BJTs in Space: ELDRS Experiment on NASA Space Environment Testbed

A. R. Benedetto
School of Electrical, Computer, and Energy Engineering
Arizona State University
Tempe, USA
arbenede@asu.edu

H. J. Barnaby
School of Electrical, Computer, and Energy Engineering
Arizona State University
Tempe, USA
hbarnaby@asu.edu

Cheyenne Cook
School of Electrical, Computer and Energy Engineering
Arizona State University
Tempe, USA
cecook9@asu.edu

Michael J. Campola
NASA Goddard Space Flight Center
NASA
Silver Spring, USA
michael.j.campola@nasa.gov

Anna Tender
Department of Statistics and Data Science
Yale University
New Haven, USA
anna.tender@yale.edu

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***Abstract*—Flight data on bipolar junction transistors (BJTs) are recorded and the effects of low dose rate space irradiation on BJTs are characterized, leading to results comparable to ground-based testing. Additionally, Gummel plots of mission data are compared for different experimental parameters.**

Keywords*—*Bipolar junction transistors, BJTs, ELDRS, GLPNP, dose rate effect, interface traps, radiation-induced, hydrogen, radiation effects, enhanced low dose rate sensitivity

I. Introduction

Linear bipolar circuits, designed with bipolar junction transistors (BJTs), are particularly vulnerable to the harmful effects of space radiation. Protons, a specific form of space radiation, are a particular concern for a variety of reasons: 1) protons are not easily blocked by shielding, 2) protons are responsible for both ionization and displacement effects, and 3) many bipolar parts and circuits, ubiquitous in spacecraft systems, are affected. These circuits, usually consisting of commercial-off-the-shelf (COTS) components, typically exhibit Enhanced Low Dose Rate Sensitivity (ELDRS). ELDRS is the enhancement of degradation in transistors or circuits when exposed to radiation at low dose rates as compared to high dose rates. Degradation is considerably greater than what is observed after post-rad anneal, signifying a true dose rate effect [5]. This phenomenon poses significant problems for the qualification of bipolar parts for use in proton rich, low dose rate environments, such as most Earth orbits.

An understanding of ELDRS in BJTs is essential for the qualification of these parts. The effect has been investigated extensively in ground-based experiments; additionally, data from the Microelectronics and Photonic Testbed (MPTB), launched in 1997, demonstrated ELDRS in linear bipolar circuits in flight [1, 2]. However, the effects of low dose rate (LDR) irradiation on individual bipolar transistors manufactured on an integrated linear process have never been characterized in space – until June 2019, when NASA's Living With a Star ELDRS experiment was launched from the Kennedy Space Center on a SPACEX Falcon Heavy.

II. Experiment Description

A. Testbed Description

This experiment was developed through the NASA Living With a Star (LWS) program. The LWS program was designed to characterize the space environment in order to better understand its impact on electronics' performance in space, validate the efficacy of the MIL-STD 1019.6 testing recommendations, and reduce design margins. The main objective of the "ELDRS" experiment is to measure ELDRS on BJTs in space and assess the impact of experimental parameters on radiation response. The ELDRS instrument is one of four experiments on the LWS Space Environment Testbeds (SET) mission. The ELDRS testbed performs real-time, in-orbit measurements of radiation-induced degradation from trapped particles by monitoring changes in the collector and base currents of active BJTs. The instrument, shown in Fig. 1, is a double-sided printed circuit board (~4"x6") consisting of 24 lateral PNP BJTs integrated onto eight die, three BJTs per die. The die are packaged in hermetically sealed 14-pin dual inline packages (DIPs) pinned out in eight 14-pin packaged die. Two of the transistors on each die are gated lateral PNP (GLPNP) BJTs. A layout of the GLPNP BJT, shown in Fig. 2, shows the four independent terminals: emitter, base, collector, and gate. In addition to the two GLPNPs, each die includes a standard LPNP BJT, without gate metallization. The DUTs are measured through a rad-hard mechanical relay multiplexer, which enables accurate low noise measurements under extreme radiation and temperature conditions. Base current (I_B) and collector current (I_C) measurements for each of the 24 DUTs are obtained in sequence by sweeping the emitter voltage (base and collector grounded) from 0 V to 0.9 V in two concurrent up-down ramp

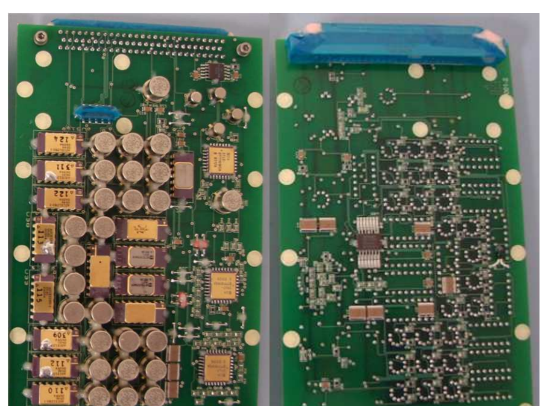

Fig. 1. ELDRS Test Flight Board

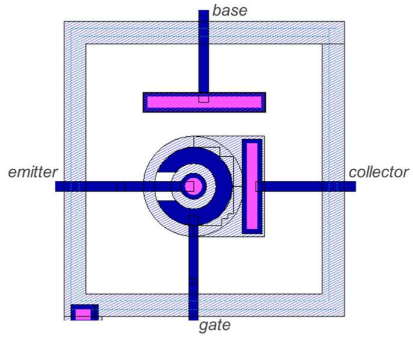

Fig. 2. GLPNP BJT Layout

cycles. The Gummel curves, I_B and I_C versus V_{EB}, have been plotted to assess the effect of the irradiation on each DUT and the impact of the experimental parameters on the radiation response.

B. Data Acquisition and Measurement Process

The ELDRS SET experiment has been acquiring data on the LPNP BJTs in flight continuously for over eighteen months at an average dose rate of 0.19 mrad(Si)/s at the time of data analysis. The acquired dose (krad(Si)) over the analysis period is shown in Fig. 3. The test board measures the current responses several times a month and records the data for download. Although the instrument was exposed to radiation during the "quiet zone," labeled on Fig. 3, the dose during that period was not recorded. The exponentially changing currents are fed through a log amplifier in response to the linear emitter voltage ramp and read out as linearly changing analog voltages. The data on both emitter voltage and base/collector current are retrieved from the analog output and stored for download in the testbed's main storage.

III. Experimental Results

A. Data Analysis Process

Data from the space flight have been downloaded and analyzed. An [R] code was developed for this project to parse the data, label the DUT and measurement variables, and produce customizable plots and data summaries based on experiment variables.

B. ELDRS Results

In this paper we report ELDRS data from DUT 6 (p-glass passivation, unmodified package, thick oxide, with gate

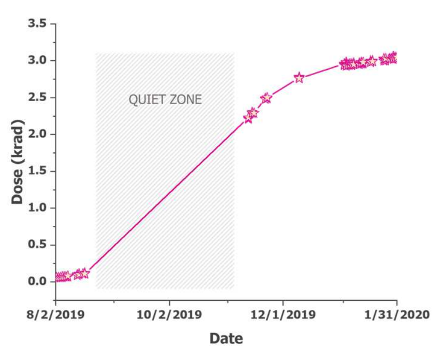

Fig. 3. On-orbit dose vs. date

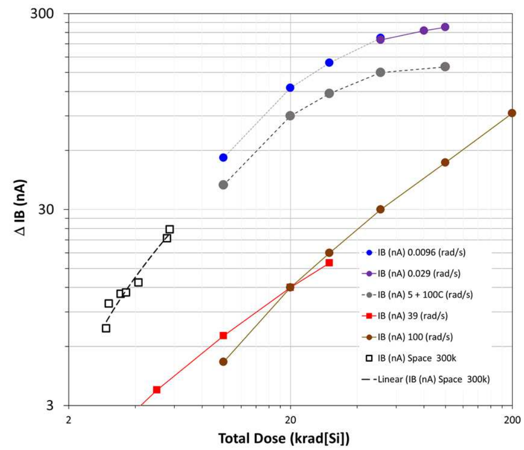

Fig. 4. On-orbit dose vs. ΔI_B

metallization, base current measured at gate voltage (V_G) = 0 V) and Gummel (log I_C and I_B versus V_{EB}) plots from selected DUTs to assess the impact of different experimental parameters. The data were downloaded and parsed as described above, then compared with either the ground-based test results previously published in literature [3-5] (ELDRS), or with other flight data to compare experimental parameters (listed in Table 1).

Fig. 4 shows the DUT 6 on-orbit data along with low dose rate (<30 mrad/s), elevated temperature irradiation (5 rad/s + 100° C), and high dose rate (≥39 rad/s) ground test data. The black dashed line with square, white-filled markers shows the DUT 6 transistor space data for ΔI_B versus dose measured at an on-board temperature ambient of ~300 K, approximately the same temperature as the ground-based tests. The on-orbit ΔI_B is increasing as dose increases, following a similar trend to that of the ground-based LDR data. The ΔI_B increase (measured at an emitter-base voltage (V_{EB}) = 0.5 V) is likely due to the buildup of radiation-induced traps at the BJT base oxide-silicon interface [10]. The space environment ΔI_B is already significantly higher than the high dose rate (HDR) ground-based data at the same dose levels; indeed, the on-orbit data appear to be closely following the LDR ground-based data slope. These results demonstrate, for the first time, the ELDRS effect on BJTs fabrication in a COTS linear bipolar circuit process.

C. Experimental Parameter Results

In addition to the ELDRS analysis, this study reports the comparison of Gummel plots for different experimental parameters. We compared I_B versus V_{EB} for each parameter, listed in Table 1. The experimental parameters are defined for the purposes of this experiment as follows:

- Prerad: A very low dose exposure shortly after the experiment launch. This is essentially "prerad," from 0.06 to 0.11 krad, from the beginning of the experiment. These data were recorded from 8/02/2019 to 8/18/2019.
- Postrad: The highest dose at the time of analysis, from 5.65-5.79 krad. These data were recorded from 11/22/2020-1/06/2021.
- Temperature: As expected, the BJT currents change with temperature. The temperature fluctuations posed

a significant challenge for this analysis by affecting ΔI_B; to avoid seeing thermal effects, each data set is plotted at a specific temperature. Each temperature is within 2 K of the temperature noted in the plot title.

- Gate Voltage: Results are reported for test voltages of 0 V and -12 V. The standby, irradiation bias for all DUTs is 0 V on all terminals.
- Modified Package: Some packages were modified at the time of receipt to release the hydrogen; although the exact hydrogen content is not known, the modified packages are assumed to have a slightly lower in-package hydrogen content then the unmodified package.
- Unmodified Package: Assumed high in-package hydrogen content, ~1%.
- Passivation: P-glass or silicon carbide (SiC) passivation, deposition method unknown.
- Thick oxide: 1.22 µm.
- Thin oxide: 0.56 µm.

Each set of Gummel plots contains the prerad and postrad V_{EB} versus I_B and I_C for each parameter as noted in the figure and caption. I_C does not change appreciably (as expected) with irradiation, whereas I_B does (as expected). These data are shown in Fig. 6 - Fig. 11.

TABLE I. EXPERIMENTAL PARAMETERS

Experimental Parameter	***Variable***
Radiation Dose	Prerad/postrad
Temperature	Temperature +/- 2K
Gate voltage	0V and -12V
Modification	Modified and unmodified
Passivation	P-glass and silicon carbide
Oxide thickness	Thick oxide and thin oxide

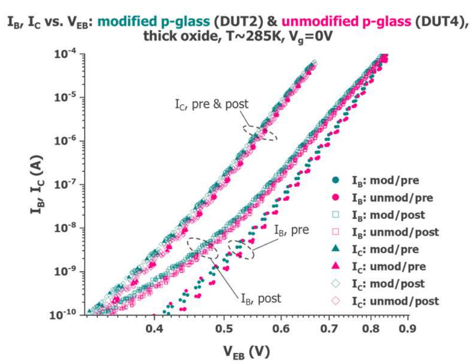

Fig. 5. Modified p-glass vs. unmodified p-glass, 0V

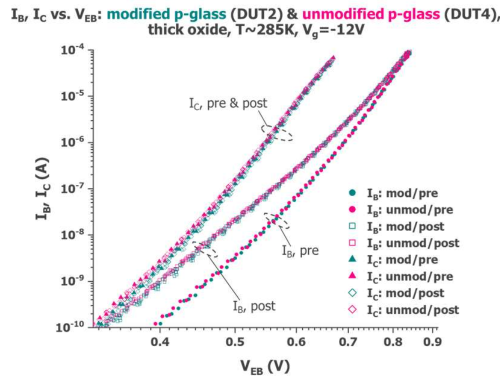

Fig. 6. Modified p-glass vs. unmodified p-glass, -12V

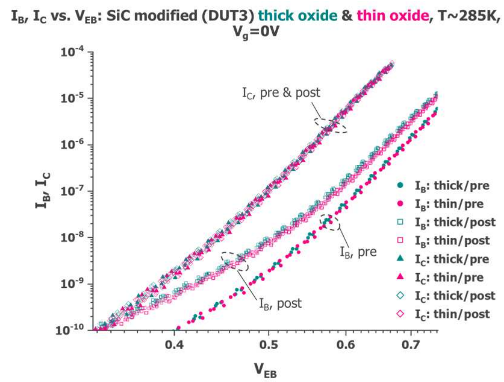

Fig. 7. SiC modified, thick oxide vs. thin oxide, 0V

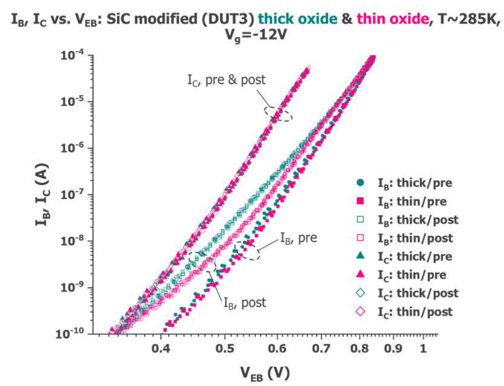

Fig. 8. SiC modified, thick oxide vs. thin oxide, -12V

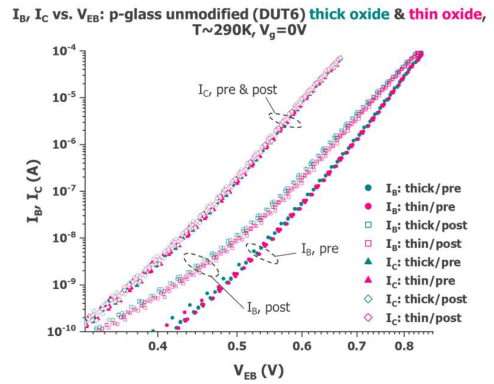

Fig. 9. P-glass modified, thick oxide vs. thin oxide, 0V

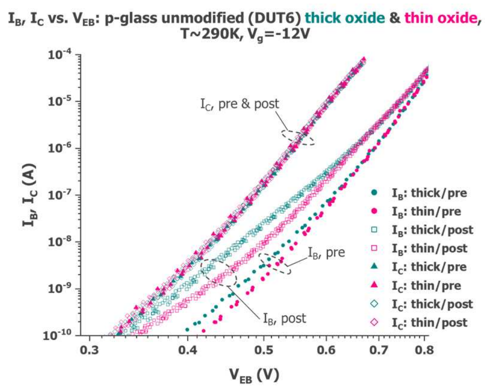

Fig. 10. P-glass modified, thick oxide vs. thin oxide, -12V

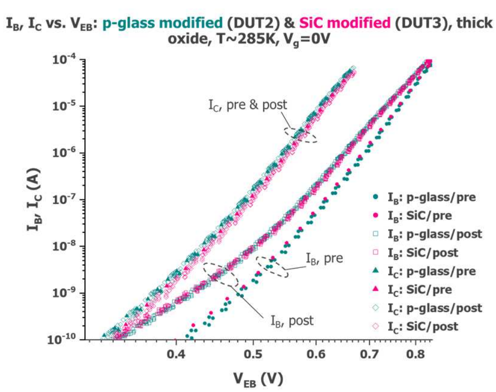

Fig. 11. P-glass modified vs. SiC modified, 0V

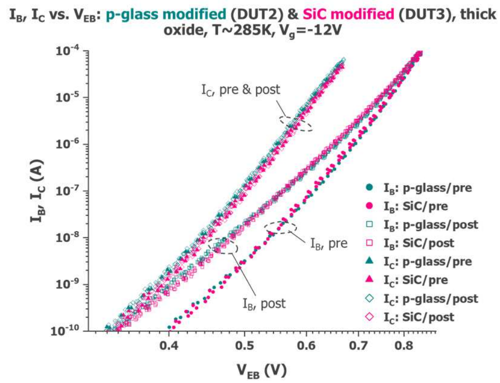

Fig. 12. P-glass modified vs. SiC modified, -12V

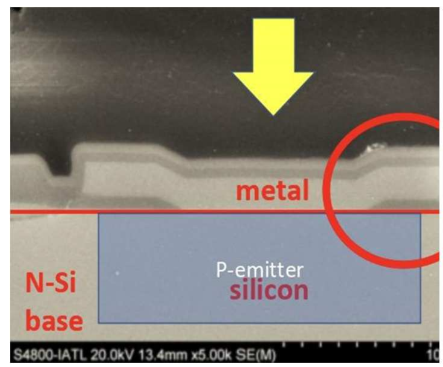

Fig. 13. NPN metal-oxide connection

Figs. 5 and 6 indicate that base current degradation is not a strong function of the package (i.e., modified or unmodified). As stated above, the (un)modified package variants were selected to monitor the possible effect of in-package hydrogen concentration, which is known to have a significant effect on BJT radiation response [5, 7, 8]. The fact that there is very little difference between modified and unmodified packages, for either bias, indicates that there is not a large difference in the hydrogen content. Figs. 11 and 12 show that there is very little difference in the responses for the p-glass and SiC passivations, regardless of gate bias. This suggests that the passivation type does not have an impact on increasing base current in irradiated BJTs. The comparisons of thick oxide versus thin oxide for either the p-glass or SiC (Figs. 7-10) show no noticeable difference at $V_G = 0$ V, but do show a difference at $V_G = -12$ V. This could reveal much about the distribution of interface traps that build up with exposure.

The oxide thickness under the emitter metal wing (Fig. 13 – red circle) is likely the same for the thin and thick oxide variants. When $V_G = 0$ V is applied, interface traps under this region likely dominate the response since much of the emitter -base depletion region is located there (i.e., excess base current is typically caused by recombination current in the depletion region). However, when $V_G = -12$ V is applied, the depletion region will spread out from under the wing, making interface traps in the thick or thin bipolar base oxide effective contributors to the excess base current; and the amount of interface traps under the thick oxide is greater [9]. This is potentially why we see the differences in thin versus thick oxides only when $V_G = -12$ V is applied. Further analysis of these results is ongoing.

IV. Conclusion

This experiment has provided the first opportunity to assess bipolar transistors in a space environment. Results correlate to ground-based studies, further confirming the efficacy of MIL-STD Test Method 1019.6 test recommendations. Acquiring this space-flight data on ELDRS in BJTs and comparing with ground-based testing may be used to improve accelerated ground test protocols for ELDRS screening.

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