Journal of
Electronic Imaging

SPIEDigitalLibrary.org/jei

Residual bulk image quantification and management for a full frame charge coupled device image sensor

Richard Crisp

SPIE

IS&T
imaging.org

Residual bulk image quantification and management for a full frame charge coupled device image sensor

Richard Crisp
Invensas, Inc.
3025 Orchard Parkway
San Jose, California 95134
E-mail: rcrisp@invensas.com

Abstract. *Residual bulk image (RBI) is significant in the KAF09000 CCD. Residual images are observed 2 h after illumination at – 20C. Trap leakage and capacity are studied as a function of temperature. A flood-flush protocol is evaluated for eliminating RBI artifacts. A substrate trap fixed pattern noise is observed and is removed by dark-subtraction. An increase of dark current shot noise due to trap leakage will occur but can be minimized by deep cooling. Operating temperature targets are set as a function of target noise levels. An operating temperature of –87C for a 30 min exposure is projected to support a read noise constraint of 5 e-.*
[DOI: 10.1117/1.3604004]

1 Introduction

Residual bulk image (RBI) is a phenomenon that can affect full-frame CCDs fabricated on epitaxial wafers that are used for long exposures. 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 near-infrared (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 such as at the substrate-epitaxy interface.[1] The density of states and critical wavelength of onset are process and design-dependent.

The telltale signature of RBI is the existence of an image from prior illumination in a subsequent integration, typically a long exposure (>5 min), as would be commonly used in astronomical applications. 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 will be examined in detail in this paper. For short-duration exposures of a few seconds, insufficient time is available for any appreciable trap leakage so RBI is less of a concern in such applications: it is primarily a problem for long exposures.

The sensor's quantum efficiency (QE) is affected by RBI.[2] When the interface state traps are unfilled, the QE of the sensor is at its lowest point since some proportion of the electrons created by longer wavelength photons are trapped in the interface states instead of being collected in a pixel. As the traps fill, fewer such electrons are so trapped and the QE increases in the process. Because the QE depends on prior illumination, there is a hysteresis in its response, hence this phenomenon is called quantum efficiency hysteresis (QEH).

QEH is wavelength dependent since only photons with a wavelength longer than a critical wavelength are involved in the trapping. For that reason, QEH can introduce significant errors into photometric measurements if left unchecked.

1.1 *KAF09000 CCD from Kodak*

The KAF09000 CCD from Kodak is a recently-introduced (late 2006) frontside illuminated 9.6 megapixel CCD that has an active imaging area of 36.8 × 36.8 mm with 12 × 12 μm pixels. Featuring a full well capacity of 100,000 e- 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 or fluorescence microscopy.[3] An engineering grade KAF09000 was evaluated in a Finger Lakes Instrumentation Proline PL9000 camera for this work.

Despite its impressive specifications, the KAF09000 CCD demonstrates significant RBI. For example, a partially saturated exposure at the hydrogen alpha wavelength (656.4 nm) resulted in an observable residual image in a dark frame taken over 2 h later (Fig. 1). In addition to the long retention of the RBI, it was found that 532 nm light stimulated the phenomenon in that sensor, which is well into the green part of the spectrum, indicating that trapping sites are not limited solely to the epitaxial/hander-wafer interface.

1.2 *Measured 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 image was taken using a camera lens. This was immediately followed by a sequence of dark frames, each of 5 min duration, similar to what are used in astronomical applications. 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

Paper 08097LR received Jun. 24, 2008; revised manuscript received May 25, 2011; accepted for publication Jun. 6, 2011; published online Aug. 16, 2011.

1017-9909/2011/20(3)/033006/4/$25.00

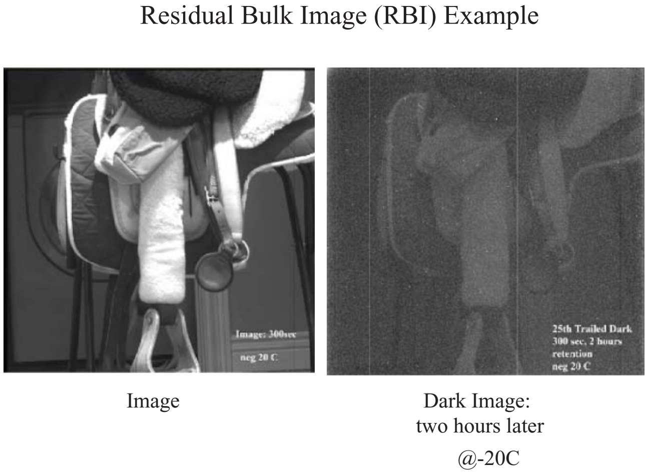


Fig. 1 Residual bulk image examples.

subtracted. The value of the remaining signal was recorded and plotted versus time for several different operating temperatures (Fig. 2). The light exposure was made using a 300 s exposure taken through a narrow band emission line filter (50×50 mm square Baader Planetarium Hydrogen Alpha filter: 7 nm FWHM with 656.4 nm center wavelength).

The second method used for filling the traps was using the built-in NIR flood that Finger Lakes integrated into the Proline camera. After flooding the sensor for 5 s, a sequence of half hour long 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 (Fig. 3).

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 nonflooded 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.

1.3 *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. Furthermore, a nonuniform density of trapping sites will introduce a fixed pattern in the residual image that leaks from the traps. Dark-subtraction was found to eliminate this RBI fixed pattern.

Minimizing the overall dark signal including the additional leakage from the prefilled RBI traps is accomplished by deep cooling of the sensor. Since the filled trap leakage is significantly greater than the thermal dark current, the additional cooling is needed but some criterion must be set to determine how much cooling is adequate. A commonly used metric for establishing the maximum operating 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 operating temperature

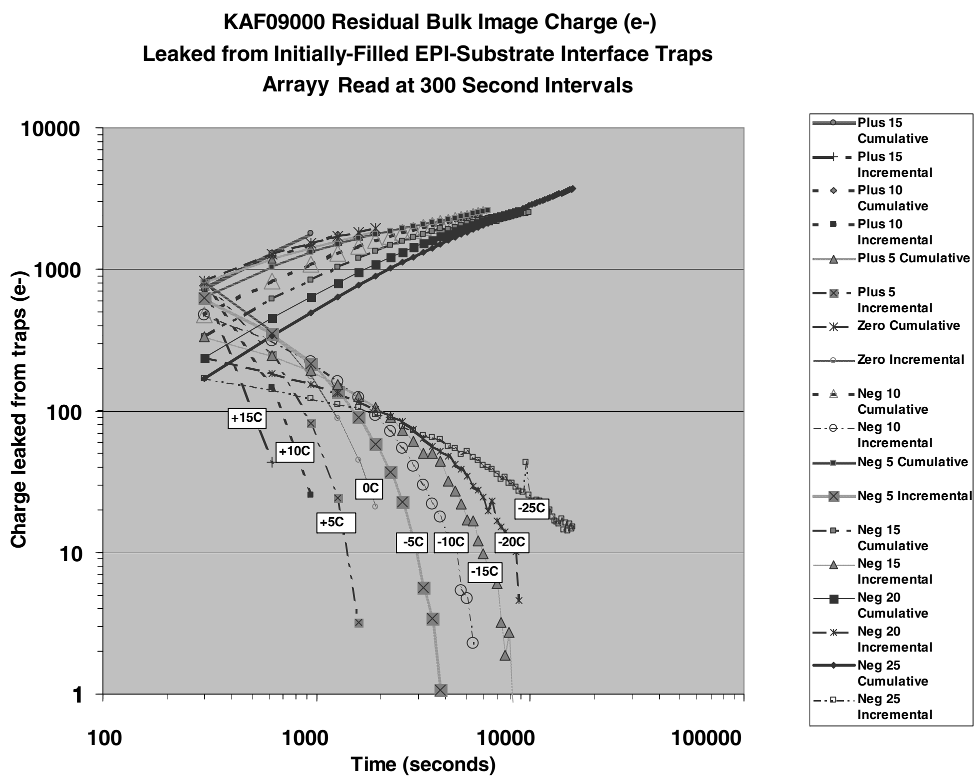
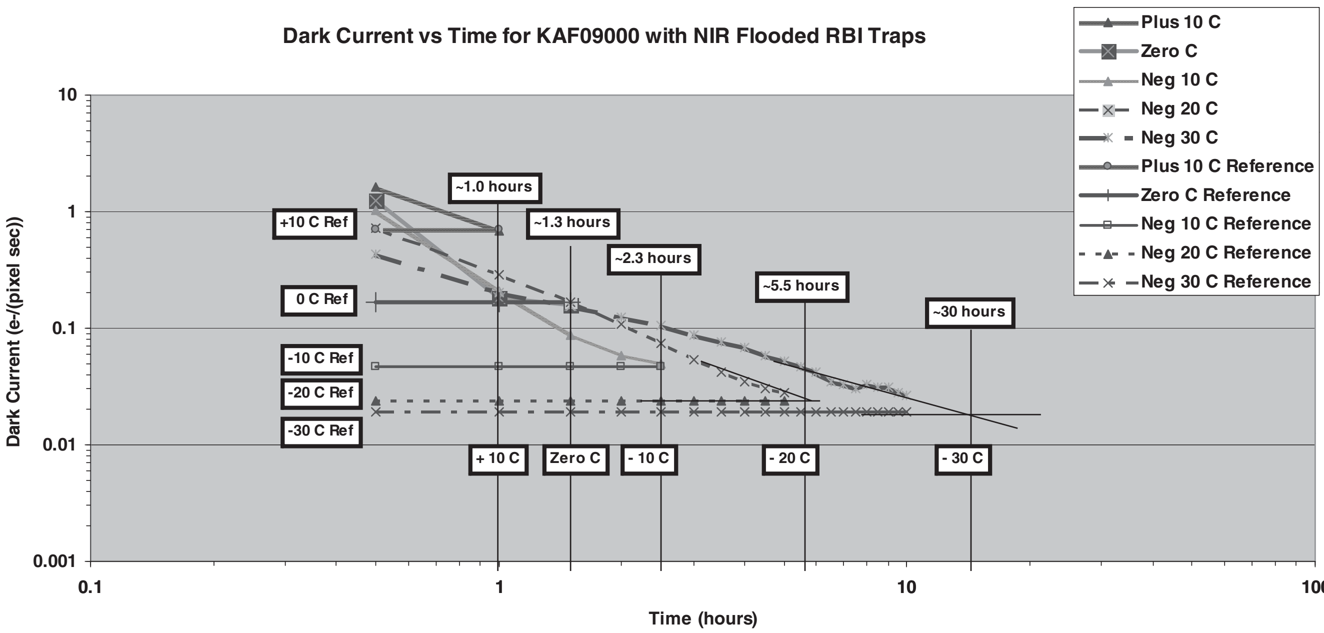


Fig. 2 Residual bulk image charge leakage from initially filled EPI/substrate traps.



Reference = Current measured in non-flooded case: "cold-start dark"

Fig. 3 Dark current versus time for KAF09000 with NIR flooded traps.

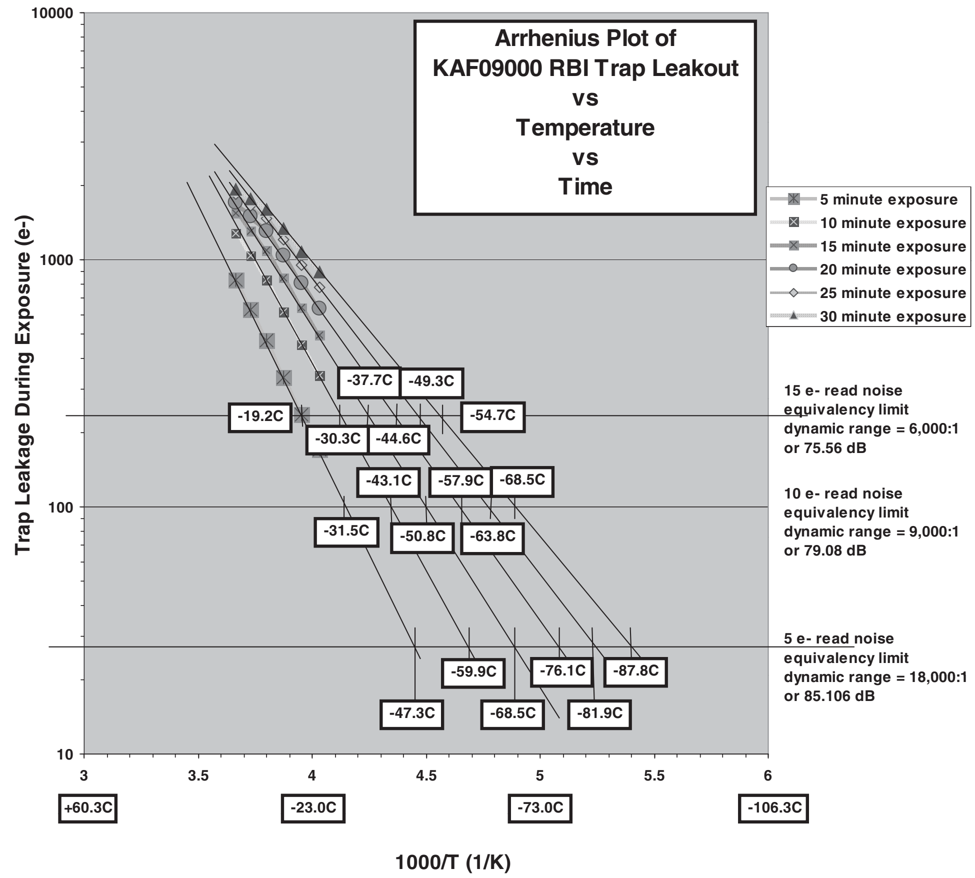


Fig. 4 Arrhenius plot: RBI trap leakout versus temperature versus time.

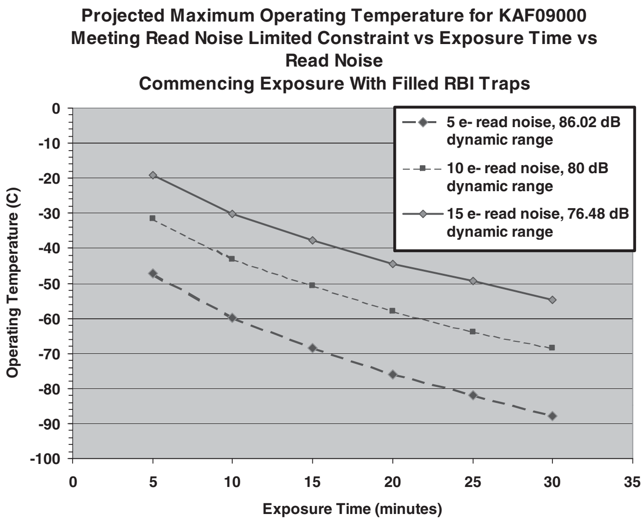


Fig. 5 Projected maximum operating temperature versus exposure time.

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 the equation below. 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 (Fig. 4).

$$\text{Camera\_noise} = \sqrt{(\text{dark\_shot\_noise}^2 + \text{read\_noise}^2)}$$
$$= \sqrt{(\text{dark\_signal} + \text{read\_noise}^2)}$$

Figure 5 shows the projected target 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 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 its associated shot noise, but is another noise factor that should be considered when planning exposures or analyzing data.

2 Summary

While well-suited for cooled long-exposure scientific applications, the KAF09000 exhibits significant RBI. Even at + 10 C, image lag is measurable 20 min after a visible light exposure. Following a protocol of NIR flood/flush/integrate, the undesirable effects can be controlled at the expense of incremental noise. The noise can be managed by deep cooling of the sensor, and curves were presented showing the relationship between cooling level and exposure time for three different read noise limits.

Acknowledgments

The author would like to thank Baader Planetarium of Germany for providing the Hydrogen Alpha filter and Finger Lakes Instrumentation of Lima, New York for providing the evaluation camera/filter wheel, and for interesting technical discussions/support including fast-turn driver modifications to assist in the collection of data.

References

1. J. R. Janesick, *Scientific Charge Coupled Devices*, p. 660, SPIE Press, Bellingham, Washington (2001).
2. J. R. Janesick, *Scientific Charge Coupled Devices*, pp. 663–665, SPIE Press, Bellingham, Washington (2001).
3. Kodak KAF 09000 Device Performance Specification Revision 2.0 MTD/PS-0986 (May 21, 2008).
4. C. Porco et al., "Cassini imaging science: instrument characteristics and anticipated scientific investigations at Saturn," Chapter 6 in *The Cassini-Huygens Mission: Orbiter Remote Sensing Investigations*, C. T. Russell, Ed., p. 468, Kluwer Academic Publishers, Dordrecht, The Netherlands (2004).

Biographies and photographs of the authors not available.