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Taming Residual Bulk Image in CCDs

Residual bulk image (RBI) is a phenomenon observed in certain types of front side-illuminated charge-coupled devices (CCDs). A CCD is an electronic light sensor used in digital cameras. In simplest terms, the sensor exhibits a memory of prior exposures resulting in ghost images appearing in subsequent images. This deferred charge can cause a number of problems in cooled long-exposure scientific applications. At a minimum, the ghost images can create the illusion of a non-existent object (Figure 1, left). Equally serious, they can lead to significant errors in quantitative measurements required for photometric applications.

Figure 1. Astronomical exposures showing a normal star field (right) and the same star field with RBI (left).

In Figure 1, the right-hand image shows a normal star field captured in a 15-minute astronomical exposure. The image on the left shows the same field, but it also includes a non-existent nebular-appearing feature that is caused by RBI. In this case, the three nebular dots are residual images from a star used for focusing the system prior to taking the exposure. During the exposure, the trapped charge leaked into the image, creating the illusion of three non-existent nebular objects. Left unchecked, the RBI renders the camera unusable for this sort of scientific application. Fortunately, there are solutions to the RBI problem.

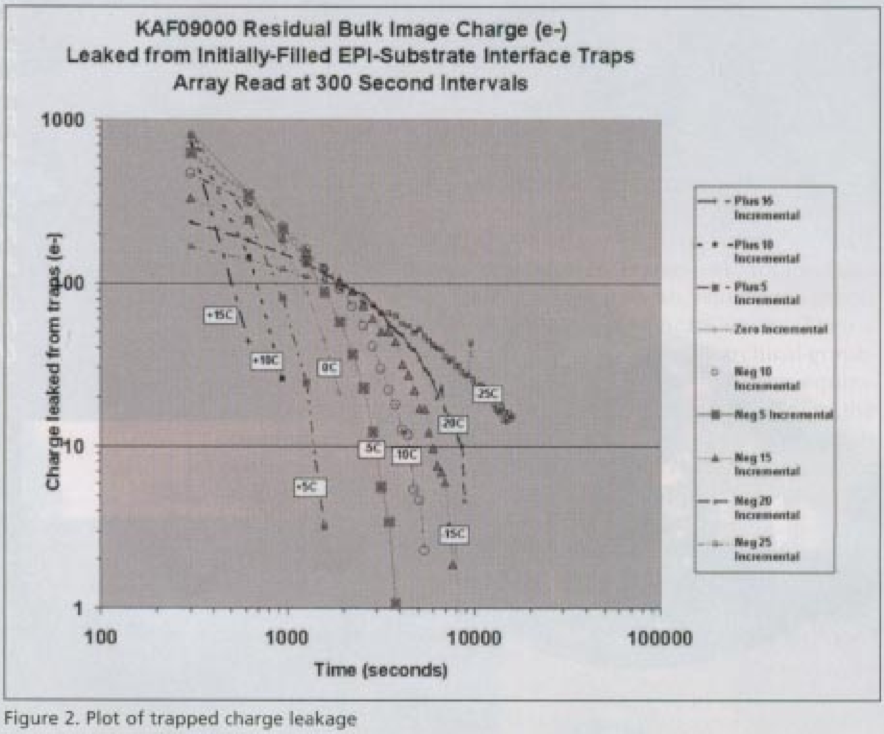

Figure 2. Plot of trapped charge leakage

For some applications RBI can be avoided by removing the longer wavelength light with a filter. However, if near infrared (NIR) and other longer wavelength light are to be studied, another method must be used. One such technique floods the sensor using NIR light and then flushes it before starting each exposure[1]. This method pre-fills the traps before the exposure destroys any residual image. Because the filled traps will leak charge during the exposure, the overall dark current shot noise is increased by this additional charge. Cooling can reduce the leakage since it is strongly influenced by temperature.

It is customary in scientific CCD applications to define the maximum practical exposure limit for any camera operating temperature as that time for which the noise contribution from dark current begins to exceed the camera's read noise. For a longer exposure, the camera noise increases beyond the read noise floor.

For the RBI solution to not add noise beyond this limit for the planned exposure lengths, the dark signal shot noise from the combined thermal and trap leakage components should not exceed the camera's read noise. The operating point of the cooling system is, therefore, chosen to meet this constraint.

The trap leakage versus temperature behavior of the sensor must first be learned in order to determine the target maximum operating temperature for the planned maximum exposure length. Measuring the traps' leakage characteristics is a straightforward but time-consuming process. First, a set of reference dark exposures is taken at different temperatures using a common exposure time. In this work, the standard exposure time was five minutes. Once this reference data is collected, the sensor is flooded using NIR light and a series of dark exposures are taken matching the length of the reference dark. After each dark exposure is captured, it is compared to the reference dark, and the difference is recorded. It is important to accurately measure and remove the offset from each dark frame. A good way to do that is by over scanning the horizontal shift register during readout and carefully measuring the zero signal level in the over scan region. Once the data is collected at several different operating temperatures, it can be plotted as shown in Figure 2.

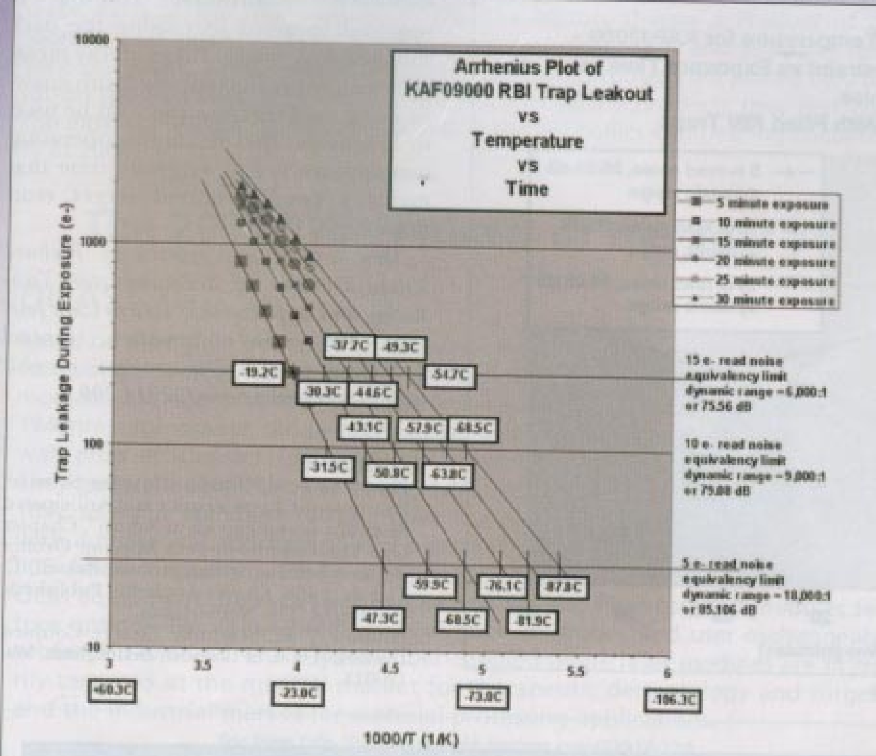

Figure 3. Arrhenius plot of trapped charge leakage.

Thermal rate-based phenomena are often analyzed graphically by making an Arrhenius plot. This plots the logarithm of a thermally sensitive rate quantity versus inverse temperature (1/Kelvin). For a single rate-limited thermally regulated process, the result plots as a straight line. The leakage data from Figure 2 was plotted in an Arrhenius plot and appears as Figure 3.

When summing uncorrelated noise components such as dark shot noise and read noise, the result is obtained by summing in quadrature — taking the square root of the sum of the squares of the individual components. Since the square of the shot noise of this leaked charge is equal to the number of electrons leaked during the exposure, the vertical axis of Figure 3 is also numerically equal to the square of the shot noise of the leaked electrons.

For each of three different read noise reference levels, a horizontal line is drawn on Figure 3 that is numerically equal to the square of the particular reference level. The intersection of these reference lines with the leakage data reveals the maximum operating temperature required to ensure the dark shot noise added by the leaking traps doesn't exceed the camera's read noise limit.

For the sensor under study, an engineering-grade Kodak KAF09000, a half-

In a CCD, RBI is caused by the trapping of photo-generated charges in localized traps formed at the interface between the epitaxial silicon device layer and the bulk silicon substrate[2]. It is only seen in front side-illuminated CCDs and is dependent on the silicon starting material properties, the wafer fabrication process, and the sensor design.

Because longer wavelength light penetrates more deeply into silicon before interacting with the lattice, photo-generated electrons are created deeper in the silicon for red light than for shorter wavelength blue light (figure on left). Under the right conditions, some of the photo-electrons may become trapped in these low-capacity interface traps instead of being collected in the pixel's potential well (figure on right). This leads to the deferred charge that causes RBI.

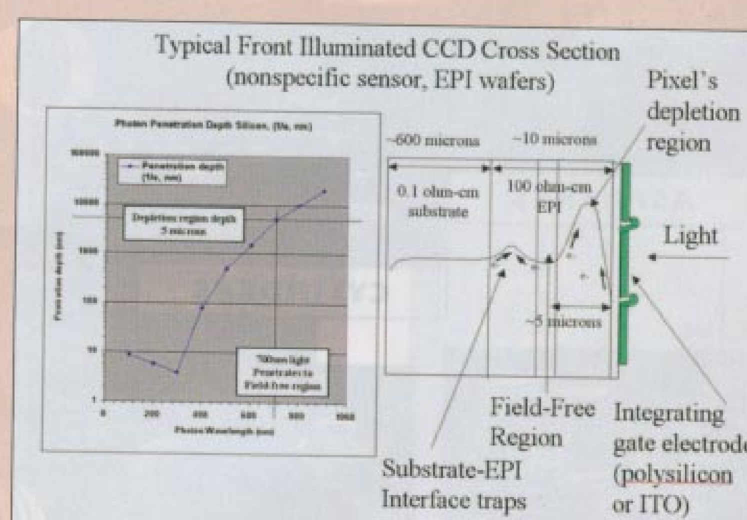

Figure on left shows photon penetration depth into silicon versus wavelength. Figure on right illustrates cross-section of CCD with the pixel depletion region and substrate interface traps shown.

Because the trapping sites are outside of the pixel's depletion region, the gate voltages in the CCD array do not affect this trapped charge. Instead, the charge leaks out of the traps at a rate strongly influenced by temperature. Over a 15-minute period, which is a typical exposure time for many astronomical applications, a significant amount of trapped charge leaks out as shown in the left hand side of Figure 1 in the article. It is clear that RBI is a serious concern for this sort of long-exposure scientific application.

hour exposure with a 5-electron read noise limit requires an operating temperature of no warmer than -87.8°C. This is significantly cooler than needed considering only the thermal dark current shot noise.

Figure 4 presents a family of curves that shows the maximum operating temperature as a function of exposure time for three different read noise targets. This can serve as a guideline for initial cooling system design planning.

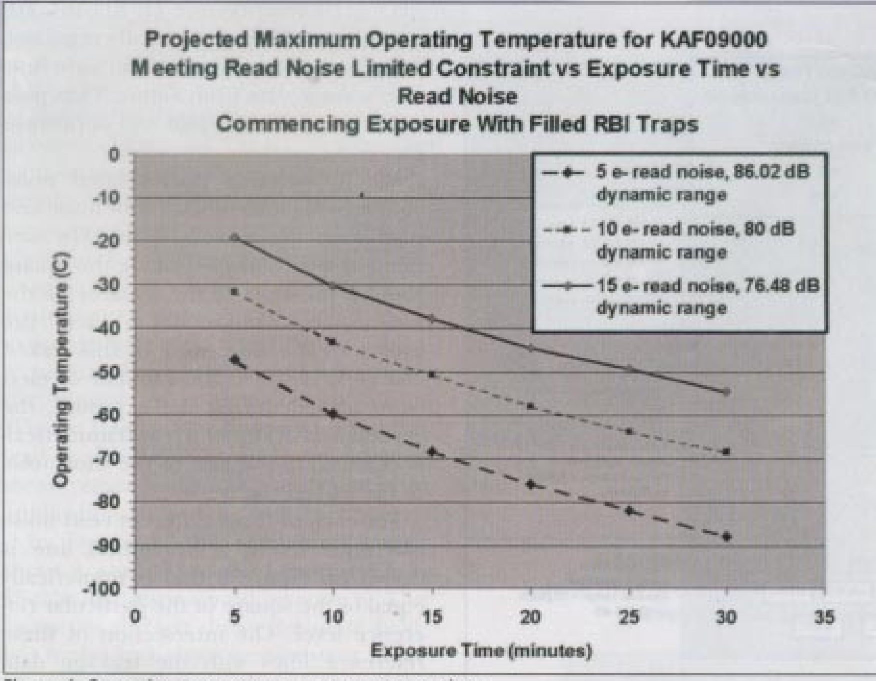

Figure 4. Operating temperature versus exposure time.

RBI is a serious problem in some long-exposure scientific CCD imaging applications. An NIR flood-flush-integrate protocol can be used to pre-fill the substrate traps to eliminate any residual image before the start of an exposure. Additional cooling is required to avoid increasing the dark shot noise. A simple flood/decay measurement protocol combined with analysis using an Arrhenius plot can be used to determine the maximum operating temperature versus exposure time that meets a predetermined target read noise limit.

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