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Test simulation of neutron damage to electronic components using accelerator facilities

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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.

1. 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 GaAs, 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.

2. 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 $\geqslant$50 microsecond (μs) width, as well as long-term, steady-state neutron radiation.

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During pulsed operations, pulse widths of approximately 50 μs (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/cm^2 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-B_4C) liner to reduce the gamma dose and harden the neutron spectra. For pulsed operation, the reactor has a nominal pulse width (FWHM) of ~10–70 ms, producing neutron fluences from 5E13 to 1E15 n/cm^2 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 × 4 mm^2 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 μs pulse. Pulse widths can be tailored from 50 ns to 50 μs 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 with 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(Ca_2F) 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.

3. Experimental metrics and work

The setup for transistor component testing is shown in Fig. 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 4–10 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 at 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.

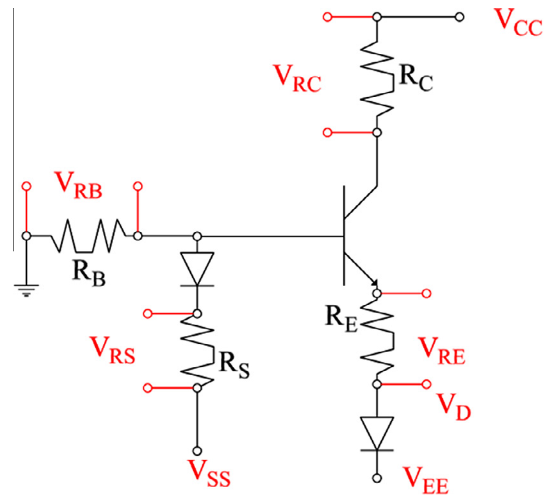

Fig. 1. The experimental circuit used in the ion irradiations. Neutron irradiations did not include the clipping diode in the base leg.

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 h 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 s 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 s 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 Eq. (2) below.

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