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Title: **Metrics For Comparison Between Displacement Damage Due To Ion Beam And Neutron Irradiation In Silicon BJTs**

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Abstract:

We report on a series of metrics used to determine damage equivalence between ion and neutron irradiated silicon BJTs. Included are late time gain degradation, deep level transient spectroscopy (DLTS) results, and early-time transient annealing.

Metrics for comparison between displacement damage due to ion beam and neutron irradiation in silicon BJTs

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Introduction:

The issue of ion-to-neutron damage equivalence is of current interest because of the lack of fast neutron sources in the United States. Previously, components could be tested in one of several fast burst reactors (FBR). As of October 1, 2006, the number of such facilities has dropped to one, the White Sands Missile Range FBR. Because of this, Sandia National Laboratories (SNL) is developing a first principles physics-based modeling program combined with alternative irradiation facilities to provide an alternative to FBR testing. This summary will discuss one such alternative facility: the Ion-Beam Laboratory (IBL) at SNL. We will suggest a series of metrics used to determine the damage equivalence between ion irradiated and neutron irradiated devices. The neutron irradiated devices were exposed at the Sandia Pulse Reactor (SPR-III).

In this summary we will consider a comparison between devices irradiated at the IBL using high energy heavy ions and devices tested in SPR-III. We will be comparing the inverse gain degradation Δ(1/G), as defined from equation (1),

$$\Delta\left(\frac{1}{G}\right) = \frac{1}{G_\infty} - \frac{1}{G_0} \tag{1}$$

where G_∞ is the final gain, and G_0 is the initial gain, deep level transient spectroscopy (DLTS) results, and early-time transient annealing in order to determine an ion-to-neutron damage equivalence that will be used in the development and verification of the physics-based models.

Experimental:

Single diffusion lot 2n2222 bipolar junction transistors from Microsemi were used in these experiments to minimize the device to device variation that is present in commercial parts. Deconstruction analysis and spreading resistance measurements were performed on these devices to accurately determine the device geometry and doping profile of the active region of the devices. These parameters are extremely important for understanding and modeling the defect formation and transport during both ion and neutron irradiations. 2n2222 devices were chosen for these experiments because they are a well established technology with a considerable defect literature.

The ion irradiations were performed at the IBL. The ion beam was focused to a size somewhat larger than the size of the transistor die (~0.5x0.5 mm^2) and was pulsed for single irradiations ranging from 10 μs to 10 ms using electrostatic deflection plates and a high voltage switch with rise and fall times of 150 ns. The currents of the transistor were monitored using current viewing resistors before, during, and after the shots. The voltages across the current viewing resistors were recorded with a Yokogawa DL750P oscilloscope-recorder. The transistors were operated in constant emitter current mode (emitter current of 0.22 mA), provided by a current limiting diode biased to -15 V on the emitter leg. The base-collector junction was reversed-biased with 10 V on the collector. The base leg was tied to ground through a relatively large resistor to ensure an accurate measurement of the base current prior to the shot. An additional diode located on the base leg was used to ensure that the base-collector junction remained reverse-biased despite the large photocurrent response to the ion beam during the shot. For more details on the experimental setup see reference [1].

The neutron irradiations were performed at SPR-III over a wide range of 1 MeV equivalent neutron fluence. SPR-III is a fast burst reactor which can be operated in either a steady-state or pulsed mode. A maximum of 1 MeV equivalent neutron fluence of 3×10^{14} n/cm^2 and a FWHM of 100 μs is possible in pulsed mode. The irradiated devices were placed in the central cavity for maximum neutron fluence and to ensure uniformity of the spectrum. The operation of the transistors was monitored prior to, during, and for 100 s after each shot. For SPR-III operations the circuit was modified by removing the diode from the base leg [2].

For the data presented here the ion irradiation was performed with a variety of ion beams from 12 MeV He to 48 MeV Si beams with fluences up to 1.5×10^{11} ions/cm^2. This results in an inverse gain degradation Δ(1/G) as large as 2. In the case of the neutron irradiations, the 1 MeV neutron fluence was varied from 7×10^{13} to 3×10^{14} neutron/cm^2 which results in a Δ(1/G) of up to 1. The inverse gain degradation was determined using the final gain of the device measured approximately 100 seconds after the shot. The DLTS spectra were taken post irradiation.

Results:

In Figure 1 we plot Δ(1/G) for both ion beam (10, 28 and 48 MeV Si) and fast neutron irradiated samples as a function of 1 MeV neutron equivalent fluence. For the ion irradiated sample the 1 MeV neutron equivalent fluence was calculated using a ratio of k_n/k_{ion} to scale the ion fluence where k is defined by equation (2). The k_n/k_{ion} ratio for 48 MeV Si is ~8,000. A discussion of the scaling technique and the method by which an accurate determination of the ion fluence was calculated can be found in [1]. The fast neutron SPR-III fluence is determined from converting sulfur response (Californium Equivalent) to 1 MeV neutrons using reference [3]. For both the 48 MeV Si irradiation and the fast neutron irradiation the response is linear at the highest measured fluence, as predicted from the Messenger-Spratt equation [4], see equation (2) where k is the damage factor and ϕ is the incident fluence.

$$\Delta\left(\frac{1}{G}\right) = k \cdot \Phi \qquad (2)$$

However, the 10 and 28 MeV Si irradiations become non-linear at 4.0 and 2.0×10^{14} n/cm^2 respectively.

Figure 2 shows a series of DLTS spectra for the 48 MeV Si irradiation where the ion end of range is beyond the DLTS depletion depth. We observe the common silicon complex defects including the vacancy-oxygen (VO) at 95 K and the silicon di-vacancy (VV) at 135 K and 233 K. The 233 K peak also includes contributions from the vacancy-donor (VP) and primary defects from the damage cascade. Note that as the fluence is increased there is at first the expected increase of the DLTS peak, but eventually there is an overall decrease of the DLTS signal. The decrease starts with the shallow peaks and eventually extends to the whole spectrum. We believe that this decrease is caused by the heavy damage in the ion end of range region between the DLTS volume and the substrate. Overlapping clusters leads to compensation of the neutral silicon thus adding a large series resistance to the measurement circuit.

In Figure 3 we show a comparison between the annealing factor for a 10 MeV Si and a SPR-III shot with Δ(1/G) on the order of 1. The annealing factor is defined as the following,

$$AnnealingFactor = \frac{1/G(t) - 1/G_{initial}}{1/G_{final} - 1/G_{initial}} \quad (3)$$

Discussion

While the results shown in Figure 1 are very positive, allowing for a method of scaling between ion and neutron irradiations in the linear regime, the dramatic changes observed in the DLTS spectrum for the 48 MeV Si irradiation (Figure 2) are problematic. Furthermore, the non-linearity observed in the 10 and 28 MeV Si irradiations must be explained. In both cases, the issue is related to the depth profile of the damage throughout the device. Neutrons have a very small collision cross-section with Si atoms (no Coulomb interaction), i.e., most neutrons pass through the device without striking a Si atom. Those that do strike a Si atom cause localized collision cascades. This results in uniform vacancy creation throughout the depth of the device. Ions tend to lose energy as they travel deeper in the device because of both a large collision cross-section (nuclear-stopping power) and ionization (electronic-stopping power). The net result is that vacancy creation varies as a function of penetration depth. The non-linearity in the 28 MeV Si data is directly related to its end of range being located in the collector of the device. At high enough fluence the low doped collector becomes compensated, changing the properties of the device and causing the non-linear response. In the case of the 10 MeV Si beam the end of range is located at the base-emitter junction, as a result the collector is less damaged and the non-linearity occurs at much higher fluence. The 48 MeV Si irradiation was chosen to ensure a relatively flat damage profile in the critical region of the device, namely the base-emitter junction. This results in a linear Messenger-Spratt response even at extremely high fluence values. While the 48 MeV Si has an end of range in the substrate there is a factor of two difference between the displacement damage (number of vacancies/ion/Å as calculated using SRIM-2003 [4]) at the base-emitter junction as compared to the end of the collector. Through capacitance-voltage (CV) measurements we have shown that the collector doping drops by a factor of two for the high fluence irradiations. As a result, the DLTS amplitude, as measured at the collector, does not scale at high fluence because the collector becomes compensated. We find that one needs to consider not only the linear response of the inverse gain degradation (probing the base-emitter junction), but also CV and DLTS measurements to ensure that the low doped collector is not compensated.

In Figure 3, we show a first comparison between the early-time transient annealing between ion and neutron irradiated samples. In both cases we have a pulse length on the order of 100 μs with final gain on the order of 1. We plot the annealing factor to normalize for differences in the fluence and pre-irradiation gain values. The similarity of the two curves is quite striking. The early-time comparison ($<10^{-3}$ s) is of limited value because of late-time gammas which mask the response of the device in the fast neutron experiments. These gammas are caused by the activation of the reactor itself and the oscillations observed in the data are due to physical oscillations (or ringing) of the reactor post shot. The subsequent comparison indicates good agreement between the time dependence of the ion and neutron irradiations.

Conclusion

We have compared ion and fast neutron irradiations to determine an ion-to-neutron damage equivalence. We find that a combination of metrics is needed to ensure a comprehensive understanding of the physics involved in the ion-to-neutron conversion. While the inverse gain degradation is linear to the highest measured fluence for the 48 MeV Si irradiation, this metric is primarily probing the base-emitter junction and is not indicating the collector compensation that occurs, as evident in the DLTS spectra. As a result, care must be taken in choosing the irradiation beam for ion exposures. The displacement damage should be peaked in the base-emitter junction to both ensure maximum gain degradation and an un-compensated collector. A detailed description of the conversion from ion to neutron fluence, as well as a discussion of the choice of ion/energy combinations used and the resulting DLTS spectra will be provided in the long paper.

Acknowledgement

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References

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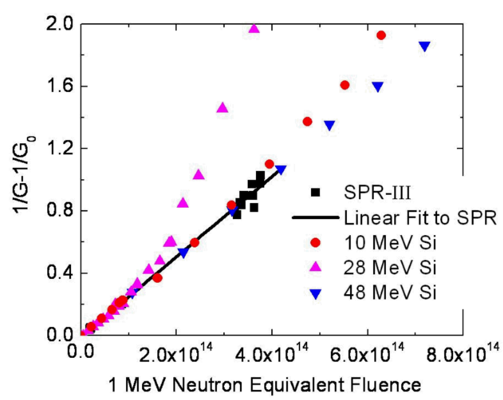

Fig. 1. The inverse gain degradation for 10, 28 and 48 MeV Si and fast neutron irradiation plotted versus 1 MeV neutron equivalent fluence. While both the ion and neutron data is linear at low fluence, the 10 and 28 MeV Si show a non-linear response at high fluence due to compensation in the low doped collector region of the device.

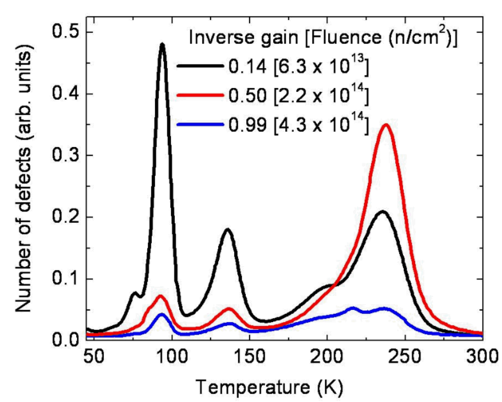

Fig. 2. DLTS spectra for 48 MeV Si irradiation at three different fluences. For inverse gain degradation less than 0.50 we observe a linear increase in the 233 K peak with fluence. For higher fluence values the DLTS amplitude changes dramatically.

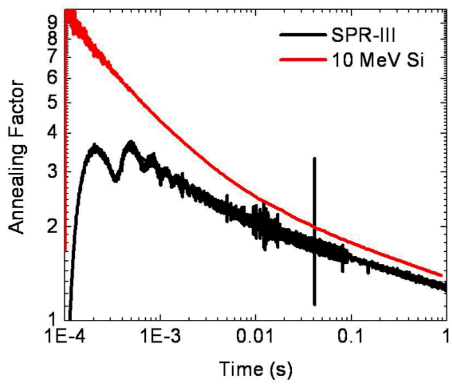

Fig. 3. Comparison of the early-time transient response for both ion and fast neutron irradiation. The annealing factor (number of defects at time t over the number of defects at t = ∞) shows a similar response for both ions and neutrons.