickness of around 2000\( \AA \) and was supported by a 75 \% transmission mesh. This filter was obtained from one of the ROSAT Wide Field camera flight spare filters that were manufactured by Barry Kent at the Rutherford Appleton laboratories (Kent et al 1990) The predicted transmission of the this Lexan film is also given in Figure 4.6 and shows the expected improvement in transmission. This thickness of this Lexan gives minimal loss of x-ray flux with a good transmission in the 0.2-1 keV x-ray band.

The filter was mounted inside the main vacuum chamber to avoid unnecessary pressure cycling of the thin aluminium coating. A series of light baffles were installed to reduce the amount of scattered light getting around the filter mounting and into the monochromator chamber. These baffles comprised of black anodised disks with central knife edge apertures. A black surface was used because of the low reflection efficiency of \( \sim 10\% \). Thus, for \( n \) reflections the attenuation of the light is given by \( R^n \), where \( R \) is the reflection efficiency. The number of baffles and arrangement was chosen to ensure that there would be a minimum of eight reflections of any light that could get round the filter and into the monochromator chamber. This would ensure that the scattered light intensity was reduced by the same amount as the light transmitted through the filter (\( \sim 10^{-8} \)).
In operation, the source was found to be stable over time scales of a few hours with a gradual decay in the count rate over longer periods. Figure 4.7 shows an MCA recorded source count rate over a five hour period. The source fluctuations are around 5% of the mean flux level and this was found to be typical for the source. However, during this time the count rate can be seen to drop from around 35 counts s\(^{-1}\) to around 28 counts s\(^{-1}\) corresponding to a 20% reduction in the source intensity. This is believed to be due to the deterioration of the source anode coating which becomes contaminated with tungsten from the filament and carbon from the decomposition of oil contaminants in the vacuum. This is further substantiated by the fact that a similar source when operated in a vacuum system having two orders of magnitude better pressure, shows only a few percent drop in the mean x-ray flux during the same operating period. However, because the source count rates in both detectors take only a few minutes to measure, this does not affect the CCD efficiency measurements. The random fluctuations in the source count rate were reduced by repeated flux calibrations before and after each CCD measurement.

4.4 Monitor Detector

A gas proportional counter was chosen to calibrate the flux rates reflected from the crystal. The reasons for this choice of detector are the low cost and the high quantum efficiency that is possible below 1 keV using thin film windows. The gas counter anode was made from a 30\(\mu\)m diameter tungsten wire attached at both ends to the counter body by glass to metal seals. The wire is held under tension by a stainless steel spring at one end. The counter body is made of stainless steel and the counter window is made of polypropylene, stretched to a thickness of around 1 \(\mu\)m in a purpose built stretching rig. Windows are stretched by heating up the polypropylene
sheet and observing the colours of the interference fringes to indicate the film thickness during stretching. To ensure the window is grounded to the counter body when installed, a thin layer of carbon was deposited on one side of the polypropylene by dipping them into a suspension of finely divided carbon particles in alcohol. The window is supported by a stainless steel mesh having a transmission of around 55%. During operation, the counter is fed with an Argon-methane gas mixture which is continually flowed through at a controlled rate.

The gas counter was operated with low gain to give signal charge pulses of less than 0.1 coulomb so that statistical variations on the gas multiplication factor which dominates the energy resolution of the detector are kept to a minimum (Knoll 1989). The lowest possible operating voltage was therefore used, consistent with keeping the noise to a negligible level. Figure 4.8 shows the peak signal charges as a function of the anode voltage for several x-ray photon energies. Typically, anode voltages of between 1.6 to 2 kV were used, depending on the x-ray energy, to give x-ray pulses of around 0.1 coulomb charge. These were then amplified in a shaping amplifier to give a 2-3 volts signal with a noise level of around 30 mV peak to peak. At higher gas gain where the signal charge exceeds 1 coulomb, the gas gain is no longer linear and the counter enters the region of limited proportionality. When operated in this region, each x-ray photon creates a space charge that distorts the electric field within the gas counter body and reduces the avalanche gain, causing a non-linear gain and reduced energy resolution in the detector. This is shown in the gas gain curve for the Fe$^{55}$ 6 keV x-ray signals. The shaped output from the gas counter was then fed to a multichannel analyser so that the pulse height spectrum could be displayed and the count rate for the x-ray line determined.

Aging Effects in the Gas Counter
Figure 4.9: Gas counter pulse height for the Fe$^{55}$ calibration source showing degraded resolution after 2 years use.

Figure 4.10: Electron microscope photograph showing region of anode wire exposed to x-ray beam and unexposed region.
TEXT BOUND INTO
THE SPINE
The energy resolution of the gas counter was found to degrade gradually over a period of two years and eventually the calibration Fe$^{55}$ spectra developed a noticeable excess of counts at low pulse heights. The loss of signal charge and the variable nature of the count rates severely affected measurements of line fluxes with the counter. Typical output spectra are shown in Figure 4.9.

This phenomenon was not affected by changing the gas mixture or the flow rate through the counter. The energy resolution also varied with position along the anode wire. Figure 4.10 shows an electron microscope photograph of (a) part of the anode wire that was not exposed to x-rays and (b) exposed region of the wire. In the unexposed region, the wire is clean and has a diameter measured from the photograph of around 29 $\mu$m. In the area exposed to x-rays the wire has become covered with particles and the diameter has increased by 2 $\mu$m. An increased wire diameter causes a decrease in the gain of the gas counter because the electric field strength is reduced. This phenomenon has been previously reported in life time measurements on gas counters and is caused by the dissociation of the methane quench gas by the x-rays which results in a carbon deposit on the anode (Boggende 1969). The energy resolution and linearity of the counter is degraded and in extreme cases the Fe$^{55}$ spectra has been shown to develop a double peak due to the gain change.

The problem was overcome by replacing the anode wire and thereafter ensuring that material deposits on the anode remained within acceptable limits.

Operating Techniques

Initially the gas counter was operated with a P10 gas mixture, 90 % Argon 10 % methane, and was found to give acceptable energy resolution for x-ray energies above 1 keV. Figure 4.11 shows the energy resolution of the counter plotted against the square root of the energy. Above 1 keV the gas counter is well behaved and resolution varies with $E^{\frac{1}{2}}$ according to equation
\[ \frac{\Delta E}{E} = \frac{n}{E^n} \]  

(4.7)

where \( E \) is the energy in keV and \( n \) is a constant that depends on the counter gas and geometry. Typically \( n \) is lies between 0.35 and 0.45 (Fraser 1989). Below 1 keV, the resolution decreases and at the C-K line (278eV) a resolution of around 100 % was measured. The pulse height spectrum also showed evidence of charge being lost in the detector noise. Such loss of counts will lead to errors in the quantum efficiency measurements for the CCD in the region which is most sensitive to the CCD's dead layers. It is believed that the deviation in the expected resolution at the very soft x-ray energies was due to the window effect and occurred when the signal charge from low energy photons absorbed close to the counter window recombined on the window surface such that only part of the initial charge cloud was amplified by the gas counter (Cooke 1968).

To overcome the problem the absorption length of the x-rays in the gas needs to be increased and this can be readily achieved by increasing the gas absorption length through the use a less dense gas mixtures (Henke). A P50 gas mixture (Ar 50 %, CH₄ 50 %) was used which increases the absorption length for C-K radiation from 0.7 mm to 1.38 mm (Pearson ). This change improved the energy resolution of the gas counter to 80 % and the pulse height distribution was observed to be gaussian indicating negligible charge loss.

Occasionally some counter windows were made that had a thinner than normal carbon layer and the pulse heights obtained with these windows were found to have a degraded energy resolution with a low energy distribution or tail of events below the x-ray line. The effect became enhanced with increasing count rate. These observations suggested that the window was charging up as a result of the positive ions created in each photon interaction. At sufficiently high flux rates the charging can take place rapidly and eventually distort the electric field distribution within the gas counter body resulting in a gain change. For low x-ray energies this may result in loss of pulse heights within the detector noise and a poor determination of the CCD's efficiency. The problem was overcome by replacing the gas counter window with one having a thicker coating of carbon.

### 4.5 Bragg Crystals

Three types of Bragg crystal, RAP, PbSt and WTC, were used as the dispersive elements in the monochromator. The crystals were obtained from the manufacturers Quartz et Silice. Table 4.1 lists these crystals, together with the lattice spacing and the Bragg angles for various x-ray line energies.

In early tests, the lead stearate, PbSt, crystal was used for x-ray energies below 1 keV. In this range, the Bragg angles are restricted to \(< 65^\circ\), larger angles prohibit measurement of the CCD quantum efficiency because the \( 2\theta \) detector angle places the gas counter in a position where it obscures the incident x-ray beam. At low energies and using the PbSt crystal, the gas counter pulse heights showed a secondary low energy peak. This effect was not seen with the RAP crystal.
Figure 4.12: O-K line pulse height (525eV) showing low energy spectral contamination in the reflected crystal beam

<table>
<thead>
<tr>
<th>X-ray Line and energy(eV)</th>
<th>Crystal Type</th>
<th>2d spacing Angstroms</th>
<th>Bragg Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (2014)</td>
<td>ADP</td>
<td>10.6</td>
<td>35.3</td>
</tr>
<tr>
<td>Si (1740)</td>
<td>ADP</td>
<td>10.6</td>
<td>42.0</td>
</tr>
<tr>
<td>Mg (1250)</td>
<td>RAP</td>
<td>26.1</td>
<td>22.3</td>
</tr>
<tr>
<td>Cu (940)</td>
<td>RAP</td>
<td>26.1</td>
<td>30.71</td>
</tr>
<tr>
<td></td>
<td>WTC</td>
<td>46.0</td>
<td>16.90</td>
</tr>
<tr>
<td></td>
<td>PbSt</td>
<td>100.0</td>
<td>7.58</td>
</tr>
<tr>
<td>F (677)</td>
<td>RAP</td>
<td>26.1</td>
<td>44.56</td>
</tr>
<tr>
<td></td>
<td>WTC</td>
<td>46.0</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>PbSt</td>
<td>100.0</td>
<td>10.55</td>
</tr>
<tr>
<td>O (525)</td>
<td>RAP</td>
<td>26.1</td>
<td>64.8</td>
</tr>
<tr>
<td></td>
<td>WTC</td>
<td>46.0</td>
<td>31.0</td>
</tr>
<tr>
<td></td>
<td>PbSt</td>
<td>100.0</td>
<td>13.66</td>
</tr>
<tr>
<td>C (278)</td>
<td>RAP</td>
<td>26.1</td>
<td>//</td>
</tr>
<tr>
<td></td>
<td>WTC</td>
<td>46.0</td>
<td>77.1</td>
</tr>
<tr>
<td></td>
<td>PbSt</td>
<td>100.0</td>
<td>26.6</td>
</tr>
</tbody>
</table>

Table 4.1: Crystal Bragg angles at several x-ray line energies for RAP, PbSt and WTC crystals. (WTC) Renium Tungsten Carbide, (RAP) Rubidium Acid phalate and (PbSt) Lead Sterate.
at larger angles nor at x-ray energies above 1keV where the x-ray line could be resolved from the low energy component. But at energies below 1 keV with the PbSt crystal, the secondary peak was merged with the x-ray line making the line count rate difficult to determine. Figure 4.12 shows the O-K line spectrum obtained using the gas counter, with the effect of the extra low energy x-ray component which merges with the x-ray line and distorts the pulse height distribution.

The origin of this additional component in the reflected beam was initially thought to be due to fluorescence of the C-K line (280 eV) from the carbon atoms in the crystal. This is because the low energy component was only observed with the PbSt crystal which has a high carbon content (56 % by mass). This idea was tested by inserting a a target of silicon carbide in place of the crystal on the holder. The target was then illuminated by the x-ray source to generate C-K fluorescence. However, a negligible emission of C-K was observed from this target even when the x-ray source emission current at a maximum level (4 mA). It was concluded therefore that fluorescence from the PbSt crystal was unlikely to be the cause of the spectral contamination.

Another possibility considered was x-ray scattering from the crystal due to the small Bragg angles. Figure 4.13 shows the count rate at low energies recorded by the gas counter, first with the PbSt crystal and then with a glass plate in place of the crystal. The data was taken with a molybdenum foil placed over the copper x-ray anode to generate more Brehmstrahlung and to suppress line emission from the source. The data showed that as the incident beam angle between either the crystal or the glass plate decreased below 20° the intensity of the low energy spectral component increased exponentially above the mean back-ground level. It can thus be inferred that the x-rays are produced by scatter from the surface of the crystal at small grazing angles.

This result explains the high spectral contamination with the PbSt crystal, where Bragg angles are in the range 7.6° and 26.6° to cover energies from 960 down to 278 eV. On the other hand the reason why the spectra with the RAP crystal do not exhibit the low energy component is because the Bragg angles lie in the range 45 to 22° at which the soft x-ray scatter is negligible.

To obtain low energy data at the O-K (525 eV) line energy, where the RAP angle is too great, a synthetic multilayer crystal of Renium Tungsten Carbide, with a 2d spacing of 24 Å, between that of PbSt and RAP was obtained. The corresponding Bragg angle for the O-K line is 31° which is sufficiently large to avoid low energy scattering of the primary x-ray beam. Figure 4.14 compares the pulse height spectrum obtained from a CCD at the O-K emission line at an energy of 525 eV with both the PbSt and WTC crystal. In the PbSt case there is a significant scattered component from the source present, but with the WTC crystal this component is not present. The events detected in the channels below the Bragg peak with the WTC crystal are due to the partial charge collection in the CCD.

Finally, Figure 4.15 shows the gas counter pulse height spectrum at the O-K line energy obtained using the WTC crystal. The pulse height shows a gaussian distribution of event energy with very few counts in the low energy channels below the photo-peak. Comparing this output with Figure 4.12 for same line energy but using the PbSt crystal, the low energy scattered component
is completely suppressed enabling the line flux to be accurately measured.

In his observation of the same phenomenon, Henke (1979) has explained the presence of a low energy component in crystal analysers in terms of scattering of the C-K emission line from the x-ray source. With the x-ray source used here, the C-K has varied in intensity between measurements and with operating time. On the basis of Henke's interpretation, it is likely that carbon layers on the source anode may be varying with time and operating conditions. Particularly with an aged anode coating, where the anode has developed a substantial carbon deposit, the low energy scatter component has been found to be dominant.

4.5.1 Crystal Calibration

To obtain the maximum line intensity from the source, the crystal needs to be accurately positioned at the Bragg angle. For the higher resolution crystals (RAP and ADP) the typical full width half maxima of the crystals reflection response are of the order of a few arcminutes in the soft x-ray region (Ball 1980). Thus the crystal needs to be set to within an arcminute of the Bragg angle if the maximum line to background intensity is to be achieved. The give sufficient positional resolution of the crystal drive, reduction gearing was employed to give 1 degree of rotation per 100 steps equivalent to 0.6 arcminute per step.

To locate the Bragg angle for a given x-ray line, microswitches on both the crystal and detector table provided reference datum points for the straight through position, $\theta = 0^\circ$. The crystal was then moved in incremental steps through the Bragg angle using the gas counter to measure the x-ray flux at each point. A $\theta$2$\theta$ relationship was maintained between the crystal and gas counter by driving the detector table at twice the crystal rate. Figure 4.16 shows the result of rotating the
Figure 4.14: O-K source spectrum obtained with a CCD using (a) WTC crystal ($\theta = 31.0^\circ$) and (b) a PbSt crystal ($\theta = 13.66^\circ$) showing the effect of Bragg angle on the spectral purity of the reflected beam.

Figure 4.15: Gas counter pulse height for the O-K line using the WTC crystal showing gaussian distribution of events with no evidence of spectral contamination.
Figure 4.16: Crystal reflection profile as a function of angle for PbSt at the C-K emission line energy (278 eV)

crystal through the Bragg angle for the C-K emission line energy (278 eV) with the PbSt crystal. As the crystal moves through the Bragg angle, the line intensity recorded by the gas counter increases to a peak at the Bragg angle (26.6°) then decreases again. The measured FWHM for this single reflection curve at this energy is around 80 arcminutes at this energy and is in good agreement with the value obtained by M.Charles (1968).

The reflection curves were repeated for each monochromator x-ray line energy. After the angular position of the crystals had been calibrated, the rocking curves could be repeated to within ±2steps corresponding to an angular reproducibility of 1 arcminute. At this degree of reproducibility, there was no necessity to repeat the crystal rocking curve for subsequent measurements.

4.5.2 Modulation of the Beam Intensity

When the higher resolution crystals (RAP and ADP) were used, the reflected x-ray line intensity was found to be spatially modulated. Figure 4.17 is an x-ray CCD image of the reflected intensity of x-rays from the RAP crystal at the Bragg angle of the Mg-K line (1250 eV). The intensity profile obtained from the image is shown in Figure 4.18 as a function of position across the CCD in pixels. The image shows a bright band of x-rays which has an intensity profile that falls to the background level either side of the peak. The FWHM from this image was measured to be around 90 pixels (2 mm) which corresponds to around 2 arcmins. By comparison, the FWHM of the rocking curve for RAP at this energy is 1.3 arcmins (Willingale 1989), thus implying that the broader, 5 arcmin. dispersion of the input x-ray beam is being modulated by the reflection profile of the crystal. This feature of the instrument performance prevents the possibility of being able to
Figure 4.17: CCD image of the reflected intensity profile of x-rays off the RAP crystal for the Mg-K line energy (1250 eV) showing the spatial modulation in the beam intensity due to the crystal resolution.

Figure 4.18: Intensity profile obtained from figure 4.16 as a function of CCD pixel. The measure FWHM is around 2 arcmin and is reasonably close to the measured RAP crystal resolution of 1.2 arcmin.
Figure 4.19: Block diagram of the CCO camera system showing the various sub-system components illuminate large areas of the CCO with a dispersed x-ray beam of uniform intensity. Collimation of the monochromator to 1 arcsecond or better is required to obtain a flat field at this energy. The resolution of the low energy crystals, PbSt and WTC, are greater than the beam divergence and the reflected x-ray beam profiles are found to be uniform. For example, the FWHM obtained for PbSt and WTC is ~ 0.4° and 0.6° respectively, at 677 eV.

4.6 CCD Electronics and Data Processing

4.6.1 Overall Description

The CCD detector is driven by a drive electronics and signal processing system, the block diagram of which is shown in Figure 4.19. The electronics provide the bias voltages and clocking waveforms needed to drive the CCD. The clock waveforms to drive the clocks and the analogue chain are provided by a sequencer. The output signal from the CCD is amplified by a preamplifier inside the CCD dewar and is fed to an analogue processing board which eliminates the CCD reset noise using a correlated double sampling technique. The processed signal is then digitised by a separate analogue to digital converter and the digital output is collected by the computer and stored in its memory. The system computer is an Archimedes which controls the running of the CCD camera system and data handling. The Archimedes computer, with 4 Mbytes of RAM, is sufficiently powerful to enable real time data processing and therefore eliminates the need for a separate frame store which has been used in previous experimental programmes (Chowaniets 1986). The next section describes a new CCD sequencer that was developed to provide a more flexible system capable of driving CCD's of any format.
4.6.2 The CCD Sequencer

Introduction

The sequencer provides pulses with bit patterns to drive the CCD clocks and provide the correct timing for the analogue processing chain. The clock waveforms to drive a CCD operating in a frame transfer mode are shown in Figure 4.20. Initially the CCD integrates an image for a fixed length of time. During this phase the image and store clocks, the IS\(\phi_{2,3}\) phases are held high so that charge can be stored. To facilitate efficient transfer of charge from the store to the read out register, the R\(\phi_{1,2}\) clock are held high. At the end of the integration period the sequencer provides the clock waveforms to transfer one row of the signals from the array into the serial read out register using the three phase clocking sequence shown (IS \(\phi\) clocks). The I and S clocks phases are driven in common since the CCD is operating in a full frame mode. The charges in the serial register are then read out by the RThis cycle is then repeated until all the line of the CCD have been read-out. A single three phase I,S clock sequence takes around 30\(\mu\)s with an R clock sequence being 2\(\mu\)s long. The CCD sequencer also provides the switching waveforms for the double-correlated signal processor. The total time to process a single pixel is around 35\(\mu\)s giving a frame read-out time of \(\sim 8s\) to read out a 400 \(\times\) 600 pixel CCD.

To provide flexibility for driving various types of CCD, the sequencer was based around a programmable signal processor, the ADSP-2100, manufactured by Analogue Devices. The ADSP has a microprocessor which can be programmed to execute a series of instructions sequentially and therefore provide the appropriate waveform bit patterns for the CCD and signal processing chain. The waveform timing is determined by the instruction cycle time of the ADSP chip which
Figure 4.21: Schematic diagram of the CCD sequencer

is 0.16μs. Figure 4.21 shows a schematic diagram of the CCD sequencer unit. The Archimedes microcomputer loads the sequencer programmes into the ADSP's programme memory via the CAMAC interface. The ADSP has seven internal registers which are used to output the bit pattern waveforms for the Rϕ, Sϕ and Iϕ clocks and the signal processing chain. These registers are address mapped to I/O ports on the sequencer board using an address decoder. This enables the ADSP to be interfaced to the external peripherals. The bit patterns are transferred to the I/O ports along the ADSP data memory data bus. A DMA control (direct memory access) allows access to the programme memory independant of the ADSP processor. In this way the programme memory can be written to via the CAMAC whilst the ADSP is executing a programme. This feature enables the sequencer programme variables to be changed when required. To provide additional timing resolution for the faster R clocks, a series of 4 bit shift registers are used to control a single output line for each of the three R clock phases, Rϕ1,2,3. The shift registers are read out at four times the rate (24 Mhz) to provide the faster timing resolution.

Waveform Generation

The ADSP can be programmed using an assembly language which is compiled before running into an executable file. The programme development was done on a PC using a Hewlett Packard logic analyser to check the timing of the waveforms from the sequencer. The cyclic nature of the CCD read out allows the use of subroutines that generate a specific waveform bit pattern e.g. a single R clock waveform. These subroutines can then be called from within a loop that controls
the number of waveform cycles. By varying the length of the loops, the same programme can be used to readout different CCD formats. A structured approach to the sequencer programme was therefore adopted and Figure 4.22 shows the main programme routine.

The first 12 lines allocate the available registers labeled 10 to 17 user-defined labels. After assembly these labels are replaced by the actual physical addresses of the bit mapped port. A set of default variables is initially loaded into the sequencer's data memory at lines 17 to 20 by the 'transf' loop. These variables provide default values for the loop counters used to vary the number of clock cycles per row or column, the pixel size and the CCD integration time. The integration length is controlled by the first loop, 'timeloop', and can provide integration times of up to 15 minutes by suitable choice of the loop counter variable. After the integration cycle a frame start pulse is generated by the 'start' subroutine. This pulse indicates the start of a new CCD frame so that only a full CCD frame of data is acquired when requested. The outer program loop labelled 'paraloop', cycles through the number of line transfers required to readout the CCD. The 'line' and 'pixshift' subroutines generate the appropriate waveforms for the parallel and serial transfer clocks respectively. The pixel bin size is controlled by the value of the 'pix-bin' and 'line-loop' counters. These determine the number of serial and parallel transfers executed before the signal charge is measured.

The signal charge from $n \times m$ pixels can be integrated up where $n$ and $m$ are integer values of the pixel in the horizontal and vertical directions. After the signal charge from the pixel has been readout by the 'pixshift' routine, the waveforms for the analogue signal processor are generated by the routine 'amplfr'. This provides the necessary waveforms for the CDS processor and the sample pulse required by the ADC to digitise the output signal at the correct time. Once all the pixels in the serial register have been readout, the next line is transferred into the readout register. This whole process is then repeated until all the CCD has been readout, at which point the 'paraloop' counter reaches zero and the program cycle repeats. In this way the CCD is continually read out within an infinite loop.

4.7 Data Analysis Techniques

The Archimedes software is used to support several utilities to allow a limited amount of processing of the CCD data and calibration of the CCD response. These functions concentrate mainly on the spectroscopic performance of the CCD since this is the main parameter of interest.

4.7.1 Pulse Height Spectral Analysis

After the CCD data has been taken, it can be processed by the Archimedes into event energy histograms. These histograms enable the spectroscopic performance of the CCD to be assessed and energy resolution to be measured. In the raw event data histogram each pixel with a signal above the threshold is recorded in the appropriate energy bin. The pulse height spectra can then
Figure 4.22: Example of assembler code to read out a CCD
be used initially to calibrate the CCD by determining the peak positions of the noise and X-ray line. This is calculated by the computer by setting an upper and lower region of interest (ROI) around the peak. The computer determines the peak position bounded by the ROI by the equation

$$x = \frac{\sum x_i n_i}{\sum n_i}$$

(4.8)

where $n_i$ are the number of events in the bin $x_i$. A weighted mean of the peak position is therefore obtained. Knowing the line energy from the source and the position of the noise peak the CCD can be calibrated in terms of a calibration factor in $eV/ADC$ units. This is calculated by the computer from the difference between the noise peak position and the X-ray line using the equation

$$\text{Calibration factor} = \frac{E_{\gamma}}{X_{\text{noise}} - X_{\text{line}}}$$

(4.9)

where $X$ is the peak position and $E_{\gamma}$ is the X-ray line energy. The histogram x-axis is then converted from ADC units into energy by the Archimedes using this calibration constant.

Once calibrated the computer constructs the isolated and whole events histograms from the raw data. The isolated event histogram records events in which the X-ray charge is confined to a single pixel provided there is no significant signal above the thresholds in any neighbouring pixels. Generally these events give the best energy resolution since all the event charge is confined to a single pixel. Where the charge is spread over two or more pixels, the signal from all neighbouring pixels is summed together to recover the event energy. This is then used to produce the whole event histogram which records the event data from both isolated and spread events in the detector. This histogram therefore records every event that generates signal within the CCD and is used to measure the detection or total quantum efficiency of the CCD.

4.7.2 Charge Transfer Efficiency Measurement

Characterisation of the CCDs charge transfer efficiency (CTE) can be determined with the computer by dividing the CCD into subarrays in either the vertical or horizontal axis. The pulse height from each subarray is built up from the counts contained within the region and the mean peak position calculated. The pulse height across the array is therefore obtained at each subarray position. The computer can then display this information as a false colour image of the pulse height distribution for each sub-array across the device. The best fit straight line to the pulse heights of each subarray enables the CTE to then be determined as the fractional energy loss per pixel. Figure 4.22 shows the computer display used to calculate the CTE.

Stack Line Trace

Another representation of the CTE is by the stack line trace. Here the serial or parallel CTE is displayed by plotting the signal only from each pixel in the CCD row or column against the row
Figure 4.23: Computer display of the routine used to determine the CTE

Figure 4.24: Computer display of a serial stack line trace showing the shift in the peak position of the x-ray line in the read-out direction
or column position. Figure 4.23 shows the stack line trace output in the serial direction for a CCD with poor CTE. X-ray signal generated furthest away from the output node suffers the most charge loss and therefore reduced pulse height. The charge left behind in the transfers can be seen as a deferred charge tail in the display. The CTE can be measured by fitting a straight line to the pulse height as before. This method can complement the previous CTE routine since it can be used on images even when bright columns are present, because bright pixel features will upset the routine which creates histograms and works out the mean peak position from sub-arrays. This method of measuring the CTE is therefore preferred for devices with bright columns.

4.8 Conclusion

A new X-ray test facility, based around a flat crystal spectrometer, has been built to investigate the low X-ray energy response of the CCD. Careful attention has been paid to the monochromaticity of the beam through the use of crystals with Bragg Angles greater than 30°. Below this angle scatter of the prominent C-K fluorescence off the crystal was found to contaminate the reflected beam. The use of a gas counter optimised for soft X-ray detection by employing thin windows <1µm thick and low density fill gas i.e. P50 enables accurate quantum efficiency measurements of the CCD to be made. Combined with the CCD data analysis software and computer controlled data acquisition a powerful test facility for the development and testing of CCDs at the energies below 1 keV has been commissioned.
Chapter 5

Simulation of the CCD's X-ray Performance

5.1 Introduction

Although the quantum efficiency of the CCD is an important parameter in assessing the detector performance, of equal importance is the ability of the CCD to provide spectroscopic resolution. This is particularly important for X-ray spectroscopy missions where the CCD will be used as a broad band non-dispersive spectrometer, enabling for the first time, the powerful diagnostic tool of spectroscopy to be applied to astrophysical plasmas.

In an ideal CCD, all the X-ray event energy is collected and the resolution is given by

$$\Delta E = 2.35\omega \sqrt{n^2 + \frac{FE}{\omega}} \text{ (eV)}$$  \hspace{1cm} (5.1)

where $F$ is the Fano factor (0.11), $n$ is the system noise and $E$ is the X-ray energy (eV). In a real CCD system, deviations from the resolution described by equation 5.1 occur if the charge collection from an X-ray event is incomplete and if charge transfer from pixel to pixel is inefficient. Severe loss of charge may also result in the event signal being sufficiently reduced in amplitude that it is lost in the system noise peak. In this case, a corresponding reduction in the quantum detection efficiency of the CCD will also occur. Signal charge loss and a finite system noise level limit the achievable resolution of the CCD that is intrinsic to a silicon detector. These limitations are particularly stringent for low energy X-ray spectroscopy where the signal charge may contain only a few hundred electrons.

The resulting distribution of signal charge from an event and the fraction of the total signal charge that is measured is dependant on where the original X-ray photon is absorbed. To illustrate this, Figure 5.1, shows a schematic diagram of the back illuminated CCD structure. There are four distinct regions in the CCD which affect the collection of charge in the buried channel of
Figure 5.1: Schematic diagram showing a back illuminated CCD in cross section. The effects on signal charge transport towards the buried channel is shown for different regions of the CCD.

The first region (i) is a depletion layer at the back surface of the CCD caused by the positive charge of the native oxide (see Chapter 3). X-ray charge generated in this narrow region will be swept, by the rear depletion field, towards the oxide/silicon interface states where it recombines. This region represents a 'dead layer' on the back of the device since events generated within this region result in no measured X-ray signal. The second region (ii) is the undepleted part of the p+ implant layer. Signal charge in this region will radially diffuse until either it reaches the rear potential well or the edge of the implant layer. The charge may also recombine because of the reduced electron life-time in this region of $10^{-6}$ s for $N_a = 10^{18}$ cm$^{-3}$ compared to around 0.1 s for epitaxial silicon. The third region (iii) is a field free layer caused by incomplete depletion of the etched silicon epitaxial layer so that charge is transported by diffusion in this region. Charge reaching the implant/epitaxial layer will be reflected back into the field-free region by the electric field induced by the dopant concentration gradient. Recombination will be less important in this region because of the increased electron lifetime resulting in a mean path length of around 1 cm before recombination. The final region, (iv), is the depletion layer. Charge diffusion will occur, but the presence of an electric field causes a rapid drift of the charge towards the buried channel, limiting the extent the charge cloud diameter. Typically events generated within this region have all the signal charge confined to a single pixel and therefore yield the best spectral information.

The final charge cloud radius and fraction of charge collected in the buried channel depends upon the region in which the x-ray interaction takes place. Charge loss through recombination will occur for events absorbed in the implant layer, but the extent of the charge cloud may also result in signal charge loss because of the use of an energy threshold in the detection process. This is necessary to discriminate between random noise fluctuations within a pixel from x-ray generated signal charge. To reject 99.99% of noise events, the threshold needs to be set to 5 $\sigma$ above the noise.
peak. If an x-ray event is spread over several pixels, in some instances the signal contained within the peripheral pixels may be less than the noise threshold. Only part of the x-ray event energy will be recovered in this case, degrading the energy resolution. This effect is particularly important for the pulse height spectra for low X-ray energies where the noise threshold is a significant fraction of the X-ray photon energy e.g. for 10 ele rms noise the threshold is 65% of the C-K line energy (280 eV). An event in which only part of the X-ray energy has been recovered is referred to as a partial event.

The pulse height output from the CCD is therefore a complicated function of the CCD structure and the detection threshold. Similarly, the measured quantum efficiency of the CCD will be dependant on the effects of signal loss due to noise thresholding. Thus the measured QE is related to the absolute QE by

\[ Q_{\text{measured}} = f \times Q_{\text{absolute}} \]  

(5.2)

where \( f \) is a factor that depends on the particular CCD geometry and x-ray signal to noise. In this chapter it will be shown how this factor varies for different CCD structures and signal to noise.

To predict the x-ray performance of the CCD requires an understanding of the charge transport of electrons within the different regions of the CCD and the effects of recombination in the highly doped p+ implant layer at the back of the device. The next sections outline the physics of radial charge diffusion and charge recombination in the various regions of the CCD to obtain a set of equations that describe these processes. These are used in a Monte-Carlo simulation programme of CCD’s response to show how the effects of detector noise, radial diffusion and charge recombination in the implant region of the device affects the final pulse height spectra and quantum detection efficiency.

The simulation program is used to predict the performance of back illuminated CCDs fabricated by EEV for this work and the results are compared with experimental data to check the validity the charge transport models used. Predictions of the effects of varying detector geometry on the spectral performance and quantum efficiency are presented. Finally the simulation is used to predict the performance of a back illuminated CCD whose parameters have been optimised for x-ray spectroscopy.

5.2 Charge Collection from the p+ Implant

As described in Chapter 3, the etched rear surface of the CCD requires ion-implantation to place the surface in accumulation. This is achieved in the EEV process by ion-implantation of the surface with 25 keV Boron ions. The surface is then annealed by a laser. The resulting p+ layer has an ion concentration of around \( 8 \times 10^{18}\text{cm}^{-3} \) and \( \sim 0.3\mu\text{m} \) deep. Figure 3.9 in Chapter 3 showed the distribution and concentration of the implant ions after annealing. X-ray photons absorbed
within this implant layer will generate signal electrons which will be transported by diffusion, either towards the rear surface or the implant limit. Signal charge reaching the rear surface will recombine with the oxide/semiconductor interface states while charge reaching the implant limit will eventually be collected in the buried channel of the CCD. Loss of energy resolution in the CCD will occur if only part of the x-ray signal charge is collected. Thus the charge collection efficiency or CCE for the implant layer is an important parameter in predicting the pulse height response of the CCD. This is particularly true where the absorption lengths of the x-rays are short. For example, the absorption length of the C-K emission line, 280 eV, in silicon is around 0.1 μm and 95% of these events will be absorbed in the implant region. In this section two models are used to predict the CCE from regions of highly doped silicon and are applied to the CCD's p⁺ implant layer. The first model can be applied to any arbitrary dopant profile while the second model assumes a uniform dopant concentration and therefore takes mean values for the charge transport parameters. The results are compared to find a suitable expression for the CCE.

5.2.1 CCE from a region having an arbitrary dopant profile

The transport of minority carriers in a p-type silicon region, is governed by the current density and continuity equations. In one dimension these are given by

\[ J_n = q\mu E_n n + qD_n \frac{dn}{dx} \]  \hspace{0.5cm} (5.3)

\[ \frac{dJ_n}{dx} = qG - q \frac{q}{\tau_n} (n - n_0) \]  \hspace{0.5cm} (5.4)

where \( E_n \) is the electric field determined by the local doping density gradient, \( q \) is the elementary charge, \( D_n \) is the diffusion coefficient, \( n \) is the electron density and \( J_n \) is the current density, \( \tau_n \) is the electron lifetime and \( G \) is the electron generation rate. All the above quantities are dependant on the dopant concentration and therefore are a function of position within the p⁺ layer. The solution of the above transport equations is therefore not a simple problem. Various analytical solutions have been derived which use simplifying assumptions to solve the transport equations and therefore give varying degrees of approximation for the charge collection efficiency (Cuevas et al. 1989). These approximations were originally used to simulate the photo-generated currents leaving the highly doped emitter regions of silicon solar cells. However, because they can be applied to any dopant profile, they can therefore be used to model the CCE of implant layer in the back illuminated CCD. Numeric computer simulations have also been written which can accurately predict values of the CCE, but this method would be difficult to implement in a Monte-Carlo simulation of the CCD's pulse height spectra (Basore et al.). However, an expression which has been found to give a good approximation to both numeric computer simulations and exact solutions of the transport equations is called the transparent approximation (Del Alamo et al.). The expression is accurate to within a few percent provided the doped region is thin compared to
the absorption length of the photo-generating radiation and that surface recombination rather than recombination in the bulk dominates. This is because the solution assumes that no recombination in the bulk takes place. Thus the electron life-time $\rightarrow \infty$. In this approximation, the degree of surface recombination is expressed in a parameter called the surface recombination velocity. For a passivated surface that has few interface states for the minority signal to recombine with, the value of the recombination velocity is $10^3$. For a non-passivated one which has a high density of states, the value is around $10^7$.

For the case of the CCD's implant layer, the depletion layer at the rear surface causes any signal charges generated within this region to be swept towards the rear interface states where they recombine. This effectively creates a value of recombination velocity that is close to the maximum value. This maximum velocity is equal to the thermal speed of electrons in silicon of $2 \times 10^7 \text{cm s}^{-1}$ (Korte et al. 1990). Furthermore, the mean path length before recombination is around $6 \mu\text{m}$ at the peak dopant concentration in the implant so the effects of bulk recombination are not significant. The transparent approximation will therefore give sufficient accuracy for the calculation of the implant's CCE.

The Transparent Approximation

The equation to calculate the CCE from the quasi-transparent approximation is given by

$$\eta_{\text{trans}}(x_g) = 1 - \frac{S_p n_0(w) A_1(x_g)}{1 + S_p n_0(w) A_1(w)}$$

(5.5)

and $A_1$ is given by

$$A_1(x) = \int_0^x \frac{dx}{D_n n_0}$$

(5.6)

In these equations the rear surface of the implant is at the spatial coordinates $x=w$ and extends down to $x=0$ at the implant limit. $S_p$ is the surface recombination velocity, $n_0$ is the equilibrium electron concentration in p-type silicon and $D_n$ is the diffusion coefficient for the electrons. Equations 5.7 and 5.8 can be evaluated at any point $x_g$ within the implant region provided the behaviour of $D_n$ and $n_0$ as a function of dopant concentration is known. In the next section a set of parameters which describe how these quantities vary with dopant concentration is presented.

Parameters for the CCE Calculation

Several sources were consulted to provide a set of parameters for silicon which give the relationship with temperature and dopant concentration. Where possible empirical equations obtained from actual experimental values were used for accuracy.

The diffusion coefficient is given by the Einstein relation

$$D = \frac{\mu kT}{q} \text{cm}^2\text{s}^{-1}$$

(5.7)
where the electron mobility, as a function of dopant concentration, is given by the following expression (Arora et al 1982)

$$\mu = 88T^{-0.57} + \frac{1252T_n^{-2.33}}{\left(1 + \left(\frac{N_a}{N_{ref}}\right)^{\alpha T_n}\right)^{\beta T_n}} \text{cm}^2\text{V}^{-1}\text{s}^{-1}$$

where $N_a$ is the dopant concentration cm$^{-3}$, $N_{ref} = 1.26 \times 10^{17}$, $\alpha = 0.88$ and $\beta = -0.146$. Finally, the electron concentration, $n_o$, is given by the empirical expression

$$n_o = \frac{E_o^2}{N_a} e^{\Delta E_g/kT} \text{cm}^{-3}$$

where $n_o$ is the intrinsic carrier concentration and $\Delta E_g$ is the band gap narrowing due to the doping level. The value of $n_o$ can be found from the expressions for $n_o$ and $\Delta E_g$ as a function of temperature and doping (Slobtoom et al 1976)

$$n_o = 3.36 \times 10^{15} T^{3/2} \exp\left(-\frac{E_g}{2kT}(0.8291 \left(\frac{1 + T/142.7}{1 + T/166.8}\right)\right)^{3/2} \text{cm}^{-3}$$

$$\Delta E_g = 9 \times 10^{-3} \sqrt{\ln \frac{N_a}{10^{17}} + \ln^2 \frac{N_a}{10^{17}} + 0.5} \text{eV}$$

This completes the set of parameters used to evaluate the quasi-transparent model. Some of these parameters are plotted out in figures 5.2 to 5.4 to illustrate the variation with doping at a silicon temperature of 300K.

### 5.2.2 Results of the Quasi-Transparent Approximation

The results of the calculation of the charge collection efficiency are shown in Figure 5.5 for two values of the surface recombination velocity, $S_p = 10^3$ and $S_p = 10^7$ cm s$^{-1}$. The results show that the fraction of charge emerging from the implant is very dependant on the value of the surface...
Figure 5.3: Intrinsic carrier concentration as a function of silicon temperature

Figure 5.4: Electron density in p-type silicon as a function of dopant concentration
recombination velocity. For a velocity of $10^3 \text{ cm s}^{-1}$ the CCE is around 80% for electrons generated at the back surface and increases to 100% towards the implant limit. At a surface recombination velocities of $10^7 \text{ cm s}^{-1}$ the CCE values decrease with a value of zero at the rear of the implant. The most appropriate value of $S_p$ is believed to be $10^7 \text{ cm s}^{-1}$ because of the rear depletion well.

5.2.3 CCE for Uniformly Doped Silicon

In the case of a uniformly doped p+ region an expression for the charge collection efficiency is given by

$$ q_{\text{total}} = q_0 \left[ \frac{R \cosh(d/L - Z_s/L) + T \sinh(d/L - Z_s/L)}{R \cosh(d/L) + T \sinh(d/L)} \right] $$

(5.12)

where $d$ is the width of the region, $Z_s$ is the absorption position of the x-ray photon, $L$ is the diffusion length in the region, $D$ is the diffusion coefficient, and $T$ and $R$ are the transmission and reflection coefficients at the back surface of the implant which is at $Z_s = d$ (Hopkinson 1987). In this equation the recombination velocity $S$ can be introduced by the relationship $S = \frac{D \pi T}{L^2}$ and $T+R=1$. As discussed in the previous section, $S$ is high, so that the value for the reflection coefficient is $\sim 0$. Substituting this into the Equation 5.12, the cosh terms cancel, simplifying the expression to

$$ \frac{q_{\text{total}}}{q_0} = \left( \frac{\sinh(d/L - Z_s/L)}{\sinh(d/L)} \right) $$

(5.13)

For a value of $L \sim 10\mu\text{m}$, appropriate to the mean dopant concentration of $N_a = 8 \times 10^{18} \text{ cm}^{-3}$, the resulting CCE as a function of implant depth was calculated. This is shown in Figure 5.6.
Figure 5.6: Implant CCE given by equation 5.13 assuming a uniform doping level and for comparison the calculated CCE from quasi-transparent approximation using a value of $S_p = 10^7 \text{cm s}^{-1}$ is also shown.

Comparing the two results, it can be seen that there is close agreement. At the rear surface both models predict a CCE of zero which increases linearly with depth into the implant. However, the transparent model predicts the CCE to reach 100% just before the implant limit. This is because the transparent model accounts for the dopant concentration gradient below a depth of 0.25 $\mu$m into the implant which increases the drift velocity of the electrons and reduces the effective width of the implant.

5.3 Theory of Charge Diffusion

The next sections outline the models used to derive the equations for calculating the radial extent of the charge clouds upon collection in the buried channel of the CCD. Expressions for radial diffusion occurring in the field free regions and depletion layer of the CCD are given.

5.3.1 Initial Charge Cloud Diameter

When an X-ray is absorbed it initially imparts its energy to an outer-shell electron. The electron has an energy $E_\gamma - E_k$ where $E_\gamma$ is the x-ray energy and $E_k$ is the k shell binding energy of silicon (1.75 keV). This electron then dissipates its energy by the creation of electron-hole pairs with a mean value of 3.65 eV per electron-hole pair at room temperature for silicon. The range of the primary electrons can be calculated from the energy depth relationship which for silicon

$$R = 0.0171E^{1.75}$$

(5.14)
Figure 5.7: Radial charge cloud profiles for several fractional absorption depths in a field free region of silicon

where \( R \) is the range in \( \mu m \) and \( E \) is the electrons energy and is equal to \( E_\gamma - E_e \) (Everart et al. 1971). The penetration depth has been investigated for electrons in solids and indicates that the charge cloud is gaussian with a 1 \( \sigma \) radius given by

\[
r(\sigma) = 0.257R
\]

(5.15)

where \( r \) is in microns (Fitting et al. 1977). Thus for a 1 keV photon the 1 sigma radius is \( \ll 1 \mu m \).

5.3.2 Charge Diffusion in a Field Free Layer

An expression for the radial distribution of charge after drifting through a field free layer of silicon is given by

\[
q(r) = \frac{Q_0}{d^2} \sum_{n=1}^{\infty} \frac{nsin\left(\frac{\pi n x}{d}\right)}{n} K_0 \left[ \frac{r}{d}(n^2 + d^2/4)^{0.5} \right]
\]

(5.16)

where \( K_0 \) is a modified Bessel function of order 2, \( d \) is the width of the field free region and \( Z_0 \) is the point of X-ray interaction (Hopkinson 1987). Figure 5.7 plots the radial profiles of charge collected from the field free region for several fractional generation depths \( Z_0/d \). The appearance of the charge cloud profiles are similar to a gaussian distribution but with extended wings.

Janesick has also looked at the effect of radial diffusion in a field free layer using a Monte-Carlo, random walk simulation of electrons drifting through a field free region (Janesick et al. 1986). The step length for each random walk is equal to the mean path length given by \( \sqrt{\Delta r} \) and upon reaching the limit of the field free layer the lateral displacement of the electron from its starting position is recorded. A reflecting rear boundary was assumed, equivalent to the p\(^+\)/p layer in the back illuminated CCD. The 1\( \sigma \) radius derived from the simulations of thousands of individual
Figure 5.8: Results of the 1σ charge cloud radii generated as a function of absorption depth in a field free region for Hopkins' model (equation 5.16) and Jansick's model (equation 5.17).

Electron random walks is given by the empirical relationship

\[ R_\sigma = \frac{d}{2} \sqrt{1 - \left(\frac{Z/d}{1}\right)^2} \]  

(5.17)

Figure 5.8 plots out the 1σ fractional charge cloud diameters \((\frac{Z}{d})\) as a function of the fractional absorption position \((\frac{Z}{d})\) for both models. Good agreement between the two models can be seen in the figure with both curves showing the final charge cloud radius to scale with distance into the field free layer. The largest radii are produced for photons that are absorbed at the back of the field free region. In this case, values of 0.5 and 0.6 \(x\) the field free layer width are predicted for the cloud diameter by Jansick's and Hopkins' models respectively.

5.4 Radial Diffusion in the Depletion Layer

Radial diffusion will occur in the depletion layer, but in this case the signal charge is rapidly collected in the buried channel because of the electric field induced drift. The charge cloud upon collection is assumed to have a gaussian profile with a 1σ radius given by \(\sqrt{2Dt}\) where \(D\) is the diffusion coefficient and \(t\) is the time taken to reach the buried channel. The drift time through the depletion layer can be calculated if the electrons drift velocity is known.

For an electric field strength \(< 1 \times 10^5 \text{ V/cm}\), the drift velocity is then given by:

\[ V_{\text{drift}} = \frac{dx}{dt} = \mu_e E(x) \]  

(5.18)

where the electric field component is \(E(x)\) and mobility \(\mu_e\). The electric field strength within the depletion layer can be found by integrating Poisson's equation assuming a uniformly doped surface channel CCD structure. The electric field strength as a function of distance in the depletion layer is...
is given by
\[ E = -\frac{dV}{dx} = \frac{eN_a}{\varepsilon_{Si}}[x_d - x] \]  
(5.19)
where \( \varepsilon \) is the silicon permittivity \((1.044 \times 10^{-12} \, \text{Fcm}^{-1})\). Substituting this into equation (5.18), and integrating, the time taken for the charge cloud to reach the buried channel is given by
\[ t = \frac{\varepsilon}{\mu e N_a} \ln \left( \frac{x_d}{x_d - z_a} \right) \]  
(5.20)
The 1 sigma charge cloud radius is therefore
\[ r = \left[ \frac{2 D \varepsilon}{\mu e N_a} \ln \left( \frac{1}{1 - \frac{z_a}{x_d}} \right) \right]^{1/2} \]  
(5.21)
where \( x_d \) is the depletion layer width and \( z_a \) is the X-ray absorption depth.

Janesick has also applied the Monte-Carlo random walk simulation of electrons to the depletion layer region. In this case an additional displacement of \( \frac{D x}{V_{th}} \), where \( x \) is the mean free path of the electron and \( V_{th} \) is the electrons thermal velocity, is added to each step in the direction of the buried channel to account for the electric field induced drift. An empirical fit to the simulation results is given by
\[ r = 1.036 \times 10^{-8} \left( \frac{10^{15}}{N_a} \right)^{1/2} \ln \left( \frac{1}{1 - \frac{z_a}{x_d}} \right)^{1/2} \]  
(5.22)
To compare the result of Hopkinsons model with the empirical expression given above, values of \( \mu = 1300 \, \text{cm}^2\text{V}^{-1}\text{s}^{-1} \), \( D = 23 \, \text{cm} \, \text{s}^{-1} \) and \( N_a = 10^{15} \, \text{cm}^{-3} \) were used to evaluate the cloud radii given by equation 5.21. The results obtained from both models is shown in Figure 5.9 which plots the charge cloud radii as a function of depth into the depletion layer.

The analytical model predicts the final charge cloud radii to be around a factor of 2 greater than that predicted by Jansick's simulation. However, both models predict the charge cloud radii...
to be $\ll$ one pixel in size so that charge splitting is negligible in the depletion layer. The analytical model was used for the simulation programme.

5.5 Summary

The above equations have been derived to account for the effects of radial diffusion in the depletion layer and any field free region of the CCD and an expression for the charge collection efficiency from the highly doped implant region of the back illuminated CCD has been derived. These equations are now used with a Monte-Carlo type simulation to predict the final charge distributions and fraction of collected signals at the buried channel of the CCD.

5.6 Monte-Carlo Simulation of the CCDs Pulse Height Spectra

5.6.1 Introduction

Simulation of the the CCDs pulse height spectra enable the factors that affect the energy resolution and quantum efficiency to be studied. By comparing the simulation with experimental data, the validity of the charge transport models derived for the various CCD structures can be tested and the contributory effects on the overall detector response investigated. If the model is sufficiently accurate, it can then be used to investigate the effects of the various CCD parameters have on its response and improvements suggested without the need for procuring expensive trial devices.

5.6.2 Schematic Description of the Computer Program

The program was developed by Holland (1990) for the study of front illuminated CCOs and adapted for back illumination for this thesis. The program obtains values of the various CCD parameters from a data file. These parameters include the depletion layer, field free and implant layer thicknesses, the system noise value, pixel size and the absorption length of the x-ray photon at the simulation energy. The structure of the CCD can be represented by a simple planar geometry, shown in Figure 5.10 comprising a depletion layer in which the drift field increases towards the front of the CCD, a field free region where charge is transported by diffusion and the implant layer where charge recombination takes place. Finally, there is a thin dead layer (0.05 μm) due to the rear depletion well. At each x-ray energy, random interaction depths into the CCD are generated from an exponential distribution of absorption depths, specified by the attenuation coefficient of the x-ray in silicon. The resulting charge cloud collected in the buried channel is assumed to be gaussian with a radius at 1 $\sigma$, $r_{\text{final}}$, given by the quadrature summation of the individual cloud radii contributions from diffusion in the field region, field free regions and the initial charge cloud.
where $\sigma_{\text{imp}}$, $\sigma_{\text{ff}}$, $\sigma_{\text{dep}}$, and $\sigma_{\text{initial}}$ are the 1 sigma radii from the implant, field free, depletion layers and the initial cloud radius respectively. $\sigma$ charge cloud radius. For events generated in the implant layer, the CCE in this region is used to determine the fraction of the signal charges collected. A $5 \times 5$ pixel matrix, centered on the event interaction position is then used to determine the fraction of charge spread into neighbouring pixels. This is calculated by combining the one dimensional error functions at each pixel boundary for both the vertical and horizontal directions.

To simulate the readout process, a random system noise value is added to each pixel with a gaussian distribution determined by the noise sigma. For each X-ray the shot noise on the charge cloud is added, with a sigma given by $\sqrt{\omega \Phi E}$ eV.

Finally the isolated event, whole event and the raw data histograms are constructed from the $5 \times 5$ matrix in the same way as the experimental data. Thus any pixel in the matrix with a signal level above the $5\sigma$ noise threshold is recorded as an X-ray signal by the CCD. In this way the effects of noise on the ability to recover all the event charge in an event spread over several pixels can be assessed. This is particularly important in the back illuminated CCD where the X-ray charge signals are small and are generated close to the back of the device where radial diffusion is important.

### 5.6.3 Simulation Results

The important features of the simulated pulse heights for a back illuminated CCD can be illustrated by considering the response at the C-K line energy (278 eV) and the Mg-K line energy (1250 eV). The C-K line energy has a short absorption length in silicon, around 0.1 $\mu$m, and the CCD response...
at this energy will therefore be dependant on the effects of charge collection from the rear implant region. Also, the small X-ray signal generated by this photon, ~85 electrons, makes it particularly sensitive to the effects of charge loss due to noise thresholding. The Mg-K line at 1250eV has absorption length around 4.5μm, and it is therefore a useful energy to assess the validity of the model in predicting the extent of radial diffusion within the CCD. Here, the effect of the noise threshold is less severe because of the larger X-ray signals generated (~340 electrons). Simulating the response of the CCD at these two line energies therefore shows how the various factors that cause the incomplete measurement of the signal charge depend on the CCD structure and signal to noise ratio.

Figure 5.11 shows the simulated pulse height histogram obtained for the C-K line energy. The histogram was produced from events whose charge was confined to a single pixel and also from events spread over two or more pixels. The CCD parameters were chosen to be similar to experimental fully depleted CCDs so that a comparison with the data could be made. The depletion depth chosen was 20 μm which is the nominal value for the epitaxial layer thickness after etching. A noise level of 10 electrons rms. was used in the simulation since this is the typical value obtained with the low energy test facility. The experimental CCDs were fully depleted so no field free layer was included in the simulation parameters. The simulation shows that for a majority of the events, the x-ray energy is only partially determined. The signal loss results in a distribution of events with energies below the C-K line energy (280eV) that extends all the way down to the noise threshold at 180 eV. The simulation suggests that a significant fraction of X-ray interactions are not detected in the CCD because of severe signal loss. The detection efficiency will therefore be lower than expected at this energy if one uses a simple model for the quantum
Figure 5.12: Simulated pulse height to C-K photons for isolated and spread events for a fully depleted CCD possessing a negligible read noise level.

The effects of noise on the quantum efficiency and the pulse height spectra is shown in Figure 5.12. The simulation uses the same CCD structure as before, but the system noise level is negligible. The large proportion of partial events in the histogram shows that recombination of charge in the implant layer dominates the energy resolution of the CCD. This figure also shows the significant loss in quantum efficiency that will occur for finite system noise thresholds. For a 10 electrons rms noise threshold, shown in the Figure, the inferred loss in the detection efficiency is around 77%.

Figure 5.13 shows the simulation results at the Mg-K line energy of 1250 eV for a fully depleted CCD with a system noise level of 10 electrons rms. The histogram was constructed from isolated and spread events. Two principle features in the histogram can be seen. The first is a photo-peak and is generated from events that have undergone negligible charge loss. This occurs for events created in the depletion layer of the CCD. The second feature is a distribution of events whose energy is only partially recorded. These events have been absorbed in the implant layer and the fractional number of these events, ~ 5, reflects the amount of absorption at this energy that occurs in the implant. The experimental data from device R292 is also shown by the circles in the Figure. Again, good agreement between the simulation and the experimental was found. The model predicts around 75% of all events are isolated compared to 72% measured for the experimental CCD. This shows that the prediction of the extent of charge diffusion in the depletion layer is
Figure 5.13: Simulated pulse height for a fully depleted CCD to Mg-K line photons at 1250 eV. The circles are data from experimental device R292.

sufficiently accurate for the CCD with this depletion depth. However, it should be noted that the model does not account for charge confinement by the CCD's potential well structure since only a planar geometry is assumed. Thus for larger depletion depths the extent of charge diffusion will be overestimated.

The above simulations have been performed for a fully depleted type of CCD. However, under-thinning of the silicon will result in a device that is not fully depleted under normal biases. Figure 5.14 shows the simulated raw, isolated and whole event pulse height spectra for an under-thinned CCD at an x-ray energy of 2015 eV (P-K line). The parameters used for the CCD were a depletion layer of 25 μm, a field-free of 4 μm and a system noise of 15 electrons rms. These parameters are similar to early under-thinned CCDs produced by EEV. These CCDs had around 30 μm of epitaxial silicon remaining after the etching and under normal bias levels, the calculated depletion depth will leave a 3 to 4 μm un-depleted silicon layer at the rear (see Chapter 6). In the test facility noise levels of 13 to 15 electrons rms were achieved. The addition of a small field free layer at the rear of the device has caused a significant degradation in the energy resolution of the CCD. A low energy tail of partial events can be seen extending down from the photo-peak giving a non-gaussian line profile. These events have been caused by the effect of the noise threshold on the events that have spread over several pixels. The increase in the amount of diffusion can be seen by the low isolated event fraction which is only around 6.0 %. The pulse height histogrammes from an under-thinned CCD, device number R66, are also shown for comparison. Close agreement between the simulated response and the experimental data can be seen with a best fit to the data obtained for a field free layer width of 3.5 μm. This agreement lends further weight to the validity of the modelling used for the diffusion in the field free layer.
Figure 5.14: Simulated and experimental data of raw, isolated and whole event pulse heights for an under-thinned CCD to P-K\textsubscript{\textalpha} x-rays
5.7 Discussion

The results of the simulation have shown that the charge loss in the CCD degrades the energy resolution and detection efficiency of the back illuminated CCD. Charge loss due to the detection threshold can be minimised by increasing the signal to noise ratio and by fully depleting the CCD so that most of the signal charge is confined to a single pixel. Recombination in the implant is significant for events less than 600 eV in energy and can be minimised by reducing the implant width.

A measure of the effects of charge loss through radial diffusion and the x-ray signal to noise on the detector response can be evaluated by calculating the integral charge collection efficiency of the CCD (CCE). This is defined as the ratio of the collected charge to the total signal charge generated at given x-ray energy. Mathematically this is given by the equation:

\[ \text{CCE}(E) = \sum \frac{n(i)E(i)}{E(\gamma)n(i)} \]  

where \( n(i) \) is the event number at energy bin \( i \), \( E(i) \) is the bin energy and \( E(\gamma) \) is the x-ray photon energy.

The simulation was used to calculate the CCE for different field free layer thicknesses at two x-ray energies. The energies chosen were 280 eV (C-K) and 2015 eV (P-K) because they represent signal to noise ratio limits in the soft x-ray band. Figure 5.15 shows the results of the simulation for a CCD with a 20 \( \mu \)m depletion layer and a noise level of 10 electrons rms. No implant layer was assumed since only the effects of the field free region are being illustrated. The CCE values for the P-K line energy can be seen to reduce from unity to 0.8 as the field free region increases from 0 to 10 \( \mu \)m. For the C-K line energy, the initial CCE value is 0.95 and then rapidly reduces
with field free layer width reaching zero at a value of 9\textmu m. At this point the detection efficiency of the CCD is lost. The reason for the initial CCE value <1 is due to events generated along a pixel boundary causing charge to be split between pixels. The detection threshold then causes loss of charge because of the low signal to noise ratio at this energy. The simulation therefore illustrates the importance of signal to noise on the measurement of the total event charge where radial diffusion is significant.

For comparison Figure 5.16 shows a plot of CCE as a function of depletion layer thickness for the same x-ray energies. The figure shows that radial diffusion is significantly less than in the field region because the CCE values are higher. At the C-K line energy a CCE of 0.85 is predicted for depletion layer width of 50 \textmu m. The P-K energy gives a better CCE which falls to a value of 0.97 at depletion depth of 50\textmu m.

Figure 5.17 shows the simulated pulse height response to C-K photons for an optimised set of CCD parameters which could be achieved with currently available technology. The CCD model uses a very narrow implant region (< .05\textmu m) and a 30 \textmu m fully depleted structure to ensure a high detection efficiency above 5 keV. The narrow implant can in principle be achieved by using lower implant energies and annealing by Excimer laser, which has a shorter absorption length in silicon of < 0.1\textmu m and these developments are discussed in Chapter 6. A noise level of 3 electrons rms can be achieved using EEV’s low noise output FET.

Comparing this response with that of back illumination devices fabricated with current technology as was shown in Figure 5.11, the simulation predicts a significant improvement in energy resolution and detection efficiency. Most of the signal charge is being collected resulting in a Gaussian distribution of events centered on the correct photon energy. The FWHM resolution is about 44 eV which is only slightly higher than the predicted value of 36 eV given by equation
Figure 5.17: Simulated C-K pulse height for an optimised CCD using a currently awaited technology to produce a narrow implant (< 0.1 μm) and a lower read noise (3 electrons rms).

5.1. Some charge loss does occur producing a partial event floor in the histogram due mainly to the absorption of x-rays in the implant layer. The simulation thus shows that with modest improvements in the noise levels and implant CCE the back illuminated CCD can achieve a performance which gives acceptable energy resolution and detection efficiency down to 280 eV. Devices fabricated with these improvements are expected to be available from EEV later in 1991.

5.8 Back Illuminated Quantum Efficiency

The Monte-Carlo model was used to calculate the quantum efficiency of the CCD. As implied by the modelling, the quantum efficiency in the soft x-ray region is dependant on the noise level and the extent of radial diffusion. Figure 5.18 shows the result of the simulated QE for events that are isolated and spread with a system noise level of 3 and 10 electrons rms. The CCD structure was fully depleted with a 20 μm depletion layer. The circles show experimental efficiency measurements obtained from device R292. Good agreement can be seen between the experimental and simulated data for a noise level of 10 electrons confirming the validity of using a Monte-carlo approach to predicting the low energy efficiency. This is necessary because detection efficiency of the back illuminated CCD is dependant on the mode in which the device is operated and that a simple efficiency model is not valid in predicting the CCD's response. Finally, for comparison, the predicted response for a CCD with a noise level of 3 el rms showing the improved detection efficiency achieved by increasing the signal to noise ratio.
5.9 Conclusion

The physics of the transport of signal charge has been outlined and a series of expressions has been obtained that enable charge cloud diameters and the fraction of charge recombination to be predicted for various regions of the CCO. These have been used in a Monte-Carlo simulation programme to predict the CCO’s soft x-ray response. Good agreement between the simulated and experimental CCO data has been observed, confirming the validity of the charge transport models used. The model has shown the contributing effects of the various regions of the CCO on the detector’s response and was used to predict the response of an optimised set of CCO parameters for soft x-ray spectroscopy.

Future work will aim at enhancing the model to account for the lateral confinement of the signal charge in the depletion well due to the fields under the channel stop regions and between the on and off electrodes. This will be particularly important for deep depletion devices necessary for good high-energy detection efficiency. In this case the depletion depths may be greater than 40 μm. Radial diffusion will therefore be significant in such large depletion layers and an accurate prediction of the splitting probability between pixels is necessary for simulation of the high energy response.
Chapter 6

Results from CCDs with Enhanced Soft X-ray Quantum Efficiency

6.1 Introduction

At photon energies below 2 keV absorption in the overlying electrode structure of a front illuminated CCD reduces x-ray detection efficiency. Methods of improving the soft x-ray efficiency are therefore concerned with minimising the dead layers of the CCD. Two approaches to achieve this aim have been investigated for this thesis. The first is the technique of illumination through the back surface of the CCD with very thin dead layers which are achieved by etching away the inert silicon substrate to the epitaxial layer. The second approach uses thin front electrode structures to minimise the absorption loss in the electrode dead layers whilst still retaining the other advantages of the front illuminated CCD.

The back illuminated CCDs investigated in this chapter fall into two categories:

- The first are fabricated on a high resistivity epitaxial silicon which is not thinned to the depletion layer edge so that the device are not fully depleted in normal operation. These CCDs were the first generation of back illuminated devices produced by EEV.

- The second generation of back illuminated devices had an over-thinned epitaxial layer in which the silicon was etched into the depletion layer. The devices were thus fully depleted, leaving no dead layers.

The front illuminated thin electrode CCDs studied for this thesis were of two different architectures,
Figure 6.1: Spreading resistance profile made on a sample of the silicon from which the back illuminated CCDs were fabricated

- The first were fabricated on 100Ω-cm resistivity silicon giving a depletion depth of around 8-9 μm.
- The second were fabricated on standard 30Ω-cm resistivity silicon but had a narrow buried channel of width 5μm.

In this Chapter, results obtained from the back and front illuminated CCDs are presented with particular emphasis on the quantum efficiency and spectroscopic performance below 2 keV. For each technique the quantum efficiency is compared to that of a high resistivity, front illuminated CCD so that the technique for enhancing the CCD’s soft x-ray efficiency can be assessed. The factors that affect the quantum efficiency and spectroscopic resolution are investigated so that a complete understanding of the x-ray performance of these device can be presented. Changes in device architecture are suggested that would further improve the X-ray performance of the CCD. Finally, the results of other CCD developments for space applications which were undertaken during this thesis are presented.

6.2 Under-thinned Back Illuminated CCDs

6.2.1 Device Description

These CCDs, numbers R44, R66 and R167, were some of the first back illuminated devices produced by EEV. They were fabricated on epitaxial silicon with the spreading resistance profile shown in Figure 6.1 which was measured on a silicon sample of the wafer from which the devices were fabricated. The doping level in the epitaxial layer has a nominal value of 8 x 10^{12}cm^{-3} which rapidly increases to the substrate level of 6 x 10^{19}cm^{-3} at the junction between the epitaxial layer
Figure 6.2: Potential profile in the depletion layer of the back illuminated CCD showing the extent of this region in the device and the substrate. This point occurs at a depth of around 45 $\mu$m into the wafer. In Chapter 2, the silicon resistivity as a function of doping level was given by an empirical expression in equation 2.2.

$$N_a = 10^{14} \left( \frac{150}{\rho} \right)$$

(6.1)

Using this, the resistivity in the epitaxial layer decreases from 2500 $\Omega$-cm near the buried channel to around 1800 $\Omega$-cm at a depth of 30 $\mu$m. In the final stages of manufacture, the silicon was thinned to the substrate/epitaxial layer boundary using a resistivity selective etch. A non-selective etch was then used to further thin the CCD into the remaining epitaxial layer. Control samples from the wafer indicated that the remaining epitaxial layer after this final etching stage was 32 $\mu$m to 34 $\mu$m thick. Using the dopant concentrations in the n-type buried channel layer and the p-type epitaxial layer of Figure 6.1, the potential profile in the epitaxial layer was calculated as described in Chapter 2. The potential profile in the epitaxial layer is shown in Figure 6.2 for two gate voltages of 0 Volts and 10 volts with respect to the substrate. The Figure shows that the depletion region extends to a depth of 30 $\mu$m into the epitaxial layer for a zero volt gate bias and up to 40 $\mu$m with a 10 volt gate bias. The electric field strength calculated from the potential gradient is shown in Figure 6.3. Over most of the depletion region the electric field is high and has a value of around $10^4$ V cm$^{-1}$ but near the depletion edge, this field strength rapidly falls to zero. The drift velocity of electrons which is linearly proportional to the field strength will therefore rapidly decrease in the weak field region and electron motion will be dominated by diffusion with only a small field induced drift component. Thus, the rear surface of these thinned CCDs will have a weak field region, the extent of which can be controlled by the gate bias.
6.2.2 Quantum Efficiency Measurements

Quantum efficiency measurements were made on several under-thinned devices and the results from a representative device of this type, number R66, will be discussed in this section. Table 6.1 shows the tabulated quantum efficiency data obtained from isolated and reconstructed event data. Columns 1 and 2 give the x-ray line and energies of each measurement. Column 3 tabulates the quantum efficiency measurements of device R66. The final column shows the quantum efficiency measurements made on a high resistivity front illuminated CCO which has a depletion depth of around 30 μm. Comparison with a standard resistivity CCO was not done because in this case the 4 μm thick depletion layer would be completely absorbing for x-ray photons with an energy below 700 eV.

The results from the under-thinned CCO show that the detection efficiency has been considerably improved compared to the front illuminated CCO within the soft x-ray band. A measure of the effective dead layer thickness of the CCO can be found by calculating the transmission of a silicon layer that best fits the quantum efficiency data. This model gives the CCOs quantum efficiency as:

$$QE = e^{-\mu x_d} \left\{1 - e^{-\mu x} \right\}$$  \hspace{1cm} (6.2)

where $\mu$ is the silicon absorption coefficient, $x_d$ is the silicon dead layer thickness and $x$ is the total thickness of the CCO. At soft x-ray energies, the transmission of the CCO is negligible and so the quantum efficiency, given by Equation 6.1, is determined by the transmission of the silicon dead layer. A value for the dead layer thickness which gives a good fit to the low energy efficiency measurements is around 0.65 μm. This result shows that the goal of producing a dead layer thickness of around 0.1 μm, necessary for good quantum efficiency, was not achieved in these
<table>
<thead>
<tr>
<th>line</th>
<th>Energy (eV)</th>
<th>QE R66 (%)</th>
<th>QE FI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-K</td>
<td>278</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>O-K</td>
<td>525</td>
<td>28%</td>
<td>8%</td>
</tr>
<tr>
<td>F-K</td>
<td>677</td>
<td>55%</td>
<td>14%</td>
</tr>
<tr>
<td>Cu-L</td>
<td>930</td>
<td>80%</td>
<td>52%</td>
</tr>
<tr>
<td>Mg-K</td>
<td>1250</td>
<td>86%</td>
<td>66%</td>
</tr>
<tr>
<td>Si-K</td>
<td>1740</td>
<td>83%</td>
<td>85%</td>
</tr>
<tr>
<td>P-K</td>
<td>2015</td>
<td>90%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Table 6.1: Quantum efficiency measurements for back illuminated CCD R66. Also shown are the efficiency measurements for a front illuminated CCD.

CCDs. Figure 6.4 shows the efficiency measurements for energies below 1 keV plotted with the transmission curve calculated for a 0.65 μm thick dead layer. An explanation for the poor fit of the model to the P-K (2015 eV) data point is explained in the discussion in section 6.2.6.

6.2.3 Pulse height Spectrum

Although the quantum efficiency is significantly improved over that of a standard front illuminated CCD, the ability of these devices to determine the event energy is inferior. Figure 6.5(a) shows the pulse height distribution produced from whole events. At the O-K line energy of 525 eV, few events can be seen that register the correct photon energy. The majority of the events are distributed below the line energy with the distribution extending down to the noise threshold equivalent to 270 eV. It is therefore probable that loss of events below the noise threshold occurs for this device.

At the Cu-L line energy of 960 eV, Figure 6.5(b), a broad distribution of events can be seen which is centred around the peak at an energy of 800 eV. The energy resolution can be measured in this case because the peak is separated from the noise. The full width at half maximum was measured to be around 47 %. Finally the response of the CCD at the P-K line at 2015 eV is shown in Figure 6.5(c). This photon has a short absorption length in silicon of 1.5 μm due to the change in the absorption coefficient at the silicon absorption edge of 1.84 keV. The absorption length of this photon is equivalent to an 800 eV photon but the signal to noise ratio is larger. The histogram for this energy shows a broad distribution of events centered around 1650 eV and the measured energy resolution of ~26 %. Also evident in the pulse height is a distribution of events below the photo-peak which extends down to the threshold energy. For these events most of the signal charge is lost and no energy information can be obtained.

Table 6.2 summarises the energy resolution measurements from R66 at all the x-ray lines.
Figure 6.4: Quantum efficiency measurements for R66. The solid curve is a best fit to the data using an effective dead layer thickness of 0.65μm.

Figure 6.5: Pulse height response of device R66 at three soft x-ray energies. The histograms are produce from the whole event data.
Table 6.2: Energy resolution measurements from R66 at 6 x-ray line energies. * Resolution not possible to measure due to excessive charge loss

<table>
<thead>
<tr>
<th>Energy eV</th>
<th>absorption length μm</th>
<th>Resolution measured %</th>
<th>Resolution predicted %</th>
</tr>
</thead>
<tbody>
<tr>
<td>525</td>
<td>0.5</td>
<td>*</td>
<td>25</td>
</tr>
<tr>
<td>930</td>
<td>2.4</td>
<td>47</td>
<td>14</td>
</tr>
<tr>
<td>1487</td>
<td>8.0</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>1740</td>
<td>10.0</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>2015</td>
<td>1.5</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>4510</td>
<td>14.0</td>
<td>3.9</td>
<td>3.6</td>
</tr>
</tbody>
</table>

It was shown in section 6.2.1 that the epitaxial layer thickness of these devices results in the CCD being not fully depleted under normal bias conditions, with the extent of the depletion layer controlled by varying the substrate potential because the field is very weak near the etch boundary. This effect was examined by operating the CCD over a range of substrate bias voltages from 1 to 5 volts. Figure 6.7 shows the pulse heights obtained from the CCD for two substrate bias levels of 1 and 5 volts. As the depletion layer width is reduced, by increasing the substrate voltage, the spectroscopic performance of the CCD degrades. The number of isolated events decreases from around 60% at 1 volt $V_{ss}$ to 20% at 5 volts because of the increased charge spreading between pixels. In the event histogram obtained from the raw data, the increased charge spreading results in...
in a downwards shift in the distribution of event energies. The pulse heights obtained from the whole event data show the position of the peak energy also to be shifted downwards in energy, reflecting the decreasing ability of the CCD to recover all the charge generated from an x-ray event spread over more than one pixel. Figure 6.8 plots the fraction of the total charge measured from an x-ray event as a function of the substrate voltage at the P-K line energy. The Figure shows that the fraction of charge measured decrease from 82 % at 1 volt to 55 % at 5 volts substrate bias. The Figure shows increasing charge loss from the x-ray events as the field free layer width increases. Finally, the reduction in the isolated event fraction arising from the increased charge spreading is plotted in Figure 6.9 for the same substrate voltages.

6.2.5 Discussion of the Results

Improved quantum efficiency of the CCD to soft x-rays has been demonstrated but the resulting spectroscopic performance of the device is poor compared with a front illuminated CCD. The reason for this is that the ability of the CCD to measure all the signal charge generated by an x-ray event is impaired.

In the simulation work of Chapter 5, it was shown that loss of signal charge will occur through recombination in the highly doped, p+ implant layer. For most of the implant region the value of the charge collection efficiency is <1, but since the implant width is around 0.3μm, charge loss in the implant will only be significant for x-rays with absorption lengths below 0.5μm (<500 eV). This mechanism alone therefore does not account for the poor energy resolution observed at higher energies.

However, it was also shown that the finite noise levels of the detector necessitate the use of a detection threshold to reject random noise events from x-ray events. In the low energy region where
Figure 6.7: Pulse height histograms of CCD R66 produced from raw, isolated and whole event data at substrate voltages of 1 and 5 volts at an x-ray energy of 2015 eV
Figure 6.8: Charge collection efficiency as a function of substrate voltage for P-K photons

Figure 6.9: Isolated to whole event ratio as a function of substrate voltage for P-K photons
the noise threshold is comparable to the x-ray energy, the distribution of charge over several pixels will result in charge loss from the event during the measurement process. As was shown in Chapter 5, diffusion of charge is only significant in the field free region of the CCD. Charge generated in the depletion layer is generally confined to a single pixel yielding good spectral resolution. The energy resolution at low energies is therefore particularly sensitive to the extent of depletion of the epitaxial layer. This was shown to be the case in Figures 6.7 and 6.8 where the charge collection efficiency and the pulse height energy resolution was shown to decrease as the field free layer width was increased. In the case of the O-K line energy (525eV) pulse height spectra sub-threshold charge loss has reduced most of the event signal levels to just above the noise threshold. The quantum efficiency will therefore be dependant on the system noise level. The complete insensitivity of the device to the detection of C-K radiation (277eV) can also be explained in terms of the signal to noise. At this energy the detection threshold is around 80 % of the photon energy so that signal charge diffusion results in most signal levels in a pixel being below the threshold level upon collection in the buried channel.

The signal to noise ratio can also account for the higher than predicted quantum efficiency at the P-K line (2015eV) of 90%. The simple quantum efficiency model for the CCD given by equation 6.1 was found to give a best fit to the low energy data for a dead layer thickness of around 0.65µm. The quantum efficiency should therefore be around 70 % for the P-K photons because the change in absorption coefficient at the silicon edge results in an absorption length equivalent to an 800 eV photon. However, because of the higher signal to noise ratio the detection efficiency is higher than predicted by the simple model.

These results demonstrate the fact that the reduction in quantum efficiency at low energies is a function of the signal to noise level and the geometry of the device. The simple quantum efficiency model can be used to account for the combined effect of these factors through the use of an effective dead layer thereby provides a method of quantifying the device response. The effective dead layer also provides a simple way of comparing the response of different back illuminated devices in the mode in which they are operated.

Finally, as the absorption length increases, a larger fraction of x-ray photons are absorbed in the depletion region of the device. Thus the energy resolution should approach that predicted by equation 6.2. Figure 6.10 illustrates this by showing the pulse height response obtained from the CCD using isolated events generated by a Ti-K line at 4510 eV. At this energy the absorption length is around 14 µm so around 80 % of events will interact within the depletion layer if the field free layer at the rear of the device is assumed to be around 3µm. These events will therefore be mostly confined to a single pixel and produce the x-ray line feature seen in the spectrum. Few partial events are produced and the low energy distribution of events above the noise threshold is believed to be due to interactions originating from within the field free layer. The energy resolution was found to be about 4 % which is slightly higher than the value of 3.6 % predicted for the measured system noise. This is due to the slight low energy tail on the photo-peak which
Figure 6.10: Back illuminated isolated event histogram for Ti-K line x-rays (4510 eV) which have an absorption length of around 15 μm.

results from sub-threshold charge loss in some events.

6.2.6 The Effect of Pixel Binning

It has been shown that the degradation of the CCDs spectroscopic performance occurs mainly because charge is not confined to a single pixel and charge loss can result because of the noise on each pixel. However, if the size of pixel matches the width of the charge cloud the energy resolution of the CCD should be improved. This can conveniently be achieved by summing up the signal charge from more than one pixel before the measurement process by using appropriate clocks waveforms to drive the CCD. This is referred to as “on chip binning”.

Figure 6.11 shows the pulse heights obtained from the raw, isolated and whole event data for pixel sizes of 1 x 1, 2 x 2, 4 x 4 and 6 x 6 pixels with P-K x-ray illumination (2015 eV). The data show the improvement in the energy resolution as the pixel size is increased. An x-ray line begins to emerge in the raw data showing that an increasing proportion of the signal charge is being collected in the larger pixel. The whole event data and isolated data show a gradual decrease in the width of the pulse height distribution and a reduction in the number of partial events. With a 4 x 4 pixel size around 90 % of events are isolated and the energy resolution has increased from 28 % to 12 % FWHM. Almost the full spectroscopic resolution has been recovered although the noise has increased due to the addition of the dark current contributions from each pixel. In the final pixel size, 6 x 6, no further improvement will occur because over 95 % of events are now isolated. Table 6.3 shows the increase in isolated event energy resolution with pixel size along with the predicted resolution for the device taking into account the increasing noise level.

Finally, although nearly all the signal charge is confined to a single pixel in the largest pixel
Figure 6.11: The effects of increasing the pixel size on the spectroscopic performance of the CCD. The histograms were produced for pixel sizes of 1 x 1, 2 x 2, 4 x 4 and 6 x 6 standard pixels and P-K x-ray illumination was used.

<table>
<thead>
<tr>
<th>Pixel Size</th>
<th>Resolution %</th>
<th>Predicted Resolution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 1</td>
<td>54</td>
<td>6</td>
</tr>
<tr>
<td>2 x 2</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>4 x 4</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>6 x 6</td>
<td>12</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 6.3: Measured and predicted energy resolution for four pixel sizes at a photon energy of 2015eV
size, a number of partial events exist in the pulse height which have distribution extending from the photo-peak down to the noise threshold. These events are believed to have been generated in the implant region and therefore have suffered some recombination of charge. This is further substantiated by the fact that the fraction of the total number of these events is about 20 % which is close to the value of 16% predicted for an implant layer of around 0.3 0.3 μm in width.

6.2.7 Summary of Under-thinned Back Illuminated CCDs

The under-thinned back illuminated CCD has demonstrated an improved quantum efficiency below 2 keV, compared to a front illuminated CCD but with a poorer energy resolution. It has been shown that the principle reason for this is because diffusion of signal charge in the field free region of the device reduces the signal levels in the pixels of an event. Charge loss may then occur because of the finite noise levels on the pixel introduced during the measurement process. The signal to noise ratio is therefore a critical parameter in assessing the spectroscopic performance of the CCD. Through the use of pixel binning most of the energy resolution of the CCD has been recovered confirming this mechanism of charge loss.

In the case of C-K photons, the small signal charges of around 75 electrons, generated within the CCD cannot be measured because charge diffusion reduces the signal levels in the CCD pixels to below that of the noise threshold. Thus although the actual dead layer of the CCD is only due to the thin native oxide which forms on the rear surface (10Å), the measured quantum efficiency of the CCD is dependant on the x-ray signal to noise ratio. A parameter was introduced to allow a comparison of the CCDs low energy response to be made which is called the effective dead layer. For the under-thinned CCDs this was found to be around 0.65μm.

6.3 Fully Depleted Back Illuminated CCDs

6.3.1 Device Description

Fully depleted back illuminated devices were produced from the same batch of silicon wafers as the under-thinned devices but were etched further into the epitaxial layer, leaving a 20 μm thick epitaxial layer. This was done to ensure that the whole device would be fully depleted under normal clock biases so that the amount of radial charge diffusion would be minimal. The rear surface of these devices was implanted using a 25 keV Boron ions implant energy which was laser annealed to bring the rear surface into accumulation.

6.3.2 Quantum Efficiency

Detection efficiency measurements were made on three back illuminated devices, R292, R293 and R340. All three devices were found to have similar performance and the results described in this section were obtained from device R292. The improved low energy sensitivity of these devices
was such that efficiency measurements were made down to the C-K line energy at 280 eV. The quantum efficiency measurements are tabulated in Table 6.4 and the efficiency is given for both isolated and whole event data. The final column in the table shows the quantum efficiency of a front illuminated, high resistivity CCD for comparison.

The fully depleted back illuminated CCD has a greatly improved soft x-ray quantum efficiency with a measured value of 17% at 280 eV. The whole event quantum efficiency data is plotted in Figure 6.12. A best fit to the measured data using the simple quantum efficiency model given by equation 6.6, for a depletion layer thickness of 20μm, gave an effective dead layer thickness of 0.23 μm for the device. The solid curve in the Figure shows the predicted efficiency for the effective dead layer thickness.

The quantum efficiency at the Silicon (1740 eV) and Phosphorous K (2015 eV) line energies, straddle the silicon absorption edge at 1.84 keV, and thus provide an indication of the thickness of the epitaxial layer because the change in quantum efficiency at the absorption edge is determined by the change in transmission of the CCD's epitaxial layer. Equation 6.3 gives the ratio of the quantum efficiency at each side of the absorption edge

\[
QE \text{ ratio} = \frac{1 - e^{-\mu_{sil} x_{epi}}}{1 - e^{-\mu_{sil} x_{epi}}}
\]

where \( \mu_{sil} \) is the absorption coefficient for silicon on either side of the absorption edge and \( x_{epi} \) is the thickness of the epitaxial layer. For a 20 μm thick epi layer, equation 6.2 gives a ratio of 0.76. The value extrapolated from the quantum efficiency measurements is 0.80±0.08 which is in close agreement with the theory.

### 6.3.3 Pulse Height Spectra

Pulse height spectra were obtained for device R292 for a range of soft x-ray line energies. Figure 6.13 shows the whole and isolated event pulse height distributions for the C-K (277 eV), O-K (525 eV), Cu-L (960 eV), Mg-K (1250 eV) and the P-K (2015 eV) emission lines.
Figure 6.12: Whole event quantum efficiency measurements for R292. The solid curve is the best fit to the data corresponding to an effective dead layer of 0.23μ.

Two distinct features of the pulse height spectra can be seen. The first feature is an x-ray photo-peak for which events have undergone little charge loss. The energy information from such events is therefore intact. The second feature is the low level pulse heights due to partial events which have lost part of their signal charge. This effect becomes increasingly dominant as the absorption length decreases. At 277eV, all the events have suffered signal loss and the resulting spectral feature that can only be partially resolved from the noise.

Figure 6.14 plots the isolated to whole event ratio for three soft x-ray energies (2015 eV, 1250 eV and 940 eV), over a range of substrate voltages from 2 to 9 volts. The high value of the ratio indicates that radial diffusion in this CCD is minimal because the epitaxial layer is fully depleted. Furthermore, the constant value of the ratio up to the maximum possible substrate bias of 9 volts shows that the device remains fully depleted over the whole range of bias voltages. This confirms that the depletion field within the epitaxial layer is broadly as predicted in Figure 6.3.

The CCD response was found to be linear for all x-ray energies except for the C-K line energy. This shows that for events in the photo-peak, except for the C-K line energy which is poorly resolved from the noise, the signal charge is being measured without loss.

The energy resolution for device R292 was determined for each x-ray line. Upper and lower energy limits were set at the point where the bin counts were at 10% of the peak. The data is shown in Figure 6.15 with the solid line the predicted value calculated from equation 6.3 using the measured noise level of 10 electrons rms. For x-ray energies above 900 eV, the data and theory are in good agreement, indicating that the energy resolution is determined by the system noise and that there are no charge loss mechanisms degrading the expected resolution. However, below 900 eV, the measured resolution deviates from the theory due to the increasing fraction of events with
Figure 6.13: Isolated event and whole event pulse height histograms for C-K (280eV), O-K (525eV), Cu-L (960eV), Mg-K (1250eV) and the P-K (2015eV) line energies
Figure 6.14: Isolated to whole event ratios for a range of substrate voltages showing the fully depleted nature of the epitaxial layer in the device.

Figure 6.15: Energy resolution measurements for R292 for both isolated and whole event data.
only part of the signal charge measured. The Figure also shows the intrinsic resolution for silicon given by

$$\text{FWHM} = 2.36\sqrt{\text{FWHM}} \text{ eV}$$

The data show that in the soft x-ray band the noise level in the CCD test facility dominates the energy resolution of the detector.

6.3.4 Origin of the Partial Events

The principle feature that degrades the spectroscopic performance of the fully depleted CCD and ultimately reduces its quantum efficiency in the soft x-ray region is the creation of events with only part of the total signal charge measured. The most dominant signal loss mechanism in this case is probably due to charge recombination in the implant rather than signal loss through radial diffusion, which was found to be the case in the under-thinned devices. To confirm this, the measured fraction of the partial events produced in the CCD can be used to determine the thickness of the implant layer based on the absorption length of the photons. The fraction of events, $f$, absorbed in an implant layer of thickness $d$, is given by

$$f = 1 - e^{-\alpha d}$$

where $\alpha$ is the absorption coefficient of the X-ray photon energy and since the absorption lengths are short compared to the CCD thickness, the epitaxial layer can be assumed to be 100% absorbing.

The partial event fractions calculated for R292 are shown in figure 6.16 which plots $\log_e(1 - f)$ against the absorption coefficient. The best fit line through the data gives a value of the implant layer width of $0.26 \pm 0.04 \mu m$. This is in close agreement to the value of the implant width produced for these devices which was shown in Figure 3.9 which has a width of around $0.28 \mu m$ (Charge collection efficiency < 100%). This results therefore confirms that the partial events are caused by recombination in the implant layer.

6.4 Dark Current in Back Illuminated CCDs

The dark current levels in the etched region of the back illuminated devices tested were found to average around 2 to 3 times higher than in the un-etched regions of the devices. The un-etched regions showed dark current signals similar to a front illuminated CCD. Figure 6.17 shows the dark current signal in electrons pixel$^{-1}$ s$^{-1}$ plotted as a function of temperature for device R367 for both the etched and un-etched regions of the device. The un-etched region has the expected temperature dependence of dark current with temperature as given by the diode law (equation 2.15) which predicts the value of the gradient for the curve to be equal to half the silicon band gap energy of 0.55 eV. The experimental data gives a value of $0.58 \pm 0.03$, in good agreement with the theory.
Figure 6.16: Partial events fractions calculated for back illuminated CCD R292. The solid line is a best fit to the data giving a value of $d = 0.26 \, \mu\text{m}$.

Figure 6.17: Dark current measurements on a fully depleted back illuminated CCD for both the etched (thin) and un-etched (thick) regions of the device.
The dark current from the etched region shows the same temperature dependence but with a 2 to 3 times higher dark current level. Initially it was thought that the origin of this additional component of dark current was due to the rear surface states of the etched oxide silicon. However, in that case the gradient in the Figure would have a an extra component, $V_{s}$, corresponding to the surface potential energy that the electrons need overcome inorder to escape from the rear depletion well. In Chapter 3, it was shown that the surface potential is around 0.2 to 0.3 volts. A dark current component with a work function of 0.2-0.3 volts is not seen in this data.

Studies on annealed ion-implanted silicon have shown that the rapid annealing of the implanted layer creates defect levels around the silicon mid-band gap energy which are not present in thermally annealed samples (Hartiti et al1989, Johnson et al1979). These defects, measured by deep level transient spectroscopy, are found at, 0.18, 0.25, 0.34, 0.43, 0.53 and 0.6 from the valence band energy and are produced during the rapid melt and recrystalisation process of laser annealing. Consequently they have been found not to depend on whether a Ruby or a Excimer laser is used. Since levels around a few kT of the band gap are effective in dark current generation only the 0.53 and 0.6 levels will be of importance. Both these energies lie within the experimental error of the gradient determination. The density of states for these defects is found to be greater than $5 \times 10^{14} \text{cm}^{-3}$ and decreases with depth into the implant layer. Treating the implant layer as a dark current generating surface of width 0.3 $\mu$m, this gives a value of $1.5 \times 10^{10} \text{cm}^{-2}$ for the surface state density. This is close to the surface state density for a thermally annealed oxide of around $10^{10} \text{cm}^{-2}$. Since the dark current in the CCD is proportional to the surface state density, dark current levels comparable to the component from the front surface states could therefore be produced by the annealed implant. This would account for the additional increase seen in the dark current of the etched region. This additional dark current will not be observed in the thick region since it is lost through recombination in the highly doped 500$\mu$m thick substrate. Further work will need to be done in the future to determine the origin of the extra dark current component in these devices.

6.5 Conclusion

The results from the back illuminated devices studied have shown that an improved soft x-ray response of the CCD can be achieved by the technique of back thinning. The factors that limit the energy resolution and quantum efficiency have been shown to be mainly as a result of signal charge loss through diffusion of charge in any field free region of silicon or through recombination in the rear implant layer. In the case of charge diffusion the energy resolution and detection efficiency of the under thinned CCDs was severely compromised. This is shown in Figure 6.18 which plots the quantum efficiency data obtained from both the under-thinned and fully depleted devices. The solid curve is a Monte-Carlo simulation of the detector efficiency which was described in Chapter 5, and uses actual CCD parameters to predict the device response. The good agreement between the
Figure 6.18: Quantum efficiency measurements obtained from the under-thinned and fully depleted CCDs. The solid line is the predicted response using a Monte-Carlo simulation.

The model and data confirm the necessity of using a Monte-Carlo approach to predicting the device performance for the back illuminated CCD.

Through the use of on-chip binning, the performance of the under-thinned CCD was found to be recovered by matching the pixel size to the charge cloud diameters. This technique can also have implications for the high energy response of the CCD which currently is limited by the resistivity of silicon available from manufacturers. At present, this is around 2000 Ωcm and the corresponding depletion depth will be 30 μm. By pixel binning, epitaxial layer thicknesses greater than 30 μm can be utilized thus extending the high energy response. Based on this, a possible structure for a JET-X or EPIC CCD could be a 90μm epitaxial front illuminated device which has a 30μm depletion layer and a 60μm field free region. Pixel binning will recover the energy resolution of events generated in the field free layer and thus extend the detection efficiency of the device. Figure 6.19 shows a simulation of the effect of pixel binning on the energy resolution of the detector. Without binning, the predicted isolated to whole event ratio is around 0.56 with a large low energy bulge of events created through charge loss as a result of diffusion in the field free layer. With a pixel size of 4 x 4 the isolated to whole ratio is 0.92 and the energy resolution has been recovered. The quantum efficiency is also predicted to be 59% which is close to the expected value of 0.61% for a 90μm epitaxial layer.
Figure 6.19: Simulated pulse height spectra of a 90\(\mu\)m epitaxial JET-X CCD in which 30\(\mu\)m is depleted to 9 keV x-ray photons for two pixel sizes of 1 \(\times\) 1 and 4 \(\times\) 4

6.6 Thin Electrode CCDs

6.6.1 Introduction

It has been shown that the back illuminated CCD can achieve high quantum efficiency in the soft X-ray band but the early development stage of these devices means that a flight detector cannot be qualified in time for the launch of the first X-ray telescope dedicated to imaging and spectroscopy. This will be the JET-X instrument flying on the Russian SPECTRUM-XG mission and is due for launch in 1994. This project also requires a number of CCD developments including fabrication of larger area devices and these technologies are more readily solved for front illuminated CCDs. Development work therefore has been carried out on ways of optimising the front illuminated CCD for soft X-ray spectroscopy and the results from a device with a new electrode structure that has a transmission optimised for low energy X-ray efficiency are presented in the next sections.

6.6.2 Device Architecture

The front illuminated devices fabricated by EEV for this work had a thinner electrode structure than a standard CCD so that absorption losses would be kept to a minimum. To reduce electrode absorption, the polycrystalline electrodes and oxide layers were made as thin as possible with the most to be gained by reducing the Poly 3 thickness because it is not overlapped by the other electrodes in the 3 phase structure. Further gains are possible by removing the vapox layer but again this is only feasible for the poly 3 electrode to prevent inter-electrode shorts. A description of this new electrode structure has been given in Chapter 3 and the dimensions are shown Column 2 in Table 6.5.
<table>
<thead>
<tr>
<th>structure</th>
<th>Standard CCD (µm)</th>
<th>Thin electrode CCD (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly 1</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Poly 2</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Poly 3</td>
<td>0.4</td>
<td>0.175</td>
</tr>
<tr>
<td>Poly1 Vapox</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Poly2 Vapox</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Poly3 Vapox</td>
<td>0.6</td>
<td>&lt; 10 Å</td>
</tr>
<tr>
<td>Phase Oxide</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Gate Oxide</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Poly1 width</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Poly2 width</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Poly3 width</td>
<td>7.3</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Table 6.5: Dimensions of a standard and the experimental front illuminated CCD electrode structures fabricated for improved x-ray transmission

To demonstrate the technique for thinning the electrode structure, experimental devices were fabricated by EEV with the poly 3 electrode thickness reduced to 1750 Å and the poly 3 vapox etched away. For comparison, column 1 in the table shows the dimensions of the standard CCD electrode structure.

6.6.3 Quantum Efficiency

The soft x-ray quantum efficiency of the experimental CCDs was measured on two devices fabricated on 100 Ω-cm silicon, with the experimental electrode structure described above. The device numbers were 9178/18/51, 9178/18/58. Figure 6.20 plots the measured efficiencies obtained from the whole event data. For comparison the Figure also shows the predicted and measured data obtained for a standard electrode structure.

The measurements show an improved soft x-ray efficiency compared to a standard CCD. A quantum efficiency of 13 ± 3 % has been measured at the lowest energy generated by the C-K emission line of 277eV. At this energy a standard electrode structure shows a negligible sensitivity.

The Figure also gives the predicted efficiency for the CCD using the equation

\[
\text{Quantum Efficiency} = \prod_i \exp^{-x_i \sigma_i} (1 - \exp^{-x_{dep} \sigma})
\]

(6.7)

where \(x_i\) and \(\sigma_i\) are the thickness and absorption coefficients of the \(i^{th}\) element of the electrode structure, \(x_{dep}\) is the depletion layer depth of the device and \(\sigma\) is the absorption coefficient for the silicon epitaxial layer. The term outside the brackets represents the transmission of the electrode.
Figure 6.20: Quantum efficiency measurements made on the experimental thin electrode CCDs. The solid line is the predicted quantum efficiency given by equation 6.6. Also shown for comparison is the measured QE for a standard electrode CCD.

<table>
<thead>
<tr>
<th>Energy eV</th>
<th>Standard CCD %</th>
<th>Experimental CCD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>278</td>
<td>&lt; 1</td>
<td>13±3</td>
</tr>
<tr>
<td>525</td>
<td>8±2</td>
<td>17±3</td>
</tr>
<tr>
<td>677</td>
<td>11±2</td>
<td>17±2</td>
</tr>
<tr>
<td>960</td>
<td>33±3</td>
<td>39±2</td>
</tr>
<tr>
<td>1250</td>
<td>35±3</td>
<td>42±3</td>
</tr>
<tr>
<td>2015</td>
<td>46±3</td>
<td>62±3</td>
</tr>
</tbody>
</table>

Table 6.6: QE measurements for standard, experimental and optimised front illuminated CCDs.

structure. At soft x-ray energies the equation gives a good fit to the data showing that the efficiency at energies below 1 keV is dominated by the transmission of the electrode structure. Table 6.6 tabulates the quantum efficiency measurements for the experimental CCD and the standard CCD. Finally, Figure 6.21 shows a scanning electron microscope image of a single pixel in cross section of the thin experimental electrode, confirming the structure dimensions used in the model.

6.6.4 Soft X-ray Pulse Height Spectra

The x-ray pulse heights obtained from both the isolated event data and the whole event data are shown in Figure 6.22 for the thin electrode devices fabricated on 100\textmu cm resistivity silicon. This resistivity gives a depletion depth of around 10\textmu m which is better matched to the absorption
Figure 6.21: Electron microscope photograph showing the experimental thin electrode structure of a single CCD pixel produced by EEV. The thinner Poly 3 and etched vapox layer can be clearly seen confirming the expected processed device electrode structure.

lengths of the soft x-ray photons generated by the monochromator, than a standard resistivity device, thus ensuring that all the events are absorbed in the depletion layer.

The pulse heights show a clearly resolved line, well separated from the noise threshold. The pulse height distributions are gaussian and centered on the photon energy, indicating that there is no charge loss in the device. At the C-K line energy (278 eV), the data does show some partial events above the noise threshold which are believed to be noise events. The data show that virtually all events are isolated in nature, reflecting the fact that soft x-ray absorption takes place in the depleted region of the CCD so little charge spreading occurs. Consequently little processing of the raw data is required to extract the energy information from the CCD data. Figure 6.23 shows the measured energy resolution for the isolated and whole event data from the CCD plotted against the square root of the energy. The solid line is the predicted resolution. The measured energy resolution was determined between the 10 % points on the spectral line. The results are in good agreement with the predicted resolution at all soft x-ray line energies investigated. This shows that there are no other additional mechanisms affecting the intrinsic energy resolution of the device other than the system noise. Charge loss mechanisms are therefore not significant in this CCD. This conclusion is further borne out by the linear output (signal vs energy ) obtained with this device.

6.7 Charge Transfer Efficiency on Energy Resolution

The ability of the CCD to transfer signal charge from pixel to pixel efficiently is also important in achieving good energy resolution. Unless this process is totally efficient charge will be left behind in
Figure 6.22: Pulse height histograms produced from the isolated and whole event data obtained from the experimental electrode CCDs
Figure 6.23: Energy resolution measurements for experimental electrode device. The solid line is the predicted resolution calculated for the same system noise levels obtained by the monochromator.

The trailing pixels and if severe the signal charge may be smeared over a number of pixels, reducing the spectroscopic efficiency of the CCD. Furthermore, poor CTE will also provide an additional source of noise which broadens the spectral lines. In this case, the energy resolution given by equation 6.2 has to be modified to account for the charge loss during transfer. The expression therefore becomes

$$\text{FWHM} = 2.335\omega \sqrt{n^2 + \frac{FE}{\omega} + \sigma_{\text{cte}}^2}$$  \hspace{1cm} (6.8)$$

where $\sigma_{\text{cte}}$ is the additional component of noise due to the charge transfer. In the simplest model this noise component can be equated to the shot noise on the number of carriers lost. Thus for $n$ transfers and a CTE value of $\eta$ the variance is given by

$$\sigma_{\text{cte}} = \sqrt{(1 - \eta^n)N_{\text{sig}}}$$  \hspace{1cm} (6.9)$$

where $N_{\text{sig}}$ is the charge packet size. The effect on the energy resolution is a combination of the line broadening due to the transfer noise and the broadening due to the displacement of the photo-peak position. For this reason, although the $x$ and $y$ coordinates of an x-ray event can be used to recover the mean charge loss in further event processing, the line will still be broadened by the transfer noise. Full recovery of the CTE can be achieved if the CTE values for each individual CCD pixel are known. Figure 6.24 shows the CTE in the serial direction before and after the CTE has been corrected. The correction is applied to an event using the equation

$$f = (1 - \eta)^{x,y}$$  \hspace{1cm} (6.10)$$

where $\eta$ is the CTE value and $x, y$ are the event coordinates, to determine the mean charge loss. Although the corrected CTE has improved from 0.99975 to 0.999987, the line peak for each position along the array varies randomly about the mean line energy due to the transfer noise.
Text cut off in original
6.7.1 Energy Dependance of CTE

Figure 6.25 shows a composite plot of the serial CTE for several x-ray lines obtained using a back illuminated CCD. The mean measured value of the CTE is $0.99996 \pm 0.00002$. This value is sufficiently high that the charge transfer will have little effect on the energy resolution. The greatest fractional charge loss is around 2% which even at the lowest x-ray energy, (278 eV), will result in only a 4 eV loss of energy. The Figure also shows that the CTE is independent of the x-ray energy to within the measurement error. This result supports the theory outline in Chapter 3 for the charge trapping and emission mechanisms which suggested that the amount of charge trapped is proportional to the number of signal electrons in the conduction band.

6.7.2 Serial CTE and Temperature

In most CCDs the serial CTE values are less than the values for the parallel direction. In a typical CCD these are

$$\eta_{\text{serial}} = 0.99997 \pm 0.00003 \quad \eta_{\text{parallel}} = 0.99996 \pm 0.000003 \quad (6.11)$$

It is believed that this difference in the CTE arises from the presence of charge trapping states within the silicon bulk. In Chapter 2, the theory of charge trapping was outlined and the equation governing the release of signal charge from a trap was given by

$$\tau_r = \frac{\exp(\frac{E}{kT})}{\sigma v_{\text{th}} N} \quad (6.12)$$

where $\tau_r$ is the release time constant, $T$ is the temperature, $E$ is the trap energy, $k$ is Boltzmann constant, $\sigma$ is the trap cross section, $v_{\text{th}}$ is the thermal velocity and $N$ is the density of states in the conduction band. The equation shows that for a given trap energy, the release time is an
Figure 6.25: Composite serial CTE plot for device R292 for several x-ray line energies

exponential function of temperature. Thus as the silicon temperature decreases, the release time constant will increase. This should result in a decrease in CTE since charge is more likely to be released into the following pixels of a transfer as the release time constant grows. In most devices the serial CTE is found to degrade as the temperature is decreased indicating the presence of a trap that is responsible for the charge transfer inefficiency. Figure 6.26 shows the serial CTE measured as a function of temperature for several devices. As the temperature decreases below about -100 degrees the CTE decreases consistent with an increase in the release time constant for the trap.

The position of the trap within the band gap can also be inferred from the difference in CTE in the serial and parallel directions. The typical serial clock cycle time is around 0.8 µs while the parallel cycle time is around 10 µs. The trap release time constant must therefore be around a few microseconds and corresponds to an energy of about 0.2 eV below the conduction band.

6.7.3 Methods of Reducing Dark Current

Dark current is generated from four main components; the oxide/silicon surface interface, the depleted bulk of the CCD, the substrate or undepleted bulk and, in the case of the back illuminated CCD, the rear implant. It was shown in Chapter 2 that the dominant source of dark current in the CCD was from the front surface states. This result can be confirmed by operating the CCD in an inverted state. In this state, the substrate bias level is increased such that the potential at the oxide/semiconductor interface for the off electrode is below the substrate bias. Holes from the p⁺ channel stop regions can therefore collect at the interface, suppressing the dark current generation due to depopulation of the interface states. Figure 6.27 shows the dark current measured for a back illuminated CCD as a function of the substrate voltage at a temperature of -56°C. As the voltage is increased, little change in the dark current rate is observed, but at around 5 volts $V_{ss}$ the dark
Figure 6.26: Variation of CTE as a function of temperature

Figure 6.27: Effect of varying the substrate voltage on the dark current
current reduces rapidly from around 7 electrons pixel$^{-1}$s$^{-1}$ down to $\sim 1$ electron pixel$^{-1}$s$^{-1}$. The CCO is inverted under the off clock phases during integration and the dark current is suppressed. Unfortunately operating a CCD with increased substrate voltage has the effect of weakening the potential well profile in the CCO. This limits the full well handling capacity of the CCO and in some cases the weaker fringing fields can result in poor CTE in some devices. Any field free regions in the CCO are also enhanced and this has been shown to be detrimental to the spectroscopic performance of the detector. Furthermore, the CCO can only be operated with only one electrode during integration because if all the electrodes were in an inverted state the CCO would not be able to store charge.

Two other methods of reducing the dark current in CCOs are described in this next section which achieve lower dark current by increasing the ratio of the inverted to depleted silicon area.

### 6.7.4 Narrow Buried Channel CCDs

The first method investigated was to fabricate CCDs with a narrower buried channel, achieving a reduction in dark current by effectively reducing the geometric area covered by the 'on' electrode. This type of device was fabricated primarily to investigate the radiation tolerance of the CCO where radiation damage results in the formation of traps within the buried channel that degrade charge transfer (Holland et al 1989). Reduction of the channel width, therefore, results in fewer traps encountered by the signal charges during readout and so improved radiation tolerance. In these devices the channel width was reduced from 15 µm to around 5 µm so that a $\frac{3}{7}$ dark current reduction is expected. Figure 6.28 shows the dark current measured for the narrow buried channel CCO over the temperature range -110 to -30 degrees. Also shown is the dark current data for a standard front illuminated CCO. The dark current is reduced by a factor of 3 in the narrow buried channel CCO compared to the standard CCD dark current levels, consistent with the expected change.

These devices were found to exhibit good serial CTE and a low noise ($\sim 8$ ele rms) performance. However, the energy resolution was much poorer compared to standard front illuminated devices. Figure 6.29 shows the whole event and isolated event histograms obtained with a narrow buried channel CCO fabricated on standard resistivity silicon (Device Number 1978/10/15) for the Cu-L (940eV), Mg-K (1250 eV) and P-K (2015eV) line energies. The pulse heights show a large number of events distributed in a bulge below the x-ray line energy. The peak position of the bulge is found to be around 70% of the incident x-ray energy. Pixel binning did not improve the energy resolution for these events, which would be the case if the charge loss was due to diffusion of the signal charge in the device. This suggests that a charge recombination mechanism is the cause of the partial events in the spectra. One possible explanation, is that the surface channel device structure created by the narrower n-type channel creates potential minima for electrons near the oxide/semiconductor interface allowing signal electrons to recombine with the interface states. Shockley Read Hall theory of charge trapping outlined in Chapter 2 suggested that the
recombination probability of electrons in the presence of interface states is proportional to the size of the signal charge. This would explain why the mean fractional charge loss for the partial events is constant and has a value of around 0.7.

The narrow buried channel CCDs exhibited the worst X-ray performance of any CCD tested and because of this a supplementary buried channel structure was devised. In this case, the same channel width is used except that a further implant along the center of the channel is made to produce a small potential well. This small 'supplementary well' confines the charge to a narrow volume whilst still in a buried channel mode. No devices of this type were fabricated during the period of this thesis work.

6.7.5 Inverted Mode

As discussed above, low dark current can be achieved by arranging for the whole imaging area to be in an inverted state. However, with the surface potential pinned in this way, the charge confinement by the potential well structure is lost. To ensure that during image integration the charge confinement is still maintained while in the inverted state, the potential minima under the charge storage electrode needs to be increased. This can be achieved by a level shifting implant under one electrode. In the devices fabricated by EEV, this implant was done under the R43 clock to produce an increased depletion layer under this electrode.

Figure 6.28 also shows the dark current generation from the inverted mode CCD over a temperature range -30 to -50 C. A reduction by around 2 orders of magnitude was obtained for this device showing that the CCD was in an inverted mode during image integration. However the spectroscopic performance was degraded at high energies (2 keV) due to the limited depletion depth of the device as a result of the inverted mode of operation.
6.8 Low Noise Amplifiers

In the soft x-ray band, the intrinsic signal variance determined by the Fano factor is small. For example at 500 eV it is around 4 electrons rms. Thus, the typical noise levels currently obtained with CCDs of around 8 electrons rms, dominate the energy resolution of the detector at low energies. Improvement of the sub keV resolution can be achieved if the noise in the CCD’s output FET can be reduced.

As described in Chapter 2, the signal to noise of the output FET can be increased by reducing the output node capacitance. Typically this is around 0.12 pF in a standard CCD and devices have been fabricated with a node capacitance of around 0.06 pF. This has been achieved through minimising the FET circuit geometry. The noise levels obtained with these devices are around 3.5 electrons rms compared to 8-9 electrons rms measured on standard CCDs.

The first devices to benefit from this development were some P88200 series devices (700 x 1100 pixels), fabricated with the higher gain FET. Figure 6.30 shows the whole event pulse height spectrum for the Ti-K line at 4510 eV obtained with a low noise and a standard FET. At this energy around 70 % of events are absorbed in the field free layer of the CCD and therefore charge diffusion over several pixels will occur. In the case of the higher noise CCD, the data shows the expected low energy tail of events below the photo-peak that have been caused by the effect of the noise threshold in the measurement process. However, for the pulse height data obtained with the lower noise FET, more of the charge is recovered from the spread events because of the higher signal to noise (5σ=50 eV at 3.5 ele rms). The pulse height shows a slight tail of partial events which does not greatly affect the measured FWHM of 120 eV for this device compared to the predicted value of 109 eV.
Figure 6.30: Whole event pulse height spectra obtained for a low noise and standard CCD FET at an x-ray energy of 4510 eV

6.9 Conclusion

This chapter has reported on experimental measurements of the factors that affect the quantum efficiency and energy resolution of CCDs. The highest quantum efficiency at sub keV energies was achieved with a back illumination device (80% at 500 eV). However, the largest QE which could be achieved with the thin 20 Å silicon oxide dead layer was not realised because of the combination of signal charge loss due to the noise threshold and recombination in the implant. The concept of an effective dead layer was introduced which shows the resultant effect of charge loss mechanisms on quantum efficiency. An effective dead layer thickness of 0.3 µm was deduced for the fully depleted CCDs.

Degraded spectroscopic performance in under-thinned devices was found to be caused by the sub-threshold loss of signal charge from the peripheral pixels of a spread event. The energy resolution was found to be greatly improved by on chip pixel binning so that the larger pixel size contains most of the event signal charge. This result also has implications for the high energy efficiency of the CCD. In this case the limit on the available resistivity silicon to around 2000 Ωcm restricts the depletion depth of the CCD to around 30 µm and therefore the high energy quantum efficiency. The technique of pixel binning can therefore be used to improve the high energy spectral resolution by permitting large field free structures in the device to be tolerated with increased quantum efficiency. This is important for future missions in X-ray astronomy where the high energy response of the X-ray optics extends up to 15 keV in energy. The full mirror response can therefore be utilised by operating the CCD in a pixel binned mode.

The highly doped p+ accumulation layer at the rear surface of the back illuminated CCD was found to result in recombination of charge and therefore give rise to partial events in the pulse
heights. The fraction of these events increased with decreasing absorption length and seriously degraded the energy resolution below about 500 eV.

Additional developments to improve the performance of back-illuminated CCDs are under development to decrease the rear implant width. Firstly a controlled anodic oxide will be grown on the rear surface sufficiently thick so that implantation through this will create a narrower dopant profile. Annealing will take place using a an excimer laser that has a shorter absorption length in silicon and is better matched than the ruby laser to the shallower implant width. The second technique will use an electrostatic field to retard the ion beam to a few keV in energy and in this way the profile can be tuned to any implant depth. Annealing using an excimer laser will then complete the rear processing. The effect of the shallower implant width will be to decrease the fraction of events that are absorbed in in this region and therefore improve the energy resolution of the CCD.

The front illuminated thin electrode devices were found to offer the best spectroscopic performance but with an intrinsically lower quantum efficiency. Further improvements in quantum efficiency for the JET-X CCDs will be made by increasing the Poly 3 electrode width too around 17 μm while maintaining the pixel size at 22μm. Thus around 70 % of the pixel structure will have the thinnest possible dead layer. The quantum efficiency of this CCD will have an extended high energy response, up to 10 keV, through the use of deep depletion silicon and extended low energy efficiency, making full use therefore of the optics band pass.
Chapter 7

CCD Optical Filter

7.1 Introduction

The high optical sensitivity of the CCD has made it the ideal detector for imaging of faint, distant astronomical objects. However for x-ray imaging applications, the charge signal generated by visible photons within the CCD will degrade the detector energy resolution because of addition Shot noise and also result in source confusion. Typical optical to x-ray flux ratios from stars are of the order $10^6$, so a light filter is required to attenuate the flux in one frame time to a level that does not impair the CCDs spectroscopic capability. This chapter is concerned with the effects that such a filter will have on the soft X-ray performance of the CCD camera for the JET-X instrument.

The CCD configuration envisaged for the focal plane coverage is by two large area CCDs (770 x 1152 pixels) arranged in two parallel sections to facilitate frame transfer operation. This chapter evaluates the performance of various thin film metalized light filters and investigates the effect of optical contamination from various point source and extended objects on the spectroscopic energy resolution.

7.2 Filter Optical Constants

A typical light filter for the CCD will be made from a plastic substrate, e.g. Lexan, coated with a thin metal layer to absorb and/or reflect the optical flux but with minimum loss by absorption of X-rays. To evaluate the possible filter combinations, the optical attenuation has been calculated within the detection band of the CCD and compared with the resulting soft x-ray efficiency for the same filter.

Data bases have been compiled of the visible, UV and x-ray reflectivity and absorption coefficients of several possible filter materials. Materials chosen for study are aluminium, carbon and beryllium combined with a Lexan substrate. Several sources of data have been consulted enabling a consistent set of optical constants for each of the materials to be compiled (Hagemann
Figure 7.1: Linear absorption coefficients and reflectivities for the visible and x-ray wavelengths for typical filter materials.

\[ T(\lambda) = \prod_i \{1 - R(\lambda)\} e^{-\mu_i(\lambda)t_i}, \]  

(7.1)

where \(\mu_i, t_i\) are the linear absorption coefficient and thickness respectively for each material. Where the complex refractive index \(n(\lambda)\) data as a function of wavelength are available the reflectivity can be calculated using the equation

\[ R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2}, \]

(7.2)

where \(n\) and \(k\) are the real and imaginary parts of \(\hat{n}\).

Figure 7.1 plots the linear absorption and reflection values at normal incidence for the visible and x-ray wavelengths (note x-ray reflectivities \(\ll 1\%\)). The ratio of absorption coefficients at the K-edge were obtained from the values of Zombek 1980. The x-ray absorption coefficients for Lexan \(\text{C}_{16}\text{H}_{10}\text{O}_3\), were calculated by weighting the absorption coefficients for each element by its fractional weight

\[ \mu = \sum_i \mu_i \omega_i, \]

(7.3)

where \(\omega_i\) is the fractional weight of element \(i\) and \(\mu_i\) is the absorption coefficient for element \(i\).
Absorption coefficients for Lexan derived in this way the same as those used for the ROSAT wide field camera XUV instrument (Barstow 1989).

To compare the various filter materials, the relationship between the x-ray transmission at a particular energy and filter transmissions in the optical band have been calculated using equation (4) at the chosen X-ray energy.

\[
\ln \left( \frac{T_x}{1 - R_x} \right) = \left( \frac{\mu_x}{\mu_o(\lambda)} \right) \ln T_o - \left( \frac{\mu_x}{\mu_o(\lambda)} \right) \ln(1 - R_o(\lambda)) - (\mu_x t)
\]

(7.4)

\( T_x \) and \( T_o \) are the x-ray and optical transmissions respectively, \( \mu_x \) and \( \mu_o \) are the x-ray and optical absorption coefficients, \( \mu t \) accounts for the x-ray transmission of the Lexan and \( R_o(\lambda) \) is the optical reflectivity. The term \( R_x \) can be ignored since x-ray reflectivities at normal incidence are very small. The material optical constants are a function of wavelength but to a first approximation they are assumed to be constant to allow the evaluation of Equation 7.4. The values chosen, therefore, for the constants \( \mu_o \) and \( R_o \) were taken at 5000 Å, the wavelength at which the CCD optical response is a maximum.

Figure 7.2 plots the calculated x-ray transmission against optical transmission for Carbon, Aluminium and Beryllium on a Lexan layer of 3000 Å. The figures show that Aluminium plus Lexan filter combination offers the best x-ray transmissions above the C-K edge energy at 0.28 keV for a given level of attenuation of optical photons. The poor x-ray transmission above the C-K edge (0.28 eV) of the Carbon/Lexan filter is because of the large thicknesses required for optical attenuation. The Lexan-Carbon filter is however more transparent to X-rays below the K-edge energy at 0.28 eV because of the low X-ray absorption coefficient of Carbon. The Be-Lexan filter combination is less x-ray transparent than the Aluminium filter over the whole x-ray band. This is because of the large thicknesses of Be required to attenuate the optical flux to the same level as the
Figure 7.3: Predicted soft x-ray transmission for the various filter materials that give an optical attenuation of $10^5$

Aluminum although the x-ray absorption coefficient is around 4 times lower. A significant improvement in the x-ray transmission will only occur below the Be absorption edge energy at 110 eV but this is below the CCD’s detection sensitivity.

In Figure 7.3 the calculated soft X-ray transmissions for each filter with an optical attenuation of $10^5$ is compared. This Figure shows the low transmission of the C-Lexan filter around the C-K edge. The transmission of Al-Lex and Be-Lex are comparable above 0.28 keV, but the Al-Lexan filter gives better transmission below 0.28 keV.

These results show that the Aluminium-Lexan filter gives the best performance. However a practical limit exists to the thickness of the Aluminium layer based on ROSAT wide field camera experience, which showed that with filters of < 1000Å of Aluminium exhibited pin holes in the metal film (Kent 1988). Transmission measurements were made at 1800 Å UV wavelengths in the ROSAT program on three Al-Lexan filters of 3000Å of Lexan on 800Å of Al and showed pinhole transmissions of around $4 \times 10^{-7}$ compared to the theoretical normal incidence transmission of 1800Å of $6 \times 10^{-9}$ in this UV band. This result showed that the transmissions were pin hole dominated. Filter combinations which were found to provide a tolerable level of UV transmission were fabricated with a 2000Å layer of Aluminium. However, for the JET-X instrument such a thick layer of Aluminium would seriously reduce the detector efficiency below 1 keV.

The theoretical optical transmission for a 800/3000 Al/Lexan filter in the CCDs optical band is around $10^{-4}$ and so based on the actual pinhole transmissions above it would seem that for JET-X the pinhole density does not dominate the filters transmission. A 800 Å aluminium layer could therefore be tolerated. Furthermore, the thickness of Lexan could be minimise since atomic oxygen erosion of the Lexan is not as severe for the high Earth orbit of JET-X as for the low Earth ROSAT orbit. Moreover the Lexan is transparent at optical wavelengths so it plays no part in
Figure 7.4: Quantum efficiency of the JET-X CCD with and without an optical filter comprising of 800 Å of Aluminium on 3000 Å of lexan. The optical attenuation of the filter so the Lexan layer can be kept as thin as possible. It would therefore seem reasonable at this stage conclude that a possible filter would comprise of < 1000 Å of Aluminium on 2000 Å of Lexan. The resulting x-ray efficiencies for a filter comprising 800 Å Aluminium layer on a 3000 Å Lexan substrate are shown in Figure 7.4. The Figure also shows the response of the CCD without the filter. In this case the reduction in efficiency is a result of the dead layer structure created by the front electrodes. The combined loss in efficiency of the CCD with the filter is < 15 % in the soft x-ray band because the CCD efficiency is dominated by the electrode layer transmission. Above around 2 keV the filter is virtually transparent to x-rays resulting in a negligible loss of detector efficiency (~ 5% at 2 keV).

7.3 The Optical Point Source Sensitivity of the JET-X Telescope

7.3.1 Introduction

Point source objects such as stars have typical x-ray to optical fluxes ranging from around $10^{-5}$ for hot A type stars to $10^{-1}$ for cooler M type stars. Within the CCD detector one electron hole pair is produced by every optical photon absorbed and the effect of optically generated signal charge is to produce an additional Shot noise component which adds to the detector dark current level. With system noise of around 3 to 4 electrons rms which is typical of CCD systems being considered for X-ray spectroscopy the optical leakage of the filter must not significantly increase the detector noise. The energy resolution of the CCD is given by
where \( n \) is the system noise, \( E \) is the x-ray energy, \( F \) the Fano factor (0.12), \( \omega \) the mean ionisation energy (3.68 eV/electron) and \( n_{\text{opt}} \) is the Shot noise component from the optical flux on which the X-ray signal resides. As a criterion to assess the tolerable level of optical flux, the total increase in the noise must be less than 10% ie

\[
\sqrt{1 + \left( \frac{n_{\text{opt}}}{n^2} \right)} \leq 1.1
\]  

(7.6)

This gives an upper value for the optical flux of 2 electrons pixel\(^{-1}\) frame\(^{-1}\) for a CCD with a noise level of 3 electrons rms per pixel. This value was used to determine the required thickness of Aluminium for the filter.

### 7.3.2 Calculations

The optical grasp of the JET-X telescope, \( G \), as a function of wavelength (\( \lambda \)) is given by

\[
G = \eta(\lambda)R^2(\lambda)A
\]

(7.7)

where \( A \) is the effective collecting area, \( \eta \) is the CCD detector efficiency and \( R \) is the mirror reflectivity and \( R^2 \) takes account of the double reflection of photons by the mirror. A black body source function was assumed for the stars so that the detected number of optical photons by the CCD is given by

\[
detected \text{ flux} = \int A \times T_f \times S(\lambda)\eta(\lambda)R^2(\lambda)\,d\lambda
\]

(7.8)

where \( T_f \) is the CCD frame time and \( S(\lambda) \) is the black body source function:

\[
S(\lambda) = \frac{6.73 \times 10^{11} \times 10^{-0.4m_b}}{P(\lambda, T_e)} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ } \text{Å}^{-1}
\]

(7.9)

where, \( m_b \) is the bolometric star magnitude and \( T_e \) is the effective star temperature and \( P(\lambda, T_e) \) is the relative Plank function (Zombek 1980)

\[
P(\lambda, T_e) = \frac{1.26 \times 10^{-8}}{\lambda^4 \text{ cm} \times T_e^2 \text{ e}^{h \lambda / kT_e} - 1} \text{ Å}^{-1}
\]

(7.10)

For the JET-X mirrors, the half power width HPW is 20 arcseconds, covering a 15 pixel diameter circle in the telescope focal plane (\( F = 3500 \text{ mm} \)). The CCD is operated in a frame store mode, with four output nodes per chip. This will give a total integration time of around 3 seconds. Equation 7.8 is used to calculate the detected flux levels as a function of filter thickness to reach the 2 ph/pixel/frame for a range of star types and magnitudes. Figure 7.5 shows the results of the calculations for the extreme limits of star temperatures, M type (3000 K) and O type (30000 K). With a 800/3000 Al-lexan filter, the upper magnitude limits for the stars range from 4.5 to 6. However the CCD detector can only x-ray photon count if the source flux is < 0.5 photons pixel\(^{-1}\) s\(^{-1}\). This limit is exceeded for stars of brighter than a visual magnitude of
Figure 7.5: Required aluminium thickness to produce negligible optical flux in the CCD as a function of star magnitude for several types of star.

5. This value is straggled by the upper magnitude limits and so for most stars, the spectroscopic resolution of the CCD is not degraded. For the M type stars useful spectroscopy can still be done up to this limit since the energy resolution is only slightly degraded by the increase in noise level to around 3.5 electrons rms caused by the additional light leakage. Finally, at a magnitude of greater than 3 the optical will result in a spurious detection of an x-ray source because the optical signal will exceed the $5\sigma$ energy threshold for the CCD.

7.4 Summary

An Aluminium Lexan filter combination provides soft x-ray transmission that causes only minor loss to the overall X-ray response of JET-X whilst providing adequate attenuation of the optical flux. The 2.0 photon frame$^{-1}$ pixel$^{-1}$ criterion adopted as a negligible optical signal can be met with 800 Å Aluminium layer for all stars up to the JET-X data rate limit of 5$^{th}$ magnitude. It was shown also that for the JET-X CCDs the level of pin holes measured for the ROSAT filters of comparable thickness could be tolerated. This filter will now need to be designed to survive the launch environment and tested to demonstrate if the optical and x-ray properties can be achieved.
Chapter 8

Conclusion and Future Work

This thesis has set out to investigate ways of increasing the detection efficiency of the CCD in the soft x-ray band (below 2 keV). This has required a new test facility to enable the quantum efficiency and pulse height response of the CCD to be investigated down to energies of around 200 eV. This first aim was successfully met with the commissioning of the low energy crystal monochromator test facility described in Chapter 4.

In Chapter 6, experimental data from two different techniques of increasing the quantum efficiency of the CCD were presented. In the first technique, back illumination, the importance of fully depleting the device to achieve the best energy resolution and quantum efficiency was shown. For these devices, a best fit to the quantum efficiency measurement below 1 keV could be made for an effective dead layer of silicon with thickness of around 0.23 μm. Typically the measured efficiency at 525 eV is around 76% compared to ~8% for a standard front illuminated CCD. The energy resolution was reduced from the predicted values because of charge loss resulting in partial events in the pulse height data. The origin of the partial events was shown to be due to recombination in the highly doped implant region of the CCD. This layer is around 0.3 μm thick and charge loss is therefore increasingly important as the photon energy decreases. The good agreement between the simulated pulse height and the experimental data at the C-K line energy verified the modelling used for the recombination of charge in the p+ implant since at this energy, all the x-rays are absorbed in the implant layer because of the short absorption length of 0.1 μm.

For the under-thinned CCDs, a thin field free layer was shown to be present at the rear of the CCD with a width of around a few microns, depending on the substrate bias. This region caused increased radial diffusion of the signal charge which was found to degrade the energy resolution. The reason for this was shown to be due to loss of signals from peripheral pixels in a spread event during the measurement process. These devices had a detection efficiency that was less than the fully depleted CCDs because the threshold induced charge loss and the effective dead layer width was determined to be 0.65 μm. At 500 eV the measured efficiency was 20%. The energy resolution was recovered for these devices by the on chip binning technique where charge from a number of
pixels can be summed together before being measured by the CCD's output node. It was proposed that this method could also improve the quantum efficiency of the front illuminated CCD at high energies because larger field free layers of the device could be tolerated before the resolution is degraded. It is now proposed that the CCDs for JET-X which have a 30µm field free epitaxial layer should use $2 \times 2$ pixel binning to increase the high energy response. Simulations have shown that the high energy efficiency is improved from 22 % to 40% through the use of binning at a photon energy of 10 keV (Wells et al 1991).

In Chapter 5, a Monte-Carlo simulation program gave a good agreement with the experimental data, demonstrating the validity of the modelling used in the various regions of the back illuminated CCD. The Monte-Carlo simulation was also used to predict the quantum efficiency of the fully depleted CCDs. Using similar parameters to the experimental devices, the simulated response was in good agreement with the efficiency measurements. The simulation also confirmed the complex relationship between the various device structures and signal to noise ratio on the sub-keV response. The simulation was also used to predict the performance of a back illumination CCD optimised for low energy spectroscopy using lower noise output FETs and a shallower implant layer. The results of the simulation show both improvements in quantum efficiency and energy resolution of the detector and these developments are therefore currently being pursued at EEV.

The final method of enhancing the low energy response was by fabricating a thinner electrode layer on the CCD to minimise absorption losses. Experimental electrode devices were fabricated with a thin Poly 3 electrode of 0.17µm thick compared to 0.3µm for a standard device. The protective oxide was also removed that covers the whole electrode structure. Efficiency measurements on these device confirmed the expected improvement in detection efficiency from modelling of the transmission of the electrode structure. The measured efficiency of the CCD at 525 eV was 17 %, an improvement of a factor of two over a standard CCD electrode structure. The cosmetic quality of these devices was excellent, with no evidence of bright columns due to inter-electrode shorts. These experimental CCDs demonstrated that the process could be introduced successfully into CCD production without affecting the device yields. Further improvements are being carried out for JET-X to optimise the electrode transmission to soft x-rays by increasing the Poly 3 electrode width whilst keeping the pixel size constant.

In the period since the main experimental programme of this thesis was completed, a back-thinned CCD, embodying supplementary buried channels and low noise preamplifiers has been fabricated for the EPIC Reflection Grating Spectrometer (RGS) programme. The design of this device embodies many of the modelling features and results researched for this thesis and reported in Chapters 5 and 6. The first results from this device have been recently reported at the McGee Symposium on position sensitive x-ray detectors and the paper is included in this thesis in Appendix 1. The RGS instrument will be flown on the XMM mission and will achieve medium energy resolution (100-500) in the band 0.1-2.5 keV by using a reflection grating to disperse the first and second orders from two of the three, high throughput telescopes. A row of 10 CCDs will be placed
tangentially to the Rowland circle of the spectrometer. These will intercept the dispersed spectra from the grating which for the energy range of the instrument has a length of \( \sim 30 \text{cm} \) along the Rowland circle. These CCDs will be large area with around \( 1024 \times 768 \) pixels and be butted together with minimal dead space \(<160\mu\text{m})

Further developments will be concerned with refining the back thinning technology to large area CCDs. Currently EEV are investigating the feasibility of thinning whole devices before packaging to ensure the whole area of the CCD is sensitive to x-rays with a uniform response. The device will need to be supported from the front face, since a thick substrate rim will not be present. This may be achieved by gluing the front surface of the CCD onto a glass substrate before packaging the device and thinning down to the bond pads which will enable the device to be wire bonded to the back of the pad.

The possibility of using the back illuminated CCD in the EUV band \((10 \text{ to } 100 \text{ eV})\) is opened up by virtue of the Silicon-L absorption edge at 114 eV. Figure 2.9 in Chapter 2 shows the change in the absorption coefficient of silicon around the absorption edge feature. The absorption length has a value of 0.04\(\mu\text{m}\) at the high energy side and increases to around 1\(\mu\text{m}\) at the low energy side of the edge. Sensitivity in the Extreme Ultra Violet (EUV) band 100 to 20 eV will therefore be possible because of the thin dead layers in the back illuminated CCD. However, below 500 \(\AA\) (25 eV), the absorption length decreases rapidly, limiting the extent of the response into this band. Figure 8.1 shows the predicted quantum efficiency of a back-illuminated CCD optimised for this wavelength region using a Monte-Carlo simulation of the device response. The CCD has a thin implant of effective width 0.05 \(\mu\text{m}\) to reduce charge recombination effects and a low noise of \(<1 \text{e}\) \(\text{rms}\) to ensure detection of the small photon signals. The technologies to achieve the narrow implant and low noise were discussed in Chapters 5 and 2 respectively. The CCD shows good detection efficiency below 1 keV with a cut off (10\%) at around 20 eV.

The EUV region is also important to astronomers as well as the soft x-ray region. Initially it was thought that the EUV band would be opaque to astronomers because of the interstellar medium Aller (1959) and thus little interest in this region of the electromagnetic spectrum was taken. However, some astronomers argued that the interstellar medium is not as opaque as was though and that it may be very inhomogeneous Cruddace et al (1974) and a EUV instrument on the Appolo-Soyuz mission Lamptonet al (1976). The results from the EUV demonstrated to a sceptical astronomical community that the EUV could return important and useful data in this band and subsequently several important future missions in this region have been proposed which include "EUV Astronomy" (1989). The most recent EUV instrument flown was the Wide Field Camera (WFC) on the ROSAT telescope (Wells et al 1990). This had a band width of around 50 to 150 eV and during the all sky survey has detected many hundreds of EUV sources confirming the rich source fields that can be observed in this band. The successful completion of the first EUV sky survey with the ROSAT WFC has established that many classes of astronomical sources have significant emission in this waveband (Pounds et al 1991). The WFC, which was designed over
a decade ago, has used grazing incidence optics and EUV sensitized microchannel plates to focus and detect the EUV photons. Broad band filters select the band pass and also reject unwanted atmospheric and geocoronal background, to which the MCP detectors are sensitive.

ROSAT's pioneering work in EUV astronomy will be followed by three other missions: EUVE, which will repeat the WFC survey; the EUVITA instrument on SPECTRUM-X and the Los Alamos ALEXIS payload, which will be launched by PEGASUS in late 1991.

The grazing incidence optics on the WFC provide a wide spectral band pass, but the filter bands are necessarily broad. Both EUVITA and ALEXIS will use multi-layer optics, which have a narrow bandpass. The instruments will therefore require six separate telescopes to cover the required spectral range, with narrow narrow bandpass but discontinuous spectral coverage.

Figure 8.2 shows the point source sensitivity of a EUV sensitive CCO coupled with grazing incidence optics compared to the actual ROSAT WFC sensitivities measured at launch. The Figure shows that the CCD/WFC combination creates a sensitive and competitive instrument for EUV spectral studies, to follow up the photometric studies currently being performed by the ROSAT WFC. The EUV CCO could also be used at the focus of a multilayer telescope or to extend the wavelength response of reflection grating spectrometers into the EUV band.

The back illuminated CCO has therefore emerged as a detector that can have many applications in the areas of soft X-ray and EUV astronomy.
Figure 8.2: Point source sensitivity of a WFC/CCD combination, compared against the sensitivities of the real WFC and the SPECTRUM-X EUVITA telescopes.
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