Chapter 5

Charge Loss in the Channel Stops

5.1 Introduction

Channel stops occupy a noticeable fraction of a CCD pixel and can seriously distort the shape of the response function of the device. The mesh experiments clearly demonstrate that X-ray photons interacting within silicon near the pixel boundary separating two columns of the array produce signal charge in two adjacent pixels and produce horizontally split events (see Figure 4-4). Such events are formed either in the heavily doped p$^+$ channel stop region or directly beneath it. The effects of the channel stop are easily seen by comparing the spectrum of vertically split events to those horizontally split. Figure 5-1 shows the response of an ACIS device to monochromatic photons at 1487 eV (the energy of the Al Kα emission line). Only the horizontal events have the noticeable shoulder extending to the low energy side of the Gaussian.

Examining changes in this feature’s behavior with energy, we found that the total number of counts in the shoulder agrees well with the calculated number of photons interacting within a thin layer of silicon near the Si-SiO$_2$ interface. The calculation predicts a sharp increase of the relative intensity of the low energy shoulder at the Si absorption edge which is indeed observed, as shown in Figure 5-2.

This means that the low energy shoulder in the response function of the horizon-
tally split events originates from electron clouds formed inside the p$^+$ channel stop region that suffer some charge loss. Their pulse heights, consequently, are shifted down in energy. Electron clouds formed below p$^+$ layer in the depleted bulk of silicon are collected into potential wells without any loss and they form the main peak in the histogram.

Figure 5-1 CCD response to monochromatic photons of energy 1487 eV. The dashed line is from vertically split events (grade 2), while the solid line is from horizontally split events (grade 3 & 4). The vertically split events are described well by a single Gaussian, while the horizontally split events have a noticeable shoulder extended to low energies. This shoulder is formed by charge clouds undergoing some charge loss.

5.1.1 Evidence for Charge Loss in the Mesh Data

With the knowledge that horizontally split events are undergoing charge loss, we re-analyzed the mesh data by generating RPs from events drawn from different parts
Figure 5-2 Fraction of shoulder events as a function of energy of incoming X-ray photons. A jump at 1839 eV suggests that these events are formed in a thin layer of silicon near Si–SiO₂ interface.
of the redistribution function. First, we separate the spectrum of monochromatic data at 525 eV (the energy of the O Kα emission line) into a photopeak region and a shoulder region. We then generated RPs separately for each part of the redistribution function, using only those 2-, 3-, and 4- events from near the channel stops (i.e. g346). Figure 4-17 (top) shows how the spectrum was divided and the resultant pixel maps for the shoulder (bottom left) and photopeak (right).

The most surprising result is that there are no shoulder events under the one gate that is held at low voltage of -5 Volts during the signal integration. Of equal importance, the intensity of the main peak drops down significantly under the two gates held at +5 Volts. The channel stop region under these two gates accounts for all the “lossy” events that migrate from the main peak into the shoulder. This means that charge loss in the region is entirely determined by the surface potential, as the penetration of the gate-generated field into the substrate is extremely small, given the oxide thickness and relatively heavily doped p⁺ silicon of this LOCOS structure. Another extremely important conclusion is that the charge loss can be entirely suppressed by applying to the gate a negative voltage that repels electrons away from surface. As I showed in §4.9, the amount of the channel stop p⁺ implant can be determined by comparing the relative intensities of peak and shoulder events under the high and low gates at two well-chosen X-ray energies. The measured thickness of ∼0.4 µm is in good agreement with the thickness of the p⁺ field-free region calculated from simulations using a software suite from Silvaco (Prigozhin 1999). This suggests the following model of the charge cloud dynamics.

Any photon interacting with silicon inside the field free region creates a cloud of electrons which spreads out in all directions due to diffusion. Some fraction of the cloud will reach the surface and recombine, if there is a potential well for the electrons at the Si-SiO₂ interface due to the positive gate voltage. If the gate voltage is negative, electrons are reflected back into silicon and eventually get collected into the CCD potential well in the buried channel. In this case the electron cloud does not suffer any charge loss. When the cloud is formed in the depleted region underneath
the p+ layer, electrons are immediately pulled by an electric field which prevent them from reaching the surface. All such clouds are also collected without losses and are detected as part of the main photopeak. Figure 5-3 illustrates the potential wells (as seen by electrons) for the scenarios with a positive and negative gate bias. (N.B. The extent of the upward (−5V) and downward (+5V) swings of the potential at the the SiO2–p+ interface is greatly exaggerated for clarity.)

5.2 Voltage and Temperature Dependence

The complete collection of charge under gates biased at −5 V and the loss of charge under gates biased at +5 V clearly indicates the existence of a transition point between partial and total collection. We acquired data spanning a wide range of voltages applied to the gates of the CCD to find this “no-loss” condition. The mesh technique, although very powerful, requires complicated analysis and requires an enormous effort of time for data acquisition. For example, the 1.4 µm mesh only has an open area of $8.5 \times 10^{-4}$, reducing the available detector area from 604 mm$^2$ to 0.5 mm$^2$. Instead, we developed a different approach to quantify the degree of charge loss.

We again used the in-line focusing monochromator (IFM) used for the second series of mesh experiments. The device was uniformly illuminated with nearly monochromatic (see below) 525 eV X-rays, corresponding to the O Kα emission line. This photon energy is ideal for studies of the channel stop, as the characteristic absorption length of silicon is only $\sim 0.5 \mu m$. Combined with the shallow depth (0.4 μm) of the implant, this guarantees that more than 70% of the incident photons interact inside the doped p+ region, thus making the shape of response for horizontally split events sharply dependent on the degree of surface charge loss. Figure 5-4 shows the rapid change of the histogram shape as a function of the high level voltage $\phi_{\text{high}}$ at the two integrating gates. For all measurements discussed below, the difference between the high gate and low gate is always five volts, i.e. $\phi_{\text{high}} - \phi_{\text{low}} = +5 V$.

When the high gate is operated at 0 V, there is no shoulder and the main photo-
Figure 5-3 Electric potential through the channel stops for two possible gate voltages. In the case of the negative bias, the potential slopes upward at the Si-SiO$_2$ interface, repelling electrons and preventing recombination. In the case of the positive bias, the potential slopes downward at the interface. Electrons that fall into the potential recombine, resulting in incomplete charge collection. The extent of the upward and downward slopes at the SiO$_2$–p$^+$ interfaces have been exaggerated to illustrate the effects of the gate voltage.
Figure 5-4 SRFs of horizontally split events at different gate voltages. Two gates were held high (voltage level $\phi_{\text{high}}$) during the data acquisition. The low gate voltage was maintained 5 Volts lower than the high gates. Incident photon energy is 525 eV.

peak is extremely Gaussian, indicating unity charge collection efficiency in the channel stop region. At 1.1 V, the peak has begun to broaden asymmetrically. At even higher voltages of 1.8 and 2.5 V, the redistribution has clearly become bimodal, with a large shoulder superimposed on the main photopeak.

Horizontally split events are not the only grade affected by charge loss. The channel stops extend more than 4 $\mu$m in width, and charge clouds that have their origin in the wings of the $p^+$ region (see Figure 4-5) will contribute only to the nearby potential well of the CCD and therefore will be detected as single pixel ($g_0$) events. If they suffer some charge loss they form a similar low energy shoulder in single pixel event histograms. At energies where X-ray penetration depth is comparable with the $p^+$ layer thickness (e.g. O K$\alpha$) this results in a dramatic increase of amplitude of the
low energy tail in a histogram.

5.2.1 Measurement method

In order to account for all the events that originate in the channel stop region under the high gates, we need to sum together grade 034 events. By only including these three events types, we ensure that all vertically split events from under the low gate (i.e. grades 2 and 6) do not affect this analysis. After properly accounting for the individual gain of each amplifier chain, all four quadrants of the device were added together.

In order to acquire statistically significant data, we used an oxidized carbon anode in the electron X-ray source that produces the radiation incident to the IFM. Although the monochromator is tuned to filter out all wavelengths except that corresponding to O Kα, there is some spectral contamination present, including low-level continuum and the C Kα emission line at 277 eV. Figure 5-5 shows a typical spectra.

As shown in Figure 5-4, the shoulder is easy to discern when the gate voltage is sufficiently high. However, during the transition from the no-loss to loss condition, the shape of the SRF changes gradually. In order to detect subtle differences between each measurement, we use the measurement with \( \phi_{\text{high}} = 0 \text{ V} \) to generate a template function. Two Gaussian function describes the main O Kα photopeak, a third Gaussian describes the C Kα photopeak, while a constant and linear terms accounts for the continuum. The high-gate voltage was stepped between 0 and 2.5 volts, in increments of 0.23 V. The same experimental conditions were maintained for all measurements, although slight variations in the current of the X-ray source and different integration times resulted in differences in the total amount of incident X-rays. To account for these small differences, the redistribution function of grade 2 events was used to normalize the individual data sets to another. All grade 2 events originate from the under the low gate, and as that voltage is always negative, the shape of the O Kα photopeak is invariant for all measurements. Comparing the total counts in the main photopeak thus provides an excellent method for relative normalization.
Figure 5-5 IFM spectrum of 1- and 2- pixel events (g034) beneath gates with a voltage of 0V. The predominant feature is the O Kα emission line at 525 eV, although there is also a low level of continuum present. The C Kα emission line, generated from the anode, is also present.

At each voltage, the template was subtracted to calculate the fraction of lossy events. Measurements were made at four temperatures, evenly spaced between -120° and -80° C. Additional measurements with higher gate voltages were also made at -120° C. Figure 5-6 shows all the results.

The measurements indicate that above 2.5 V the fraction of lossy events remains constant, although the shape of the histogram continues to change. This is consistent with the assumption that any electron cloud originating inside the heavily doped p⁺ region, where no internal electric field is present, loses some charge due to diffusion towards the surface and subsequent recombination. The amount of lost charge in the individual cloud depends on the field distribution near the surface and continues to
Figure 5-6 Fraction of events undergoing charge loss in the channel stop region as a function of gate voltage. At warmer temperatures, the transition to the no-loss condition occurs at more positive voltage. For $T = -120^\circ$, notice that the fraction of lossy events plateaus above $\sim 2.5$ V.

grow at more positive $\phi_{\text{high}}$, shifting the shoulder to lower energies in the SRF.

The transition voltage shifts with temperature, as shown in Figure 5-6. Measurements of the flat band voltage as a function of temperature were performed on a test structure\(^1\) equivalent to the channel stop configuration. It showed an identical temperature behavior as the shift shown in Figure 5-6. Thus, the dependence on both gate voltage and temperature on the extent of the charge loss mechanism can be understood as arising from a temperature shift in the flat-band voltage. Similar measurements that involved changing the integration time over a wide range, did not

\(^1\) This test structure consists of a MOS transistor with a gate on the top the LOCOS layer.
produce any changes in the shape of the response. Thus, no de-trapping of electrons were detected.

5.3 Future Prospects

The improvements to the mesh technique (§4.9) and our better understanding of the physical processes that occur both in the channel stops (this Chapter; see also Prigozhin et al. 1999) and near the gates (Prigozhin et al. 2000) suggest a number of additional investigations. The most obvious of these is to determine the dimensions of the gate structure. Previous attempts to constrain these parameters using the mesh experiments (§4.5) were inconclusive for a number of reasons. The marked improvement in spatial resolution now available (see Figure 4-21), coupled with measurements at low energies where the characteristic absorption length is small, will clearly allow study of each gate.

However, measurements with the mesh are incredibly time-intensive, both in terms of data collection and analysis. There is also risk to the detector associated each time the mesh is placed on the CCD. (In fact, one device was “killed” during the course of the experiments described in Chapter 4.) In Appendix C, I describe a novel approach for determining the dimensions of the polysilicon gates and oxides.