Residual bulk image characterization and management in CCD image sensors

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ABSTRACT

Residual Bulk Image (“RBI”) was evaluated in a recently manufactured large format CCD (KAF09000). Operating at –20 C, RBI was observed more than four hours after an image exposure. A number of parameters were measured in an engineering grade CCD including charge trap capacity, filled trap leakout rate, and total trap exhaustion time for temperatures ranging from +10 C to –30 C. A NIR Flood/Flush/Integrate protocol was tested as a candidate to eliminate the RBI by pre-filling the traps and it was found effective at eliminating the RBI as well as the amplifier luminescence observed in non-flooded test exposures. It was also found that the leakage from the pre-filled traps greatly exceeded the thermal dark current over the tested temperature range leading to an increase in the overall dark shot noise. Deep cooling is required to suppress this additional dark noise component. An Arrhenius plot was used to project the required cooling levels as a function of exposure time for various read noise limits. For half hour exposures with a target 5 e- read noise limit, an operating temperature of –87.8 C was indicated. A plot of the maximum operating temperature as a function of exposure time was created from the data.

Keywords: CCD, NIR, RBI, substrate traps, epitaxy, luminescence

1. INTRODUCTION

Residual Bulk Image (RBI) is a phenomenon that can affect front side illuminated CCDs fabricated on epitaxial wafers. The telltale signature of RBI is the existence of an image from prior illumination in a subsequent integration. For example a KAF09000 CCD had a partially saturated exposure at the Hydrogen Alpha wavelength (656.4 nm) that resulted in an observable residual image in a dark frame taken over 2 hours later (Figure 1).

At the heart of RBI is the wavelength dependence of the penetration of photons into silicon: the longer the wavelength of the light in the visible and NIR range, the deeper the photons penetrate before interacting with the silicon lattice to create hole-electron pairs. Electrons created by photons that penetrate deeply enough to interact in the field-free regions below the pixel potential wells may be trapped in interface states at the substrate-epitaxy interface [1] (Figure 2).

The density of states and critical wavelength of onset are process and design-dependent. The charge trapped in the interface states leaks out of the traps as a deferred charge and is collected in the potential wells in the pixels above, appearing in subsequent images or dark frames. The rate of the leakage is a strong function of temperature and is examined in detail in this paper.
Residual Bulk Image (RBI) Example
(656.4nm light)

Image

Dark Image: two hours later @ -20C 

Figure 1

Typical Front Illuminated CCD Cross Section
(nonspecific sensor, EPI wafers)

Pixel’s depletion region

Light

Field-Free Region

Integrating gate electrode (polysilicon or ITO)

Substrate-EPI Interface traps

0.1 ohm-cm substrate

700nm light penetrates to field-free region

Depletion region depth 5 microns

Penetration depth 1000 nm

Penetration depth (10um nm)

Photon Penetration Depth Silicon (um, nm)

~600 microns

~10 microns

Figure 2
1.1 Evaluated CCD

The KAF09000 CCD from Kodak is a front side illuminated 9.6 Megapixel CCD that has an active imaging area of 36.8 mm x 36.8 mm with 12 x 12 micron pixels. Featuring a full well capacity of 110,000 electrons, along with low read noise (7 e-) and low dark current, it is well suited for many scientific applications, including cooled long-exposure use in astronomy [2]. An engineering grade KAF09000 was evaluated in a Finger Lakes Instrumentation Proline PL9000 camera for this work.

Despite its impressive specifications, the evaluated KAF09000 CCD demonstrated significant RBI through a significant portion of the visible spectrum. In addition to the RBI demonstrated at 656.4 nm, it was found that 532 nm light stimulated the phenomenon in the sensor, which is well into the green part of the spectrum (Fig 3). The 532 nm exposure was a 1 second exposure from a green laser pointer. The operating temperature of the CCD was -10 C and the 5 minute dark was taken immediately following the exposure to the laser light.

RBI initiated by 532nm laser light

![Image of RBI initiated by 532nm laser light](image1)

Figure 3

2. EXPERIMENT AND RESULTS

In order to better understand the RBI characteristics of the sensor, parameters associated with the traps were sought, specifically: leakage versus temperature, leakage versus time and trap capacity. The traps were first filled, and then the decay was measured.
Two different methods were used for filling the traps. In the first method, a partially saturated focused image was taken using a camera lens. This was immediately followed by a sequence of dark frames, each of five minutes duration. For each dark frame, the signal remaining in a region that had been saturated in the initial light image had the reference dark signal and offset subtracted. The value of the remaining signal was recorded and plotted versus time for several different operating temperatures. Figure 4 shows the incremental charge leaked during a sequence of five minute long dark integrations. Figure 5 shows the cumulative charge leakage over the same five minute long dark integrations. The light exposure was made using a 300 second exposure taken through a narrow band emission line filter (50 x 50 mm square Baader Planetarium Hydrogen Alpha filter: 7 nm FWHM with 656.4 nm CWL).

![Figure 4](image.png)
The second method used for filling the traps was using a built-in NIR flood mechanism incorporated into the test camera. After flooding the sensor for 5 seconds followed by flushing it, a sequence of half-hour dark frames was taken and the RBI signal was recorded as above to measure the trap capacity, the trap decay rate and time for total trapped charge exhaustion (Figure 6).
Total exhaustion was defined as that time when the flooded sensor’s dark current matched its reference dark current, indicating no trapped charge remained. The reference dark current was defined as equaling the average dark current for the same duration exposure at the same temperature in a non-flooded operational regime from a cold start: no residual image trapped. The flooded sensor’s dark current was averaged over half hour integrations for the trap exhaustion measurements.

Figure 7 shows a comparison of half hour dark exposures taken with and without the NIR flooding. Amplifier luminescence was observed in the non-flooded dark exposure (Figure 7 left). The luminescence was greatly reduced in the flooded case (Figure 7 right).

Additional investigation revealed the luminescence to decay in the non-flooded case in a manner identical with RBI. This suggests there is a large transient luminescence occurring between initial application of power and the first integration. The transient amplifier luminescence is believed to load the substrate traps with photoelectrons created by the NIR luminescence that subsequently leak into the following integrations. Because the luminescence monotonically decays with time, this argues that the luminescence is triggered by a single event, such as could occur with a fully saturated sensor being flushed after the initial application of power. Upon initial power-up, the source follower transistor in the output amplifier’s first stage can be placed in a bias regime conducive to creating impact ionization, generating NIR light, ideal for aggravating RBI [3].

Figure 8 shows the trap capacity as a function of operating temperature. The capacity was computed by summing the cumulative charge leakage from the traps shown in Figure 5. Since the camera always performs a flush prior to any integration, some charge is lost with the flush and is not

Reference = Current measured in non-flooded case: “cold-start dark”
recorded. Because the trap leakage is highest with completely filled traps at the warmest temperatures, the charge loss is greatest in those cases. In a 5 minute long integration taken at +10C immediately after flood/flushing of the sensor, approximately 900 electrons are leaked. It takes approximately 45 seconds to cycle between exposures (readout, download, flush) so it is estimated that approximately 300 electrons are lost in the flush. For this reason the reported trap capacity is underreporting the true value at the warmer operating temperatures. This could explain the apparent reduction of trap capacity at the warmer operating temperatures. Figure 9 shows the time for total exhaustion as a function of operating temperature.

3. MANAGING RBI

An accepted method for managing RBI is flooding the sensor with NIR light followed by flushing it prior to any integration [4]. However since filled traps leak charge, such leakage increases the shot noise of the overall dark signal, adding noise to the image. The total charge leaking from the traps versus the total thermally generated charge is compared in ratio form over the measured temperature range. As is seen in Figure 10, the charge leaking from the prefilled traps is significantly larger than the thermally generated charge, even for exposures as short as 5 minutes.

Minimizing the overall dark signal including the additional leakage from the pre-filled RBI traps can be accomplished by deep cooling of the sensor but some criterion must be set to determine how much cooling is adequate. A commonly used metric for establishing the maximum operating temperature is...
temperature of a sensor is constraining the noise contribution from the dark shot noise to be less than or equal to the read noise contribution for the maximum planned exposure time.

Plotting the leakage data as an Arrhenius plot provided a convenient way to determine the projected operating temperature that satisfied the camera noise constraint for any given read noise scenario. It should be noted that for the camera noise calculation, the read noise term is squared in the quadrature summation with the dark shot noise term as shown in equation (1). The target read noise limits are therefore squares of the numerical value of the read noise and are plotted as intersecting lines on the Arrhenius plot of the dark leakage data (Figure 11).

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dark \_ \ camera \_ \ noise = \sqrt{\text{dark \_ \ shot \_ \ noise}^2 + \text{read \_ \ noise}^2} = \sqrt{\text{dark \_ \ signal} + \text{read \_ \ noise}^2}
\] (1)

Figure 8
Figure 9

Figure 10
Figure 12 shows the projected maximum operating temperature as a function of exposure time for three different read noise limited cases. The graph shows that the projected maximum operating temperature for a half hour exposure with a 5 electron read noise constraint is –87.8 C. From a noise perspective it should be noted that if the deep operating temperatures are not met the result is a reduction of dynamic range in the same way as if the read noise was increased. That may or may not affect the final image quality depending on image signal level and the associated shot noise but is another noise factor that should be considered when planning exposures or analyzing data.

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![Projected Maximum Operating Temperature for KAF09000 Meeting Read Noise Limited Constraint vs Exposure Time vs Read Noise Commencing Exposure With Filled RBI Traps](image)

**Figure 12**

**REFERENCES**