Effect of Dislocations on Dark Current in LWIR HgCdTe Photodiodes

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ABSTRACT

In recent years, Teledyne Imaging Sensors has begun development of Long Wave Infrared (LWIR) HgCdTe Detector Arrays for low background astronomical applications, which have a high percentage of low dark current pixels but a substantial high dark current tail. Characterization of high dark current pixels in these devices has produced I-V curves with unusual behaviors. The typical theories of diffusion current, tunneling current, and even surface current have been unable to accurately model the observed I-V curves. By modeling dislocations in and near the p-n junction as trapping sites and those near the surface as leakage channels, the behavior of these unusual I-V curves is successfully modeled, pointing to the need to reduce the number of these dislocations in order to produce LWIR HgCdTe photodiodes exhibiting very low dark current with sufficient well depth.

Keywords: Long Wave Infrared (LWIR) Detector, HgCdTe, Dark Current, Dislocation, Surface Current, Tunneling Current

1. INTRODUCTION

Teledyne Imaging Sensors has been working with the University of Rochester to develop space-based passively cooled (operation temperature $\sim$ 30 K) detector arrays capable of low background ($< 100 e^-/s$)\textsuperscript{*} astronomical observations in the 5 $\mu$m to 10 $\mu$m wavelength range. By the end of 2005, Teledyne Imaging Sensors had delivered four HgCdTe detector arrays with cut off wavelengths of 9.3 $\mu$m, 8.5 $\mu$m, 8.4 $\mu$m and 10.2 $\mu$m. It has been observed for these arrays that while a large majority of pixels exhibit dark currents at or below the desired level, a histogram of the dark currents of the pixels will show a high dark current tail, as indicated in Figure 1.

It is this high dark current tail that limits the percentage of pixels exhibiting dark current in the desired range. Though the figure shown here cuts off at 4 $e^-/s$, the complete high dark current tail includes pixels with substantially higher dark current. It is also true that as reverse bias is increased beyond that shown in Figure 1, which is approximately 50 mV (corresponding to 40,000 electrons well depth), the number of pixels in the high dark current tail increases. It is this high dark current tail that we examine here specifically for the long-wave Teledyne devices we have obtained, addressing pixels that are always in this high dark current tail in addition to those pixels that become part of this tail at higher reverse biases or temperatures.

Understanding the dark current mechanisms that cause pixels to exhibit high dark currents in this tail is crucial to reducing or eliminating them. The source of the limiting dark current mechanism points towards the necessary steps to make the diodes even better. For example, if the limiting mechanism is trap-to-band tunneling, this points to the need to reduce the number of traps during processing, thereby reducing the dark current.\textsuperscript{2} During recent dark current characterizations of a selection of these Teledyne HgCdTe detector arrays, unusual I-V curves were measured, for which there were no known dark current mechanisms that produced the particular observed shapes.

Nearly all dark current mechanisms show increased current with an increase in reverse bias voltage. The larger the reverse bias across the diode, the larger the dark current. In fact, when the reverse bias increases

\textsuperscript{*}Zodiacal light in the 5 $\mu$m to 10 $\mu$m wavelength region results a maximum photocurrent of $\sim 100 e^-/s$.\textsuperscript{1}

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into the breakdown region of the diode, the current typically exponentially increases with increasing reverse bias. Traditional dark current mechanisms indicate that once the diode enters this breakdown region it does not recover (level off or exhibit a slower exponential rise) at higher reverse biases. However, the observed I-V curves level off at higher reverse biases than the initial exponential breakdown, sometimes in between sequential exponential rises, as can be seen in the figures below, contrary to traditional theories. These behaviors led us to investigate alternative models.

For the detector array devices we obtained, we generated dark current versus reverse bias (I-V) curves for a range of biases (applied reverse biases from 0 mV to 200 mV) at 30 K and temperatures (focal plane temperatures from 30 K to 37 K) at 50 mV applied reverse bias. Not all ranges were used on all detector arrays. Some pixels maintained nearly flat low dark current over the entire bias range at 30 K, but increased in dark current as temperature increased. Other pixels maintained low dark current over a portion of the bias range at 30 K. Even others had high dark current over the entire bias range. We evaluate a selection of pixels with these characteristics in order to ascertain their limiting dark current mechanism. As we will see, the limiting dark current mechanism at one temperature is the same at another temperature. In some cases, specific parameters of the mechanism (such as dislocation trap activation voltage) may change with temperature, though the form (or I-V curve shape) remains the same.

2. PIXELS WITH LOW DARK CURRENT OVER ENTIRE BIAS RANGE AT 30 K

Modeling the I-V curves at various temperatures for the same pixel allows us to address temperature and bias dependent mechanisms simultaneously. Though the shape of the I-V curve for some pixels resembles that of generation-recombination (G-R) current or diffusion current (see Figure 2), neither are limiting factors for these diodes. This is because G-R current depends upon temperature too strongly for the diodes represented here and diffusion current is too low for any reasonable set of parameters. The shape can also be modeled by either a very slight glow or leakage current or surface current. The functional form used in modeling of the glow or leakage current is given by Equation 1,

\[
I_{ph} = I_o \left( e^{\frac{qV_b}{kT}} - 1 \right),
\]

where \( I_o \) is the level of the measured current, \( q \) is the charge on an electron, \( V_b \) is the actual diode reverse bias voltage, \( k \) is Boltzmann’s constant and \( T \) is the temperature in Kelvin. Many pixels depend slightly more upon bias than Equation 1 would suggest. Surface current shown in Equation 2 has a similar form, but as the depletion
region width also depends upon actual diode bias, it has a slightly stronger bias dependence. This form is given by\(^3, 4\)

\[
I_s = \frac{s_0 n_i W A}{2 \tau_s} \left( e^{qV_b/kT} - 1 \right),
\]

(2)

where \(s_0\) is the surface recombination velocity coefficient, \(n_i\) is the intrinsic carrier concentration on the surface, \(W\) is the depletion region width, \(A\) is the diode area, and \(\tau_s\) is the lifetime of minority carriers on the surface. In order to fit the level of observed dark current, the value for the molar concentration of Cadmium on the surface is reasonably adjusted to a lower value.\(^5\)

**Figure 2.** Dark current versus bias and temperature modeling for a representative pixel that has a very flat bias and temperature dependence to its limiting dark current mechanism, maintaining low dark current and staying out of the high dark current tail with both bias and temperature.

An example of one of these pixels is illustrated in Figure 2. Due to the quantity and quality of the data obtained on one LWIR device, most of the pixels shown here are from that device. However, the exact same characteristics can be seen in the other LWIR devices as well. The two graphs show the temperature data from 31 K to 37 K at 50 mV applied bias and from 0 mV to 200 mV applied bias at 30 K. (Note that the data at 30 K are over a larger bias range than the data at the other temperatures. This will be true for all other pixels modeled as well. The restricted data range for the higher temperature data was due to time constraints in the data taking process.) It is apparent that the limiting mechanism is not very dependent upon temperature in this pixel. There are even other pixels for which the temperature dependence is so minimal the data for the individual temperatures overlap. In that case the pixels are strongly limited by the leakage or glow current.

The data for various applied biases and for various focal plane temperatures shown here were obtained on separate cool-downs of the device. Therefore, the data are not necessarily comparable to each other. While the exact cause is unknown, the detector pixels have been observed to exhibit different dark current for the same applied bias and temperature on separate cool-downs. This difference may result in an offset in the dark current level or even a different I-V curve altogether. (For example, the pixel shown in Figure 2 has a higher level of dark current in the 30 K data than at the other higher temperatures.) However, within a given cool-down each pixel’s behavior is consistent. It is possible that during cool-down specific traps may be frozen dependent upon the speed of cooling or that mercury may be more mobile on the surface at warmer temperatures, causing a shift in the molar concentration of Cadmium at the surface or the trap energy level between cool-downs. It is also
known that stresses within the device will vary from one cool-down to another and this can affect dislocation properties. All of these factors may affect the behavior of a given pixel between cool-downs. It is also possible that there is a slight amplifier glow that exhibits a non-linear dependence upon temperature. Whether due to stresses, defects or amplifier glow, further testing is required to determine the exact cause of this offset current.

While still nearly flat with bias at 30 K, some pixels are more strongly affected by increasing temperature. Modeled in Figure 3 are two such pixels. Both of these pixels have an exponential rise during some portion of their bias range. Pixel A, shown on the left of the figure, reaches a dark current plateau that changes level with temperature. At 37 K, this pixel levels off around $200 \text{e}^{-}/\text{s}$ for reverse biases greater than 40 mV. The current climbs exponentially to this level from approximately 10 mV to 25 mV and levels off between 25 and 40 mV. Pixel B, shown on the right of the same figure, does not appear to reach a plateau in the data, though the slope of the rise changes with temperature similar to pixel A. Though no traditional dark current mechanisms can reproduce such behavior, both pixels can be modeled by incorporating a dislocation-induced increase in the surface carrier density at a temperature dependent activation voltage, assuming the plateau is not reached over the range for which we have data for pixel B.

**Figure 3.** Dark current versus bias and temperature modeling for pixel A (left) and pixel B (right), pixels that move into the high dark current tail with increasing temperature.

It is known that dislocations such as elementary screw dislocations can cause an increase in dark current.6, 7 These dislocations have dangling bonds which may become trapping sites as they become incorporated into the p-n junction. In the past, we have used this knowledge to incorporate this trapping mechanism into trap-to-band tunneling (shown in Section 4). However, it is obvious that the temperature dependent dark current plateau exhibited by pixel A does not follow the shape of trap-to-band tunneling. We therefore suggest that the dislocations causing the behavior in Figure 3 must be located on or near the surface, giving rise to an additional surface current. A functional form of the increase is given in Equation 3.8

$$n_t = n_{t_i} + \frac{n_{t_d}}{1 + \exp\left(\frac{(E_a + \gamma qV_b)}{kT}\right)}$$

In this equation, $n_{t_i}$ is the initial trap density and $n_{t_d}$ is the density of traps added by the dislocation, $\gamma$ is a scaling factor that pertains to the properties of the dislocation (i.e. orientation) and $E_a$ is the dislocation
activation energy. Note that $V_b$ is negative for reverse bias. In the case of surface current, this additional trap density is incorporated into the surface carrier density. The dislocation may also be located near the $p-n$ junction, causing the dislocation to be incorporated into the depletion region of the diode at higher biases. While pixel B does not reach a dark current plateau like pixel A, it can still be modeled in the same manner, assuming the plateau is beyond the data range. Other known dark current mechanisms do not fit the shape of the exponential rise.

Many pixels exhibit the same behavior as pixels A and B with varying dislocation parameters ($\gamma$), activation voltages and temperature dependences. We see many such pixels with activation voltages above 100 mV reverse bias at 30 K. These will be addressed in the next section. There are also other pixels which do not appear to have an activation bias because they do not exhibit an obvious exponential climb at a higher reverse bias, such as those exhibited by the pixels in Figure 3. One such pixel is illustrated in Figure 4. Since G-R current increases much more rapidly with temperature than this pixel exhibits, surface current once again appears to be the limiting mechanism. Utilizing the same model as was used for pixels A and B, but with a different carrier density temperature dependence and an activation voltage less than 10 mV, the I-V behavior of pixel C can be modeled. This pixel can also be modeled with a temperature dependent leakage current.

Figure 4. Dark current versus bias and temperature modeling for pixel C, a pixel that increases in dark current with temperature, moving it into the high dark current tail.

3. PIXELS WITH LOW DARK CURRENT OVER PART OF BIAS RANGE AT 30 K

Pixels that have low dark current over part of the bias range typically reach a bias at which their dark current increases beyond an acceptable value. This increase is usually exponential in shape and may or may not reach a dark current limit, such as the plateau exhibited by pixel A. For many of these pixels exhibiting an increase at higher reverse biases, the behavior can be modeled with dislocation induced trap-to-band tunneling current. For trap-to-band tunneling, the most general equation assumes a parabolic barrier and uniform electric field,$^9$

$$I_{\text{trap-to-band}} = n_t W \frac{\pi^2 q A_{\text{eff}} E M^2}{h^3 (E_g - E_t)} \exp \left( -\frac{\sqrt{m_{\text{eff}} E_g}}{2qE\hbar} \right),$$

(4)

$$I_{\text{trap-to-band}} = n_t W \frac{\pi^2 q A_{\text{eff}} E M^2}{h^3 (E_g - E_t)} \exp \left( -\frac{\sqrt{m_{\text{eff}} E_g}}{2qE\hbar} \right),$$

(4)
where
\[ F(a) = \frac{\pi}{2} - a\sqrt{1 - a^2} - \arcsin a, \quad (5) \]
and
\[ a = 2 \frac{E_t}{E_g} - 1. \quad (6) \]

In the trap-to-band tunneling equations, \( n_t \) is the trap density, \( M \) is the transition matrix element, \( m_{eff} \) is the effective mass of the minority charge carriers, \( E \) is the electric field across the junction, \( E_g \) is the energy gap between the valence and conduction bands and \( E_t \) is the energy of the trap level with respect to the conduction band. In the dislocation induced model, the number of traps, \( n_t \), increases as a dislocation is activated at a given bias according to Equation 3. The range through which this activation takes place depends upon dislocation parameters.

**Figure 5.** Dark current versus bias modeling for pixel D, a pixel that increases in dark current exponentially at higher reverse bias and reaches a level at which that rise takes on the shape of trap-to-band dark current at higher trap density, moving it into the high dark current tail with higher reverse biases.

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Figure 5 shows pixel D which illustrates this behavior. At around 90 mV reverse bias, this pixel exhibits a sharp rise after which it follows traditional trap-to-band tunneling. This is likely due to the incorporation of a defect with an activation voltage near 100 mV. Pixels exhibit this behavior to varying degrees. Some do not reach a bias at which traditional trap-to-band tunneling takes over within the range over which we have data. One example is pixel E in Figure 6.

In Figure 6, no limit or plateau is reached within the data range. However, this pixel exhibits an exponential rise that is steeper than trap-to-band tunneling, yet shallower than band-to-band tunneling. Incorporating a dislocation into the model for trap-to-band tunneling, this pixel can also be modeled. The fact that this model can fit the majority of pixels with increasing dark current above a specific reverse bias indicates it is likely that many pixels have dislocations affecting their I-V curves. The exponential rise exhibited by these pixels is often referred to as soft breakdown and can occur at any bias for different pixels.

The dislocation parameters for a given pixel may change with temperature. Typically the activation bias decreases with temperature while the dislocation trap density increases. Occasionally even the dislocation parameter \( \gamma \) will also change. If a plateau or limit is reached, it indicates that all dislocation-induced traps are fully activated. This may result in an increased surface current (as seen in Section 2) or trap-to-band tunneling.
Figure 6. Dark current versus bias modeling for pixel E, a pixel that increases in dark current exponentially at higher reverse bias, moving it into the high dark current tail.

Because trap-to-band tunneling current increases strongly with increased reverse bias, many pixels that increase in dark current past the acceptable value with increasing reverse bias are subject to this form of dark current. It often occurs at higher reverse biases (100 mV or greater) and is likely to be brought on by some form of dislocation. Some pixels exhibit more than one dislocation, causing a step-like behavior to their I-V curves. The region between exponential rises may either follow surface current or trap-to-band tunneling current, dependent upon the properties of the given pixel.

4. PIXELS WITH HIGH DARK CURRENT OVER ENTIRE BIAS RANGE AT 30 K

Pixels that have high dark current over the entire bias range exhibit the same I-V curve characteristics, such as an exponential rise, at low applied biases. These pixels often experience soft breakdown with an exponential climb at biases less than 50 mV and usually reach a dark current plateau (if such a plateau is reached) above 100 e⁻/s. These pixels will often continue to climb in dark current with increased reverse bias, though not as quickly as band-to-band tunneling, nor as slowly as surface current.

Shown in Figure 7 is pixel F which encounters a sharp rise at approximately 20 mV of reverse bias. The dark current of this pixel begins to level at 40 mV reverse bias and shortly thereafter trap-to-band tunneling becomes the dominant mechanism. This pixel is unusual in that it requires two types of dislocations occurring simultaneously in order to model its behavior. These dislocations are in two different locations, one on the surface and the other in the p-n junction. The dislocation property parameter $\gamma$ is the same for both dislocations, which may indicate a single dislocation that starts in the p-n junction and ends on the surface.

Some pixels with high dark current will exhibit what appears to be very high surface or leakage current from the very lowest applied bias. One such pixel is shown in Figure 8. This pixel exhibits a current that is nearly constant with bias, but is too high to be G-R current or surface current as is modeled in Equation 2. This pixel was modeled using a leakage current with the same form as surface current but with an ideality factor of two. This changes Equation 2 to Equation 7,

$$I_s = \frac{s_0 n_i W A}{2\tau_s} \left( e^{\frac{qV_b}{2kT}} - 1 \right).$$

Also noticeable is the increase in dark current at the very highest shown bias. This is modeled using trap-to-band tunneling with a dislocation, since traditional trap-to-band tunneling is not sufficiently steep.
5. CONCLUSIONS

As shown in this paper, dislocations can cause an increase in surface current or contribute to trap-to-band tunneling, causing LWIR HgCdTe detector array diodes to exhibit dark current beyond the acceptable range. Continued development of these devices will need to consider the source of these dislocations in order to minimize the high dark current tail and improve individual diode performance at higher reverse biases. With the new processing and manufacturing techniques Teledyne Imaging Sensors has developed since the last delivery, we

**Figure 7.** Dark current versus bias modeling for pixel F, a pixel that increases in dark current exponentially at low reverse bias and reaches a level at which that rise takes on the shape of trap-to-band dark current at higher trap density. This pixel is in the high dark current tail for most reverse biases.

![Graph of dark current versus bias for pixel F](image1)

**Figure 8.** Dark current versus bias modeling for pixel G, a pixel with high surface current. This pixel is in the high dark current tail for all reverse biases.

![Graph of dark current versus bias for pixel G](image2)
expect that the high dark current tail exhibited by potential future devices will be much smaller than that we have encountered in the devices we have. Incorporation of this new information on dislocation induced dark currents and subsequently further adjustments to the processing and manufacturing techniques will further reduce the high dark current tail, increasing the reverse bias range over which pixels will exhibit low dark current and making future deliveries significantly higher quality.

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REFERENCES


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