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Residual Bulk Image Characterization using Photon Transfer Techniques

Richard Crisp

Etron Technology America, Santa Clara, California USA

Abstract

Trapped charge can lead to a source of error when making low level Photon Transfer (“PTC”) measurements. Residual signal can corrupt low level dark and light-on measurements leading to incorrect signal measurements when performing frame differencing required for the data reduction in the PTC procedure. To quantify the effect of trapping, the trap characteristics of capacity and decay rate versus temperature were studied for a commercially produced full frame CCD. Photon Transfer noise analysis was used to measure trap capacity, trap leakage rate, dark shot noise and thermal generation of dark signal as a function of cooling.

Overview

Charge trapping can introduce a source of error when making low signal level Photon Transfer measurements. For example low level dark signal measurements may be compromised by residual charge leakage of similar magnitude. This can lead to measurement challenges for some low-signal level Photon Transfer characterizations. This work was inspired by a difficulty encountered caused by a spurious light source contained within a camera being studied. A light-flood LED would flash upon application of power to the camera and this led to inconsistent measurement results when operating the sensor in a cooled (-25 C) state.

A commercially-produced Full Frame CCD image sensor exhibited significant Residual Bulk Image (“RBI”) when operated cooled to -25C. Operating at chilled temperatures is necessary to minimize dark signal when taking exposures of dimly illuminated targets which may require exposures of several minutes. The residual image, a form of image lag, results from trapping sites in the bulk silicon that can be formed via several different mechanisms. One proposed mechanism suggests trapping sites are formed at the epitaxial interface in the case of epitaxial type wafers [1].

A simple example of RBI can be seen in Figure 1. In this image four brief exposures were taken of a well illuminated target with the aiming changed slightly between exposures. After four such exposures a five minute dark exposure was taken that revealed significant residual image remaining in the sensor that leaked out of the trapping sites during the dark exposure.

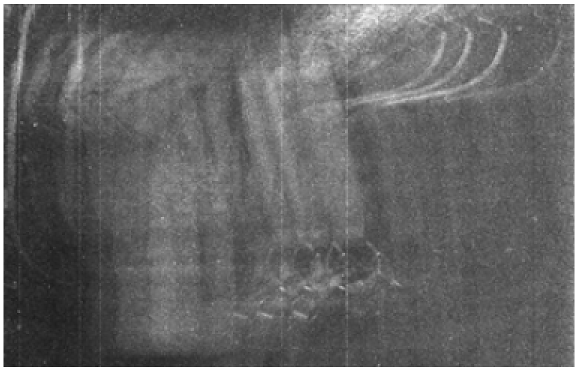

Figure 1: Residual Bulk Image

For long exposure scientific imaging using such image sensors, the RBI problem is severe enough that a mitigation scheme is often required. The standard method used is flooding the sensor with light followed by flushing it prior to any integration [2]. The intent behind this scheme is to ensure the traps are placed into a known (filled) state at the beginning of each exposure.

During the exposure some trapped charge leaks into the image introducing both increased dark shot noise as well as dark fixed patterns that must be removed in the image calibration process. These are the two principal challenges presented by the mitigation protocol. The purpose of this work is to quantify the contribution of the trap leakage to the total dark shot noise as a function of operating temperature and integration time.

Figure 2 shows a 300 second dark exposure with trap leakage resulting from the light flood protocol. The arc-like shapes comprise a dark fixed pattern that be removed via despiking (dark frame subtraction). However, unless the traps are in the same identical state at the beginning of the exposure, these patterns may not be fully removed.

Another proposed trapping mechanism relates to residual microstresses in the silicon wafer formed during crystal growth process: the crystal is rotated as the boule is pulled from the melt and this has been theorized to explain the patterns seen in the dark fixed patterns as shown in Figure 2. This theory was strengthened by wafer mapping of sensors performed by the manufacturer which was communicated verbally to the author at a technical conference by the R&D manager for the manufacturer of the sensor.

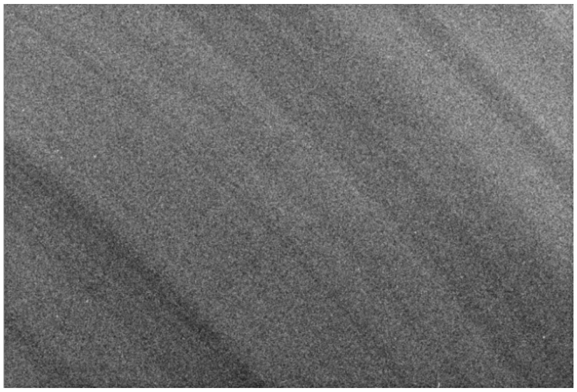

Figure 2: Dark Fixed Pattern Post Light-Flood

There is a well-known relationship between dark signal and dark shot noise. Numerically the dark shot noise is equal to the square root of the magnitude of the dark signal. Using electron units, a 100 e- dark signal will have a shot noise of 10 e-. It is unimportant if the dark signal originates from trap leakage or from thermal generation, both components are summed in the pixel's well and contribute to the dark shot noise.

Because dark signal accumulates with time there is an integration time where the dark shot noise will equal the camera's read noise. From a camera noise perspective, integrations longer than this time will be dominated by dark shot noise versus read noise. This integration time is customarily considered the maximum practical exposure limit and can be used as a metric to determine the sensor's operating temperature needed to attain a particular target noise floor for a planned maximum exposure time.

The experimental procedure was designed to permit the trap leakage to be quantified and separated from the thermally generated dark signal so that the two components of the overall dark signal can be separately studied. Photon Transfer noise analysis was selected because the results are robust and the method is simple.

Experimental Procedure

The KAF3200ME CCD image sensor was characterized in a camera containing an integrated thermoelectric cooling system capable of cooling the sensor to -40C with a room temperature ambient of 25C.

Photon Transfer Methods were used to measure the read noise, conversion gain and full well capacity [3]. Photon Transfer Methods involve plotting noise components against signal using logarithmic axes. The slope of the various noise components reveal the order of the noise components: for example the slope of the shot noise will be +1/2 indicating a square-root relationship of the noise to the signal. Likewise the Fixed Pattern Noise components (dark FPN or light-on FPN), will have a slope of +1 showing a linear relationship with respect to signal level.

Using PTC analysis the measured results were Read noise = 5.162 electrons ("e-"), conversion gain = 0.8668 e-/DN and full well = 59,500 e- respectively.

A baseline dark signal was next measured. To avoid trapping charge the camera was energized with the sensor initially in a room temperature state. The cooler was left switched off and the sensor was flushed for five minutes before cooling it to operating temperature. Data was collected operating the sensor at -15C, -20C, -25C, -30C, -35C and -40C. Integration periods were 60, 300, 600, 900, 1200 and 1800 seconds.

It is vital that this dark reference signal be free of any trap leakage in order to have reliable results. If the sensor had been chilled at the time of energizing the camera, there's a strong possibility that traps would contain charge. This actually highlights a potential issue for generic Photon Transfer Characterization: a sensor left unpowered for minutes or hours will be saturated at the time it is energized and that can lead to charge trapping that can prevent accurate low level signal measurements. This is a hazard to be considered in generic Photon Transfer analysis. It is therefore a good idea to ensure the sensor is warm when energized and to flush continuously for a few minutes to make certain any trapped charge has decayed.

A second set of dark signal data was collected using the same operating temperatures and integration times. Once the sensor reached the target operating temperature the sensor was flooded with Near Infrared Light ("NIR") supplied by LEDs mounted inside the camera chamber. The sensor was then flushed and the dark signal integration immediately followed. This process was repeated for each operating temperature and integration times used for the reference dark data.

Data Reduction

Equation (1) below is the familiar noise equation with all terms involving light exposure set to zero. Total noise was measured empirically from the data by taking the standard deviation of a 100 x 100 pixel region in each image. The dark shot noise was determined by subtracting the read noise from the total noise as shown in Equation (2). The total dark signal was obtained by squaring the dark shot noise as shown in Equation (3). The dark shot noise and thermally generated dark signal for the non-light flooded case are shown graphically in the upper part of Figure 3. Note that the thermally generated dark signal is a straight line with a slope of +1 when plotted using logarithmic scales for the X and Y axes. Likewise the dark shot noise is also a straight line but with a slope of +1/2 in the plotted data.

The total dark signal is equal to the thermal dark signal in the non-light flooded case (Equation (5)) and this is used in the calculation of the trap leakage as shown in Equation (6). The trap leakage and total dark shot noise for the light flooded case are also graphically presented in Figure 3. For the light flooded case the dark shot noise is significantly higher than for the non-light flooded case for any integration time or temperature shown.

The upper set of curves show the total charge leaked from the traps as a function of temperature and time and can be extrapolated to show the total trap capacity. In this case the trap capacity is approximately 78 electrons making the ratio of trap to well capacity approximately 0.13%.

Figure 4 shows dark current (e-/pixel/sec) for the light flood and non-light flooded cases. As can be seen from the plots the dark current for the light flooded cases is approximately 100x that observed for the non-light flooded cases for short exposures and is about 10x for long exposures. The trap leakage accounts for the differences.

Discussion:

Analysis of Figure 3 shows that for a 300 second exposure with light flood the operating temperature of the image sensor should be approximately negative 27C to keep the dark shot noise less than the read noise of 5.16e-. For a 900 second exposure the required operating temperature is negative 40C.

Because an image sensor left in its unpowered state for many hours will tend to be saturated when energized, care should be taken to ensure trapping sites are fully exhausted prior to making quantitative measurements such as a Photon Transfer Curve. This is particularly true if the sensor is stored in a cooled state, which can result in trap decay times lasting many tens of minutes.

The camera used for this work has an FPGA that’s used to control the shutter and also the light flood LEDs used for RBI mitigation. When initially energized the FPGA causes the both the shutter and the LEDs to pulse momentarily. This brief light pulse has been discovered to cause erroneous dark signal measurements, particularly for low level signals due to the trapping and decay of charge in the sensor: charge leaks out of trapping sites and that corrupts thermal dark signal measurements. Of particular concern were momentary power interruptions of the camera when in a cooled state.

Investigation of the root cause of erroneous low level thermally generated dark signal measurements made in the course of standard Photon Transfer camera characterization has led to this work. The author cautions other researchers to be mindful of trapped charge when making routine quantitative measurements with image sensors that may be affected by RBI. Full Frame CCDs have the vulnerability as may some CMOS pixel architectures.

Conclusion:

Photon Transfer methods can be used to evaluate the trap capacity and trap leakage characteristics of an image sensor. Using noise methods for the analysis provides a convenient way to characterize the dark signal components, both thermally generated and trap leakage, by manipulating familiar noise equations to solve for the components of interest.

Trapped charge may introduce errors in low level dark signal characterization as encountered in Photon Transfer Characterization of electronic imaging cameras. It is of particular concern for cooled image sensors such as used for many long exposure applications such as Scientific or imaging in low light conditions as may be encountered outside under starlight or other low light conditions.

$$Total\_noise = \sqrt{Read\_noise^2 + Dark\_shot\_noise^2} \quad (1)$$

$$Dark\_shot\_noise = \sqrt{Total\_noise^2 - Read\_noise^2} \quad (2)$$

$$Dark\_shot\_noise = \sqrt{Total\_dark\_signal} \quad (3)$$

$$Total\_dark\_signal = Thermal\_dark\_signal + Trap\_leakage \quad (4)$$

For no-light flood case, Trap_leakage is zero:

$$Total\_dark\_signal = Thermal\_dark\_signal \quad (5)$$

$$Trap\_leakage = Total\_noise^2 - Read\_noise^2 - Thermal\_dark\_signal \quad (6)$$

References

[1] J. Janesick, Scientific Charge Coupled Devices, Bellingham WA: SPIE Press, 2001. P659.

[2] R. Crisp, “Residual bulk image quantification and management for a full frame charge coupled device image sensor”, Journal of Electronic Imaging 20(3), 033006 (Jul–Sep 2011) pp. 033006-1 – 4, July-September 2011.

[3] J. Janesick, Photon Transfer: DN to Lambda, Bellingham, WA: SPIE Press, 2007.

Author Biography

Richard Crisp received his BS in EE (cum laude) from Texas A&M University (1976) and has designed CPU & Memory ICs and advanced multi-die semiconductor packaging for Motorola, Intel, MIPS, Rambus, Tessera, Invensas and Etron. He was chairman of the ISSCC Program Committee in 2000 and was the memory subcommittee chair from 1997-1999. He has over 95 issued patents, many peer-reviewed conference and journal papers and is a specialist in scientific imaging technology. He’s currently Vice President of New Product Development for Etron Technology America where he is developing next generation memory and imaging systems.

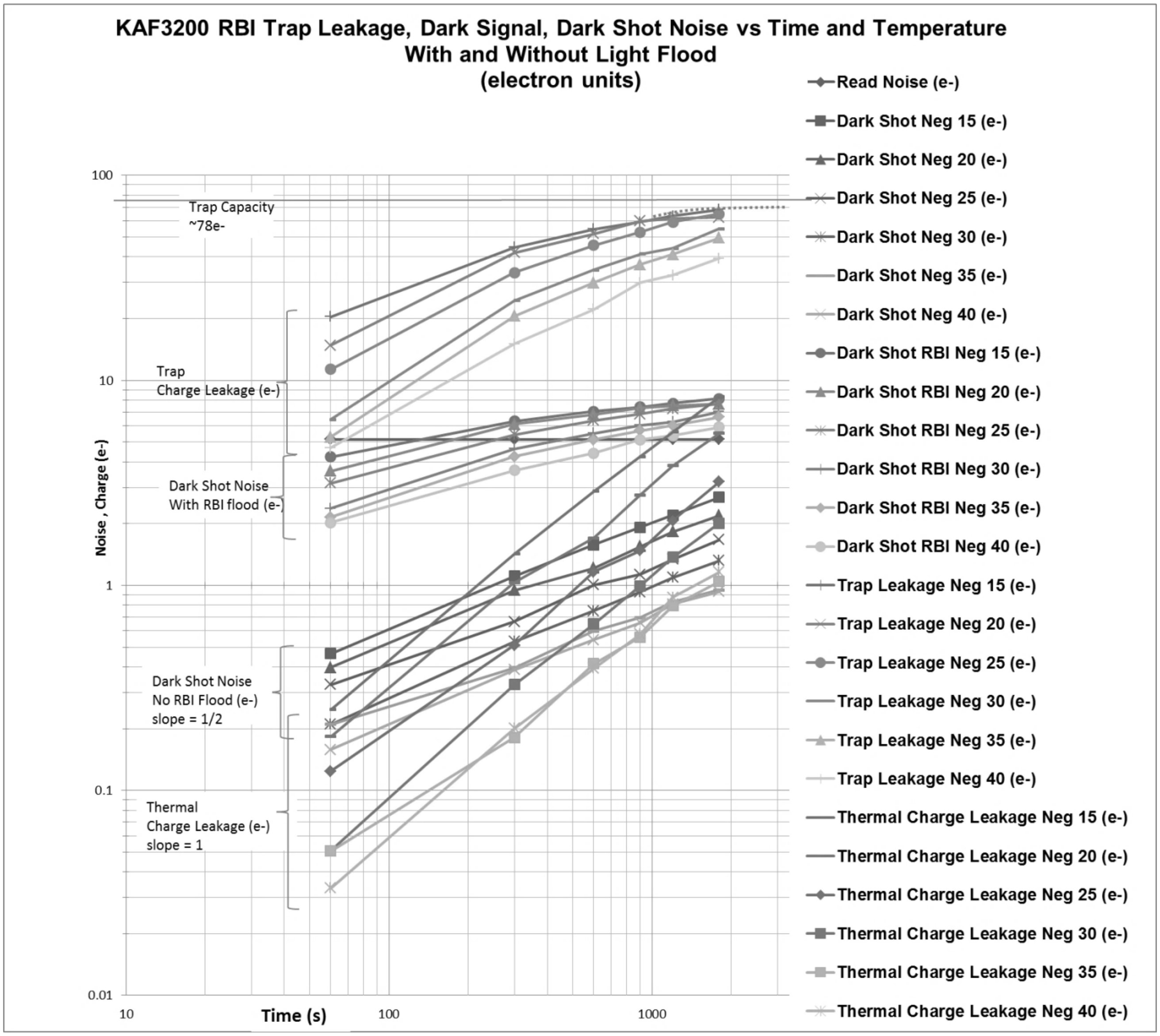

Figure 3: Dark Shot Noise, Thermal Dark Signal and Trap Leakage vs Time and Temperature, with and without Light Flood

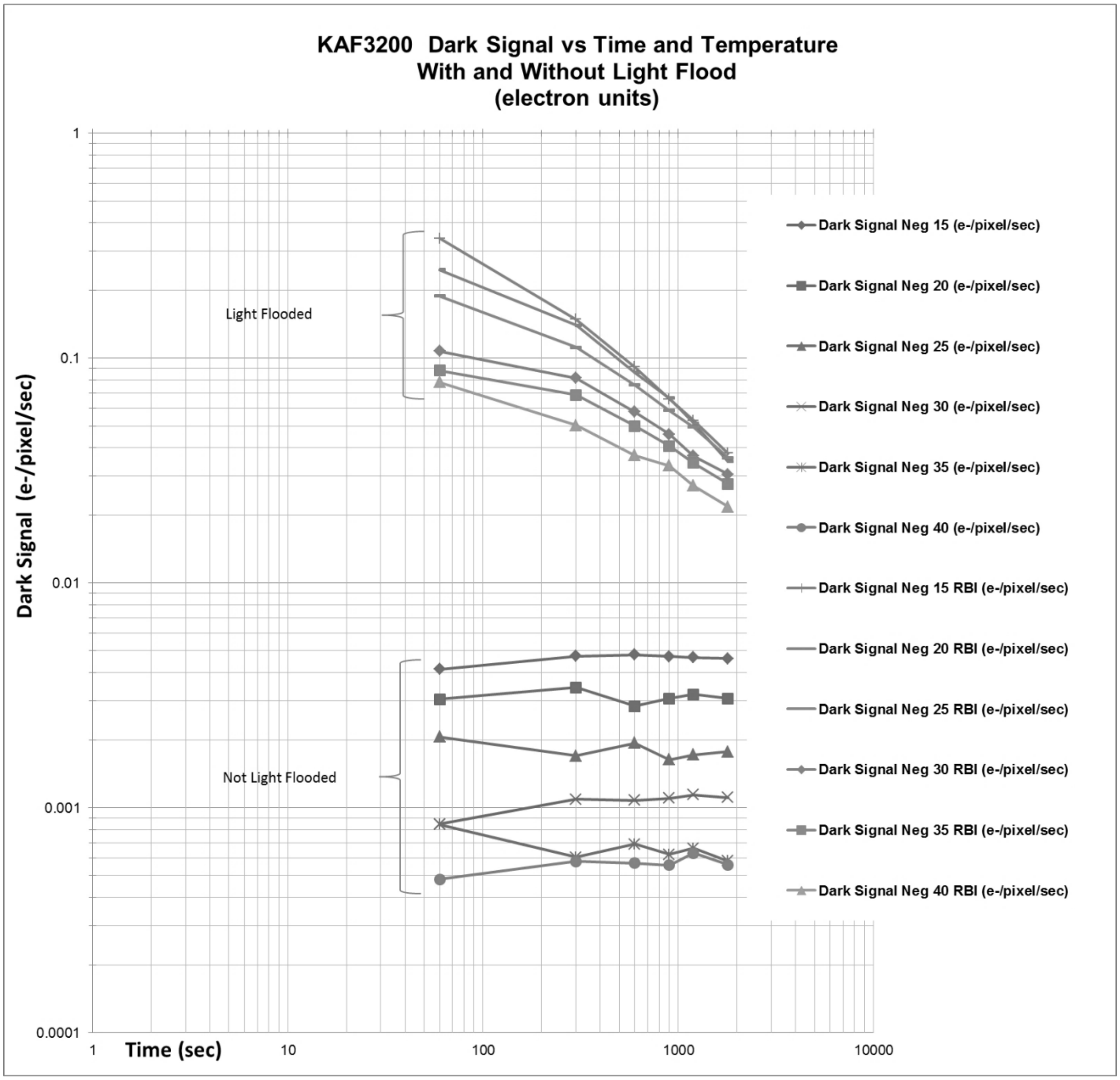

Figure 4: Dark signal vs temperature for light-flooded and non-light-flooded cases