U.S. DEPARTMENT OF ENERGY

Radiation and Self Heating Effects in Hetero-Junction Bipolar Transistors

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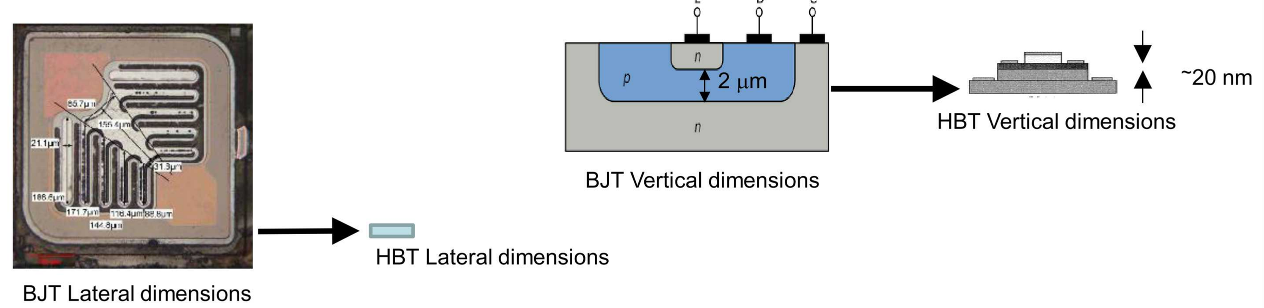
Introduction

RADIATION EFFECTS in semiconductor transistors depend on the type of radiation and the make-up of the transistor. In recent years, III-V transistors have generated interest due to their small size and intrinsic hardness to displacement damage from radiation. The small size of these devices stems partially from fabrication techniques and these same techniques also reduce displacement damage from radiation. The magnitudes of generated photocurrent from ionizing radiation are also reduced by the small vertical dimensions of these transistors. Other advantages of the smaller size are reduced power requirements and higher switching speeds. Associated with these advantages is the disadvantage of reduced heat transmission and dissipation capabilities.

It is of interest to analyze the self heating of these devices in general and study effects of photocurrent generation on the self heating. Begin by using a simple analytic expression for the self heating.

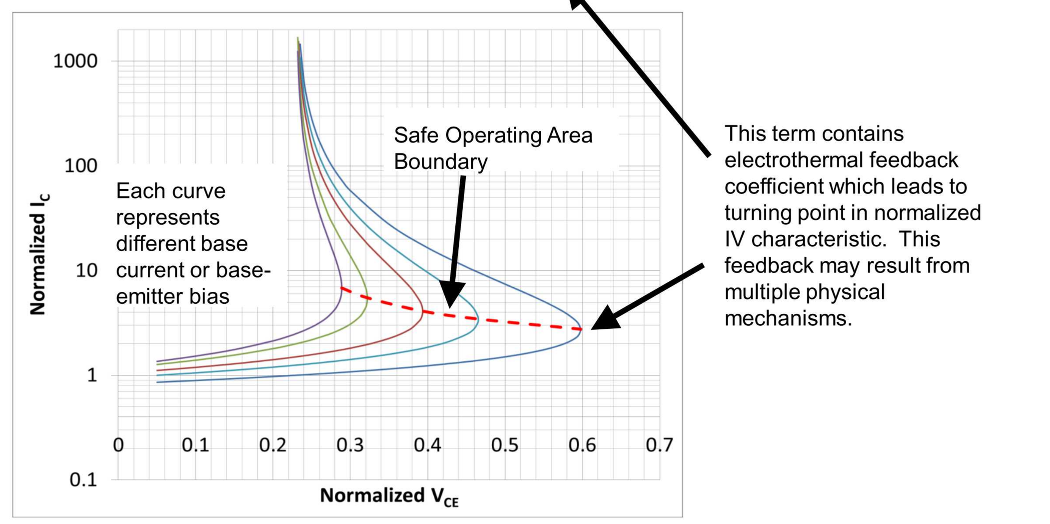


Size Comparison of BJT to HBT to illustrate thermal property differences. Clearly, the HBT devices possess less thermal mass and thus cannot dissipate heat like the silicon devices.

Analytic Model

The effect of Self Heating on the collector current in BJTs and HBTs is customarily represented by an expression of the form [1]

$$I_c = I_o exp\left[\frac{q}{kT}(V_{be} - R_eI_e - R_bI_b + R_{th}\varphi I_cV_{ce})\right]$$



The preceding equation can be normalized and approximated by an equation of the form which allows the generation of multiple turning point curves.

$$i = c_2 exp(c_2 i(v - c_1))$$

This equation can be used to predict (with calibrated constants) the turning point for each base-emitter bias and hence a safe operating curve for a particular device. The equation for collector current can be modified to describe self heating in BJTs and HBTs with the addition of photocurrent.

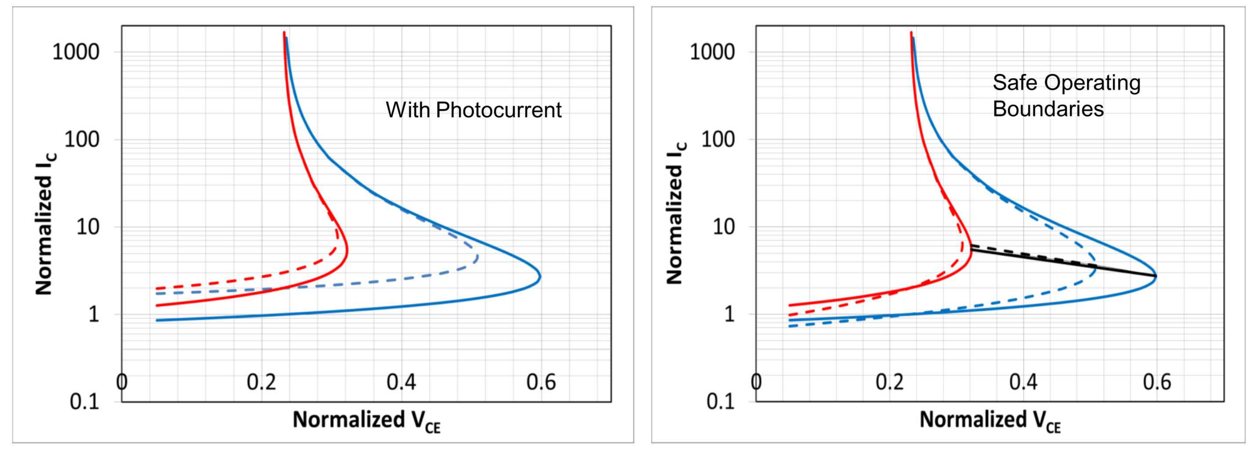
$$I_c = I_o exp\left[\frac{q}{kT}(V_{be} - R_eI_e - R_bI_b + R_{th}\varphi I_cV_{ce})\right] + I_{photo}$$

Where I_{photo} can take multiple forms depending on whether the photocurrent source is steady state or transient and whether the transistor is operating in forward active, off, or in saturation.

$$I_{photo} = I_{SS} = aAG(W_t + L_p + L_n)$$ Worth-Rogers steady state photocurrent across reverse biased junction

$$I_{photo} + I_{operation} = I_o exp\left[\frac{q}{kT}V_{be}'\right]$$ Secondary photocurrent across forward biased junction can be expressed as a modification of forward bias

As an experiment, assume a constant steady state photocurrent with no time dependence. The photocurrent modification to self heating expression leads to a shift in the turning point curve. In this case a constant normalized photocurrent of 1 has been added to the normalized collector current expression and the new collector current has been evaluated. The result is that the turning points move to smaller values of V_{CE} and the current curves shift upwards.



The constant photocurrent is subtracted from the photocurrent modified curves in the right plot to determine the operating current of the device. A safe operating area curve is generated for both the original I_C curves and the shifted I_C curves. The curves are colinear but the photocurrent curve is shifted to smaller values of normalized V_{CE}.

This method of analysis is extendable but is complicated by transient photocurrent behaviors and thermal time constants of devices and the packaging associated with the devices. An alternative approach is to construct a technology computer aided design (TCAD) model of the device and the package and use this to inform a more sophisticated model in a circuit simulation tool.

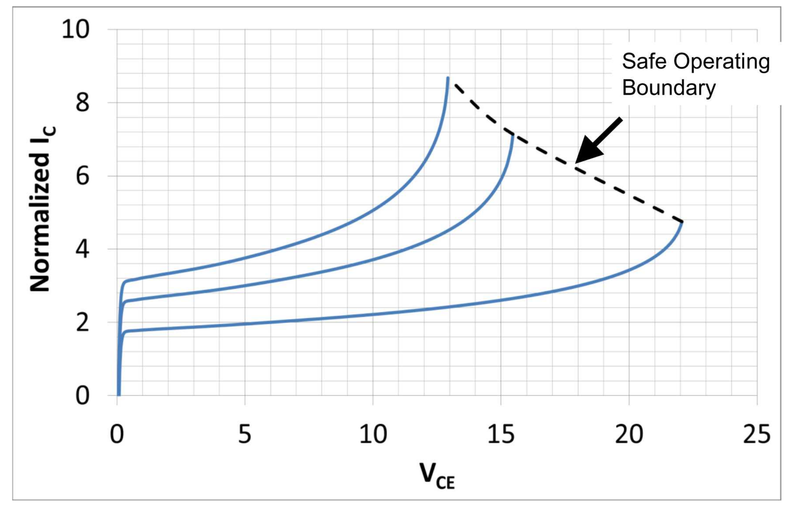
1 C. Lee, F. Chau, W. Ma, N Wang. The Safe Operating Area of GaAs-Based HBTs, *IEEE Trans. On Electron Devices*, V. 53, N. 11, Nov. 2006

Circuit Solver Analysis

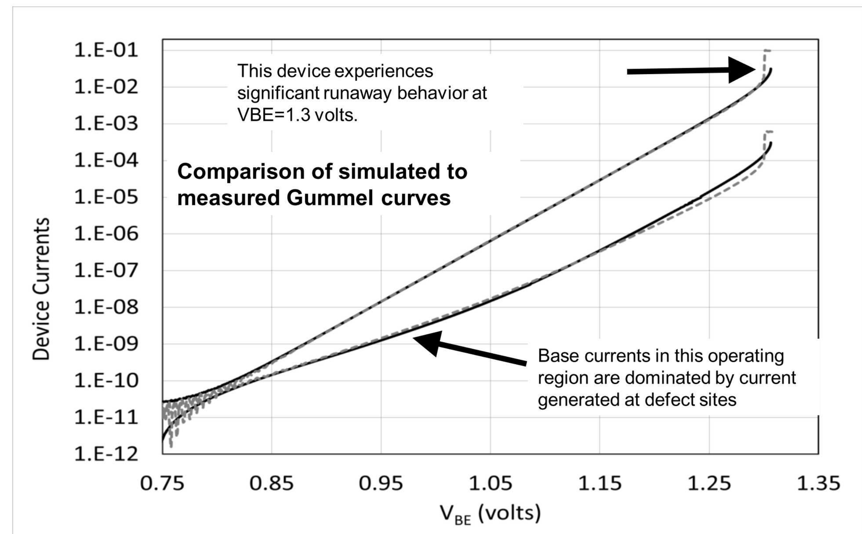
The simple analytic model explored here exhibits behaviors that yield insight into self heating processes. More complicated versions of this model also include a reversal of the flyback behavior at the turning point on an I_C versus V_{CE} curve. This reversal leads to a higher current curve at $V_{CE} > V_{flyback}$ and the system can exhibit jumps from the lower curve at $V_{flyback}$ to the higher current curve representing thermal runaway. One means of representing this more realistic behavior is with a device model in a circuit simulator that includes photocurrent, avalanche, and self heating effects. The circuit simulator Xyce^{TM} contains such models and work is underway to explore the behavior of a full featured self heating transistor with this tool.

Technology Computer Aided Design Modeling

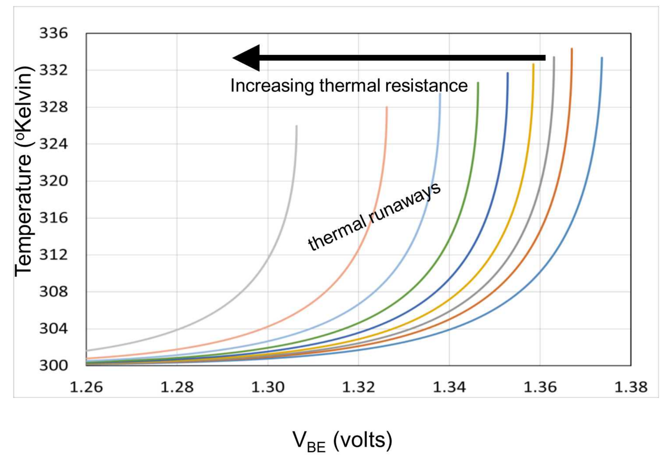
Starting with a generic Heterogeneous Bipolar Transistor TCAD model, the collector current is calculated as a function of the collector to emitter voltage for several base current values. Under standard I_C versus V_{CE} sweeps the calculation is stable up the turning points where it then becomes unstable and requires methods of arc length continuation to continue. These turning points are of interest and are determined by the various mechanisms included in the calculations including lattice heating and avalanche.

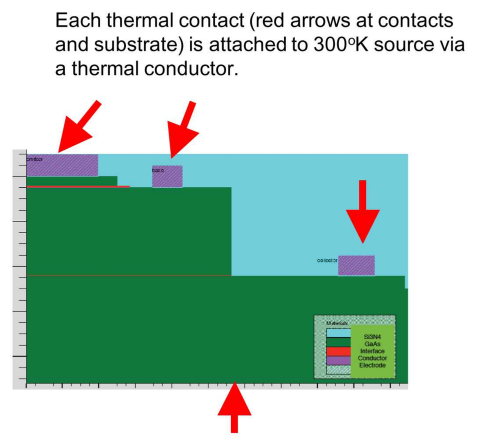


The safe operating boundary is extracted from these TCAD calculations and establishes the region where the device is stable and will not thermally runaway during operation. The behavior as calculated here is in qualitative agreement with the simple model analysis to this point. Matching measured device currents with TCAD generated Gummel Curves requires a TCAD model with correct dimensions, dopant impurities, and including traps for low base current fidelity and self heating for thermal runaway effects. Fidelity of the model is required to determine the full effects of photocurrent upon Gummel curves and device operation.



The following plot shows calibration by varying the thermal conductivity representing device and package thermal characteristics. The V_{BE} at which thermal runaway occurs depends on the thermal resistance attached to the heat sinks. Matching the measured thermal runaway of a data point gives confidence in the TCAD model setup. The range in thermal conductivities in the plot varies by a factor of 10 with the left most trace representing the runaway of the smallest thermal conductivity.





Acknowledgements

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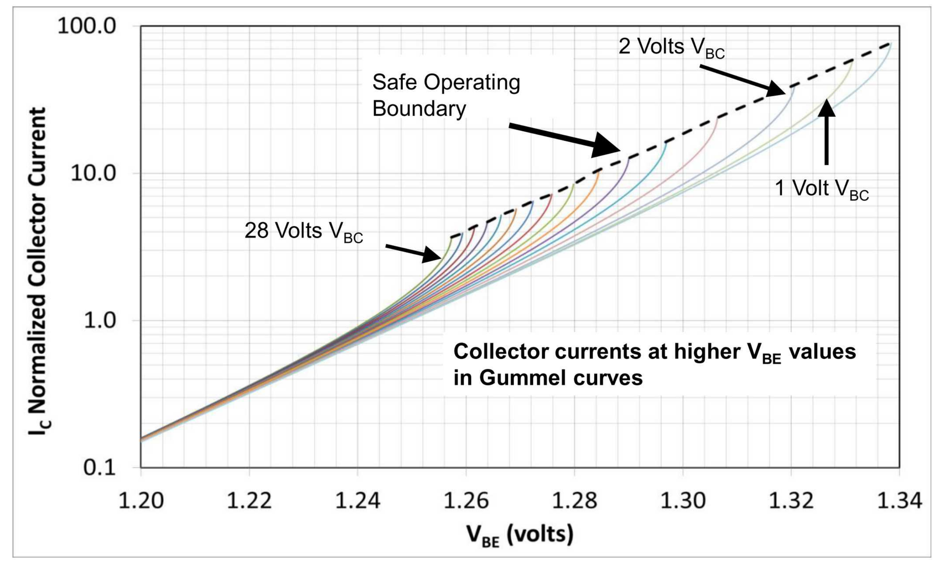
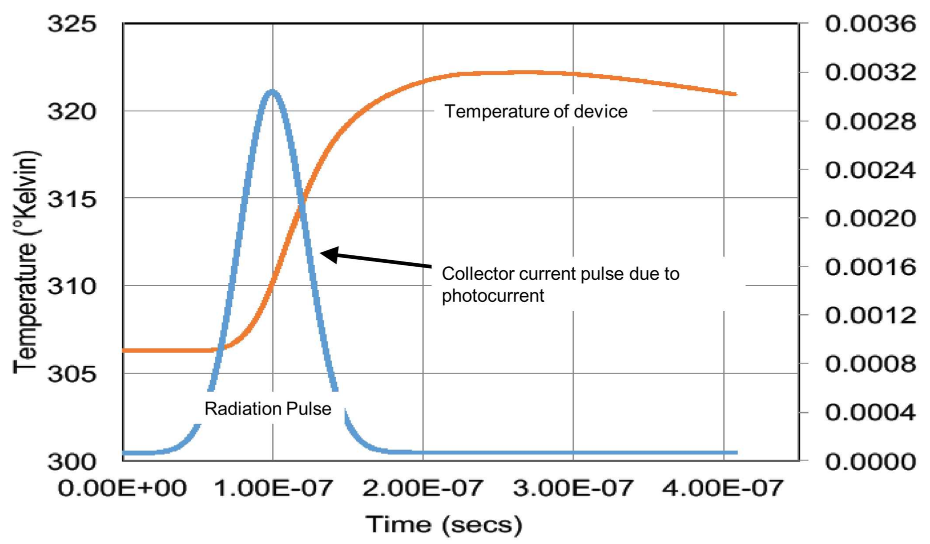
With the calibrated thermal 'equivalent circuit' model, it is possible to examine the behavior of the collector current Gummel curve for thermal runaway onset. These are conducted as steady state TCAD calculations. Higher V_{BC} voltages experience thermal runaway at lower values of V_{BE} and at lower values of a *critical current*. This critical current is an important reference current for transient as well as steady state calculations. The lower values of V_{BC} experience thermal runaway at higher V_{BE} values and critical current values.

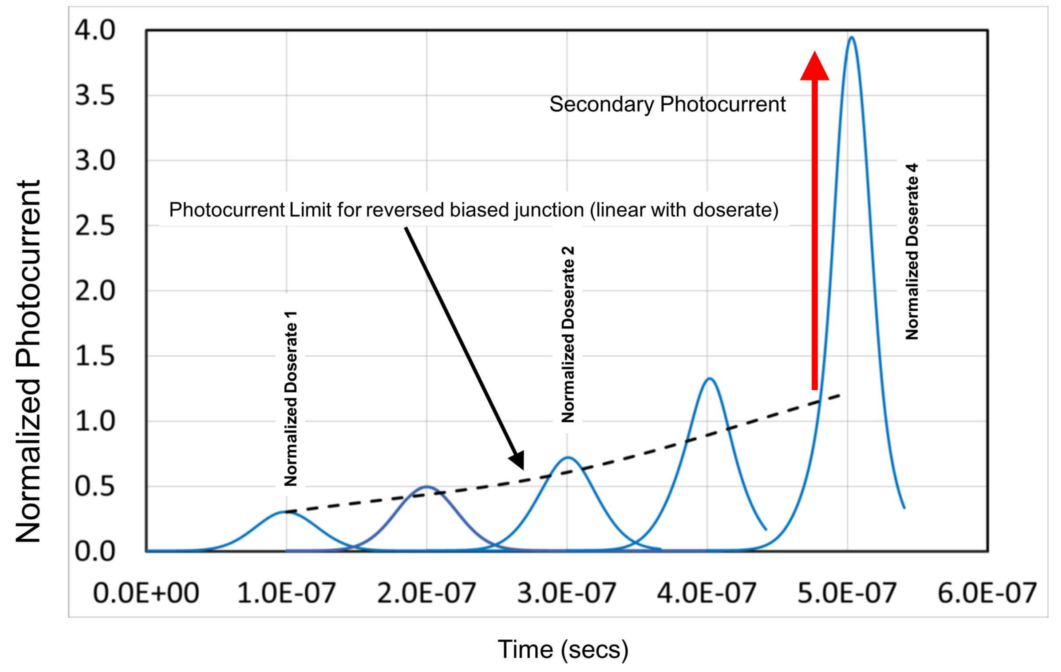
These calculations are performed with lattice heating, optical transition, impact ionization, and avalanche models enabled. For values of V_{BC} < 10 volts, these calculations have been performed in the absence of these models (except lattice heating) with the results unchanged implying that the low V_{BC} thermal runaway calculations are purely thermal caused. For a given V_{BC} and V_{BE}, the maximum critical current is determined and at currents less than the critical current experimental simulations are run to determine the effect of photocurrent on the collector current of the device and the resulting effect on self heating.



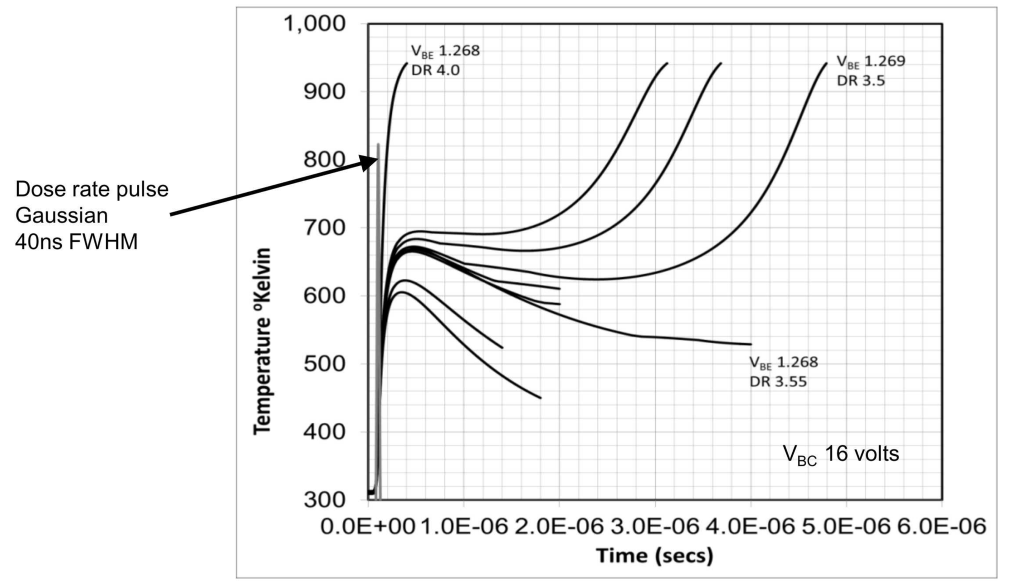


Shown is a demonstration Gaussian pulse with a normalized unitless dose rate of 1. Other pulses in this study will be referenced to the magnitude of this pulse. The Full Width Half Maximum of this pulse is approximately 40 nsecs which is not atypical for dose rate test facilities. Note here that this pulse produces a warming of the device of approximately 15 °Kelvin. This warming is a combination of the increased current from the dose rate pulse with the resulting Gaussian pulse of current leading to lattice heating and the subsequent increased temperature leading to a higher steady state current after the pulse compared to the steady state current prior to the pulse.

This work is focused on determining the effects of dose rate generated photocurrent on the operation and the temperature of the device. In general photocurrent is measured in bipolar devices with the device off, the emitter and base are biased together and the collector is reversed biased. This characterizes the largest pn junction in the device for photocurrent. In this work, we are more interested in the device operating so it is biased in a forward active regime. Generated photocurrent is added to the operation of the transistor and is amplified via transistor action.

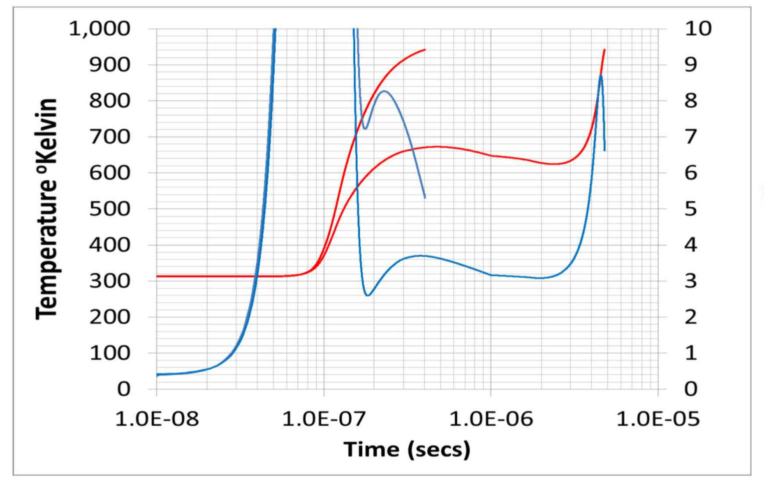


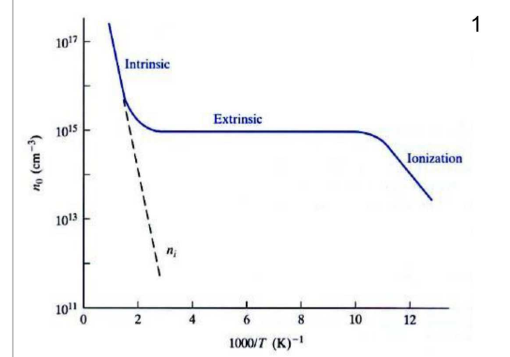
The resulting total photocurrent is the primary generated photocurrent plus the amplified photocurrent sometimes called secondary photocurrent. In this scenario, the total photocurrent increases super linearly with dose rate and thus adds to the joule heating caused by the current. The manner of simulation is to bias the device in steps along a Gummel curve until the desired operating current is reached and to fix this V_{BE} during a dose rate exposure. Operating these devices at currents close to the critical current with exposure to a high intensity dose rate pulse exposes the devices to several mechanisms which can lead to thermal runaway and device malfunction or failure. These mechanisms include lattice temperature increase due to joule heating, avalanche induced thermal heating, and device operation failure due to carrier over generation. Part of this work is to examine and characterize these mechanisms and some are shown here. The plot below shows temperature versus time curves for HBTs exposed to various dose rates and V_{BE}. Some of the temperature increases range from 100 to 500+ °Kelvin. All V_{BC} in this plot at 16 volts.



The data in the plot exhibits different notable behaviors. The curve with a normalized dose rate (NDR) of 4 shows a rapid temperature increase rising to 940 degrees immediately after the pulse (shown in gray). The calculation becomes unstable for reasons shown in the next plot. Several of the simulations also show this same terminal behavior of the calculation although at later times up to 5 µsecs. This behavior is surprising since in the 3.5 NDR curve for example, the device exhibits cooling prior to the thermal runaway. Also of note are the simulations which show rapid cooling after the pulse.

The following plots shows a closer look at the 4.0 and 3.5 NDR simulations from the previous plot. The calculation fails at temperatures above 900 °Kelvin although this result is unrealistic, a real device would fail at temperatures much less than 900 °Kelvin and these mechanisms are explored subsequently. In this case, the left plot shows both the temperatures (red curves) and collector currents (blue curves) for the simulations. The temperatures are shown to increase up to 940 °Kelvin at which point the calculation fails. The currents show an increase up to ~850 °Kelvin and then a rapid decrease as the temperature continue to rise. The cause of this behavior is the elevated temperature forcing the device material to become an ambipolar semiconductor leading to loss of transistor action. This is shown in the right plot as the boundary between intrinsic and extrinsic silicon semiconductors at low 1000/T (~500 °Kelvin) values.





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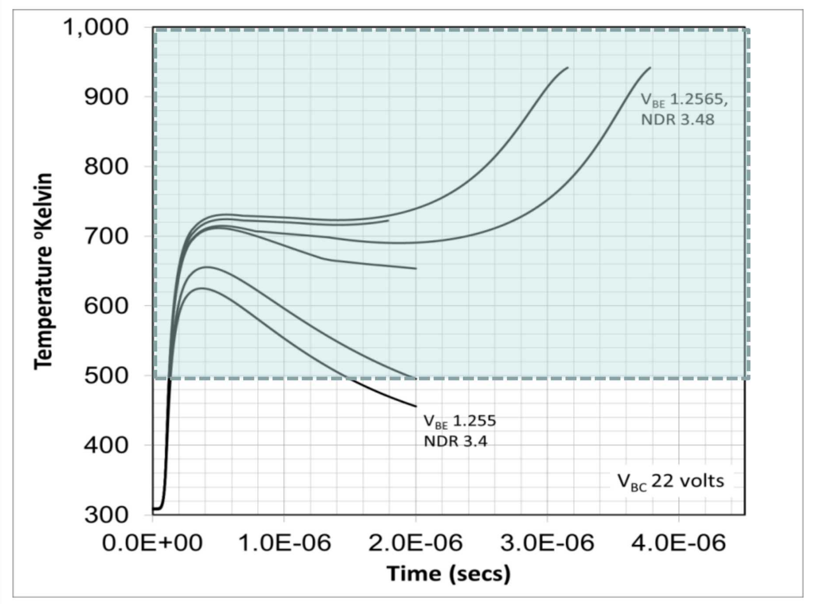
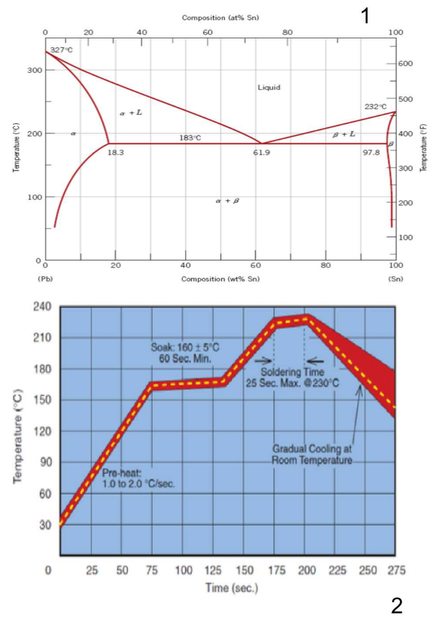
1 *Solid State Electronic Devices* Streetman Prentice Hall

At temperatures larger than 500 °Kelvin for silicon the right plot above shows that the intrinsic carrier concentration n_i of the semiconductor dominates over the doping levels (extrinsic). A transistor in these circumstances ceases to function and experiences reduced transistor action. As temperature increases beyond this point, the collector current begins to drop rapidly because of the loss of transistor function.

In the plot below, temperature versus time curves are shown for simulations with V_{BC}=22 volts. These curves are similar to the V_{BC}=16 volt simulations in that a variety of behaviors are represented. Delineated in this plot is the temperature region above approximately 500 °Kelvin and the simulations can be categorized into a group that stays above this temperature indefinitely and a group that despite initially experiencing this temperature falls below 500 °Kelvin in the long term. The top right plot shows that most electronic solders (lead-tin based) are liquid above the 200 °Celsius (500 °Kelvin) point. This is a steady state chart and the bottom right plot shows the time scales required to melt solder at elevated temperatures. Since the simulation plots are in µsecs, the melting solder chart shows reflow at 8 orders of magnitude longer time scales. This means that the HBT's are in danger of solder reflow only for the situations where the temperature remains elevated indefinitely.





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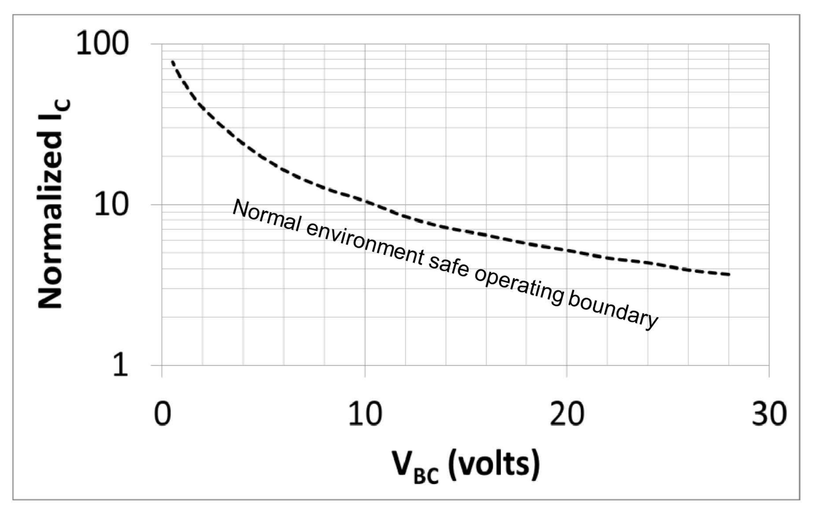
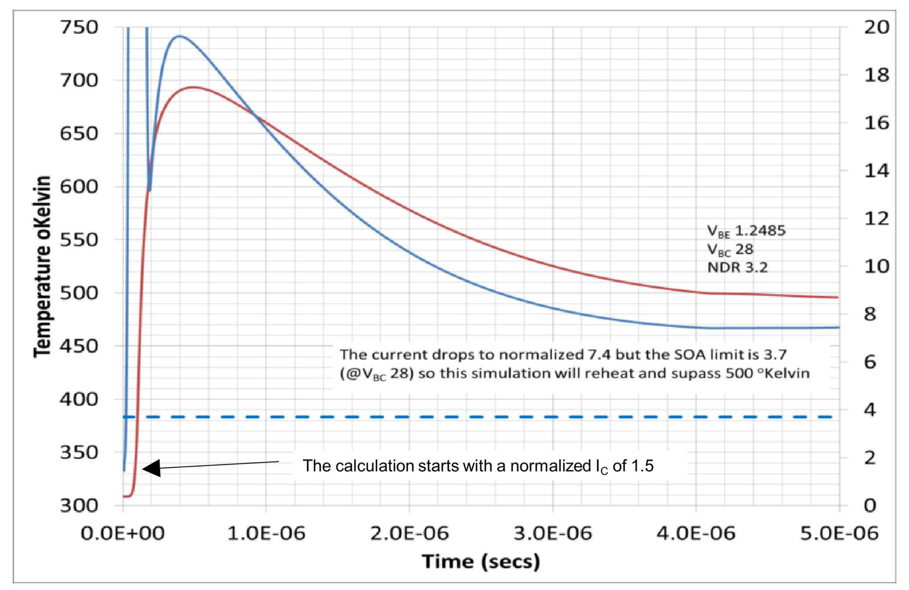
1 Binary Alloy Phase Diagrams, 2nd Edition, Vol. 3 T.B. Massalski 1990 ASM International Materials
2 Johanson Technology

The onset of thermal runaway in the Gummel curves can be used to generate a steady state collector current versus V_{BC} curve for normal conditions and this is displayed below. This curve can be used as a boundary in the same way that the 500 °Kelvin line is used a boundary to define HBT failure due to solder reflow. In this case, the concept is to use the current limit in the below plot as an upper limit for increased sustaining current in the presence of dose rate photocurrent. To be clear, a dose rate induced total current (operating plus photocurrent) that is above this limit for a short transient time is most likely not detrimental to the HBT but a total current that stays above this line for an extended period will lead to thermal runaway.



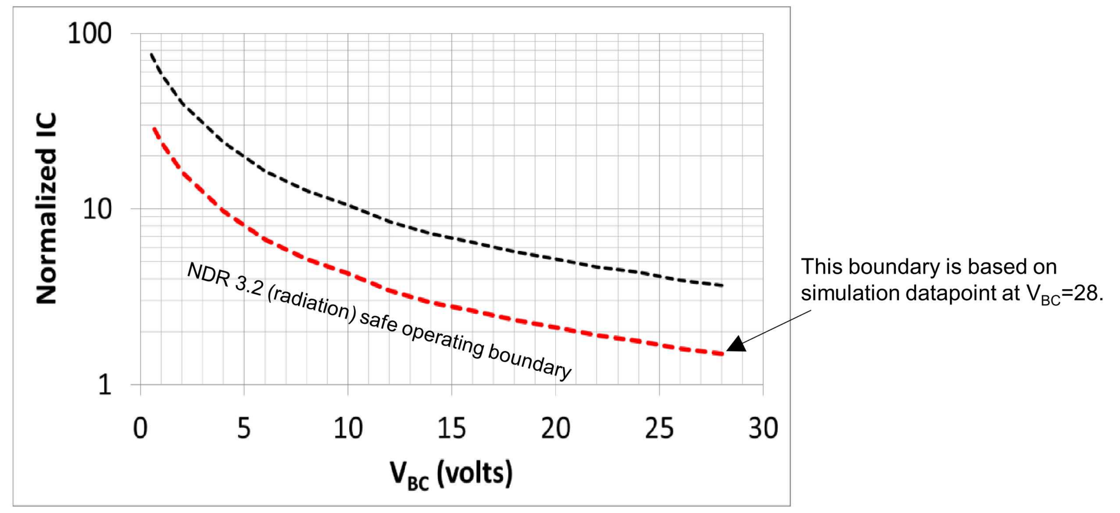
An example can be seen in 2 V_{BC}=28 volt simulation below. This simulation is performed at a reduced NDR and reduced V_{BE} since the V_{BC} of this device is 28 and avalanche at these voltages plays a role in the thermal runaway. In the simulation the temperature (red) is seen to increase to almost 700 °Kelvin after the dose rate pulse but cools to less than 500 °Kelvin by 5 µsecs. The simulation at 5 µsecs shows a continuing cooling trend. However, the sustaining collector current at 5 µsecs is ~7.4 normalized which is far above the SOA boundary current of 3.7 normalized. This indicates that the device should start to reheat and in the simulations, the sustaining collector current is showing an upwards trend at 5 µsecs. This upward trend will drive the temperature higher after 5 µsecs and the device will again cross the 500 °Kelvin temperature and proceed higher until calculation failure due to ambipolar carrier densities.

Note that the operating conditions (V_{BE}) for this device start pre radiation with a normalized collector current of 1.5 which is well below the critical sustaining current for thermal runaway without radiation.



Therefore, for this normalized dose rate (NDR) of 3.2 the safe operating area boundary can be updated based on the information from this 28 volt simulation. It is known that the starting operating I_C of 1.5 will eventually fail at this radiation level so it is a clear upper boundary at V_{BC} of 28 volts. If the same fraction of the normal environment SOA boundary is used along the entire boundary the result will appear as in the following plot. It is known that the thermal runaway is dominated by avalanche at high V_{BC} and by joule heating at lower V_{BC} so this fraction most likely cannot be extended over the entire range but it is a starting approximation.

The same NDR 3.2 simulation should be performed at other values of V_{BC} to determine the nature of this curve of lower V_{BC}. The simulations should also be performed at other radiation values to determine dependence on radiation magnitudes.



Conclusions

The simple analytic model of self heating can be extended to include dose rate radiation. A steady state exposure is demonstrated here and time dependence may be incorporated.

The next step is to deploy a calculation using a SPICE like circuit simulator which includes radiation models. SNL has such a tool (Xyce^{TM}) but the thermal modeling in this tool needs refinement. This tool can provide a high speed mapping of radiation and bias spaces to determine safe operating areas.

High fidelity TCAD simulations are productive in providing insight into operational boundaries and contributions from fundamental mechanisms. Various forms of runaway and defined failures can be incorporated in these simulations. The simulations can be configured with realistic thermal dissipation behaviors so that time dependent results can provide insight into behaviors. These calculations are time consuming but a representative and sampled mapping of radiation and bias spaces can be assembled to compare with faster running Xyce^{TM} results.

A long term goal of this work is to construct a SOA metric that incorporates, V_{BC}, V_{BE}, and radiation magnitude.