Charge Loss in the Channel Stop Regions of the X-ray CCD

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Charge Coupled Devices (CCD) made on a high resistivity silicon have become a popular tool in high energy astrophysics for imaging and spectroscopy in the soft X-ray band (from 0.2 to 10 keV). As a part of the calibration program of the CCD Imaging Spectrometer which will be launched on board the Chandra X-ray Observatory (formely known as AXAF) we have studied the response of frontside illuminated CCDs to monochromatic X-ray radiation.

Channel stops occupy a noticeable fraction of a CCD pixel and can seriously distort the shape of the response function of the device. X-ray photons that interact within silicon near the pixel boundary separating two columns of the array produce signal charge in two adjacent pixels, forming so-called horizontally split events. Such events are formed either in the heavily doped p^+ channel stop region or directly underneath it and can be used to study charge transport in the channel stop. The shape of the pulse height histogram of these events (see Fig. 1) produced by 1487 eV monochromatic X-ray illumination reveals a pronounced shoulder on the low energy side of the main peak.

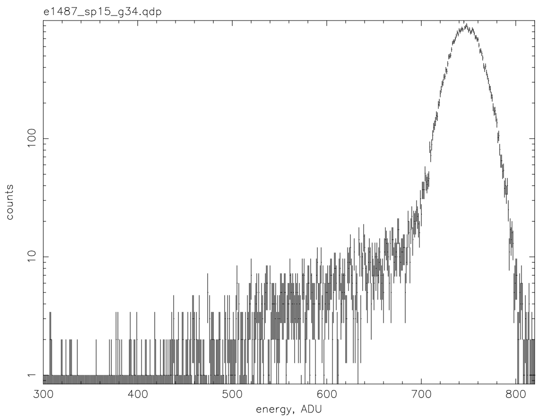

Figure 1: Histogram of horizontally split events (they come from the channel stop region) at photon energy of 1487 eV. The low energy shoulder is formed by charge clouds undergoing some charge loss.

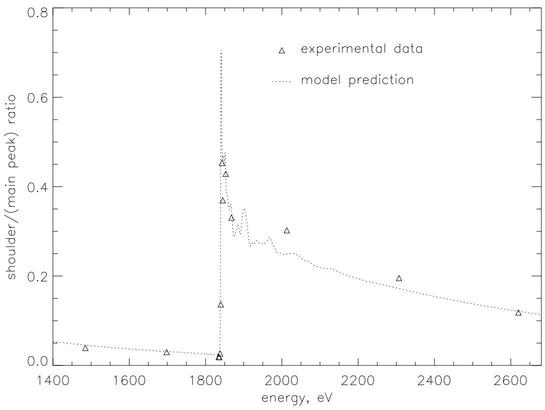

Figure 2: Fraction of "shoulder events" as a function of energy of incoming X-ray photons. A jump at 1839 eV suggests that these events are formed in a thin layer of silicon near $Si-SiO_2$ interface.

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 (Fig. 2), which is indeed observed.

The low energy shoulder in the response function of the horizontally split events originates from the electron clouds formed inside p^+ channel stop region and suffering some charge loss. Their pulse heights, consequently, are shifted down in energy. Electron clouds formed below p^+ are collected into potential wells without any loss and they form the main peak in the histogram.

To further investigate this phenomenon we used a "mesh technique" (see [1]) which allows us to reveal the details of the distribution of the events inside a single CCD pixel. We place on the surface of the device an opaque metal foil with an array of tiny square 1.4 x 1.4 micron holes. The pitch of the holes is the same as the pitch of the CCD pixels, but due to a small rotation of the mesh relative to the CCD, each hole sees slightly different portion of the pixel. A CCD is then illuminated by low energy X-rays that are stopped by

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the foil. A proper analysis of the data under assumption that all the CCD pixels are identical produces a distribution of X-ray intensity inside one pixel. Spatial resolution of such a map is determined by the hole size.

In Fig. 3 the upper plot shows a histogram of combined together 1-, 2-, 3-, and 4-pixel events which were then sorted according to their amplitude into "shoulder events" and "main peak events". Then we looked into the details of the map of the horizontally split events combined with 4-pixel-square events (such events come from the corner of a pixel and, hence, are also formed in the channel stop region, being complementary to the horizontally split). Two lower false color diagrams in Fig. 3 show the intra-pixel distribution of "shoulder events" and "main peak events". 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. On the other hand, 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.

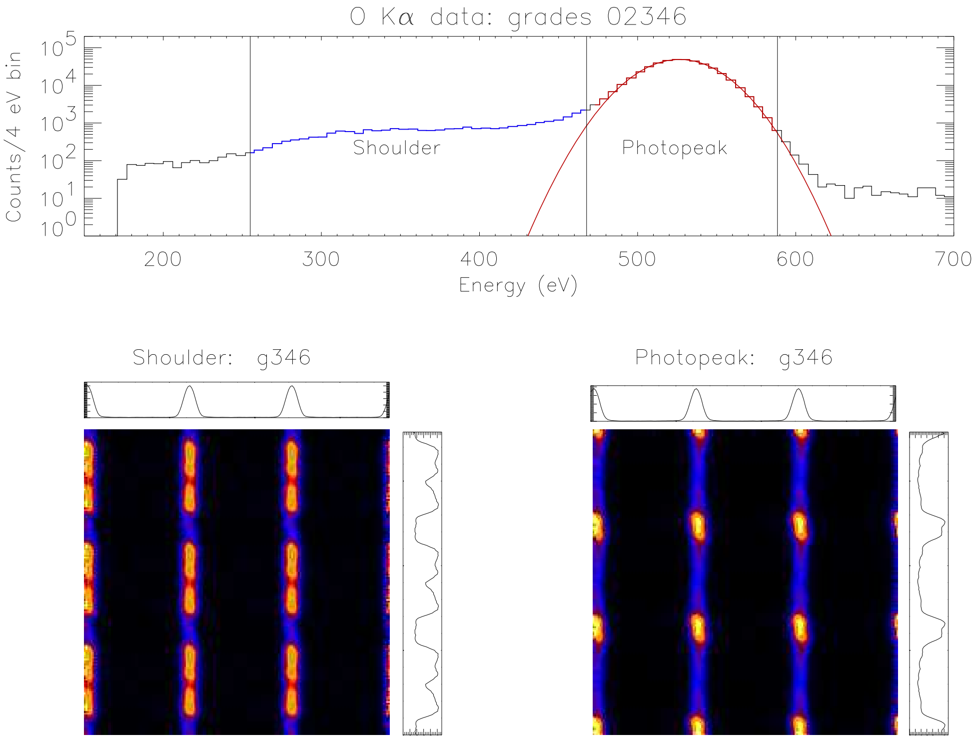

Figure 3: Histogram of combined 1-, 2-, 3-, and 4-pixel events showing limits for "main peak events" and "shoulder events" (upper plot); intra-pixel distribution (3 x 3 array of pixels shown) of the "shoulder events" (lower left) and the "main peak events" (lower right) for horizontally split and 4-pixel events only. Incident photon energy is 525 eV (oxygen K emission line).

This means that charge loss in the region is entirely determined by surface potential because gate field penetration into the substrate is extremely small in this LOCOS structure with thick oxide and relatively heavily doped p^+ silicon. 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.

Analysis of the relative intensities of the peak and the shoulder under different gates at several X-ray energies allows to determine thicknesses of the layers comprising the CCD gate structure, including the p^+

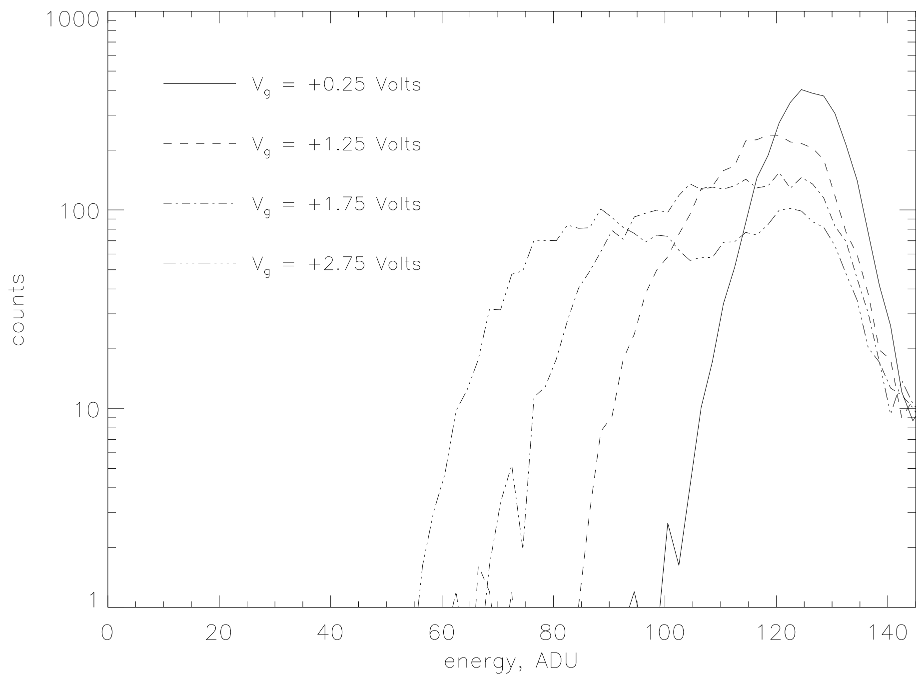

Figure 4: Histograms of the horizontally spit events at different gate voltages. Two gates were held high (voltage level V_g) during the data acquisition. The low gate voltage was maintained 5 Volts lower than V_g. Incident photon energy 525 eV.

layer responsible for the production of the "lossy" events. From such analysis the thickness of the layer where such events are formed appears to be about 0.35 microns, in a good agreement with the thickness of the p^+ field-free region as calculated using the process and device simulators from Silvaco. This suggests the following model of the charge cloud dynamics. Any photon interacting with silicon inside field free region creates 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 $Si - SiO_2$ 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 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.

In order to find the transition point to the "no-loss" condition we acquired data with different voltages applied to the gates of the CCD. The mesh technique, although very powerful, requires a large amount of data and very complicated analysis. This lead us to develop a different technique to evaluate the degree of charge loss. The device was uniformly illuminated by 525 eV photons with no mesh applied. At this energy photon penetration depth in silicon is only 0.5 microns and significant fraction of photons interacts inside p^+ region, thus making the shape of response for horizontally split events sharply dependent on the degree of surface charge loss. Figure 4 shows the rapid change of the histogram shape as a function of the high level voltage V_g at the two integrating gates.

At $V_g = 0$ there is no shoulder in the histogram, the number of counts in the low energy tail is extremely small and main peak has a gaussian shape, indicating a unity charge collection efficiency in the channel stop region. As V_g increases, the peak broadens significantly and there appears a second low energy peak formed by the electron clouds which lost significant fraction of charge.

Not only horizontally split events are affected by the charge loss. Charge clouds that have their origin in the wings of the p^+ region will contribute only to the nearby potential well of the CCD and therefore will be detected as single pixel events. If they suffer some charge loss they form a low energy tail in a single pixel event histogram. At energies where X-ray penetration depth is comparable with the p^+ layer thickness

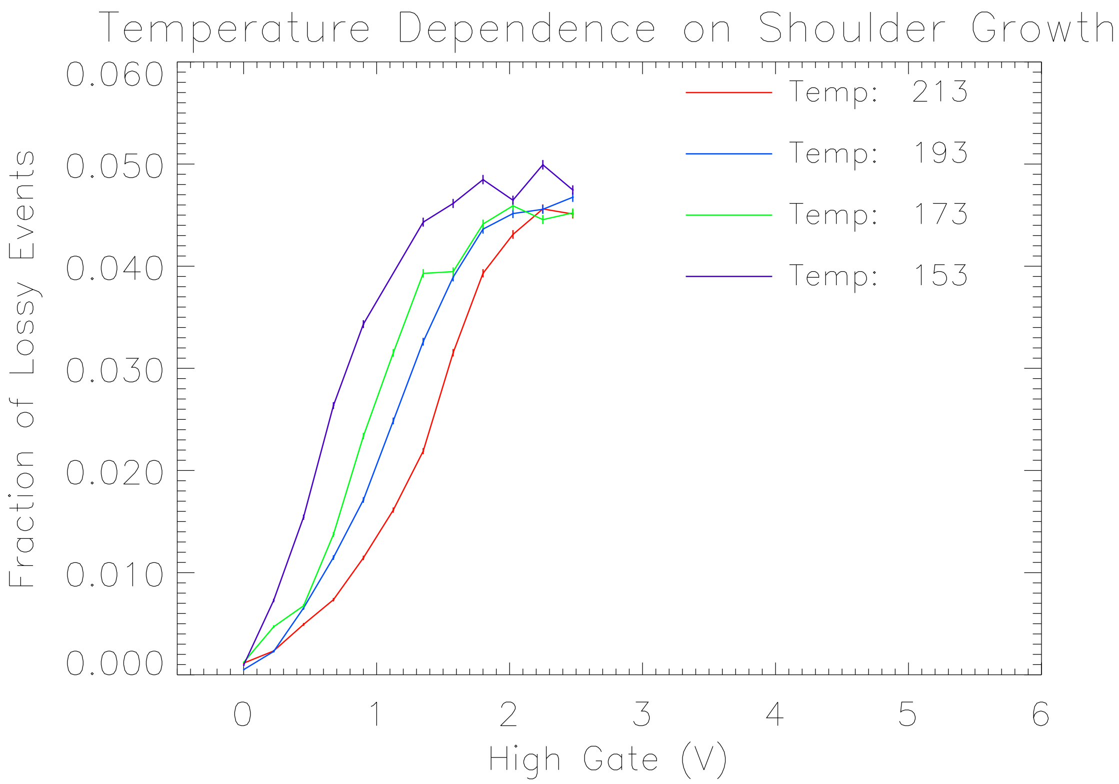

Figure 5: Fraction of events undergoing charge loss in the channel stop region as a function of gate voltage. At warmer temperatures transition to the "no loss" condition occurs at more positive voltage.

this results in a dramatic increase of amplitude of the low energy tail in a histogram. In order to account for all the events coming from the channel stop region we summed together 1-,2-,3-,4-pixel events and used a histogram at $V_g = 0$ as a no-loss template. Subtracting the template from the histogram at a given V_g allowed us to measure fraction of all events formed inside the p^+ layer as a function of gate voltage (see Fig. 5).

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 an assumption that any electron cloud originating inside heavily doped p^+ region where there is no internal electric field loses some charge due to diffusion towards surface. The amount of lost charge in the individual cloud depends on the field distribution near the surface and continues to grow at more positive V_g, shifting down the shoulder part of the histogram.

The transition voltage shifts with temperature, as shown in Fig. 5, reflecting, we believe, a temperature shift in flat-band voltage. Changing the integration time over a wide range did not produce any changes in the shape of the response. Thus, no detrapping of electrons could be detected.

Our results can help explain the poor energy resolution in many types of X-ray sensors having a heavily doped region at the detecting surface.

References

[1] M.Pivovaroff, S.Jones, M.Bautz, S.Kissel, G.Prigozhin, G.Ricker, H.Tsunemi, E.Miyata, "Measurement of the subpixel structure of AXAF CCD's", *IEEE Transactions on Nuclear Science*, vol. 45, No. 2, pp. 164-175, (April, 1998)