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The Physics of Single Event Burnout (SEB)

Introduction

Single Event Burnout in a diode, requires a specific set of circumstances to occur, since there is no intrinsic current gain in the device itself to amplify the currents created by the charge from a single event strike. What has to happen for Single Event Burnout (SEB) to occur in a device with no intrinsic gain, for realistic levels of Linear Energy Transfer (LET), for any given bias is fundamentally simple:

The total charge created by the SEU strike itself, plus any additional charge from avalanche multiplication, has to sustain a minimum current for a minimum time, to create sufficient localized self heating, that the I-V curve of the diode centered around the strike point, is modified sufficiently, such that the current becomes locally self sustaining. This self sustaining current will eventually spread throughout the device, since higher mobilities exist in the surrounding cooler parts, creating an ever expanding preferential current path, until irreversible damage through melting or cracking of the device occurs.

If the localized self heating is insufficient to modify the I-V characteristics into a secondary stable high conduction regime before the charge pulse dissipates, the device will recover from the ionizing single event strike.

In this article we will attempt to provide evidence for this postulation with a methodical approach to this subject, using a high voltage PiN diode as an example.

Theory

It is unlikely that an SEU strike of any realistic Linear Energy Transfer (LET) is going to deposit a sufficient concentration of energy, that the SEU strike alone will immediately create irreversible damage from melting or thermally expansive cracking. If this were the case, power diodes would experience periodic permanent failure, without any applied bias. In other words, previously working diodes could fail, even if they were simply being stored as individual components, without even being connected to any circuit. The author is not aware of any proven cases of such phenomenon.

If we accept that the deposited energy from the SEU strike alone cannot create Single Event Burnout (SEB) phenomenon, then we must accept that additional energy from the applied bias in the circuit surrounding the diode is responsible for providing the destructive energy. This statement suggests that circuit and component design criteria can therefore play a role in the probability of an SEB event occurring in a circuit.

At this point the postulation needs to be re-stated that a current of sufficient magnitude is required to eventually heat the device to destruction, and that this current must be present for a sufficient length of time for the critical temperature rise to occur before the device recovers. What limits the rate of temperature increase with time is the specific heat capacity of the substrate material (silicon in this case study) and heat removal from thermal conduction to cooler parts of the device. These considerations strongly suggest, therefore, that in order for SEB to occur, the effected device must be transferred to a secondary stable state in the IV characteristics, so that regenerative feedback can occur, to continue supplying high power in that stable state, eventually causing irreversible thermally induced damage.

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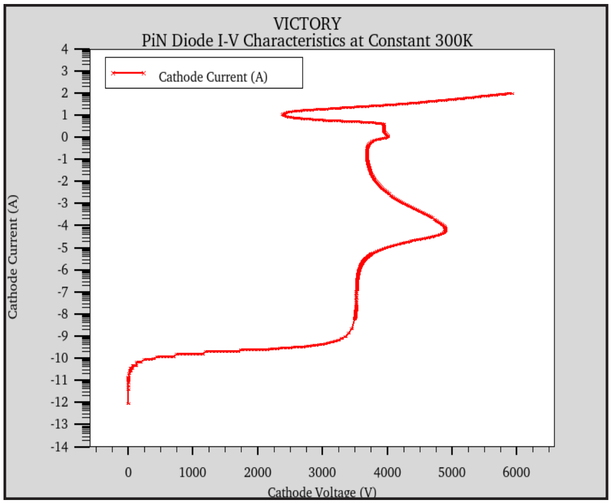

Figure 1. Constant temperature (300K) I-V curves of the 3,500 volt power PiN power diode.

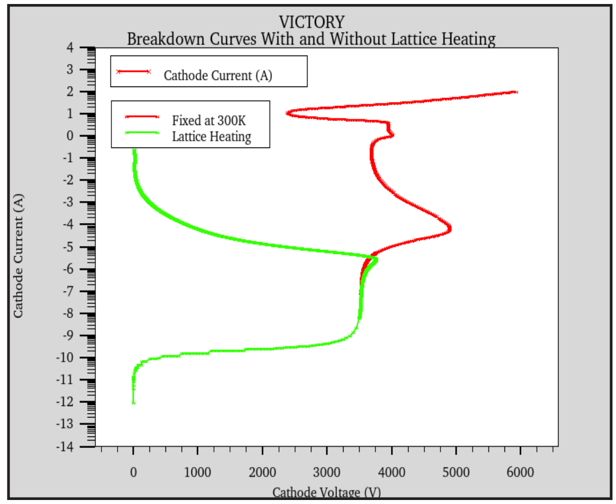

Figure 2. Comparing the no self heating, with a thermal equilibrium curve.

In simple terms, the postulation above, requires that the IV curve of the structure has a "snapback" type of characteristic, such that for some of the possible range of applied bias voltage, there will be at least two possible current densities that are stable. One a low current density "off" state, and one self sustaining "on" state, where the current density is sufficient to melt the device after a certain time. If this "snapback" condition in the device IV characteristics is met, then the SEU strike simply acts as a trigger to transfer the IV characteristics from a stable cold "off" state, to a new hotter and also stable "on" state.

Despite the fact that "snapback" characteristics are usually only associated with devices that have intrinsic gain, we will show that "snapback" characteristics also occur in PiN diodes, and is especially severe when self heating effects are taken into account. We will attempt to show in this article, that It is these temperature dependent IV characteristics that are the root cause of Single Event Burnout (SEB) in high power PiN diodes. These simulations will also demonstrate a new and simple methodology to assess the approximate sensitivity of other devices to SEB, using a simple D.C. I-V simulation. Testing the applicability of this new method to other diode device types, however, will be left as future work.

D.C. Simulations

In this article, examples of power PiN diodes described in a paper by A.M. Albadri et. al., [1] will be used to demonstrate the simulation of Single Event Burnout. These PiN power were designed for a maximum operating voltage of 3,500V. The diodes were essentially one dimensional in nature, so simulation of the 3D effects using circular symmetry with a central SEU strike location was sufficient. The diodes had an intrinsic drift region 400um thick with an unintentionally doped n-type concentration of 3.1e13/cm3, as described in reference [1]. The only difference in the simulations described here, is that in the interests of simulation speed and other reasons described later in this article, the radius of the diode in the simulation space was only 5um rather than the full 400um of the real device.

From the arguments put forward as to the root cause of SEU being a stable "snapback" characteristic, the first step is to simulate the full I-V characteristics of the diode. Figure 1 shows the full I-V characteristic of the PiN power diode at a constant temperature of 300K.

The I-V curve shown in Figure 1 immediately shows us important information as regards the sensitivity of this device to a "fast" SEU event. By a "fast" SEU event, it is meant, "an event providing a sufficient level of current injection after avalanche multiplication is taken into account, that the device transfers to a self sustaining high current state without even considering any significant self heating effects".

From Figure 1, it can be deduced that this diode is not susceptible to such as event for any reverse bias less than 2,400 volts, because a secondary and stable high current condition simply does not exist below 2,400 volts. However the currents required directly from the SEU strike in order to transfer the diode to it's high current "on" state are in the range of Amps, making this an unlikely event. From this I-V curve, we can immediately deduce that a Single Event Burnout (SEB) is very unlikely without self heating effects transforming the secondary stable high current state towards a lower current density.

The curve from Figure 1 shows that if the diode was biased at 3500 volts, a current of approximately 5 amps would be required to initiate a stable self sustaining "on" state. Extrapolating from SEU current curves versus LET energy discussed later in this article, this would require a strike with an LET value of over a thousand MeV.cm2/mg which is not a likely event.

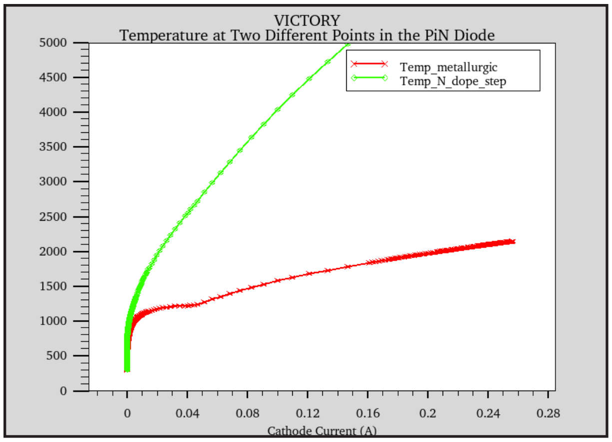

Figure 3. Temperatures inside the PiN diode at the metallurgic junction and at the N+ to intrinsic boundary.

The usefulness of this constant temperature I-V curve, is that it defines one of the two operating boundary conditions. In this case, the boundary condition being where no self heating occurs.

Now let us define the other boundary condition, where the current from an SEU strike continues for sufficient time, such that localized "thermal equilibrium" occurs. Figure 2 shows the original constant temperature curve of Figure 1, but this time over-lays the I-V curve simulated with the localized self heating model activated. Since this is a DC bias sweep, then at each point of the I-V curve, thermal equilibrium has been established.

Figure 2 immediately shows how vulnerable a power PiN diode could be, when the effects of self heating are taken into account. Now a sustained current of only tens of micro Amps is required at higher reverse bias voltage, in order for a self sustaining, thermal runaway event to occur. The required current for thermal runaway rapidly increases at lower bias voltages giving rise to the expected behavior that an SEB event is more likely at high reverse bias voltages, or saying the same thing in another way, an SEU with a higher value of LET is required at lower bias voltages in order to trigger an SEB event.

Figure 3 shows the temperature at two significant regions in the device, the red curve showing the metallurgic junction temperature and green curve at the intrinsic to N+ boundary. It should be noted that the heat sink was defined as coinciding with the anode contact, which is the closet to the metallurgic junction, which is why metallurgic boundary curve has a lower temperature.

Since in a transient SEU strike, thermal equilibrium is not usually obtained, we now know our realistic I-V curve will trace a path somewhere between these two extremes. The most useful predictor of device behavior is therefore to emulate I-V curves that show a more realistic current temperature curve, between the two extremes shown in Figure 2, to approximate the IV curve followed by an SEU current pulse being far from thermal equilibrium.

In the author's opinion, the most relevant way to plot these intermediate I-V curves is to artificially increase the thermal conductivity of the substrate material. This results in a temperature rise with conduction current that does not occur if the method of using different constant temperature simulations are used, as in the case for some of the simulations shown in reference [1]. Another method to produce a non equilibrium I-V curve would be to use a voltage time transient simulation, but this method suffers from the complication that another variable has to be accounted for, namely the avalanche multiplication time, which can result in serious voltage overshoot as the avalanche multiplication process builds up. The voltage overshoot also depends on the chosen ramp rate.

Using this new method of increasing the thermal conductivity to emulate transient, heating effects, a number of simulations were run multiplying the thermal conductivity by x10, x100, x1,000, x10,000 and x100,000. These additional curves are added to the original curves shown in Figure 2 and are now plotted in Figure 4.

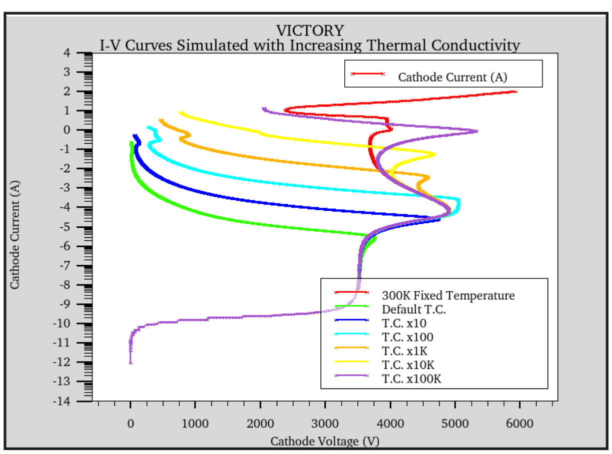

Figure 4. I-V curves using increasing thermal conductivity to emulate non thermal equilibrium effects from an SEU strike.

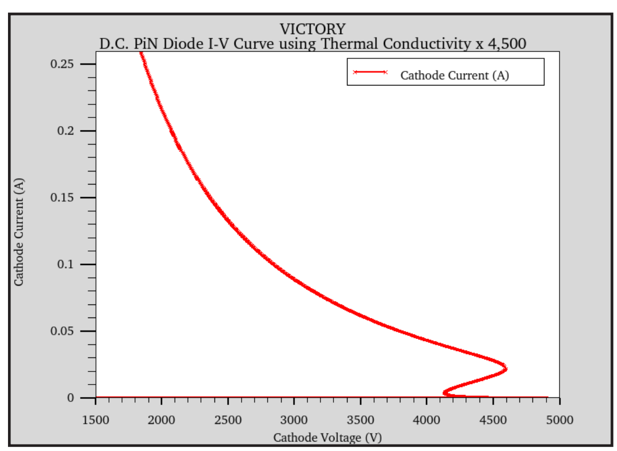

Figure 5. Showing the relationship between LET required (induced current) to induce an SEB event and applied reverse bias.

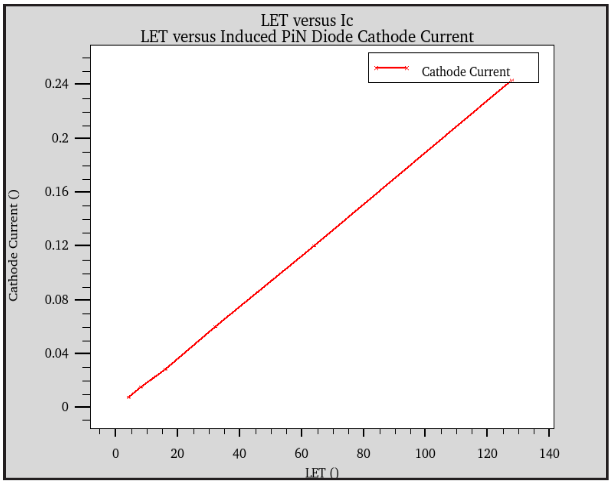

Figure 6. Conversion between Induced Cathode Current in Figure 5 and LET Value.

From Figure 4, several effects are apparent. From the original constant 300K temperature (red) curve, it seemed that Single Event Burnout (SEB) could not occur for reverse applied voltages of less than approximately 2,400 volts. However, as can be seen from Figure 4, the longer the SEU transient current lasts and therefore the hotter the local temperature gets, the lower this critical reverse applied voltage becomes where SEB can occur. In addition, to a lower critical voltage, the hotter the local temperature becomes, the lower the current required before the secondary high current stable "on" condition is reached. It will be shown later, that the yellow curve, representing the thermal conductivity increased by 10,000 times, is a reasonable approximation to the real transitory curves. Further simulations showed that the appropriate value of thermal conductivity multiplier for this particular PiN diode was between, 4,500 and 5,000.

Figure 5 shows D.C. simulations using a thermal conductivity 4,500 times the equilibrium value, with cathode current plotted on a linear scale between zero to 0.25 Amps, versus reverse applied voltage. It will be shown later, that the cathode current range between zero and 0.25 Amps represents the same range of currents induced by the Single Event Upset in this study, with a Linear Energy Transfer values of up to 128 MeV.cm2/mg. On this curve, by converting the cathode current on the vertical axis to equivalent LET value, you can directly read off the LET required to trigger a single event burnout event for any given reverse bias on the PiN diode. Clearly, the reverse bias cannot exceed the 3,500 volt breakdown voltage, so bias voltages shown in Figure 5 above 3,500 volts are not meaningful. In this curve, the initial breakdown currents at 3,500 volts are simply disguised by the linear scale on the Y axis.

This conversion between LET value and induced current in the diode is plotted in Figure 6. It should be noted that in order for a similar thermal conductivity multiplier value to apply to other devices, there is a general requirement that before the onset of the destructive SEB event, the temperature laterally across the device width (ie the X direction in this case) is approximately uniform within a fraction of a micro second or so, which results in the general requirement that the width of the simulated section of the device be in the order of a few microns. If this new concept is to be applied to a very wide device, then the concept of localized current density in the region of the SEU strike should be applied rather than simply total current. This requirement is a secondary reason for the simulation width of the device being only 5 um.

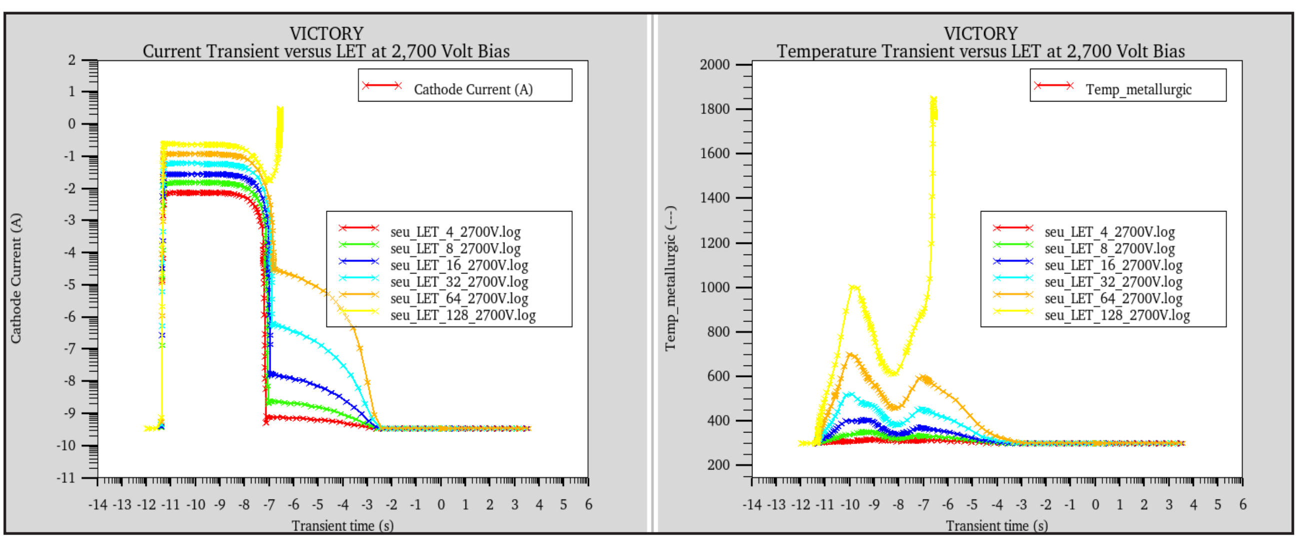

Figure 7. Temperature and Current Simulations of SEU strikes with LET values from 4 to 128 MeV.cm2/mg at a reverse bias of 2,700 volts.

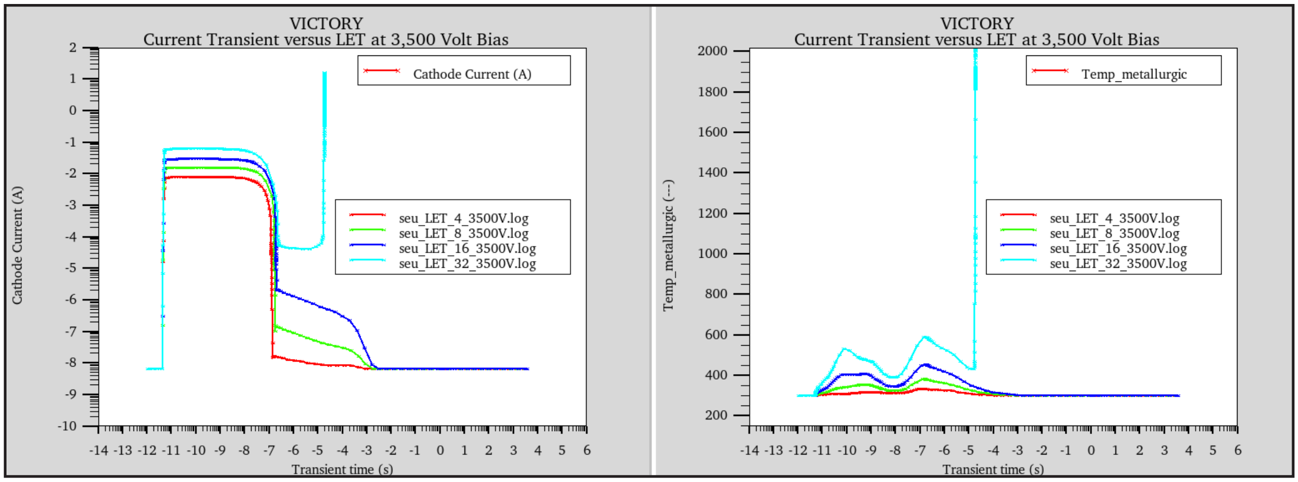

Figure 8. The same simulations as in Figure 7, but with a reverse bias of 3,500 volts.

Transient Simulations

Transient simulations of a Single Event Upset (SEU), for various levels of Linear Energy Transfer (LET) were investigated for two reverse bias points for the PiN diode, namely 2,700 and 3,500 volts. The first bias was chosen based on the results from reference [1], where it was shown that Single Event Burnout (SEB) in this particular diode was unlikely for a reverse bias of much less than 2,700 volts, and the second bias of 3,500 volts was chosen since it was close to the maximum operating voltage of the diode, so a lower value of LET would be expected to trigger Single Event Burnout (SEB).

The characteristics of the SEU pulse were chosen to match those in reference [1], meaning that the centroid of the pulse occurred at a simulation time of 5 pico seconds and the width of the pulse was 0.2 pico seconds with an effective radius of 20 nano meters.

The LET of the first SEU pulse transient simulation was 4 Mev.cm2/mg, and this LET value was then subsequently doubled and re-simulated in an automated loop until an irreversible SEB event occurred. The results of the transient simulations for the two reverse bias points of 2,700 volts and 3,500 volts are shown in Figures 7 and 8 respectively. Also shown are simulations at a fixed temperature of 300K in Figure 9, showing that no SEB event occurred as predicted by the I-V curve shown in Figure 1, where as previously discussed, an LET value of over a 1,000 would be required for an SEB event to occur.

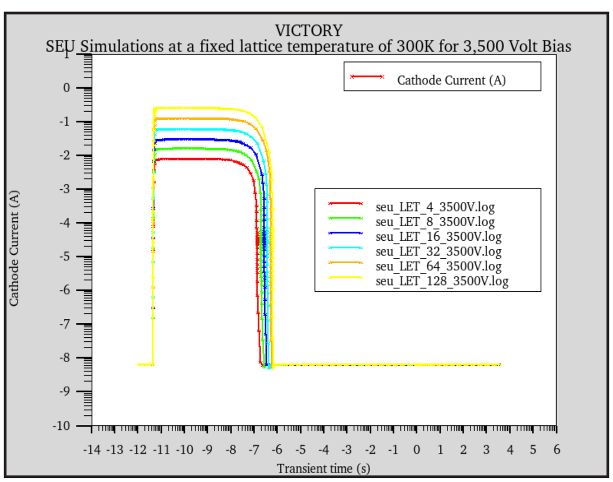

Figure 9. The same simulations as Figure 8, but without localized lattice heating and a substrate temperature of 300K.

It can be observed from Figures 7, 8 and 9, that transient simulations of SEU strikes with any realistic LET value, result in an initial induced current pulse that is approximately constant over many orders of magnitude of time, and further is almost proportional to the LET value of the SEU strike. This is how the simple conversion from LET value to cathode current can be calibrated and is the source of the data shown in Figure 6. It is this flat portion of the current with time translates to the current in the DC I-V curves in Figures 4 and 5.

Form the transient simulations we can deduce that for an SEB event to occur at a bias of 2,700 volts, an SEU strike with an LET value between 64 and 128 MeV.cm2/mg is required, whilst at a bias of 3,500 volts, an SEU strike with an LET value of between 16 and 32 MeV.cm2/mg is needed. Using the conversion shown in Figure 6, a bias of 2,700 volts equates to a required current of between 0.12 and 0.24 Amps for an SEB event and a bias of 3,500 volts equates to a required current of between 0.029 and 0.06 Amps to trigger and SEB event.

Placing these error bars on to Figure 5, we can see that our approximately calibrated DC simulations with a thermal conductivity multiplier of 4,500 results in an IV curve which just about predicts these results to within these error bars, validating this technique as a reasonable approximation for a first pass predictive tool for silicon based devices. Clearly, further calibration would be expected for other materials due to significantly differing thermal properties.

Conclusions

It has been shown in this article that the fundamental cause of single event burnout, results from the existence of two stable currents in the I-V curve of the device. An SEB event occurs when an ionizing strike allows the transition between a stable low current bias point on the I-V curve to an alternative stable high current bias point on the I-V curve. Whilst the high current conducting state is a moving target during the transitory strike because of temperature effects, it appears that the mechanics of single event burnout are simple in essence.

A novel concept in this article was also introduced, in which the results from a series of transient, non thermal equilibrium SEB simulations can be predicted reasonably well from a single DC thermal equilibrium I-V curve simulation, by modification of the thermal conductivity, to emulate the real non thermal equilibrium event. This simple modification to the DC simulation approximately captures the "moving target" of the I-V curve caused by the transitory non equilibrium temperature rise of the device during the SEU strike.

The single value of thermal conductivity required for the predictive DC simulation has been approximately calibrated in this work and the multiplying factor was found to be about 4,500 to 5,000 times the thermal equilibrium conductivity value. Further work is required to find out how universally applicable this approximately calibrated value is to other diode types and designs. In any event, the multiplier approximately calibrated in this work can be a reasonable first guess for other device types.

References

[1] "Coupled Electro-Thermal Simulations of Single Event Burnout in Power Diodes", IEEE Transactions on Nuclear Science, Vol. 52, No. 6, December 2005.