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Damage Separation in a Bipolar Junction Transistor following Irradiation with 250-MeV Protons

Steven C. Witczak, *Member, IEEE*, Scott R. Messenger, Daniel M. Fleetwood, *Fellow, IEEE*, Ronald D. Schrimpf, *Fellow, IEEE*, Michael S. Langlois, M. Codie Mishler and Dennis A. Adams

***Abstract* – Irradiation of 2N5339 NPN Bipolar Junction Transistors with either 250-MeV protons or 10-keV X-rays shifts the input characteristics to lower values of V_{BE} while degrading the current gain and drive current. The degradation is consistent with increased recombination in the neutral base and emitter-base depletion region. A decrease in collector current following proton irradiation suggests that recombination in the neutral base is significant. At a given ionizing dose, degradation is worse for proton irradiation than for X-ray irradiation due to the presence of displacement damage and a higher charge yield. A comparison of degradation produced by the two radiation sources suggests that ~40% of the excess base current resulting from 250-MeV proton irradiation is due to ionization damage. When compared with previous results for other devices, these results suggest that ionization-to-displacement damage ratios in bipolar devices may increase with proton energy in a way that is consistent with trends in charge yield and NIEL.**

I. Introduction

THE current gain of bipolar junction transistors is important in satellite amplification applications such as radio transmitters and RF power generation [1]. Energetic protons in space degrade bipolar current gain by producing both ionization damage in the oxide overlying the emitter-base (E-B) junction and displacement damage in the semiconductor bulk [2]. In contrast, 10-keV X-rays produce only ionization damage, since the secondary electrons that they produce have energies below the displacement damage threshold [3]. Consistent with an approach for damage separation outlined in ASTM E1855-15 [4], Arutt, et al. have estimated the contributions of ionization damage to 4-MeV proton-induced degradation of bipolar devices from several technologies by comparing the proton responses to those of 10-keV X-rays [5], [6]. To date, however, ratios of ionization damage and displacement damage at larger proton energies, characteristic of radiation environments in low-earth orbits [7], have not been examined.

In this work, the portion of proton-induced degradation due to ionization damage is estimated for a commercial bipolar transistor following irradiation with 250-MeV protons. The amount of ionization damage at the larger proton energy is greater than that reported for 4-MeV protons by a factor of more than two, suggesting that ionization-to-displacement damage ratios in bipolar devices may depend strongly on proton energy. The trend in damage ratios is consistent with the dependencies of charge yield and NIEL on proton energy. Mechanisms leading to current gain degradation through increased base recombination are reviewed. Differences in degradation due to radiation source type are related to the relative amounts of ionization damage and displacement damage accumulated in each case. Finally, implications for using proton irradiation to screen bipolar devices for displacement damage are discussed.

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S. C. Witczak, S. R. Messenger, M. S. Langlois, M. C. Mishler and D. A. Adams are with Northrop Grumman Corporation, Linthicum Heights, MD 21090 USA (telephone: 410-765-7567, e-mail: steven.witczak@ngc.com).

D. M. Fleetwood and R. D. Schrimpf are with the Department of Electrical and Computer Engineering, Vanderbilt University, Nashville, TN 37235 USA (telephone: 615-322-2498, e-mail: dan.fleetwood@vanderbilt.edu).

II. Experiment

A. Irradiation

The test device is a 2N5339 npn silicon transistor rated to operate at a maximum collector bias of 100 V. The device is situated in a surface mount U3 package. Seven test devices were irradiated with 250-MeV protons at the Loma Linda University synchrotron. The devices were irradiated to five fluences up to 2×10^{12} cm^{-2} at a flux of 2.25×10^{10} cm^{-2} min^{-1}. Table I shows the total ionizing and non-ionizing dose levels following each proton irradiation step. Corresponding equivalent 1-MeV(Si) neutron fluences for non-ionizing dose are included for comparison. The values of stopping power and NIEL used for the calculations of ionizing dose and non-ionizing dose, respectively, come from the PSTAR database [8] and the MiB Monte Carlo particle transport code [9]. An additional three test devices were irradiated with 10-keV X-rays at a dose rate of 5.23 krad(SiO_2)/min using an Aracor 4100XP Irradiator. The test parts for the X-ray exposures were delidded to mitigate dose attenuation. The levels of ionizing dose delivered by the X-rays were chosen to match those resulting from proton irradiation. All device terminals were grounded for both sets of irradiation.

B. Electrical Characterization

Device characterization was performed with a National Instruments PXIe-1082 Chassis having two high-precision PXI-4132 Source Measure Units (SMUs) and a PXIe-2524 Multiplexer Switch Module. The two SMUs were configured into a two-channel parametric analyzer using LabVIEW. The test devices were mounted onto surfboards and inserted into sockets on a custom, multi-channel test board for irradiation biasing and electrical characterization. To minimize the an-

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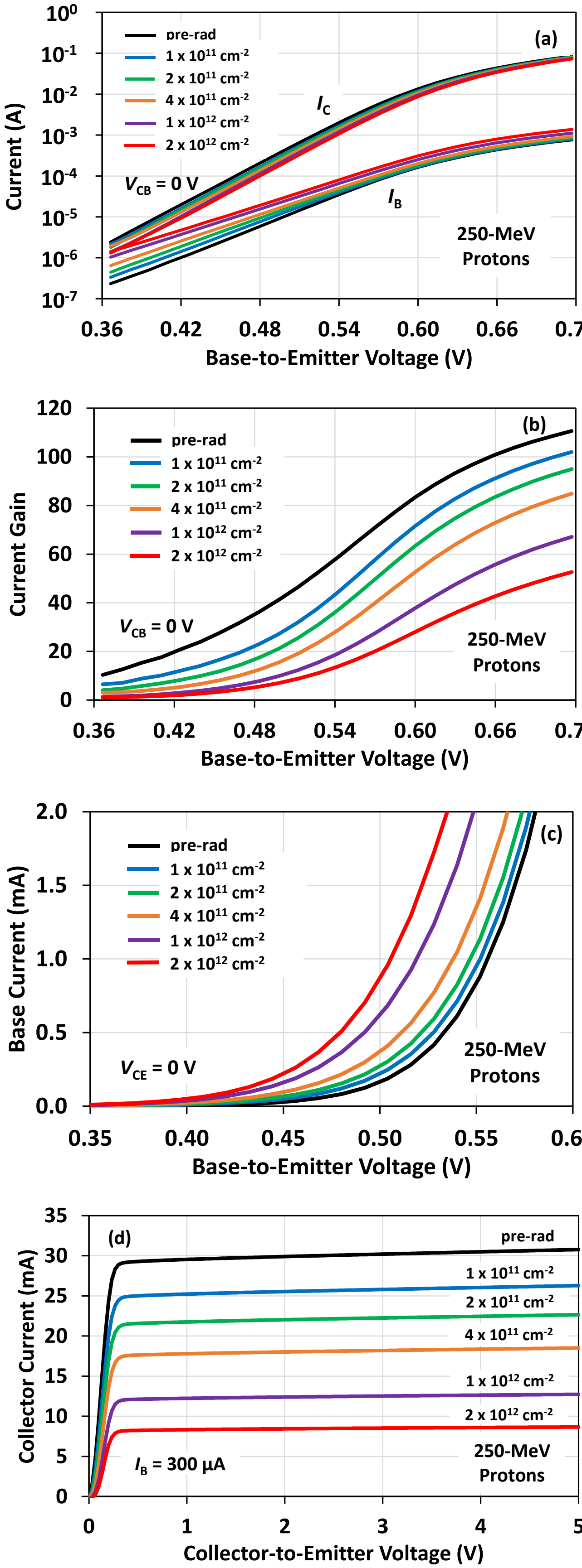

Fig. 1. Representative (a) Gummel, (b) current gain, (c) input and (d) output characteristics following irradiation with 250-MeV protons. Irradiation shifts the input characteristics while degrading the current gain and output current.

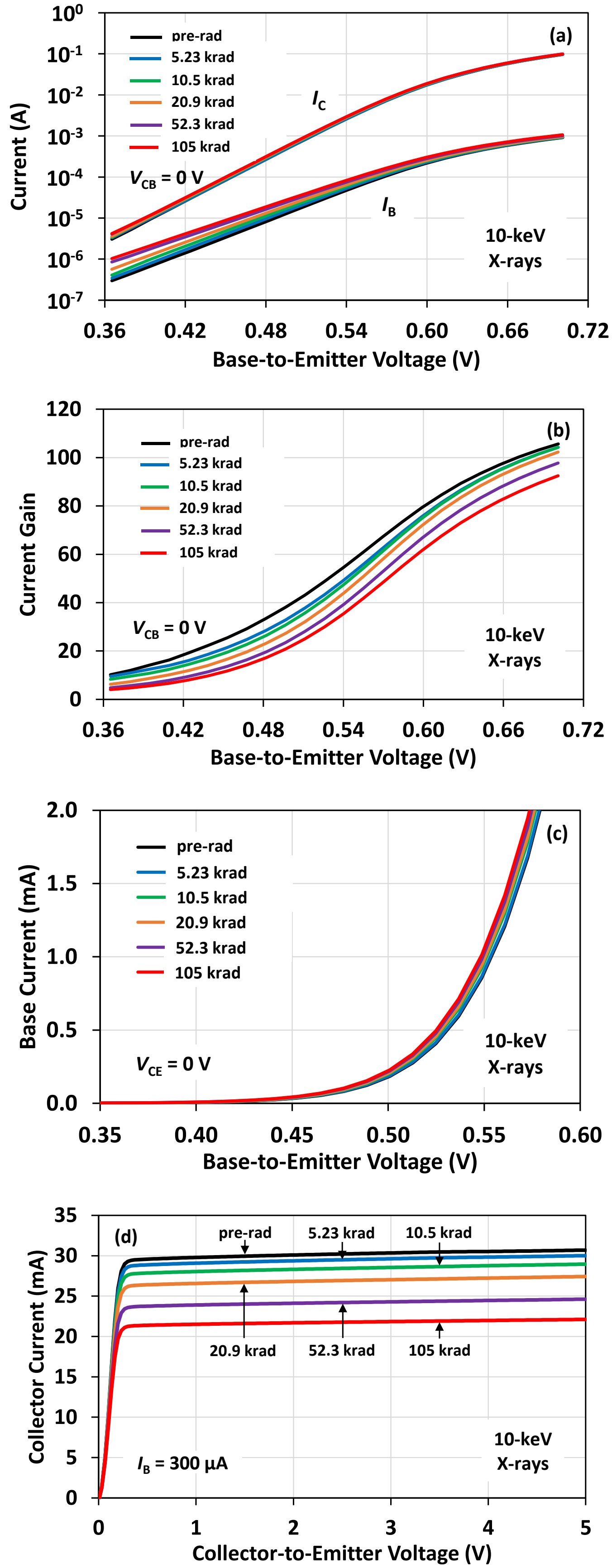

Fig. 2. Representative (a) Gummel, (b) current gain, (c) input and (d) output characteristics following irradiation with 10-keV X-rays. Degradation in the characteristics results primarily from increased base recombination current.

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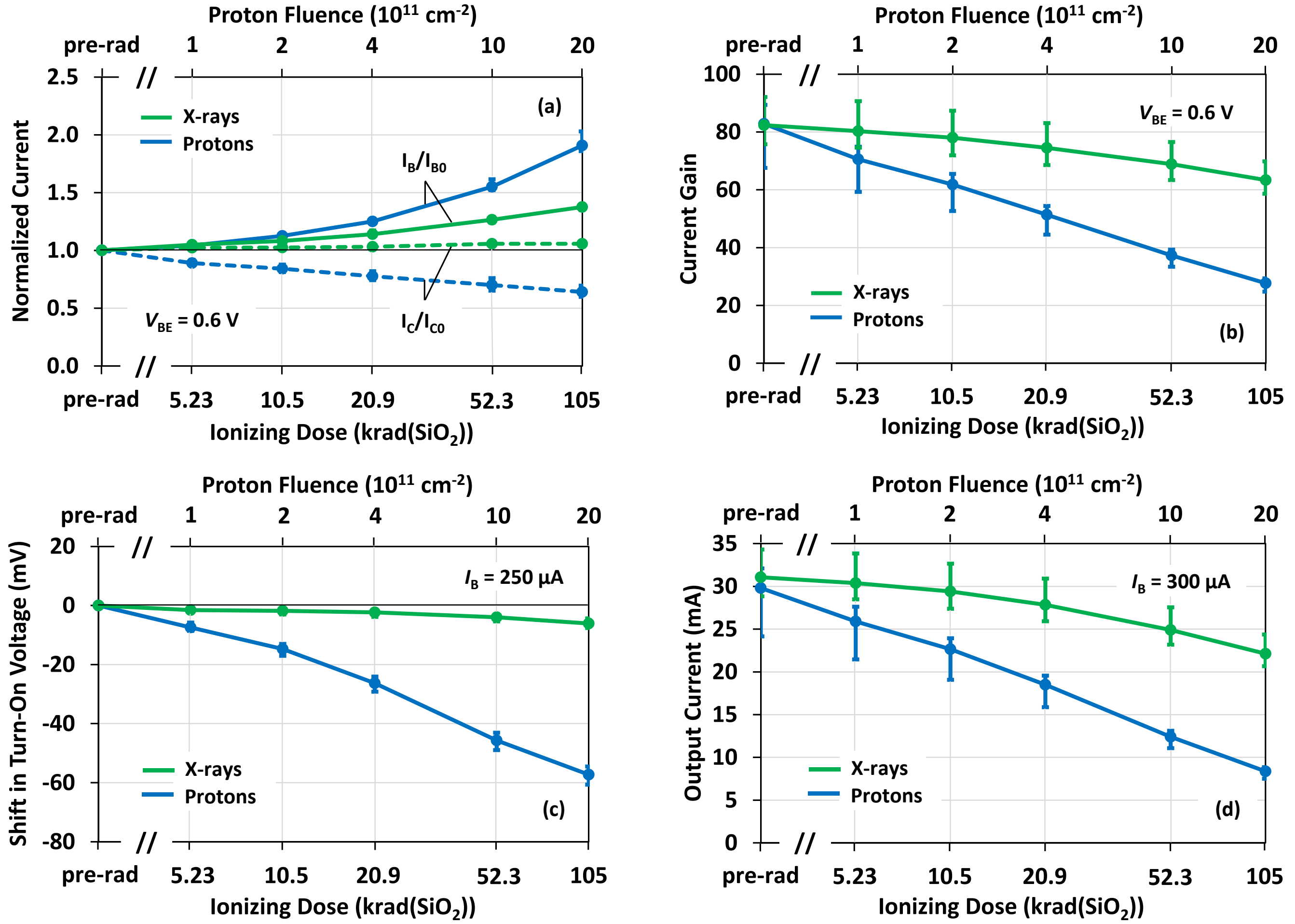

Fig. 3. Plots of (a) normalized base and collector currents, (b) current gain, (c) shift in turn-on voltage and (d) output current as a function of ionizing dose following irradiation with either 250-MeV protons or 10-keV X-rays. At a given ionizing dose, degradation is worse for proton irradiation than for X-ray irradiation due to the presence of displacement damage and higher charge yield.

nealing of radiation damage, electrical characterization of the test devices was performed within 30 min following each irradiation step. Current gain measurements of control devices were used to confirm that the ambient temperature varied less than ± 0.5°C over the course of the experiments.

The following electrical measurements were taken as a function of irradiation step:

1. Current Gain Characteristics – I_C/I_B vs. V_{BE} with the collector tied to the base.
2. Input Characteristics – I_B vs. V_{BE} with the collector tied to the emitter.
3. Output Characteristics – I_C vs. V_{CE} at a base current of 300 μA.

III. Parametric Degradation

Figs. 1 and 2 show representative Gummel, current gain, input and output characteristics following the proton and X-ray irradiations, respectively. Irradiation shifts the input characteristics to smaller values of V_{BE} while degrading the current gain and output current. Both radiation sources degrade the current gain by increasing the base current at a given base voltage. In addition, proton irradiation degrades the current gain by decreasing the collector current at a given base voltage. The shifts in input characteristics reflect the increases in base current at a given base voltage. The reductions in output current likewise follow from increased base current at a given bias. Following irradiation, a lower V_{BE} is required to maintain a constant base current, which in turn produces a lower collector current. Degradation is worse for proton irradiation than for X-ray irradiation. Additional measurements performed on samples that were biased (V_{CE} = 40 V) during proton irradiation showed no significant differences in degradation from those obtained under grounded bias conditions.

In Fig. 3, degradation in key parameters following proton irradiation is compared with degradation due to X-ray irradiation, where the data at each irradiation step are plotted at a common ionizing dose. In these figures, the current gain and terminal currents are measured at V_{BE} = 0.6 V. The turn-on voltage is functionally defined as the value of V_{BE} corresponding to I_B = 250 μA for the input characteristics. Further, the output current is defined as the value of I_C (V_{CE} = 5 V) measured at I_B = 300 μA for the output characteristics. Each data point indicates a mean, while the error bars indicate the high and low values among the sample set. The current gain and drive current are degraded by more than 50% at a proton fluence of 1 x 10^{12} cm^{-2}. The current gain

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TABLE I
DOSE LEVELS

Proton Fluence(a)	Ionizing Dose(b)	Non-Ionizing Dose(c)	Equivalent 1-MeV(Si) Neutron Fluence(a)
1×10^{11}	5.23	1.75×10^{8}	7.08×10^{10}
2×10^{11}	10.5	3.50×10^{8}	1.42×10^{11}
4×10^{11}	20.9	7.00×10^{8}	2.83×10^{11}
1×10^{12}	52.3	1.75×10^{9}	7.08×10^{11}
2×10^{12}	105	3.50×10^{9}	1.42×10^{12}

(a) in units of cm^{-2}
(b) in units of krad(SiO_2)
(c) in units of MeV/g

degradation results from a 55% increase in base current and a 30% decrease in collector current. The excess base current is sublinear with proton fluence (not shown), indicating appreciable ionization damage [10] following proton irradiation. Further, the excess base current has an ideality factor of 1.87 ± 0.03 for $V_{BE} \lesssim 0.6$ V, which is consistent with a mix of surface and bulk damage [11].

IV. Mechanisms

Fig. 4 depicts the type and location of defects produced in an npn bipolar junction transistor by proton irradiation. Protons deposit both ionizing and non-ionizing dose, whereas 10-keV X-rays deposit only ionizing dose [12]. The ionizing component degrades the current gain by introducing net-positive trapped charge and interface traps into the oxide overlying the base. Since recombination is at a maximum when the concentrations of electrons and holes are equal [13], positive oxide-trapped charge increases recombination in the base by reducing the imbalance in carrier concentrations near the silicon surface. Radiation-induced interface traps, especially those near midgap, serve as recombination centers through which recombination current in the base is further increased due to enhanced surface recombination velocity [14]. Displacement damage occurs when incident protons dislodge atoms in the silicon bulk. The displacement damage typically is manifested as a mixture of isolated and clustered defects such as divacancies or vacancy-impurity complexes [15]. Defects located in the E-B depletion region or neutral base increase base recombination current by adding energy states in the silicon band gap. The energy states act as recombination centers, thereby reducing the minority carrier lifetime in the base [16].

V. Source Dependence

At a given ionizing dose, degradation is worse for proton irradiation than for 10-keV X-ray irradiation, because displacement damage results only from the protons. In addition, the amount of ionization damage is greater for high-energy protons than for 10-keV X-rays due to larger charge yields [17], since more holes are available to do damage via transport and trapping mechanisms [18]. The decrease in collector current following proton irradiation implies that appreciable recombination occurs in the neutral base, since neutral base recombination results in fewer injected electrons reaching the collector [19]. In contrast, recombination in the E-B depletion region increases the emitter and base currents without affecting the collector current. Neutral base recombination can be significant in older bipolar technologies that employ large transistor base widths [20]. Proton irradiation may also reduce the collector current by increasing series resistance in the collector [21]. Further, as an alternative to 10-keV X-rays for ionizing radiation, ^{60}Co γ-rays may be used with a tradeoff. Although ^{60}Co γ-rays provide a charge yield that is closer to that of 250-MeV protons than do 10-keV X-rays [22], they can cause residual displacement damage by generating Compton electrons [23].

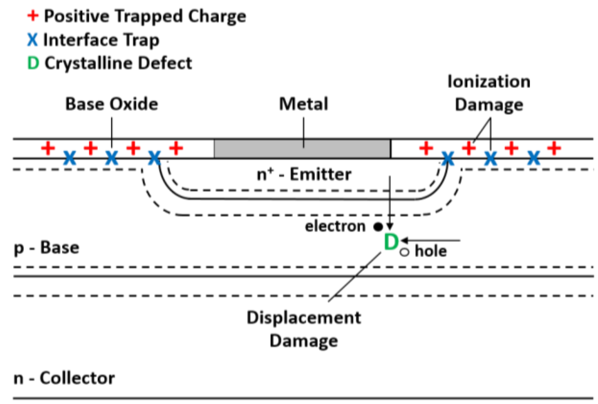

Fig. 4. Cross-section of an npn bipolar transistor showing the location of defects produced by proton irradiation. Ionization damage occurs in the oxide overlying the emitter-base junction, whereas displacement damage occurs in the semiconductor bulk.

VI. Implications

A. Damage Separation

Comparing the degradation produced by protons to that produced by 10-keV X-rays allows one to estimate the relative contributions of displacement damage and ionization damage to proton-induced degradation [5], [6]. Since 10-keV X-rays produce only ionization damage, the excess base current produced by the X-rays should be similar to the ionization portion of excess base current following proton irradiation when the charge yield ratio is taken into account. At low electric fields, the charge yield for proton irradiation is determined primarily by proton energy [17]. Charge yield increases with proton energy, since increasingly larger proton energies produce greater initial separation of the resulting electron-hole pairs by virtue of smaller mass-stopping powers. At low electric fields, the charge yield for 10-keV X-rays is similar to that of 20-MeV protons, since 20-MeV protons and the secondary electrons produced by 10-keV X-rays have approximately the same mass-stopping power [24]. The small electric fields in bipolar base oxides under zero terminal bias ($\lesssim$ 0.1 MV/cm) typically have little additional impact on the charge yield [25].

Charge yields for protons of low to moderate energies ($\lesssim$ 60 MeV) are adequately described by the columnar model [26], whereas charge yields for high-energy protons are better described by the geminate model [27]. Based on calculations from these recombination models presented elsewhere [24], charge yields of 0.52 and 0.35 are assumed for 250-MeV protons and 10-keV X-rays, respectively, in this work. For our test devices, the excess base current following 10-keV X-ray irradiation is 25–30% the amount of excess base current due to 250-MeV protons when measured at a constant collector current (I_C = 10 mA). If one assumes that the charge yield from 250-MeV protons is 50% higher than that of 10-keV X-rays, then approximately 40% of the excess base current following proton irradiation is due to ionization damage. For simplicity, we have emphasized excess base current as it relates to current gain degradation in our analysis. However, similar contributions of ionization damage to degradation of the input and output characteristics are implied, since degradation of these characteristics also results directly from increased recombination in the E-B depletion region and the neutral base.

B. Screening for Displacement Damage Sensitivity

Arutt, et al. performed damage separation analysis of several types of silicon bipolar transistors in evaluating the transistors for potential use as particle fluence sensors [5], [6]. They found that ionization damage accounts for 10–20% of the excess base current produced by 4-MeV proton irradiation of their devices over wide ranges of fluence. The charge yield and NIEL for the 250-MeV protons used in this work are larger and smaller, respectively, than those for 4-MeV protons [8], [9]. The total amount of radiation damage can be expected to vary among bipolar technologies, because the efficiency of the defect creation processes and device sensitivity to the defects generally are process dependent. However, the relative contributions of ionization damage and displacement damage measured for our samples appear reasonable given that a larger charge yield and smaller NIEL both act to increase the ionization-to-displacement damage ratio. When compared with the cited work, our results suggest that ionization-to-displacement damage ratios in bipolar devices may increase with proton energy in a way that is consistent with trends in charge yield and NIEL.

The susceptibility of bipolar transistors to displacement damage normally is assessed through neutron testing [28], since the ionization damage resulting from either direct neutron ionization or ionizing reactor products, such as prompt and delayed fission γ-rays, is typically negligible [29]. When neutron testing is impractical, proton irradiation has been suggested as a means of screening bipolar transistors for sensitivity to neutron-induced displacement damage [5], [6]. In this case, degradation from neutrons at a particular energy is predicted from proton-induced degradation after accounting for ionization damage and scaling the proton fluence by an appropriate ratio of NIEL values. Since this approach requires subtracting the contribution of ionization damage from the excess base current measured in the proton environment, this correction may not be sufficiently accurate if it constitutes more than 20% of the total excess base current [4]. Given that ionization damage can become important for large proton energies, certain bipolar devices may be better suited for monitoring displacement damage in low- to moderate-energy proton environments.

VII. Summary

2N5339 NPN Bipolar Junction Transistors were assessed for radiation tolerance to 250-MeV protons and 10-keV X-rays under zero irradiation bias. Proton irradiation produces both ionization damage and displacement damage, whereas 10-keV X-rays produce only ionization damage. The ionization damage results from charge trapping and interface trap formation in the base oxide, while displacement damage results from the creation of crystalline defects in the base. Irradiation with either source type shifts the input characteristics to lower values of V_{BE} while degrading the current gain and drive current. The degradation is consistent with increased recombination in the neutral base and E-B depletion region. A reduction in collector current following proton irradiation implies that recombination in the neutral base is significant. At a given ionizing dose, degradation is worse for 250-MeV proton irradiation than for 10-keV X-ray irradiation due to accumulated displacement damage and greater charge yield.

Separation of the proton-induced damage was performed by utilizing the device X-ray response in accordance with ASTM 1855-15. When accounting for charge yield, the relative amounts of excess base current produced by the two sources suggest that approximately 40% of the 250-MeV proton-induced degradation results from ionization damage. The contributions of ionization damage to degradation of the current gain, input and output characteristics are similar, since these characteristics are all degraded primarily by increased base recombination. This is more than twice the contribution of ionization damage previously attributed to degradation of commercial bipolar transistors following 4-MeV proton irradiation. The observed trend in ionization-to-displacement damage ratios is consistent with the dependencies of charge yield and NIEL on proton energy. When using protons to screen bipolar devices for sensitivity to displacement damage, potential errors due to accounting for ionization damage can increase with proton energy. As such, irradiation at low to moderate proton energies is preferable when attempting to project neutron-induced degradation.

VIII. Acknowledgment

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