Test simulation of neutron damage to electronic components using accelerator facilities

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1. Abstract

The purpose of this work is to demonstrate equivalent bipolar transistor damage response to neutrons and silicon ions. We report on irradiation tests performed at the White Sands Missile Range Fast Burst Reactor, the Sandia National Laboratories (SNL) Annular Core Research Reactor, the SNL Sphinx accelerator, and the SNL Ion Beam Laboratory using commercial silicon npn bipolar junction transistors (BJTs) and III-V Npn Heterojunction Bipolar Transistors (HBTs). Late time and early time gain metrics as well as defect spectra measurements are reported.

2. Introduction

Historically, reactors have been used to test the transient response of electronic systems to neutron displacement damage. Other example applications for neutron studies include displacement-induced embrittlement in reactor pressure vessel materials, efficiency degradation in solar cells, gain degradation in bipolar transistors, damage to Instrumentation and Control systems in commercial and space reactor systems, and many more. With the diminishing availability of pulsing reactor facilities, an ongoing effort exists to use alternative facilities and radiation types, such as light and heavy ions as well as electrons, to simulate the displacement damage of neutrons in electronics. The concept of “equivalent” damage between these types of irradiation is a topic of much interest. Describing equivalence between neutrons and other types of radiation is much more than simply measuring a single quantity such as transistor gain in two radiation fields. It requires knowledge of both the type of defect that is produced by the damage as well as an understanding of which parts of the device are most sensitive to damage.

This paper examines the relations between several measured damage metrics of bipolar junction transistors after irradiation by reactor neutrons and by ions and electrons generated by particle accelerators. Metrics considered to measure displacement damage in III-V Npn heterojunction bipolar transistors (HBTs) and III-V diodes as well as silicon npn bipolar junction transistors (BJTs) include early- and late-time gain degradation and deep level transient spectroscopy (DLTS). Gain is an important metric that identifies how well a bipolar transistor will operate in a circuit after particle irradiation. DLTS performs two roles. Combined with the available literature on radiation damage in silicon and Gas, DLTS can be used to identify the relative concentrations of defects created by the damage. In addition, by performing annealing studies that sequentially remove radiation defects, DLTS can be used to correlate specific defects with the amount of gain reduction.

Reactor facilities used to test electronics included the White Sands Missile Range Fast Burst Reactor (WSMR FBR) and the Sandia National Laboratories Annular Core Research Reactor (SNL ACRR). The ion facility used in this work is the SNL Ion Beam Laboratory (IBL). The electron facilities used are the Little Mountain Test Facility linear accelerator (LMTF LINAC) and the SNL SPHINX facility. In summary, we will demonstrate that alternate accelerator facilities have utility in replacing the use of reactors to test discrete diodes and bipolar transistors when the appropriate damage metrics are selected.

3. Test Facilities

The WSMR FBR is an unmoderated and unreflected cylindrical assembly of uranium and molybdenum alloy. The WSMR FBR, covered with a boron-lined aluminum shroud to decouple the core from experiments, produces high-yield pulses of ≥ 50 microsecond (μ s) width, as well as long-term, steady-state neutron radiation. During pulsed operations, pulse widths of approximately 50 μ s (FWHM) can be obtained at maximum pulses. The neutron fluence level from a maximum pulse at a close-in test position is nominally $5E13$ n/cm² 1-MeV Si Equivalent.

The Annular Core Research Reactor (ACRR) is a pool type research reactor capable of steady state, pulsed, and tailored-transient operation. The reactor has a large central irradiation cavity. ACRR is used primarily for testing electronics and for reactor-safety research. Neutron-to-gamma ratios and neutron spectra can be widely varied using attenuators and converters. The experiments described here were fielded in the central cavity using a lead boron bucket (Pb-B₄C) liner to reduce the gamma dose and harden the neutron spectra. For pulsed operation, the reactor has a nominal pulse width (FWHM) of ~ 10 ms to 70 ms, producing neutron fluences from $5E13$ to $1E15$ n/cm² 1-MeV(Si). The pulse width and neutron flux can be tailored for individual irradiations. Fluence and dose uniformities of 10% may be achieved over

volumes of 7 by 5 by 15 cm in the central cavity. Photocurrents generated in devices and circuits are generally low because the large reactor pulse widths limit the peak neutron/gamma ionizing dose rate.

The IBL is a DOE user facility for ion beam analysis (IBA) and radiation effects microscopy (REM). With four accelerators, a 6 MV tandem Van de Graaff (including an RFQ booster for gold ions at 380 MeV), a 3 MV single ended Pelletron, a 350 kV Cockroft Walton, and a 100 kV focused ion beam system with a Wein filter for mass resolution, numerous ion sources and multiple dedicated beam-lines, the IBL can provide a wide variety of IBA and REM techniques. For the application in this work, a high ion flux was used to simulate a pulsing reactor environment. We have modified our beam-line to achieve as large as a 4 x 4 mm² spot size with excellent uniformity over the central region of the spot with beam current large enough to provide sufficient flux on target to match or exceed the defect creation rates observed in pulsing neutron facilities. For the experiments discussed in this paper we used a 3 and 4.5 MeV Silicon ion designed to maximize defect formation at the base-emitter junction of the device.

The LMTF LINAC is a linear accelerator operated in electron beam mode located at the Little Mountain, Hill AFB, Utah. The LMTF has a unique capability among linacs to provide a long, 50 microsecond pulse. Pulse widths can be tailored from 50 nsec to 50 µsec with beam currents ranging from 0.05 to 2 Amps. The electron beam peak energy can be tuned from 3 to 30 MeV. Electron fluences from 1E3 to 1E6 rad(Si) are achieved through the use of a variety of diffusers, target positions, and pulse widths. Useful electron beam diameters (with ~ 80% uniformity) range from ~1.5 cm for high electron fluences to 30 cm for low electron fluences. The LMTF can operate with a maximum repetition rate of 2 pulses per second to achieve large electron fluences.

The SNL SPHINX facility consists of an 18 stage, low inductance Marx generator; two oil pulse forming lines and a vacuum pulse forming line. Several sets of voltage and current monitors are included in the lines. The pulse width of SPHINX is continuously variable from 3.5 ns to 10 ns and the pulse rise time of 2 ns is independent of pulse width. Endpoint voltage up to 2.5 MeV can be achieved. A dose of 4E3 rad(Ca₂F) can be obtained in a single pulse. With a shot rate of about one shot per five minutes, test objects in SPHINX can accumulate large doses.

4. Experimental Metrics and Work

The setup for transistor component testing is shown in Figure 1; VRC, VRE, VRS, and VRB indicate the measurement points across the current viewing resistors. The transistors were operated with a constant emitter current of 0.22 mA, provided by a current limiting diode biased to -15 V (VEE) on the emitter leg. The base-collector junction was reverse-biased with 4 to 10 V (VCC) on the collector. The base leg was tied to ground through a relatively large resistor (RB) to ensure an accurate measurement of the base current prior to the shot. The additional clipping diode and resistor (RS) located on the base leg was optional and used to prevent large base potential excursions due to the large photocurrent response during irradiations. The currents of the transistor were monitored using current viewing resistors (RB, RC, RE) before, during, and after the shots. Gain is defined as the ratio of the collector current to the base current. The voltages across the current viewing resistors were recorded with a Yokogawa DL750P oscilloscope-recorder.

Figure 1. The experimental circuit used in the ion irradiations. Neutron irradiations did not include the clipping diode in the base leg.

A comparison of neutron and ion late-time gain degradation using the Messenger-Spratt [1] damage factor allows us to directly relate neutron and ion fluences and to calculate a late-time ion/neutron damage equivalence. The Messenger-Spratt analysis has historically been the standard of describing damage relationships. The expression from the original Messenger-Spratt derivation is given by

$$\Delta(1/G) = (1/G_{\infty} - 1/G_0) = k\phi \quad (1)$$

where k is the Messenger-Spratt damage factor, G_{∞} is the gain measured at a defined late time after the radiation pulse, G_0 is the gain measured before the radiation pulse, and ϕ is the radiation particle fluence. For BJTs, an ASTM standard[2] defines late-time gain as the gain measured after a 2 hour 80 °C thermal stabilization anneal. This thermal stabilization anneal is designed to aid in comparisons of stable late-time damage created by different irradiation conditions and often

read at different times after exposure without maintaining a consistent environmental temperature. For HBTs, no ASTM late time gain standard exists and we define late-time gain as the gain measured 300 seconds after the facility radiation pulse. In addition to temperature/time annealing, current injection can anneal out displacement damage. The selection of late time gain at 300 seconds after a short pulsed exposure is based on the current-induced annealing and thermal annealing characteristics of the HBT. To determine the equivalent late time gain degradation between ions and neutrons, we determine an ion fluence such that $\Delta(1/G)_{ion} = \Delta(1/G)_{neutron}$. Therefore, the ion fluence that is equivalent to a given neutron fluence is given by the ratio of the damage factors and is shown by equation 2 below.

$$\Phi_{neutron} = \frac{k_{ion}}{k_{neutron}} \Phi_{ion} \quad (2)$$

Figure 2 illustrates the late-time inverse gain damage, $\Delta(1/G)$, for 4.5 MeV and 36 MeV Si ions and ACRR and WSMR neutrons plotted in terms of an equivalent 1 MeV silicon neutron fluence. For example, the $k_{ion}/k_{neutron}$ ratio for 4.5 MeV Si ions and ACRR and WSMR neutrons was measured to be approximately 1.34E5. Using the ratio, a fluence of 3.7E8 4.5 MeV Si ions would be equivalent to 5E13 1-MeV Silicon Equivalent neutrons in terms of late-time gain degradation.

Figure 2. $\Delta(1/G)$ as a function of effective 1-MeV Si Eqv. neutron fluence for neutrons and 4.5 MeV Si. For 0.22 mA, $k_{neutron} = 6.68E-16$, $k_{Si} = 2.88E-10$.

The damage relationship shown in Figure 2 validates the Messenger-Spratt relationship for transistor gain degradation. It does not establish “equivalence” in that the defect species that produce the changes in gain after ion or neutron damage are not known and need not be the same. Knowledge of these species is required to build a physics-based microscopic model of the gain recovery following damage. To provide this information we use a defect spectroscopy tool, DLTS[3], to provide information on both the number and type of traps. DLTS is a well-established technique that has been employed for over forty years to measure trap concentrations in semiconductors (see, for example textbook descriptions of DLTS[4]). DLTS employs a diode (e.g. a transistor emitter-base or base-collector junction) and measures the carrier emission from traps by analyzing the capacitance transient that follows a voltage pulse. In addition to its suitability for use on an actual BJT device, DLTS is quite sensitive and can detect defects at concentrations of 10^{-4} of the doping density. Our use of DLTS to examine defects after neutron damage differs from much of the literature in that we concentrate on defects in damage cascades rather than the isolated point defect distribution present after electron damage. We use a literature-based knowledge of radiation defects in silicon after electron damage (isolated point defects) and combine that with measurements of DLTS defect spectra from clustered defects.

DLTS of the base-collector diode of silicon npn transistors are shown in Figure 3. Damage has been introduced with electrons, neutrons and two energies of silicon ions. The defects that produce these DLTS spectra are located in the low-doped n-type collector, thus they are not important for device gain degradation. Nevertheless they are useful to illustrate the changes in defect DLTS spectra due to damage clusters. This understanding will then be applied to defects near the emitter-base junction that do affect device gain. The VO peak at about 90 K is the vacancy oxygen defect and is quite shallow, about 0.17 eV below the conduction band. The VO defect contributes very little to gain reduction because of its location within the bandgap, so we won't discuss it further. The two peaks at about 130 and 230 K are from two charge states of the same defect, the silicon divacancy (V_2). The lower temperature peak is from emission from the -2 charge state of V_2 ($=/-$), while the higher temperature peak is from emission from the -1 charge state of V_2 ($-/0$). The singly-occupied defect, V_2 ($-/0$), being deeper in the gap at 0.42 eV below the conduction band, is important for gain reduction (when the defect is located near the emitter-base junction). Note that the two divacancy peaks have the same height after electron damage, shown in the lower left panel, as expected for isolated defects. Note also that if the defects are clustered, as from neutron damage (upper left panel of Figure 3), the singly charged V_2 is now considerably larger than the doubly-charged V_2 . We interpret this as indicating that additional defects are formed within the damage cascade that have an

energy level about the same as $V_2(-/0)$. From annealing studies we conclude that the additional defects are a variant of the divacancy.[4, 5] We refer to this new defect present in damage cascades as the strained divacancy V_2^* . The two right hand panels of Figure 3 illustrate the effect of changing the ion energy. High energy ions that are not at end-of-range pass through the collector. They produce a trail of small cascades and a DLTS spectrum that resembles electrons. Lower energy ions that stop within the collector produce larger damage cascades and a DLTS spectrum that is more like that after neutron damage. For this reason when measuring the transistor gain response, we choose the ion energy so that that the end-of-range occurs near the emitter-base junction where the maximum recombination occurs.

It is well known that defects that contribute to gain reduction of a BJT are primarily located with the depletion region of the emitter-base junction. Defect spectra from the n-type base of a Si pnp transistor are shown in Figure 4 for neutron and Si ion damage. The energy of the Si ions was tuned to 4.5 MeV to put the peak of the ion end-of-range at the emitter-base junction. In a manner similar to the normalization of the Messenger-Spratt plot of Figure 2, the ion fluence has been normalized to overlap the spectra. We achieve a near perfect overlay indicating that composition of the defects is the same for both neutrons and the end-of-range Si ions. With the larger P doping from the n-type base compared to the collector, we expect that the 235K peak to be composed of three types of defects, the doubly-charged V_2 , the V_2^* and the VP. We were able to decompose this peak by successive high temperature anneals that sequentially remove the defects. This has allowed us to measure the relative composition of the different types of gain-killing defects.[6, 7]

Figure 3. DLTS from the collector of an npn 2N2222 transistor showing spectra for electrons, neutrons, and ions of two different energies. Neutrons and lower energy ions that have an end-of-range within the collector have the largest damage cascades and non-equal V_2 acceptor levels. The VP contribution to the DLTS in the collector is negligible.

Figure 4. DLTS from the base of a pnp bipolar transistor. Gain reduction occurs primarily due to the defects represented by the DLTS peak at 230K, which has contributions from the standard V_2 , the strained divacancy V_2^* and the vacancy phosphorus (VP).

While the damage factor, as determined from the Messenger-Spratt late-time inverse gain degradation, is an excellent metric for late-time gain comparisons between the facilities, damage equivalence studies also require an understanding of early-time transient annealing. The early-time metric presented in this paper is the annealing factor, $AF(t)$ [8], defined below,

$$AF(t) = \frac{1/G(t) - 1/G_\infty}{1/G_0 - 1/G_\infty} \quad (3)$$

where $G(t)$ is the time varying gain measured before, during, and after the irradiation, G_0 is the initial pre-irradiation gain, and G_∞ is the late-time gain. The annealing factor is the ratio of the number of defects at any time to the number of defects at late-time. We also note that the numerator of equation (3) is also the time dependent version of $\Delta(1/G)$ found in equation (1).

Figure 5 compares the BJT annealing factor response for equivalent neutron and ion irradiation pulses. The annealing factors show excellent agreement from 500 microseconds through 100 seconds after the reactor and ion pulses. The reactor gamma environment during the neutron irradiation creates photocurrent in the BJT that masks the AF response at early times. The effect of photocurrent due to the gamma environment is obvious through several hundred microseconds. The agreement between the annealing factors indicates that the annealing kinetics are similar for ion and neutron irradiations. The concept of late-time gain G_{∞} was developed for studying silicon based BJT's where the defect annealing has a large thermal component. In silicon devices, there is little change in gain after long times, so G_{∞} is well-defined quantity for calculating the annealing factor. We have retained the concept of the annealing factor when analyzing the response of III-V HBT's, but there is an important caveat. In the III-V devices the thermal annealing rate of defects at room temperature is very small and changes in gain are driven almost entirely by charge recombination annealing. Unlike the silicon devices, the gain of III-V devices does not saturate with time when the current is on. Nevertheless, we choose a standard time (300 s) for calculating the annealing factor at all of our device current biases.

Figure 5. Annealing Factor comparison of equivalent neutron and ion irradiation pulses.

DLTS defect spectra from HBT's present special challenges not present for the silicon BJT's. First, the base of the HBT is very highly doped, so DLTS is not a viable technique to measure the damage spectra in that part of the device. Second the capacitance of the HBT is too small to measure a capacitance transient. Instead, large area GaAs diodes of varying doping have been used to measure defect spectra created by electrons, neutrons, and ions. A further complication is that DLTS spectra of clustered damage in GaAs are known to have very broad features instead of distinct peaks. This behavior is illustrated in Figure 6 where we show the DLTS spectra of n-type GaAs damaged with electrons and with neutrons. The origin of the broad DLTS feature (termed the "U-band") seen after neutron damage is still not fully understood. One suggestion is that it represents a broad density of defect states that span the middle of the GaAs defect band.[9] Another contributing factor is that GaAs is known to have significant phonon assisted tunneling that will accelerate electron emission in high electric fields and broaden DLTS peaks.[10] So, unlike the case of the silicon BJT, DLTS spectra after neutron and ion damage cannot be related by simple scaling.

Figure 6. DLTS following neutron and 2 MeV electron irradiation. Clustered defects such as those made by neutrons produce a "U-band", a broad DLTS feature.

Defect spectra of low doped n-type GaAs measured after damage from neutrons, electrons and ions of varying mass are shown in Figure 7. The vertical axes are numbers of defects normalized by the calculated number of vacancies V_{calc} . Like the silicon example shown in Figure 3 the shallow defects ($T < 100K$) are not important for gain reduction and can be disregarded. The change in the low-temperature peaks with mass of the incident ion is due to clustering and a Coulomb

barrier to trap-filling due to charge on nearby defects. As clustering increases, the amplitude of the DLTS signal decreases. Note that for defects that are deep in the gap (those with DLTS peaks at temperatures $\sim 150 - 350$ K), the number of defects is approximately the same for all types of damage. This validates our use of the normalization, V_{calc} . The data of Figure 7 illustrate the changes in DLTS as the mass of the incident particle increases and the number of damage subcascades increase. Electron damage produces isolated point defects that produce a finite number of sharp DLTS peaks. Ion damage looks more neutron-like as the mass of the incident ion increases, but there is no point where the DLTS spectra overlap the neutron example (unlike the case with silicon devices). Despite this, similar changes in gain can be correlated with overall numbers of defects, V_{calc} . This indicates that the DLTS is highly sensitive to details of clustering, but gain changes are less sensitive.

Figure 7. Normalized DLTS from n-type GaAs following neutron, electron and ion damage with varying ion masses. As the mass of the incident particle increases, the amount of defect clustering increases and DLTS feature broaden.

After matching late-time gains as described with silicon BJTs, HBT response to facility pulses can be shown in terms of the annealing factor. Figure 8 compares the HBT annealing factor response for the ion and neutron irradiations. The ion and neutron annealing factors do not match until shortly after 0.2 second due to the effects of gamma ionization photocurrent and late time neutrons from the reactor. The annealing factors do not agree well at early times because the IBL delivers all of its ions in a 40 μsec rectangular pulse while the FBR pulse delivers roughly 85 to 90 % of its neutrons in approximately 500 μsec . Late time neutrons driven by the reactivity decay of the multiplying assembly account for 10 to 15% of the neutrons delivered by the reactor pulse after 500 μsec from the initiation of the reactor pulse. Therefore, the neutron annealing factor will be lower than that of the IBL annealing factor until nearly equivalent numbers of ions and neutrons are delivered. The annealing factors match very well after 0.1 seconds. Agreement between the annealing factors indicates that the annealing kinetics are similar for ion and neutron irradiations.

Figure 8. Annealing Factor comparison of equivalent neutron and ion irradiation pulses.

We have found that Npn HBTs used in this work have interesting annealing characteristics that make a second type of neutron test possible. HBTs have almost no thermal annealing at room temperature for hundreds of seconds. In contrast, Si BJTs have significant thermal annealing at room temperature. HBTs only show appreciable annealing when they are on (current injection annealing). With no thermal annealing, we can turn off the HBTs and pulse the reactor. The HBTs are then turned on after all the neutrons are delivered by the reactor (after ~ 10 seconds). Figure 9 illustrates the technique described above. An irradiation with the transistor turned off during the reactor pulse is referred to as the “delayed on” case. When the transistor is on during the reactor pulse, the case is referred to as the “continuous on” HBT. Agreement between the annealing factors for the “delayed on” HBT at the reactor and the “continuous on” HBT at the IBL indicates that the annealing kinetics are similar for ion and neutron irradiations for early and late times.

5. Conclusion

We have demonstrated equivalent damage between both ion and neutron irradiations for Si npn BJTs using late- and early-time gain metrics as well as DLTS. We can match the late-time defect spectra and late-time gain using reactor neutrons and 4.5 MeV Si ions. After matching late-time gain degradation, we confirmed early time damage equivalence and subsequent annealing to late times through the measurement of annealing factors. Gamma radiation effects at reactors prevent very early time comparisons of damage equivalence. With III-V HBTs, the DLTS metric is not useful in matching late time defect spectra due to the clustering created by neutrons and heavy ions. However, we can still match late-time gain degradation between ions and neutrons for III-V HBTs. Annealing factor comparisons based on the late-time gain matching agree very well for ion and neutron irradiations.

Figure 9. Annealing Factor comparison of equivalent neutron and ion irradiation pulses for continuous on and delayed on HBTs.

6. References

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