Paper 7249-22: Residual bulk image characterization and management in CCD image sensors

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Page 1:

Good afternoon. Thank you for your attendance.

Outline

- Examples of Residual Bulk Image (RBI)
- Root cause of RBI
- Characterization of RBI
- Management of RBI
- Impact on noise
- Summary

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My talk will consist of:

Examples of Residual Bulk Image (RBI)

Root cause of RBI

RBI characterization for a particular sensor

A way to manage RBI

Impact on noise

Summary

RBI example in scientific image (@ 656 nm)

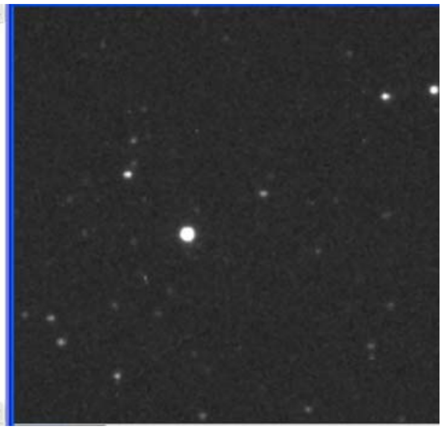
Image with RBI
(is that a nebula beside the bright star?)

Page 3:

Here is an example of a scientific image where RBI can cause a problem. In the middle of the image we see a nebular-like object to the right of the bright star. Is this a real object or is this just RBI?

RBI example in scientific image (@ 656 nm)

Image with RBI



Actual starfield
(the "nebula" was RBI)

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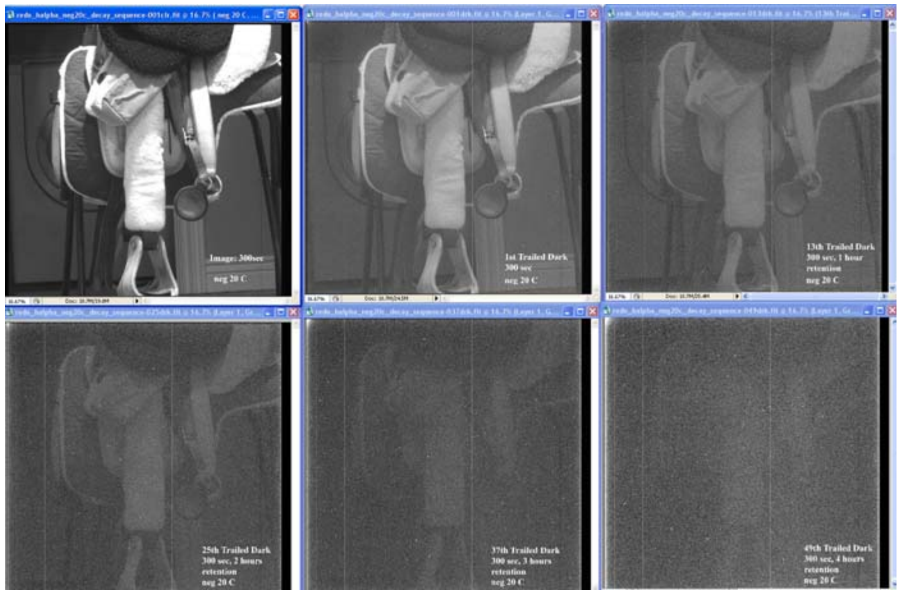
As we see comparing the two images, the leftmost image doesn't contain a nebula, instead it is just RBI. It is worth noting that ten images were combined to make the image containing the RBI and each image was aimed slightly differently or "dithered". Despite this precaution, there is still an RBI artifact in the final image.

Long retention RBI example (656 nm light)



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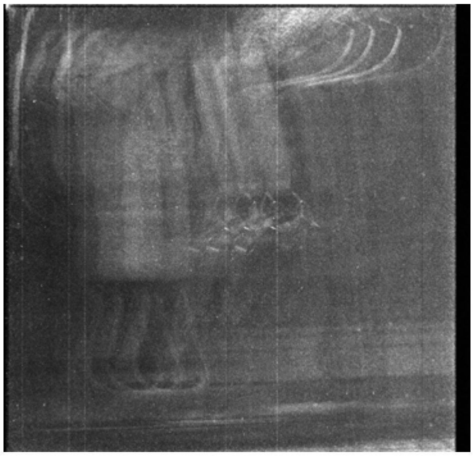
This is an example of the persistence of RBI. For these images all exposure times were five minutes and the operating temperature was –20C. In the upper left is an image taken using a narrowband emission line filter centered at 656.4nm, the Hydrogen Alpha wavelength. Just to the right of that image is a dark exposure taken immediately following the light image. As you can see, the image of the prior scene is quite prominent in this shutter-inhibited image. To the right of it at the end of the upper row is the thirteenth subsequent dark exposure, taken one hour after the light exposure. Again the original scene is easily observed. On the lower row at the far left is a dark taken at two hours, in the middle it is at three hours and finally the lower right shows the dark taken four hours after the light image.

In all cases the image from the original scene is visible in the dark exposure.

Another RBI example: unfiltered tungsten light



Five minute dark exposure following
four 0.1 second light exposures

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This is another example of RBI. This is a dark image of five minutes duration taken immediately after a sequence of four unfiltered tungsten light images, each of a tenth second duration, with camera motion occurring between each light image. The result is a multi-ghost RBI image in this dark image frame.

Root cause of RBI

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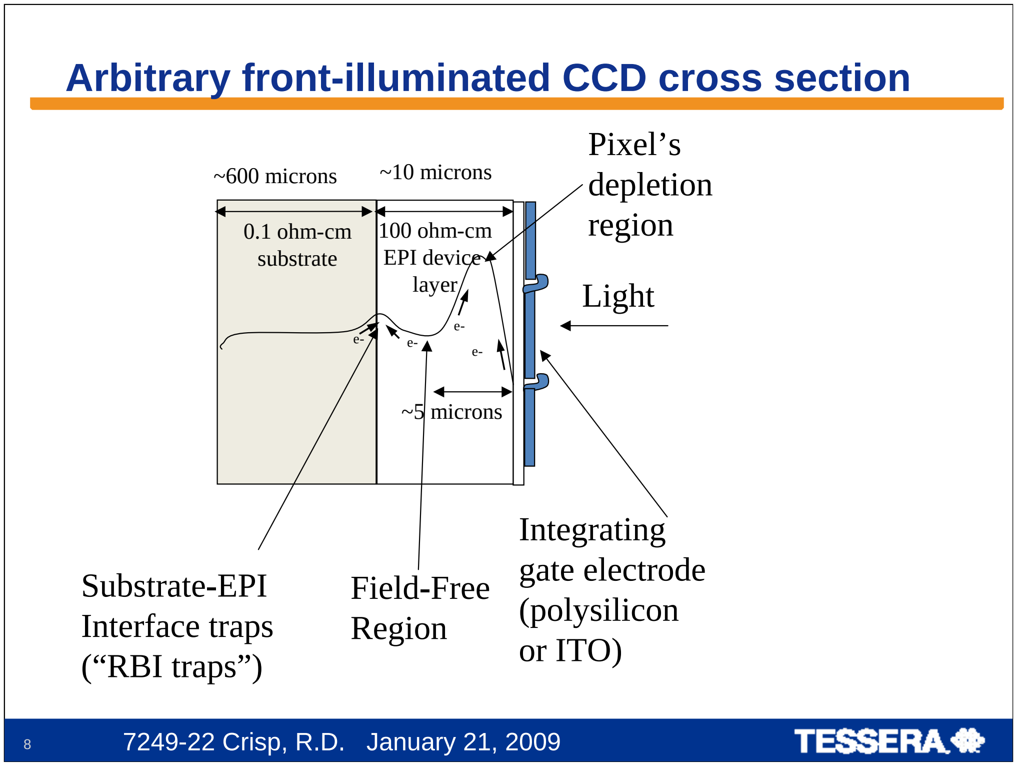
Now let’s discuss the root cause of RBI



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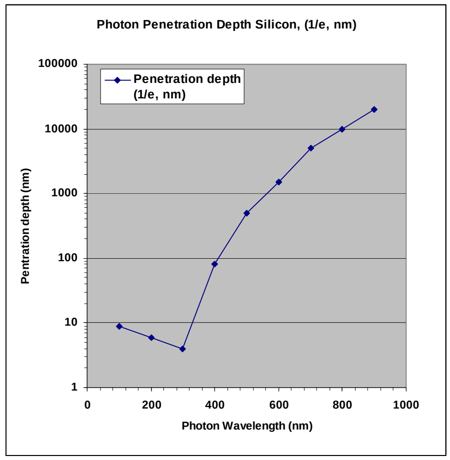
In this slide we see a cross section of an arbitrary frontside illuminated CCD manufactured on an epitaxial silicon wafer. The epi layer is 10 microns thick and the handler wafer below is 600 microns thick. At the interface between the epi and the handler wafer is a region that can contain many trapping sites. If photo electrons are created within these regions they will become trapped. In fact if photo electrons are created within the field free region below the pixel's potential well, there's a good probability that they will end up being trapped in these trapping sites.

Once trapped the photoelectrons are not influenced by the potentials in the pixel wells: instead they leak out of the traps due to thermal energy and with a time constant that is a strong function of temperature.

Photon penetration depth in silicon vs wavelength



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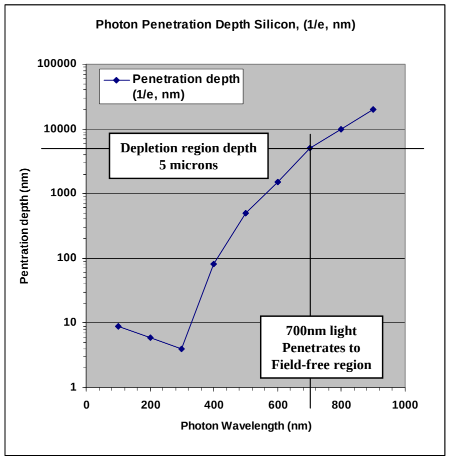
Here we see a graph showing the penetration depth of a photon into silicon as a function of wavelength.

Photon penetration depth in silicon vs wavelength



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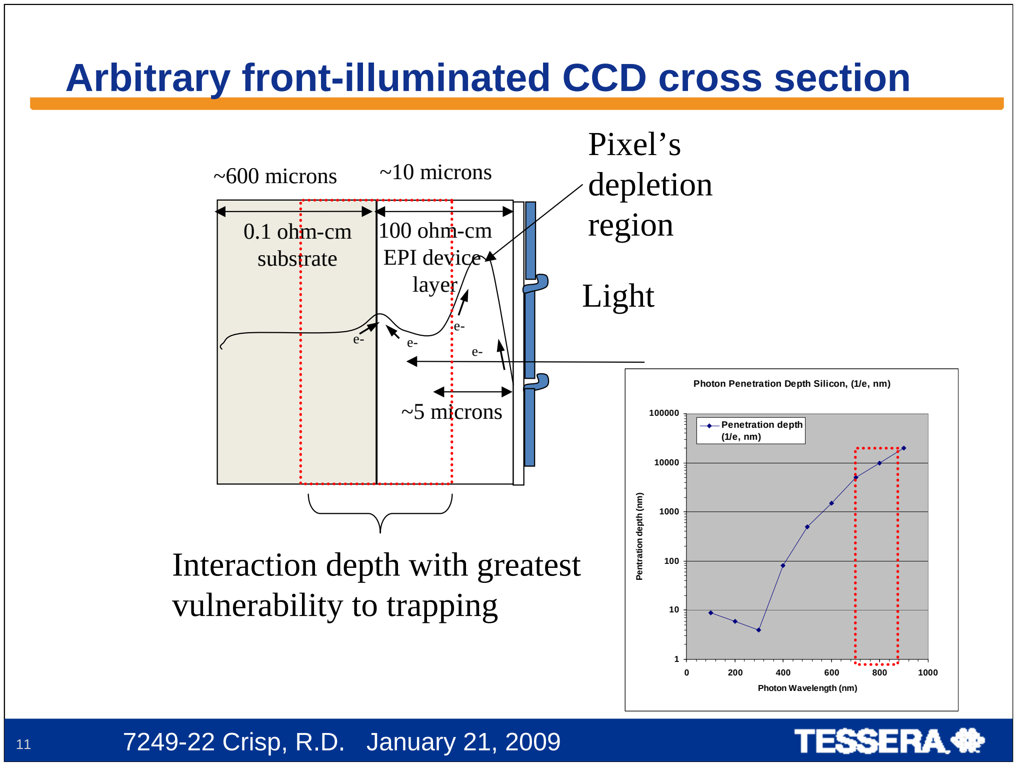
As we see, for wavelengths of 700 nm, the penetration depth is about five microns, which is about the depth of the depletion region in our arbitrary CCD we are discussing



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So for wavelengths between about 700 nm and 900 nm we have a "sweet spot" for capturing photoelectrons in this sensor's substrate trapping regions

Characterization

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Now let's talk about characterization of the RBI properties of the analyzed sensor

Goals of characterization

- What is the capacity of the traps?
- What is the thermal dependence of trap leakage?

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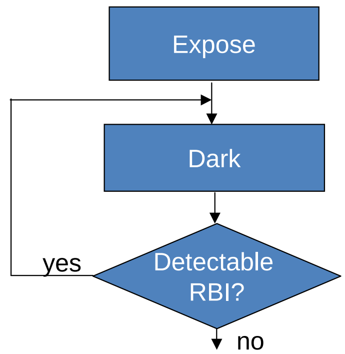
The goals of the characterization are to learn the charge capacity of the traps and what the thermal dependency is of the trap leakage.

Characterization: part 1, hydrogen alpha images

- The sensor was exposed to light through a focused lens using a 656.4 nm narrowband emission line filter (Baader Planetarium, 7 nm FWHM passband)
- Light exposures were five minutes, saturating the brighter parts of the image
- Dark exposures were five minutes
- Darks were taken until no RBI was detected



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The first part of the characterization used the camera in conjunction with a lens and a narrowband emission line filter with a center wavelength of 656.3 nm and a passband of 7 nm FWHM. For various operating temperatures, a five minute long image was taken of a target. The exposure resulted in the brighter portions of the image being saturated while other parts were not. Immediately following the image, a sequence of dark images was taken. Each was five minutes long. The dark image sequence continued until no RBI was observed.

Data Reduction: part 1, hydrogen alpha images

- “Cold-start” reference dark frames were taken at each operating temperature, overscan was used for accurate offset determination
- A filtered light image of five minutes duration was taken using a focused camera lens. The brighter portions of the image saturated. This image was used to initiate RBI.
- A selection box was chosen in a saturated portion of the RBI-initiating image for characterization. The same selection box was used for all subsequent data evaluation.
- Each subsequent five minute dark image was measured to determine the number of electrons that leaked from the traps during its integration
- A running tab was kept of the total accumulated leaked charge to measure the trap capacity
- Once the leakage matched the reference dark, the traps were deemed exhausted

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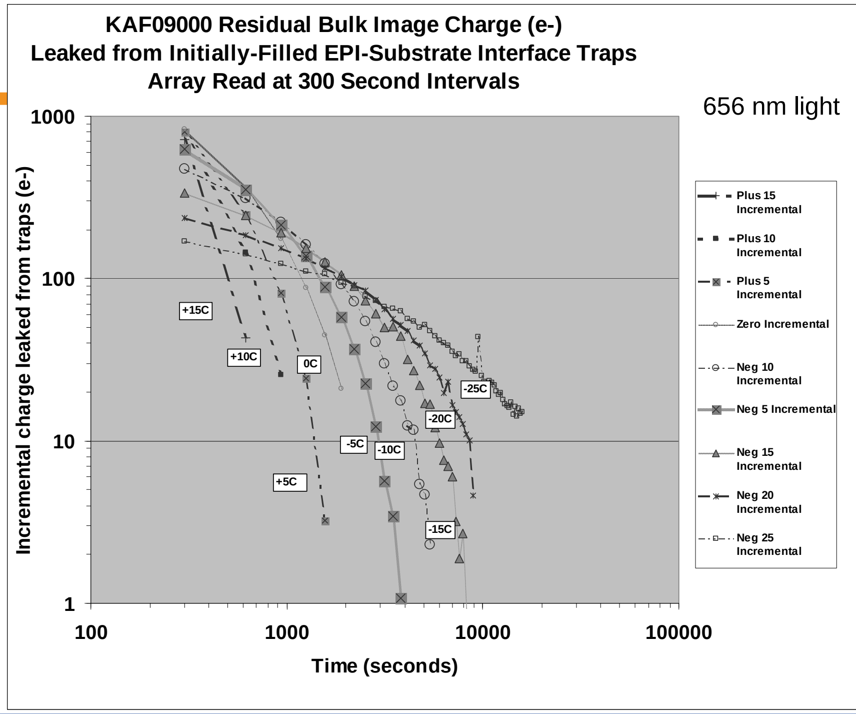
For each operating temperature, a five minute long cold start reference dark was taken. A selection window was placed over a saturated portion of the image and all measurements were performed on this region in all frames so that the same pixels were analyzed.

Removing the offset measured in each frame’s overscan region, the reference dark was subtracted from each dark from the sequence and the delta noted as RBI leakage charge. A running total of the leaked charge was summed for each temperature, providing a measure of the trap capacity.

When the sequential dark matched the reference dark, the traps were deemed to be fully exhausted.



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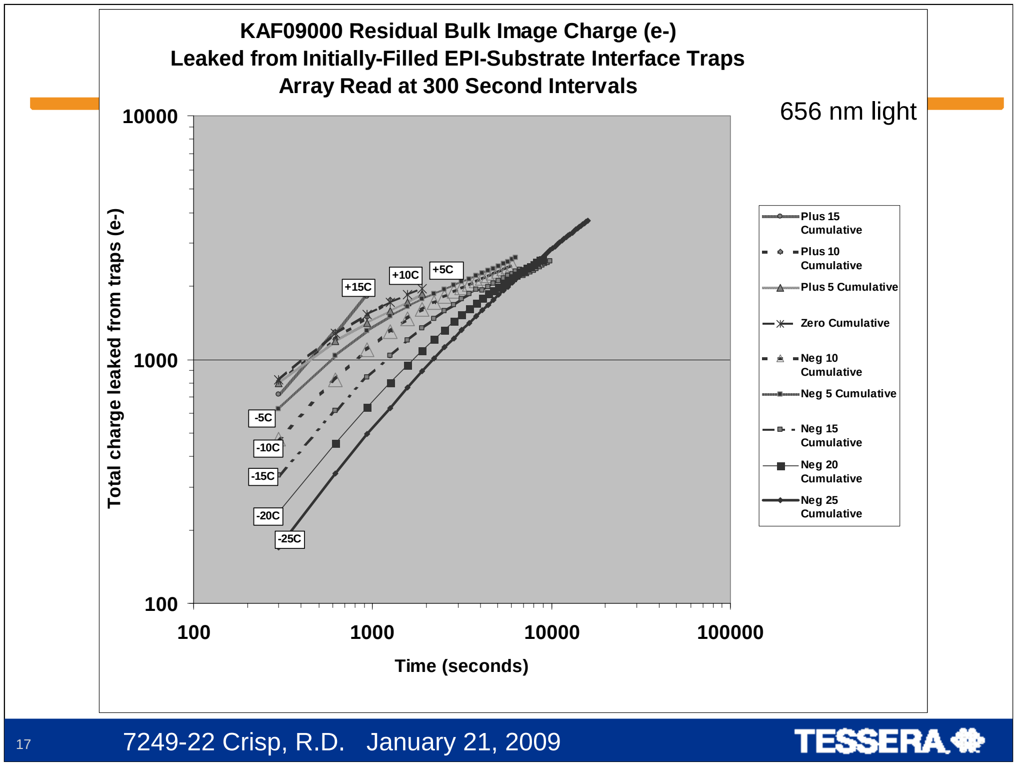
This chart shows the incremental leaked charge measured in each sequential dark for each operating temperature measured. Note that even a modest operating temperature of –20 C will result in multi-hour RBI decay.



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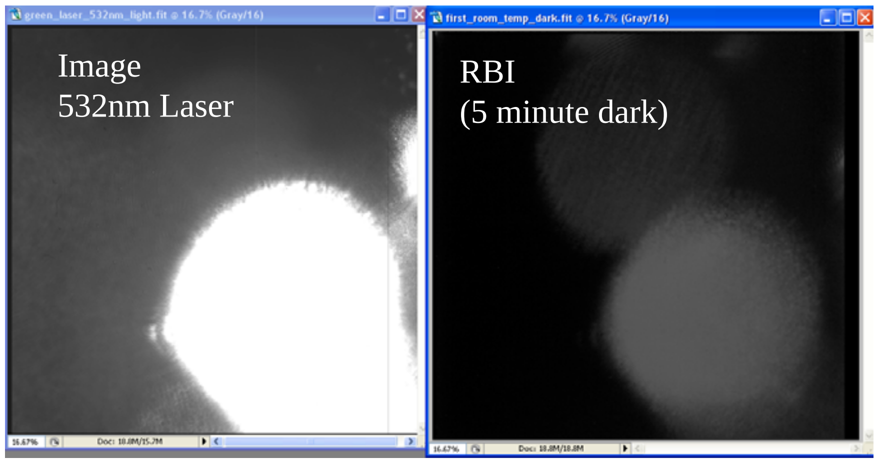
This chart shows the cumulative leaked charge for each operating temperature as a function of time. There were some anomalies in the collection of some of the data points as will be explained in a moment below. In order to get a more accurate measure of the trap capacity a second data set was taken using a modified procedure for filling the traps.

RBI initiated by 532 nm laser light



Although weak compared to 656 nm light, at 532 nm there is RBI visible

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The image on the left was taken using a green laser pointer of 532 nm wavelength to illuminate the sensor. On the right RBI can be observed. The intensity of the RBI was significantly reduced versus 656 nm light, but due to the intensity of the laser, a small amount of charge was trapped.

So RBI in this sensor is not restricted solely to NIR and longer wavelength light.

Characterization: part 2, internal NIR flood

- The tested camera (FLI Proline 9000) includes NIR LEDs that are arranged to provide a means to flood the sensor with NIR light
- The sensor was flooded for 10 seconds and then flushed twice to fill the traps for leakage measurement
- Using the internal flood LEDs provided a consistent and reproducible method to initiate RBI avoiding some of the uncertainties associated with the first method that is based on analyzing an image containing variable regions of RBI
- The internal NIR flood was used for the remaining RBI tests in this report

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A second pass at the characterization was performed using internally mounted NIR LEDs to charge the sensor's traps. In this case the LEDs flooded the sensor for 10 seconds followed by two flushes of the array. For this measurement set, all sequential darks were a half hour duration.

This method provided more consistent results than the image method used earlier, primarily because slight movement of the camera aiming did not impact where the image saturated. Although there was not a visible image per se, versus the lens method used previously, the RBI leakage was unambiguously quantifiable as before.

For the remainder of the RBI testing, the NIR LEDs were used to fill the substrate traps.

Data Reduction: part 2 internal NIR flood

- "Cold-start" reference dark frames were taken at each operating temperature, overscan was used for accurate offset determination for all evaluated frames
- The same selection box was chosen as in the previous case for characterization.
- Once the leakage matched the reference dark, the traps were assumed to be exhausted

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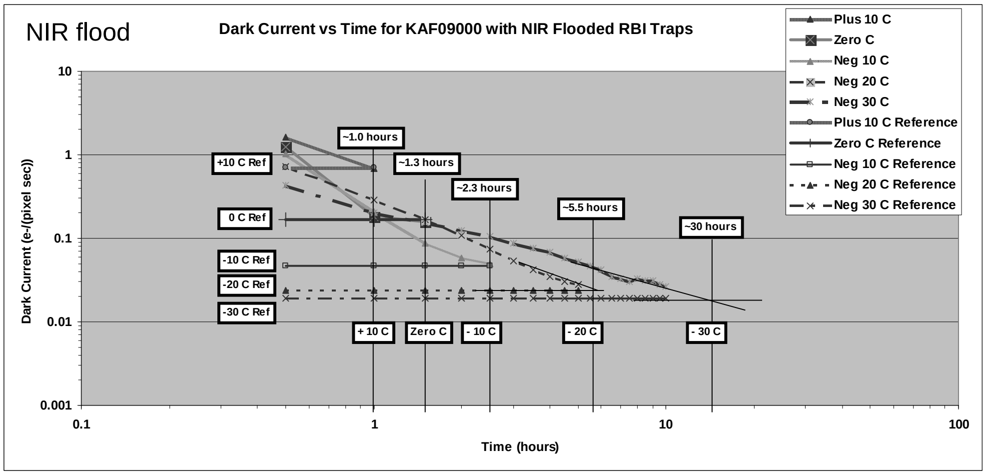
Data reduction was done as before, noting the exhaustion point being reached when the incremental dark's leakage matched the reference dark's leakage current.

RBI trap decay vs time vs operating temperature



Reference = Current measured in non-flooded case: “cold-start dark” (half hour integrations)

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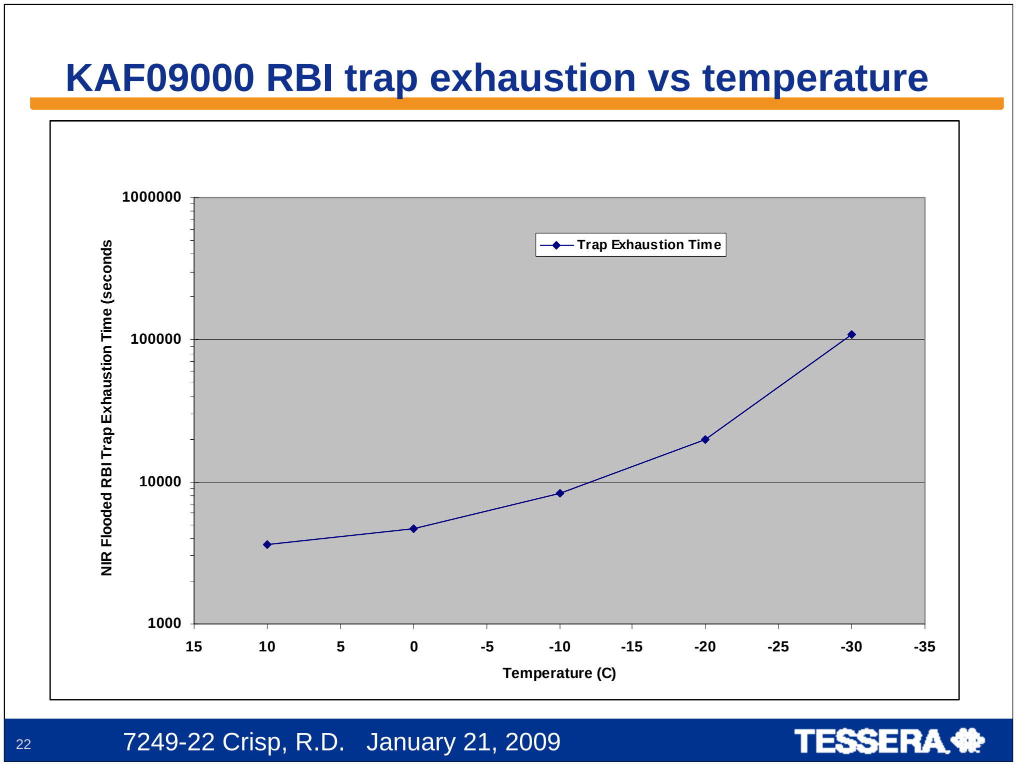
This chart shows the decay of the trapped charge as a function of time for operating temperatures ranging from +10 to –30 C in 10 C increments. Again like previously shown, multi-hour decay is observed for modest operating temperatures.



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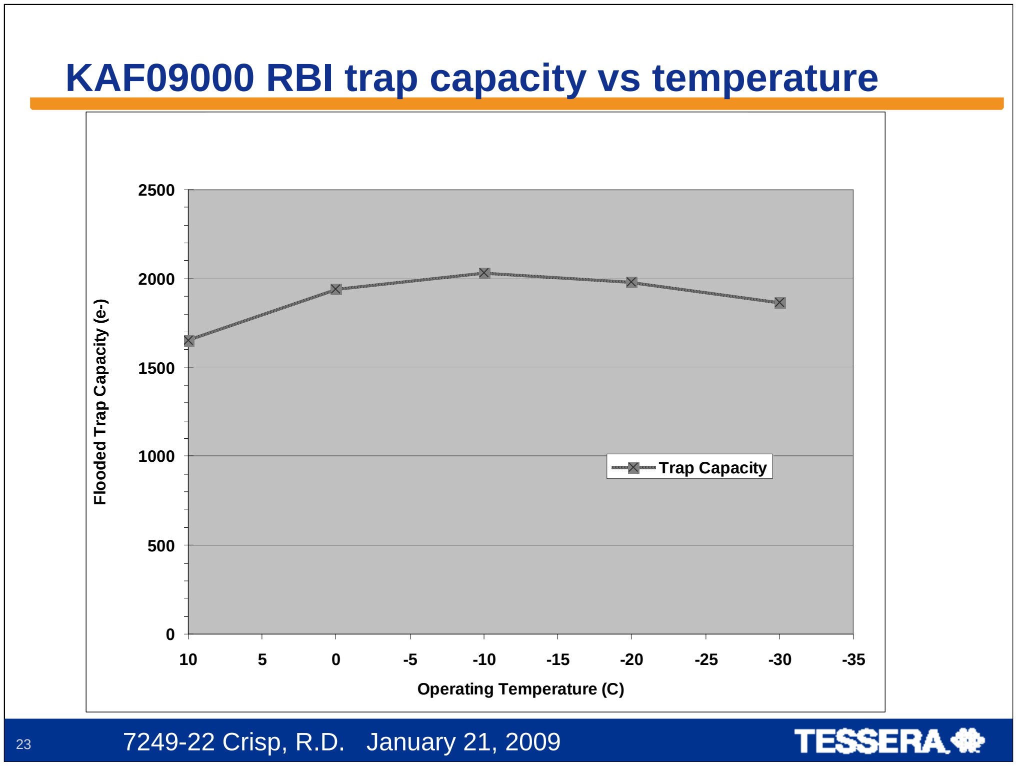
This chart shows the time for total trap exhaustion as a function of operating temperature.



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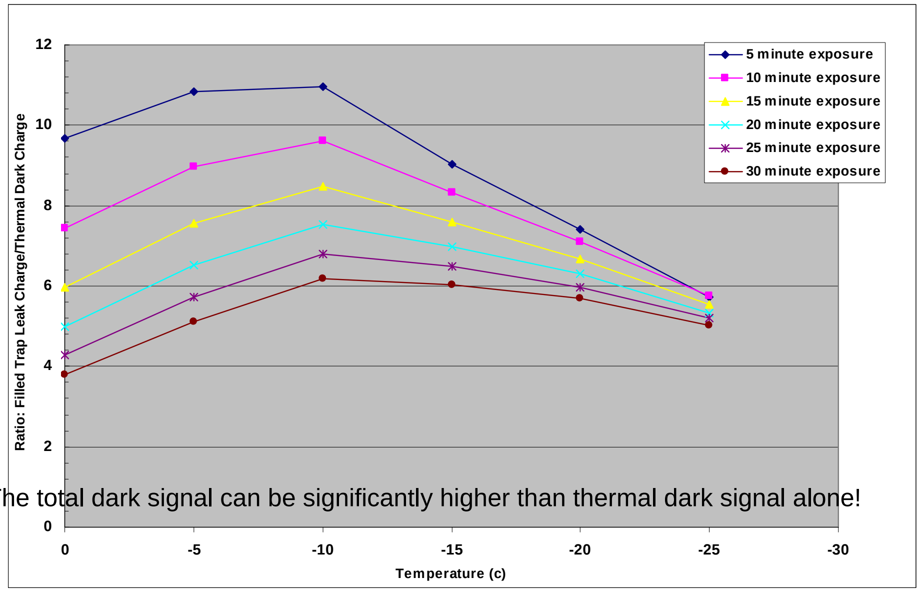
This chart shows the trap capacity as a function of temperature.

The reduction of capacity at the warmer operating temperatures is due to the fact that the camera performs a flush prior to any operation. So during the time between an exposure and the first dark, a flush is performed and that will sweep away any RBI leakage charge during that time, causing the trap capacity to be underreported. This happens for all operating temperatures and between all exposures but it is only at the warmer temperatures and the initial period between the exposure and first dark, when the most charge is lost.

For the coldest operating temperature, the trap was not fully exhausted at the time the data set ended so the cumulative charge was not at its maximum level. This also resulted in an underreporting of the trap capacity.

Ratio: KAF09000 RBI trap leakage charge / thermal dark current charge vs exposure time vs temperature



The total dark signal can be significantly higher than thermal dark signal alone!

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This chart shows the ratio of the RBI trap leakage charge to the thermal dark charge that leaks during a given exposure time as a function of temperature

Management of RBI

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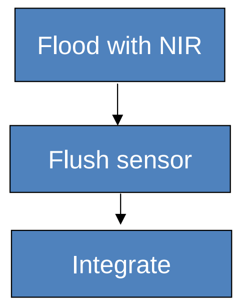
Next, let's discuss management of RBI

Management of RBI

- A method to manage RBI is to begin all integrations with filled substrate traps
  The filling procedure is:
  - Flood the CCD using NIR light
  - Flush the saturated sensor
  - Begin integration



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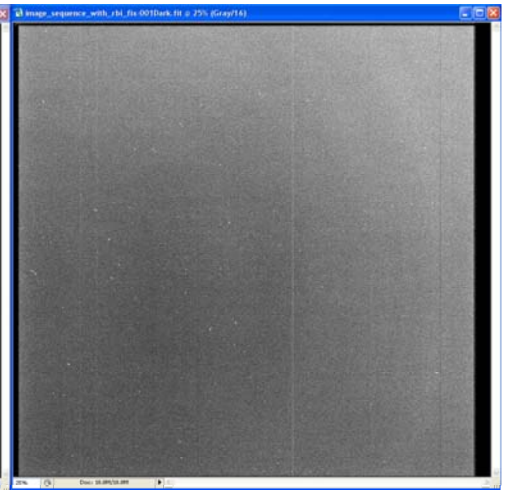
A method to manage RBI is to begin all integrations with filled traps. One way to do that is to flood the sensor with NIR light and then to flush the pixels just prior to any integration. This sequence is followed for any integration: light or dark.

Management of RBI: Flood-Flush-Integrate protocol

Image



First subsequent dark

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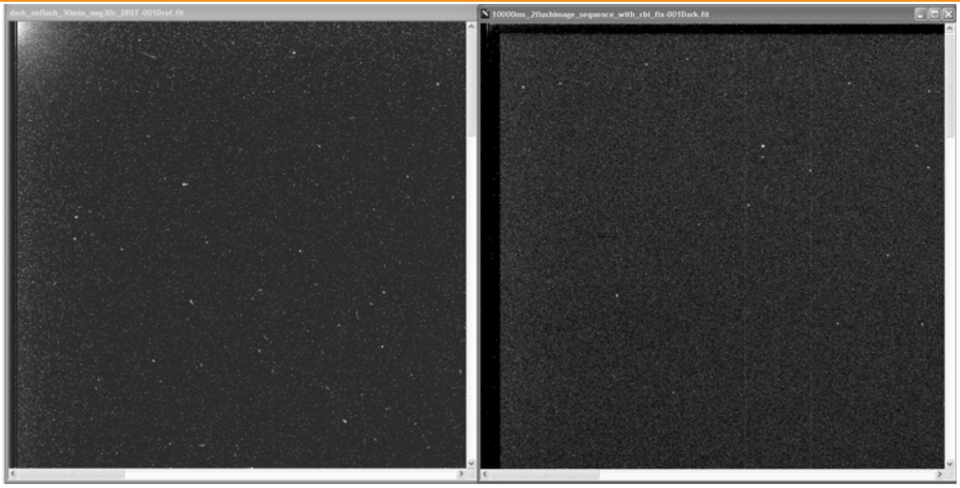
This shows the result of using the flood/flush/integrate protocol to fill traps prior to any exposure. On the left is a normal image, taken using a five minute exposure through the same hydrogen alpha filter as before, but this time with the traps filled prior to the light and the dark exposure. On the right is the first five minute dark image taken after the light exposure. As can be seen no ghost image or RBI is observed in the dark image.

Serendipitous discovery:
Amplifier luminescence reduced via flood/flush/integrate



30 minute cold-start dark with no flood.
Significant amplifier luminescence

Post-flood 30 minute dark frame
Minor amplifier luminescence

The result hints at a power-up transient bias condition initiating impact ionization in CCD's output amplifier

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A serendipitous discovery was made: a small amount of amplifier luminescence was noted in the cold-start dark reference images. However using the flood/flush/integrate protocol, virtually no luminescence was observed.

Additional investigation showed that the luminescence decayed after a cold-start in a manner similar to RBI. These facts strongly suggest a power on transient event that momentarily places the CCD's source follower into a bias region conducive to impact ionization. Such impact ionization generally creates NIR light and that is trapped in the substrate traps.

Because the observed luminescence decays in a long sequence of dark frames after a cold start, it further indicates this to be a single event that isn't repeated after the camera is powered up and stable.

Impact on noise

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Next let's examine the impact of the flood/flush/integrate protocol on noise

Impact on noise: trap charge leakout

$$dark\_noise = \sqrt{read\_noise^2 + \underbrace{dark\_signal}}$$

thermally_generated_charge + trap_leakage_charge

[ignoring dark fixed pattern noise]

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Looking only at the dark noise terms while ignoring dark fixed pattern noise, we see the noise to be the quadrature sum of the read noise and the dark signal shot noise

The dark signal shot noise now has two basic components: the thermally generated charge and the charge that leaks from the RBI traps during the exposure. Since the trap leakage charge is often six times the amount of the thermally generated charge or more, the dark signal term can become significant in the overall noise equation and may dominate the camera's contribution to the noise in the image.

If that proves to be the case then cooling can be used to solve the problem

How much cooling is needed for a given exposure time?

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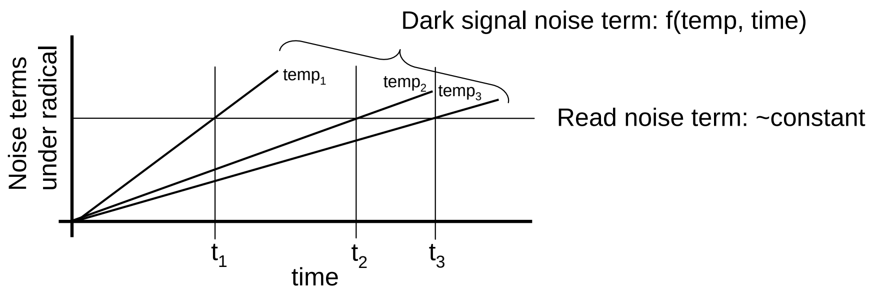
But how much cooling is needed?

Maximum operating temperature

$$dark\_noise = \sqrt{read\_noise^2 + dark\_signal}$$

(time-invariant) (time-dependent)

The ***maximum operating temperature*** is reached when the two terms are equal for the desired exposure time



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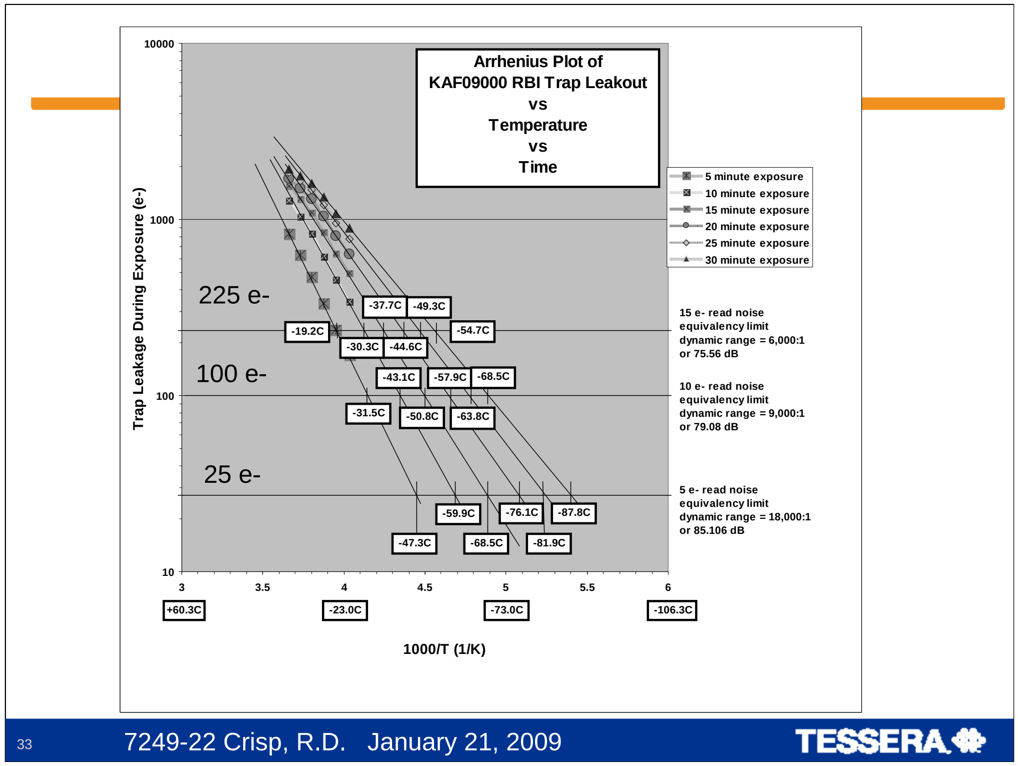
It is common to talk of the maximum operating temperature as that temperature where the dark shot noise just matches the read noise. Since the dark shot noise grows with time and the read noise does not, for any operating temperature there is an exposure time for which the dark shot noise will just match the read noise. For a longer desired exposure a cooler operating temperature would be indicated.

As was seen earlier, the leakage from the filled traps is usually much greater than the thermally generated leakage, so we'll limit our noise analysis to the trapped charge in a sensor with completely filled RBI traps for the cooling analysis. So we will ignore the thermal dark current when determining the cooling requirement.

To answer the question as to how much cooling is needed we need to be able to predict the RBI trap leakage as a function of exposure time and operation temperature.



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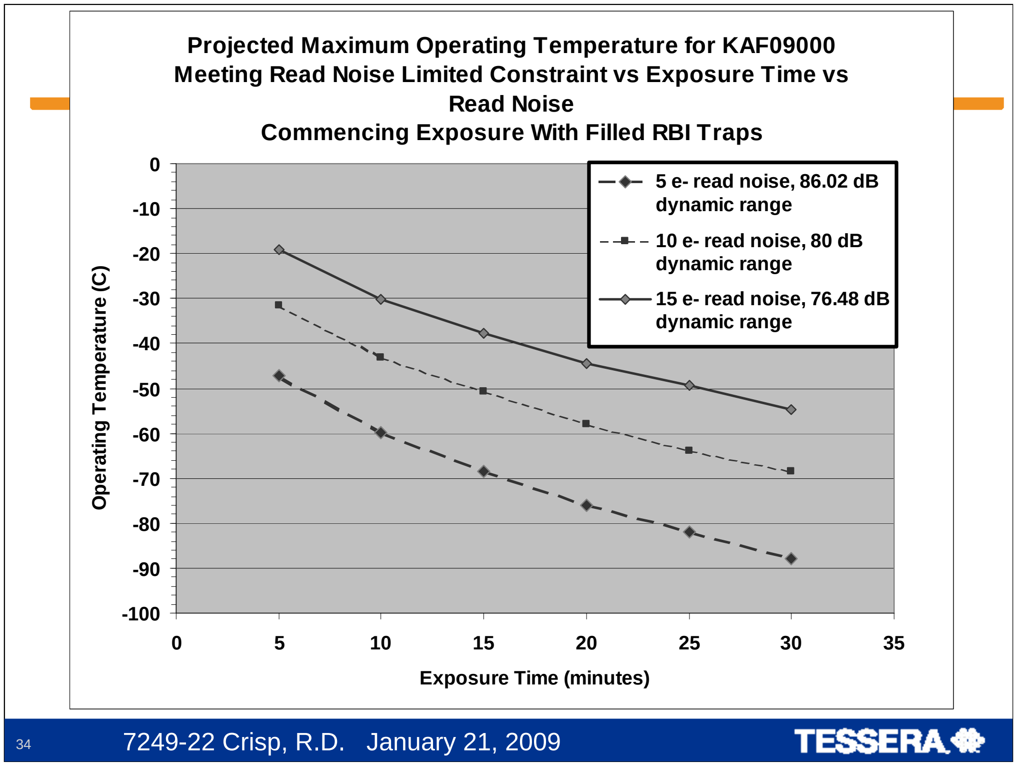
For a single rate-limited thermally activated process, plotting the logarithm of the rate versus the logarithm of inverse temperature will yield a plot with straight lines. This is called an Arrhenius plot. Using the characterization data presented, an Arrhenius plot was created plotting the total leakage in electrons for a given exposure duration versus operation temperature of the sensor.

The horizontal intersecting lines at 225, 100 and 25 electrons show the maximum operation temperatures where the given exposure durations meet the noise criteria for read noise targets of 15, 10 and 5 electrons respectively.



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Plotting the intersecting points from the Arrhenius plot versus exposure time, we have a chart showing the maximum operating temperature versus exposure time for 15, 10 and 5 electron read noise constraints. Note that a half hour exposure with a 5 electron read noise constraint indicates an operation temperature of –87 C. This is a significant challenge using conventional TEC based coolers for a low cost camera.

Summary

- RBI can disrupt the integrity of scientific images unless managed
- RBI is severe in the evaluated sensor (Eng Grade KAF09000): residual image detectable 10 hours after exposure with modest cooling (-30C)
- Flood-Flush-Integrate protocol is effective at removing RBI
  - Also minimizes observed amplifier luminescence
- Leaked charge from prefilled trap is typically much larger (>6x) than dark signal charge for moderate cooling (down to –30C) in average duration scientific exposures (5 – 30 minutes)
- Deep cooling (down to approx -90 C) indicated to manage shot noise associated with prefilled trap leakage for half hour exposures with 5 e- read noise target

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In summary:

RBI can disrupt the integrity of scientific images unless managed

RBI is severe in the evaluated sensor, which was an eng Grade KAF09000.

Residual image was detectable 10 hours after exposure with modest cooling (-20C)

The Flood-Flush-Integrate protocol is effective at managing RBI

-and it also minimizes amplifier luminescence

Leaked charge from prefilled traps is typically much larger, often six times greater or more, than dark signal charge for moderate cooling such as down to negative 30 C for average duration scientific exposures of 5 to 30 minutes.

Deep cooling, down to approx -90 C, is indicated to manage shot noise associated with prefilled trap leakage for half hour exposures with 5 e- read noise target.

This concludes my presentation. Thank you for your attention.

Are there any questions?

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

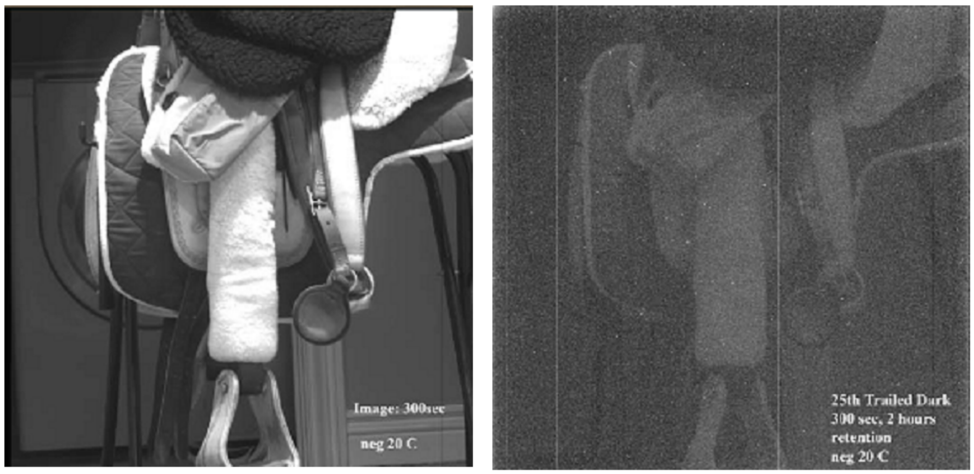
1. INTRODUCTION

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)

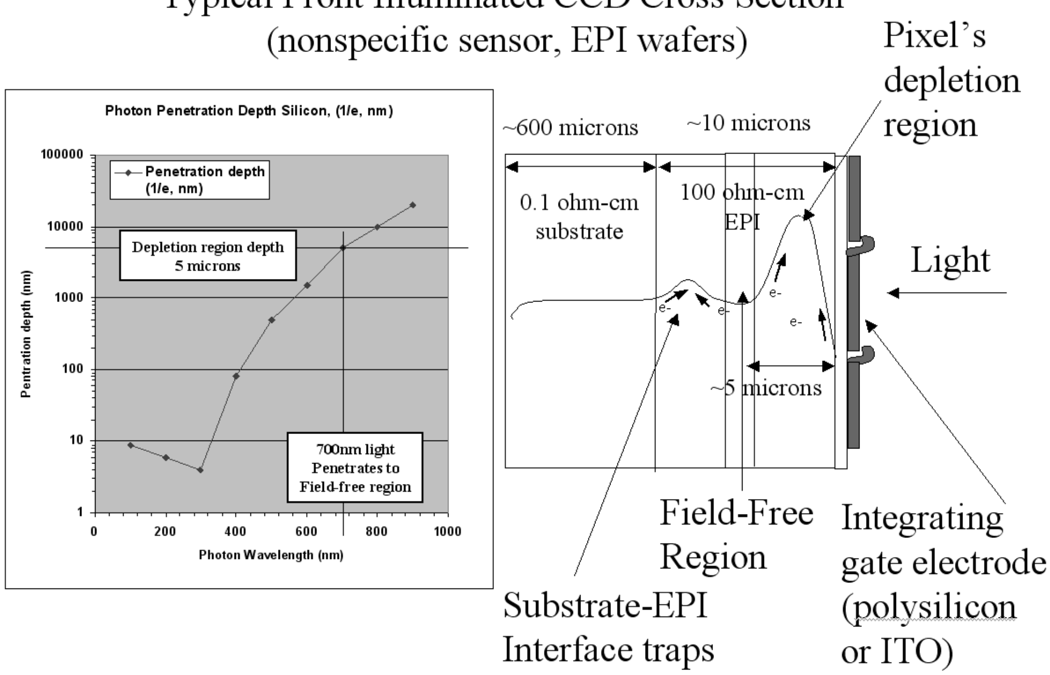


Figure 2

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

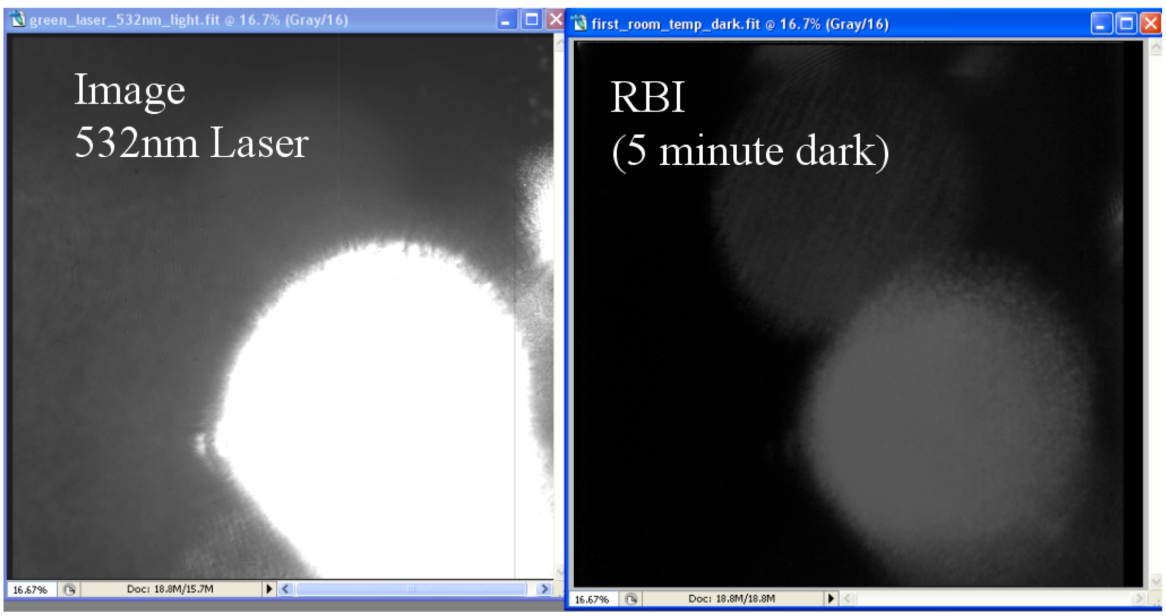


Figure 3

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: 7nm FWHM with 656.4 nm CWL).

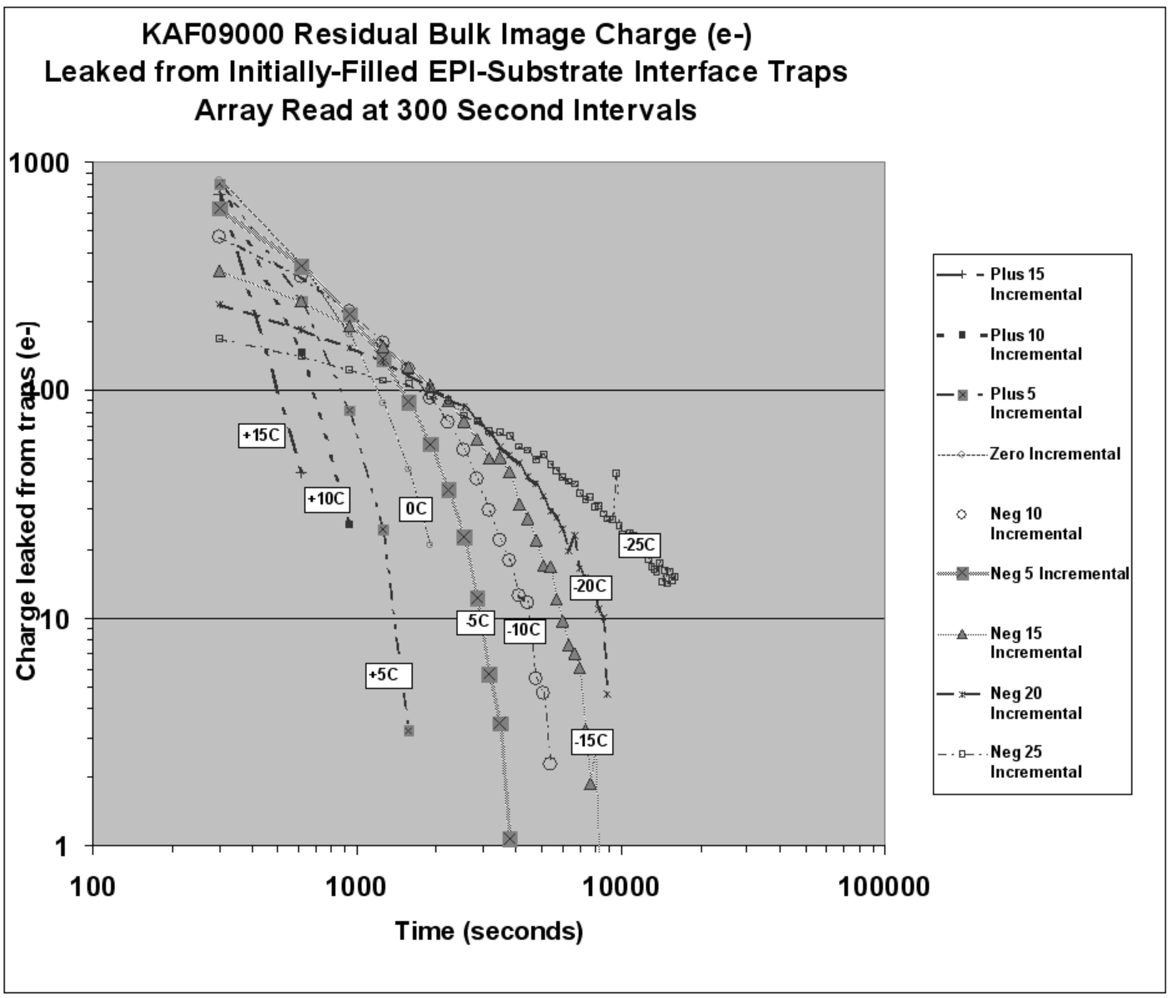


Figure 4

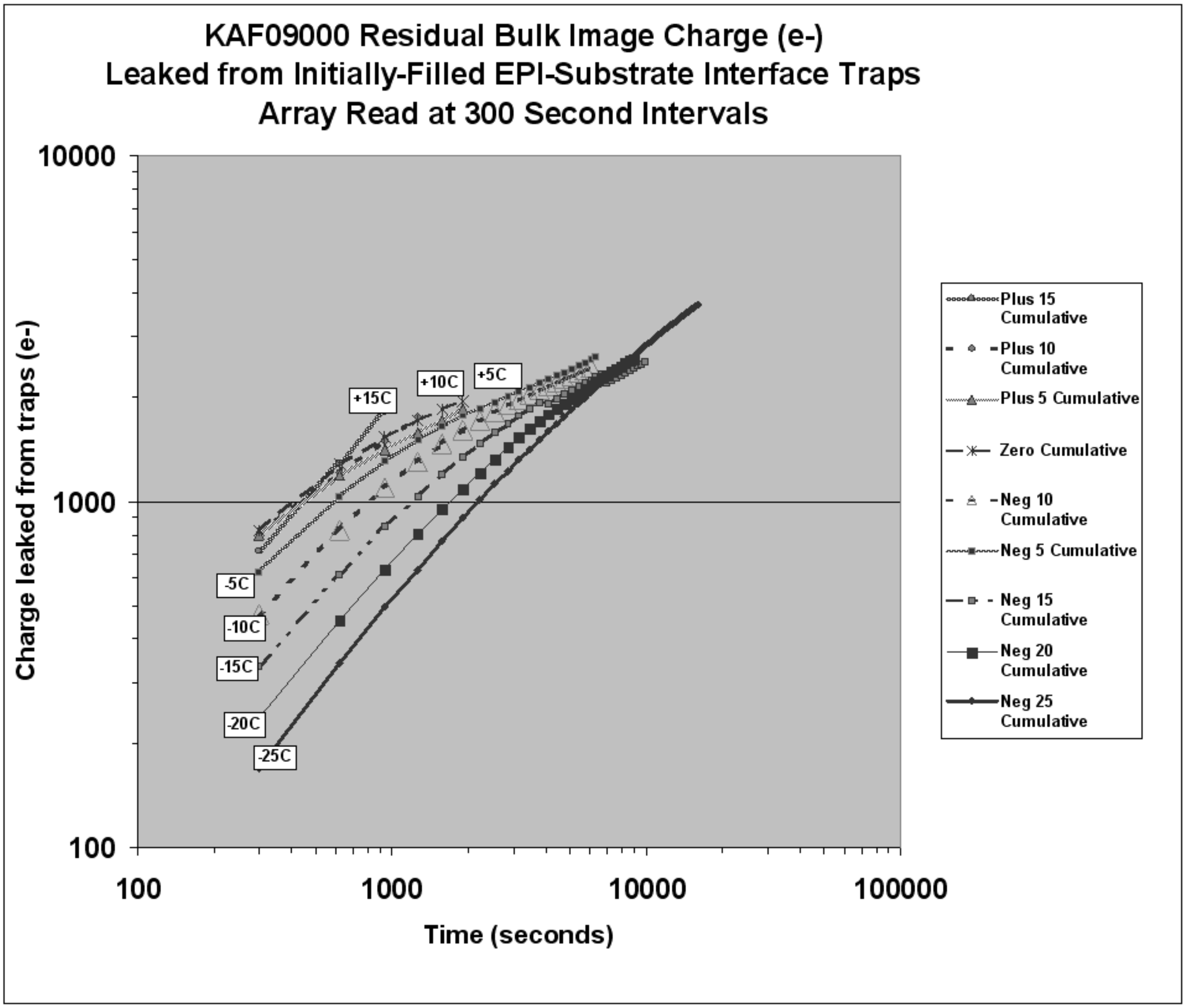
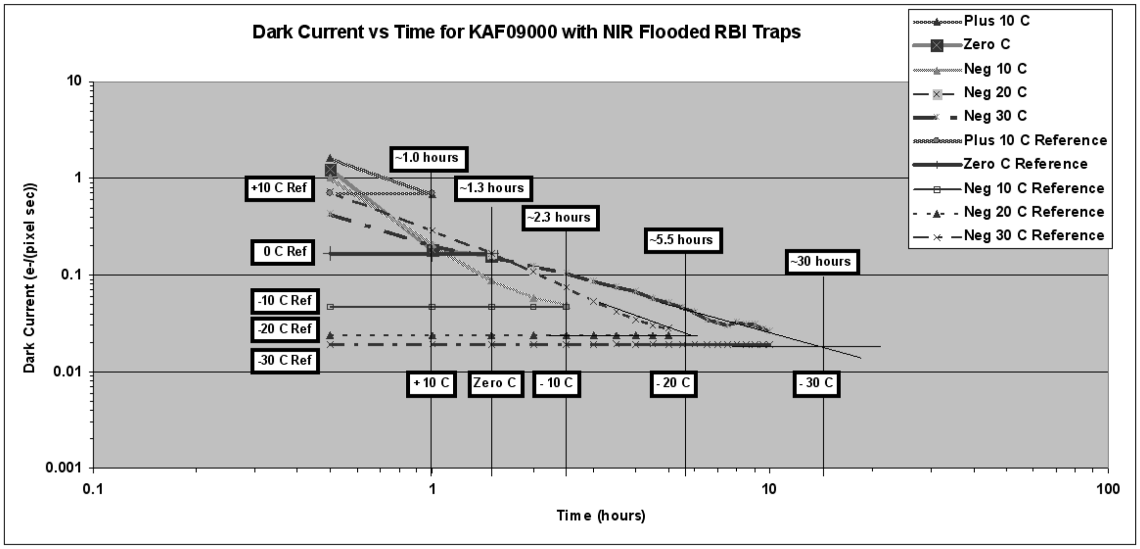


Figure 5

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).



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

Figure 6

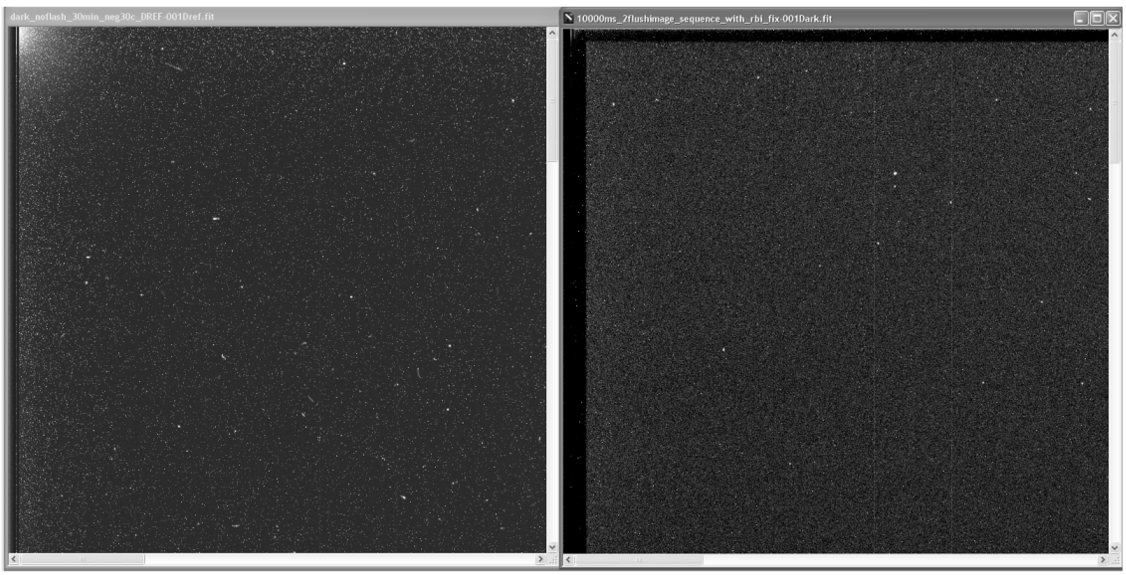
Total exhaustion was defined as that time when the flooded sensor’s dark current matched its reference dark current, indicating no trapped charge remained. The reference dark current was defined as equaling the average dark current for the same duration exposure at the same temperature in a non-flooded 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 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.

KAF09000 with /without NIR flood



30 minute dark with no flood. Significant amplifier luminescence

Post-flood 30 minute dark frame Minor amplifier luminescence

Figure 7

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 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).

$$dark\_camera\_noise = \sqrt{dark\_shot\_noise^2 + read\_noise^2} = \sqrt{dark\_signal + read\_noise^2} \quad (1)$$

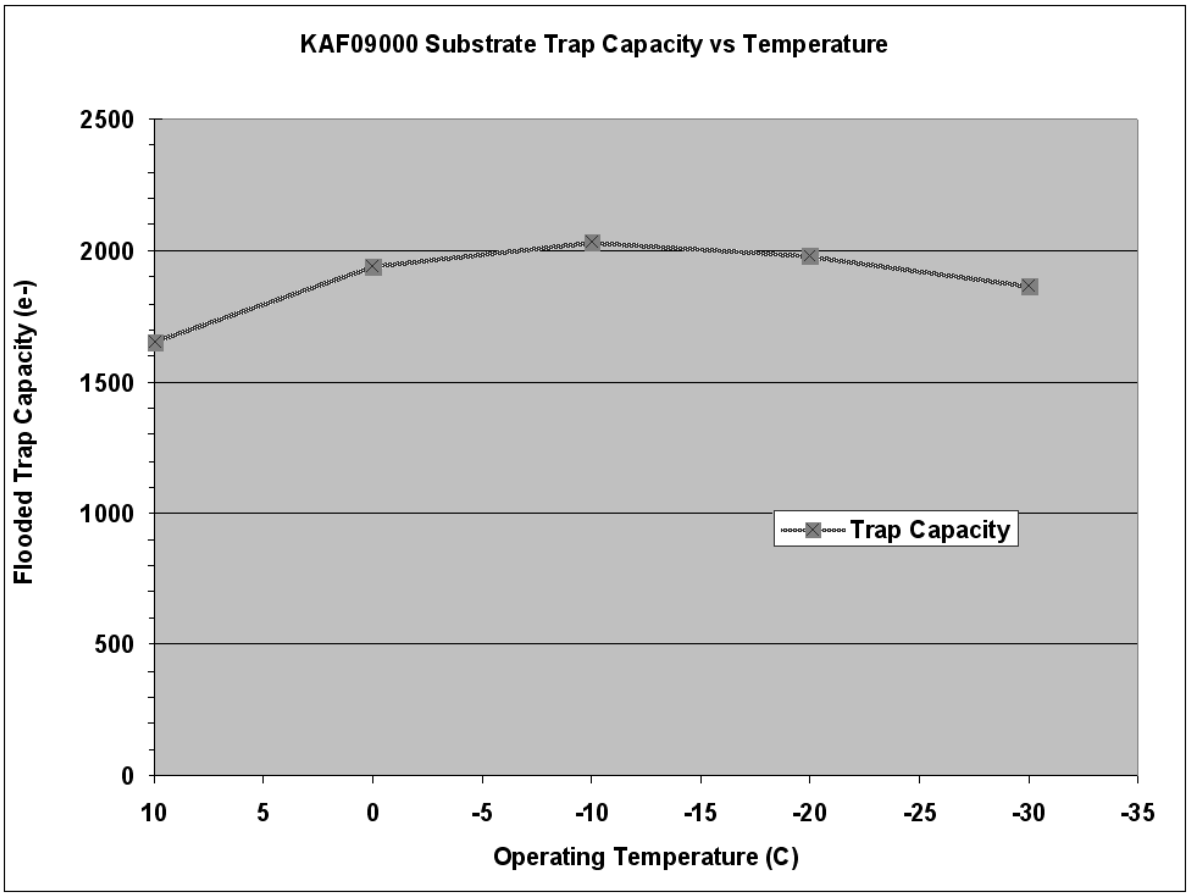


Figure 8

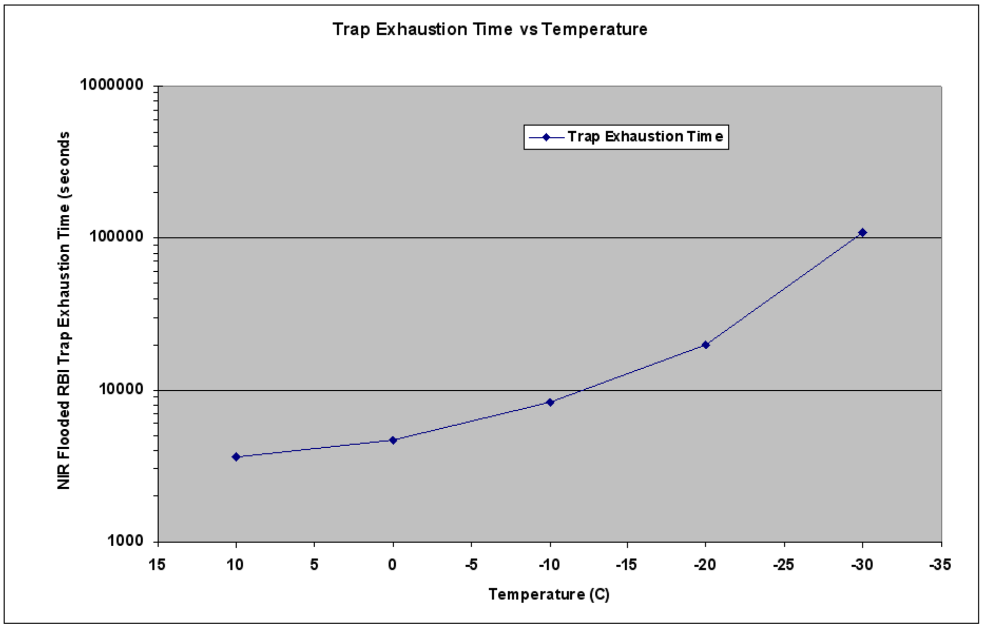


Figure 9

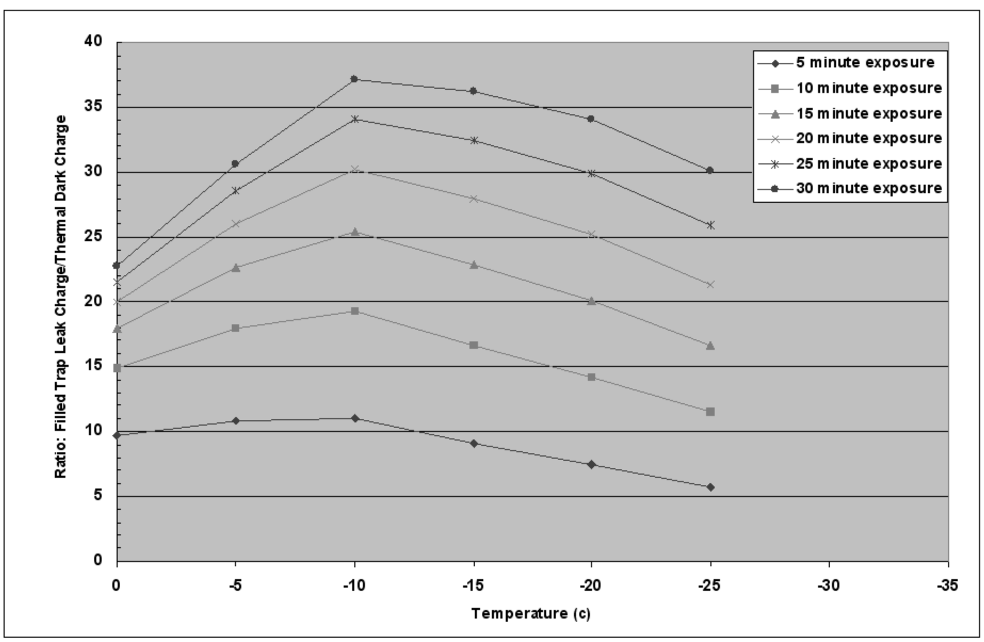


Figure 10

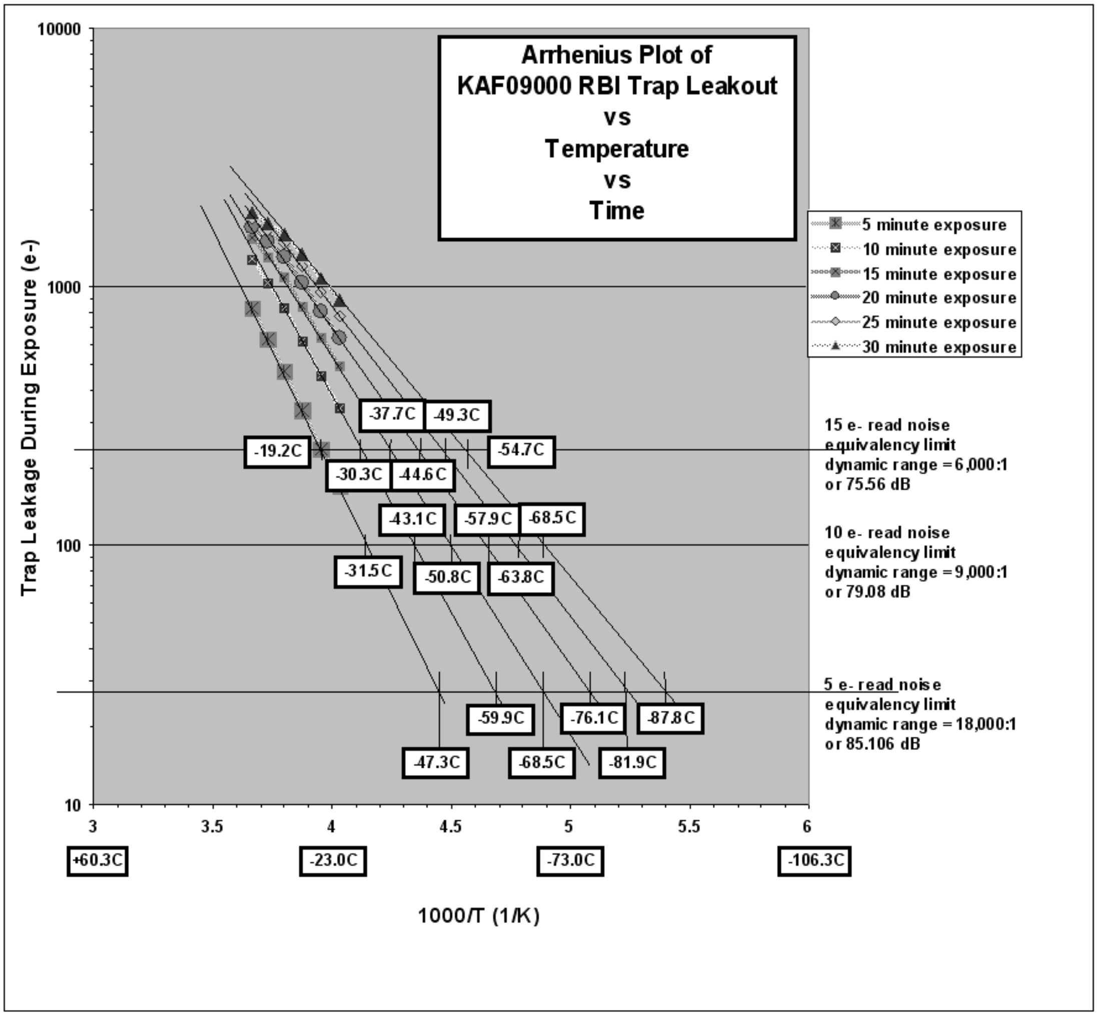


Figure 11

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.

4. ACKNOWLEDGEMENTS

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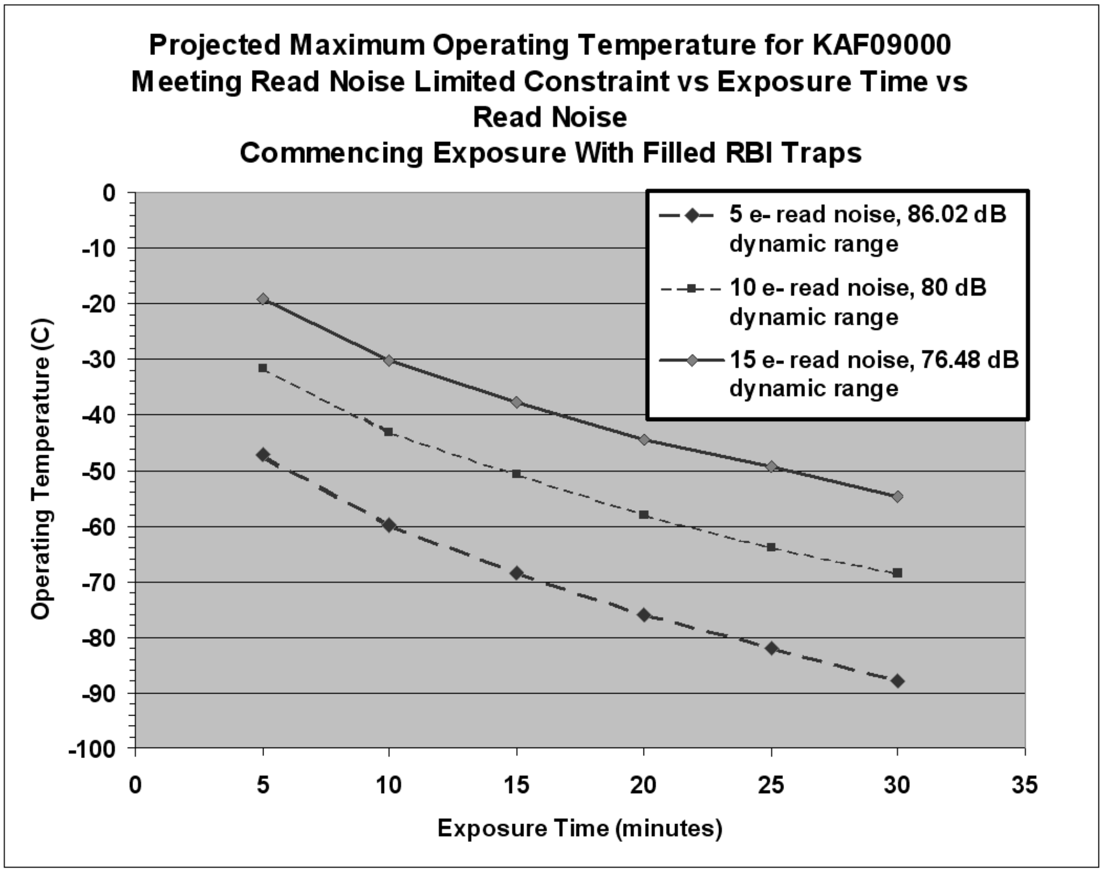

Figure 12

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