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Enhanced Photocurrent Annealing in a Combined Ion and Electron Irradiation

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Introduction:

The combined effect of high dose ionization radiation in conjunction with displacement damage is of critical importance to understanding the response of semiconductor devices to radiation environments. While prior work [1-7] has concentrated on either ionizing radiation or displacement damage individually; few experiments [8] have independently probed both simultaneously. We are independently varying both the ionizing dose rate and displacement damage levels using a combination of simultaneously pulsed ion and electron irradiations. In this summary we report experimental results showing enhanced photocurrent annealing in Silicon Bipolar Junction Transistors (BJTs) at early times after pulsed irradiations.

Experimental:

Previously, we developed the experimental techniques necessary to relate damage effects between heavy ion and neutron irradiations of discrete silicon npn and pnp BJTs [9-12]. The key feature of this ion-to-neutron damage relation is the conversion between ion fluence and 1 MeV equivalent neutron fluence through the resulting device degradation. We have demonstrated the ability of heavy ion irradiations to match or exceed the damage creation rates observed in fast burst reactor testing environments. Furthermore, extensive work in understanding the effects of the ionization under heavy ion irradiation has been started with some preliminary quantification for both oxide and bulk ionization effects. Overall, we can define both an effective 1 MeV equivalent neutron fluence (based on the Messenger-Spratt damage constant) and the effective dose rate for a given heavy ion irradiation condition.

For the experiments described here we used single diffusion lot NPN 2n2222 BJTs from Microsemi. Single diffusion lot devices were chosen to minimize the device-to-device variation. We decided to initially use 2n2222 devices because they are a well established technology and display gain degradation both due to total dose and displacement damage. We have characterized the effects of total dose, dose rate and displacement damage in these parts using experimental exposures at a series of neutron, gamma and ion facilities.

The independently controllable ionization exposures and displacement damage irradiations were performed at the Ion Beam Laboratory (IBL) at Sandia National Laboratories using combined ion (for displacement damage) and electron (for ionizing dose) irradiations. The ion beam irradiations were provided using our 6.5 MV Tandem Accelerator. Here the beam was focused to a size somewhat larger than the size of the transistor die (~0.5x0.5 mm^2) and was pulsed for a single100 μs irradiation using electrostatic deflection plates and a high voltage switch with rise and fall times of 150 ns. The electron beam irradiations were provided by a Kimball Physics EGH-8102 electron gun capable of a maximum energy of 100 keV and a DC beam current of 20 mA. The configuration is such that we perform simultaneous irradiations with both the ion and electron beams (or with a variable delay); see figure 1 for a schematic overview. The ion beam was incident perpendicular to the device, while the electron gun was incident at 45 degrees. Similar to the ion irradiations, the spot size of the electron beam was focused to ~0.5x0.5 mm^2 and the electron beam was pulsed for a single 100 μs irradiation. For both ion and electron irradiations the currents of the transistor were monitored using current viewing resistors before, during, and after the irradiation. The voltages across the current viewing resistors were

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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 (or 20 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 in 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 circuit see reference [9].

Results:

Figure 2a shows a plot of the device gain as a function of time after ion only, electron only and combined ion+electron irradiations. The spread in the initial gain is as expected for this series of devices. The post gain behavior is also as expected for these devices, with the electron only irradiation changing the gain to ~40 at 300 seconds after the irradiation. This is in good agreement with gain degradation studies using Co-60 gamma irradiation for these same type of devices, obtained at the Gamma Irradiation Facility at SNL. In figure 2b we plot the post shot gains for the ion only and the combined ion+electron irradiations. Here we observe substantial similarities at late times greater than ~1 second, with a consistent variation of a factor of two or more between the early-time behaviors. We observe that the combined ion+electron irradiation produces less gain degradation at early time for nominally the same fluence (the fluence varied by at most ~10% between the series of the shots that we present in this summary).

Figure 3a shows a plot of the annealing factor (AF) as a function of ionizing dose. Here we irradiate with a fixed ion fluence and vary the ionizing dose to observe the impact on the early-time AF. The AF is traditionally used to compare early-time behavior between irradiations by allowing for normalization of both the initial and final gain values. The AF is defined by the following:

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

where G(t) is the time varying gain, G_0 is the initial gain and G_∞ is the late-time gain. While this formulation is appropriate for displacement damage (as it can be thought as the ratio of time varying defects to the stable late-time defect configuration) we are applying this to the ion only (displacement damage), combined ion+electron (displacement damage and ionizing dose) and the electron only case (ionizing dose only). The observed decrease in the AF is directly related to the ionizing dose rate (or photo-carriers) that we are injecting into the device. Figure 3b shows a plot of the base photocurrent of each of the shots in figure 3a.

Discussion:

The main issue addressed with these experiments is the synergetic effect between ionizing dose and displacement damage in Si BJT devices. With ion beam irradiations we provide both displacement damage and ionization (both in the device oxide and in the bulk Si of the device). However, we can do selective target displacement damage or ionization depending on the energy/ion combination and the desired location of the damage within a given device. For the ion irradiations discussed here we used a relatively low energy (4.5 MeV) Si beam to directly target the base-emitter (BE) junction of this device type. This will predominately produce displacement damage in the BE junction, greatly degrading the device gain with a limited ionization effect. Prior work has estimated an oxide effect on the order of ~10's of krad(Si) [12] and a bulk ionization rate of 1E7 rads(Si)/s (from cross-calibrations to Little Mountain Test Facility high energy electron irradiation datasets). To this predominately displacement damage irradiation we have added a variable dose rate of electrons. As seen in figure 3b we can vary the injected photocurrent over a wide range of values. The saturation of the photocurrent response of the base current occurs when we de-bias the base-collector (BC) junction. The resulting AF (see figure 3a) indicate the injected photo-carriers from the electron irradiation can have a profound impact on the early-time transient annealing. This enhanced photocurrent annealing can be of critical importance for qualification exercises where one may have an unintentional combination of both ionization and displacement damage effects.

For the results discussed above we have concentrated on a combined ion+electron environment where we have simultaneously irradiated the devices. In figure 4a we illustrate the ability of our combined system to vary the delay between the electron and ion irradiations. Here we have separated the irradiations by 0.5 seconds. For many applications this ability to vary the delay will be of critical importance.

Conclusion:

We report our first experiments at SNL using combined ion+electron irradiation to produce an independently controllable mixed field environment. We have observed an enhanced photocurrent annealing which can lead to a factor of two enhancement in early-time gain recovery, compared to displacement damage only irradiations. As mentioned above the effect of enhanced photocurrent annealing can be of critical importance for qualification exercises. While there are many unanswered questions regarding the effects of nonuniform ionization and the effects of energy loss in the incident electrons (the low energy electrons used in this experiment tend to range before reaching the substrate of the device), we plan on addressing these issues in the full paper submission through an in-depth modeling/experimental study of simpler PN diodes (similar to reference 13). Furthermore, we intend to expand this work by comparing electron and laser irradiations to address the issue of oxide versus bulk Si ionization effects. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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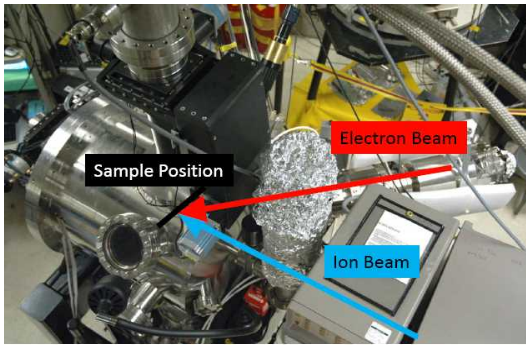

Fig. 1. Schematic of the combined ion+electron configuration showing the orientation of the ion and electron beams relative to the device position.

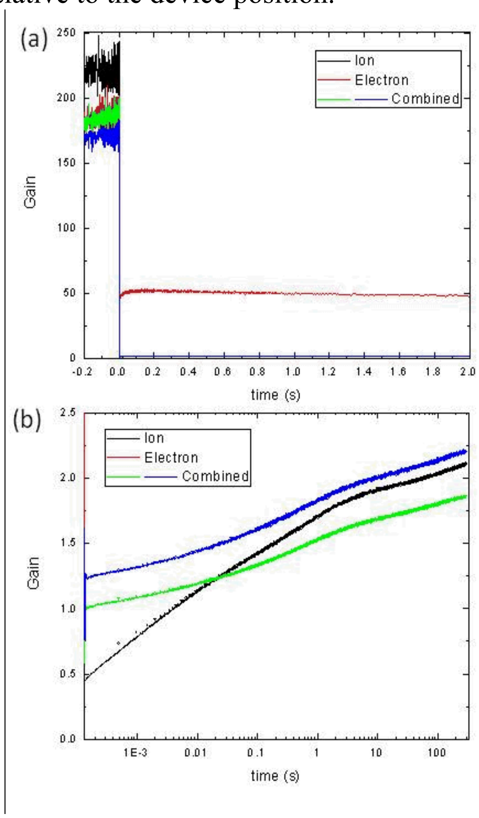

Fig. 2. (a) Plot of pre and post device gains for ion only, electron only and combined ion+electron irradiations. For comparison purposes the ion fluence and electron dose rate were fixed for each of the individual irradaitions. (b) Shows a rescaled plot to illustrate the early-time gain behavior of the ion only and combined ion+electron irradiations.

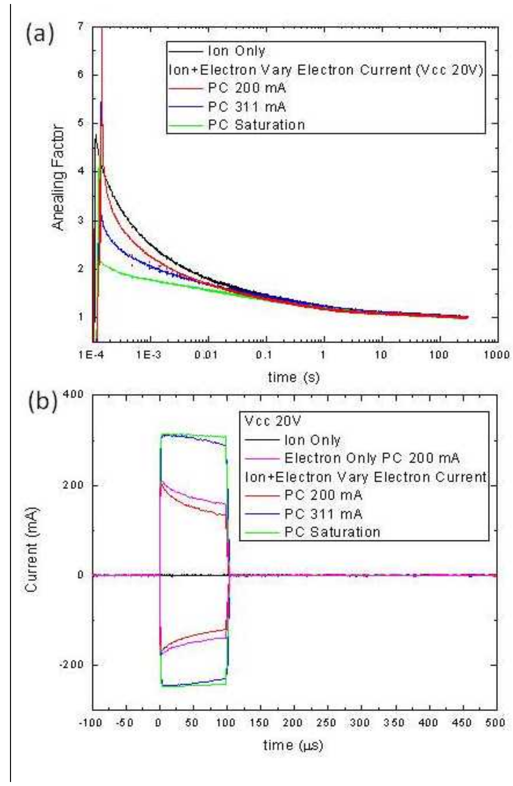

Fig. 3. (a) Plot of the annealing factor as a function of increasing electron dose rate. (b) Shows the resulting photocurrent as measured in the base leg of the device for each of the irradiations shown in (a), the photocurrent is directly proportional to the electron dose rate.

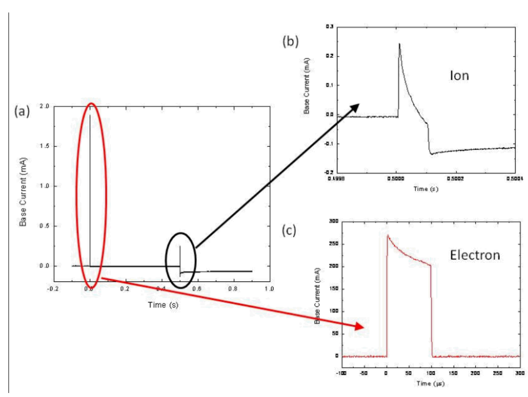

Fig. 4. (a) Shows a plot of a pulsed electron and ion irradiation with a user controlled delay of 0.5 second between irradiations. (b) and (c) show the individual base photocurrent and degradation effects.