Radiation-Induced Defects in BJTs on NASA ELDRS Space Experiment

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Post-exposure flight data on BJTs are analyzed with a Silvaco model to extract interface traps.

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I. Introduction

While most digital integrated circuits today are fabricated in CMOS processes, many analog systems still use linear bipolar parts (e.g., operational amplifiers, voltage regulators, etc.) designed with bipolar junction transistors (BJTs). This is especially true of analog components used in spacecraft electronics, where the long flight heritage and continued effectiveness of linear bipolar technologies play a major role in part selection. To control costs and maintain supply chain access, space system designers typically select commercial off-the-shelf (COTS) linear bipolar parts, which are susceptible to damage from high ionizing radiation environments such as those in electron- and proton-rich Earth orbits [1-4]. Total ionizing dose (TID) sensitivity in bipolar technologies is primarily related to the buildup of defects in BJT base oxides and the silicon-oxide interfaces [5,6]. Among the most destructive of these defects are interface traps (N_{IT}), which increase surface recombination and lead to a precipitous rise in base current (I_B) [5-7]. A measured change in I_B can thus provide insight to the buildup of these traps via extraction of a BJT's surface recombination velocity (*srv*), which can then be plugged into an analytical model to obtain a quantitative measure of the N_{IT} buildup [7].

The base current response due to irradiation on individual BJTs manufactured in an integrated linear bipolar process has been well-documented in ground-based studies [5,6,8-12]. However, direct measurements in space of base current degradation on these types of BJTs had never been performed until the ELDRS experiment, launched June 2019 on the NASA Living With a Star (LWS) Space Environment Testbed (SET). The mission data from this experiment have been reported in [13, 14]. In this summary, we use these data to extract N_{IT} buildup as a function of TID.

II. Experiment Description

The ELDRS experiment was developed for the NASA LWS program and its goal to characterize the space environment and understand its impact on electronics in space. The ELDRS instrument is one of four experiments on the LWS Space Environment Testbeds (SET) mission. It performs real-time, in-orbit measurements of changes in the collector and base currents of active BJTs in order to analyze radiation-induced degradation from trapped particles. The ELDRS flight board, shown in Fig. 1, is a double-sided printed circuit board (~4"x6") consisting of 24 lateral PNP (LPNP) BJTs integrated onto eight die (three BJTs per die). The die were packaged in hermetically sealed 14-pin dual inline packages (DIPs).

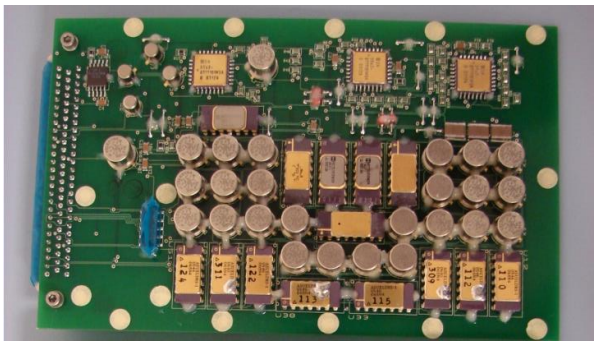


Fig. 1. ELDRS Flight Board

Two of the transistors on each die are gated lateral PNP (GLPNP) BJTs. The gate was added to facilitate independent analysis of ionization and displacement damage in these parts but is also ideal for quantifying N_{IT} build-up through an extraction of *srv* [7]. A layout of the GLPNP BJT is provided in Fig. 2 and 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.

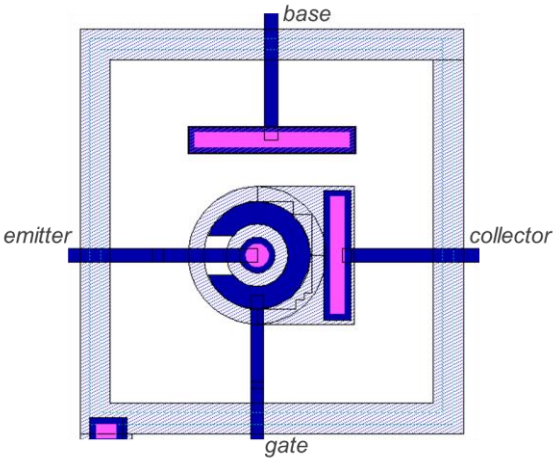


Fig. 2. GLPNP BJT Layout

The data analyzed in this summary were taken from DUT package 6, device 1 on the ELDRS flight board, which is a GLPNP fabricated with a p-glass passivation and a thick base oxide (1.2 μm). The reported base current was measured at gate voltage (V_G) = 0 V.

Changes in the BJT currents are measured through a radiation-hardened mechanical relay multiplexer, which enables accurate low noise measurements under extreme radiation and temperature conditions. Collector current (I_C) and I_B measurements for each of the 24 DUTs are obtained in sequence by sweeping the emitter voltage (base and collector grounded) from 0 to 0.9 V (Gummel curves) in two concurrent up-down ramp cycles. Gummel curves are recorded under four different static gate bias conditions: 0 V, 6 V, -6 V, and -12 V.

The ELDRS experiment has been acquiring in-flight data on the (G)LPNP BJTs for over twenty months at an average dose rate of approximately 0.12 mrad(Si)/s. The test board measures the emitter voltage and base/collector current responses several times a month and stores the data from the analog output for asynchronous download. The exponentially changing currents are fed through a log amplifier and read out as linearly changing analog voltages in response to the linear emitter voltage ramp.

III. Experimental Results

A. Data Analysis and Silvaco Modeling Process

The data collected by the testbed have been analyzed using an [R] code written for this project. The code parses the data, labels the DUT and measurement variables, and produces customizable plots and data summaries based on experiment variables such as date, temperature, and radiation dose. The data include the base current for each device, which can be plotted against dose to monitor the effects of ionizing and non-ionizing radiation on base current response. The gate voltage can be used to enhance or suppress ionizing radiation response [15]. For these parts, only gate voltages above 5 V seem to effectively suppress the effects of TID-induced interface traps, so for V_G = 0 V, it is comfortably assumed the ionizing effects are dominant. However, base current response is also significantly affected by temperature, which fluctuates throughout the data acquisition, as shown in Fig. 3.

The temperature is recorded for each measurement, making it possible to separate temperature effects from radiation effects on the base current response. To separate thermal effects out, we use a device simulation structure, representative of the thick oxide GLPNP, shown in Fig. 4. The structure was built and simulated using the Silvaco TCAD tool suite. The simulated device has been shown to accurately model the base current response over a wide range of temperatures. Thus, simulation fits, performed by adjusting the *srv* parameter to post-irradiation data obtained at one temperature, can be adjusted to accurately estimate base current response at a different temperature using the same *srv*.

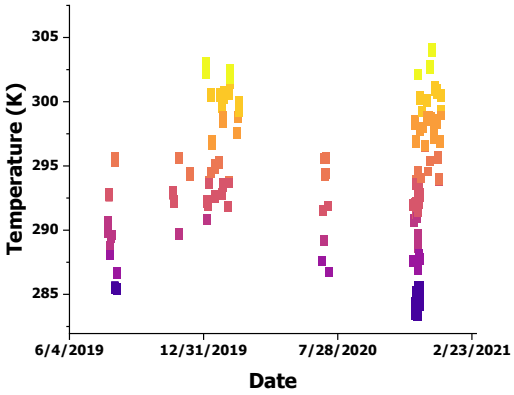


Fig. 3. Temperature fluctuations on ELDRS board during SET mission.

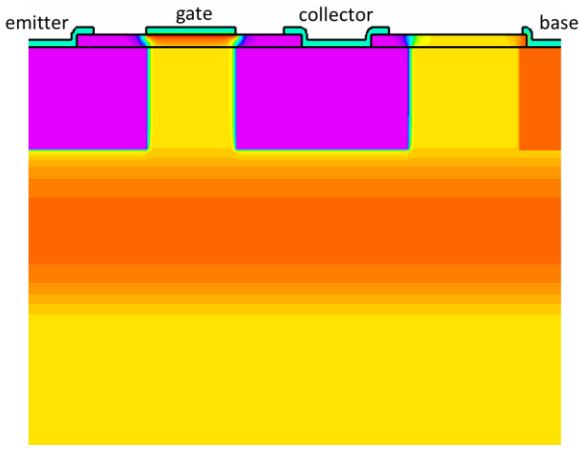


Fig. 4. GLPNP thick oxide simulation structure.

To create the structure, the GLPNP BJT dimensions and doping profiles as well as the metal work functions were adjusted to match the actual DUT 6 device. A mesh grid is concentrated around the borders of each doped region of the model as well as the metal and contacts for fine adjustments. We have built and calibrated structures for all three device types. However, only thick oxide GLPNP simulations are reported in this summary; thin oxide GLPNP and no-gate LPNP devices are undergoing further analysis. I-V (Gummel)

characteristics obtained through the simulation were shown to accurately reproduce the pre-irradiation data over temperatures ranging between 280 K – 305 K.

B. N_{IT} Extraction

In order to calculate the N_{IT} from base current, we must first extract *srv* at a given dose level. Analytically, *srv* can be related to TID-induced based current as [7]

$$srv \cong \frac{2I_B}{qn_i P_E x_{dB} \exp\left(\frac{V_{EB}}{2V_T}\right)}. \quad (1)$$

However, while this analytical model, as well as others, have been shown to reproduce the effects of radiation on base current [7, 16, 17], it was determined that computer simulation was much better at accurately capturing the complex physics of thermal effects on these parts. Thus, the TCAD simulation on the GLPNP structure was used for extracting *srv*. Fig. 5 shows the fits to the based data at multiple mission dose levels (0.06, 2.21, and 5.65 krad[Si]), all simulated to an adjusted junction temperature of 300 K. The *srv* values obtained at four doses are listed in Table I.

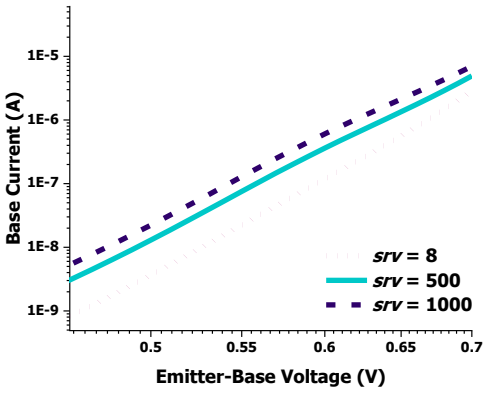


Fig. 5. Simulated I_B vs. V_{EB} for T=300K

Table I.
Dose and *srv* values

Dose (krad[Si])	Surface Recombination Velocity (cm/s)
0.06	100
2.21	500
3.68	800
5.65	1000

After extracting *srv*, we can calculate the N_{IT} using the relationship

$$N_{IT} \cong (\sigma v_{th})^{-1} * srv, \quad (2)$$

where $\sigma = 2.3\text{x}10^{-16}$ [7]. Fig. 6 plots the extracted N_{IT} vs. dose.

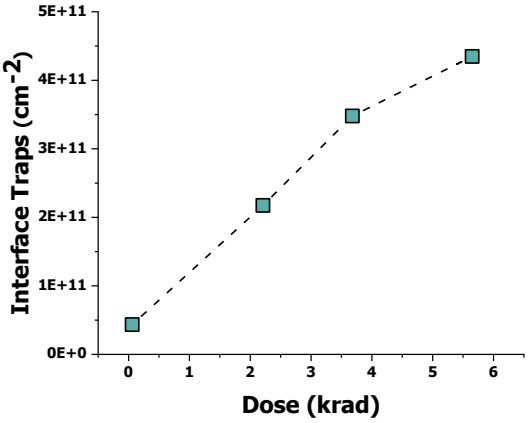


Fig. 6. N_{IT} vs dose

IV. Conclusion

This experiment has provided the first opportunity to assess bipolar transistors in a space environment. The data provides base current at a given temperature and dose, which is used to extract the *srv* for the given dose by normalizing the temperature response to 300 K. The increase of N_{IT} with dose reflects the effect of ionizing radiation on BJTs used in a COTS linear bipolar process. Similar analysis will be performed on the rest of the ELDRS data set and will be reported in the final paper.

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