A Comparison of High-Energy Electron and Cobalt-60 γ-Ray Radiation Testing

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Abstract—In this paper, a comparison between the effects of irradiating microelectronics with high energy electrons and Cobalt-60 gamma-rays is examined. Additionally, the effect of electron energy is also discussed. A variety of part types are investigated, including discrete bipolar transistors, hybrids, and junction field effect transistors.

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Introduction

Instruments for Heliophysics and Planetary missions are frequently faced with extreme total ionizing dose (TID) radiation challenges coupled with limited mass and power resources. These challenges can be addressed in three ways: (a) identification of parts that can withstand the radiation environment, (b) conceptual redesign of instruments to use those parts and optimize shielding mass, and (c) development of a common radiation-hardened electronics architecture that can minimize instrument development costs.

As a case in point, both Europa Jupiter System Mission (EJSM) spacecrafts (the NASA-led Jupiter Europa Orbiter [JEO] and the ESA-led spacecraft currently called Jupiter Icy Moons Explorer [JUICE]) are examples of upcoming NASA missions with high TID requirements and tight mass and cost budgets. Currently, neither Instrument Announcement of Opportunity (AO) is currently scheduled for release due to potential changes in mission description, considerable effort has been, and continues to be, expended in preparing instruments for the proposals. While there is some overlap in potential instruments to be flown on JEO and JUICE, the design of those instruments proposed for each will be considerably different due to their distinct radiation environments.

Compared to JEO, JUICE has a more reasonable TID requirement of 85 krad(Si) behind 315 mil of Al shielding, which allows the use of radiation-hardened parts with a guaranteed tolerance of 300 krad(Si). The challenge, however, is that the radiation environment of the current mission design for JEO (2.9 Mrad(Si) behind 100 mil of Al) is unlike any ever experienced before for such durations. The dose-depth curve for JEO can be seen in Figure 1. No parts exist with guaranteed radiation tolerances acceptable for the requirements of JEO, so clever
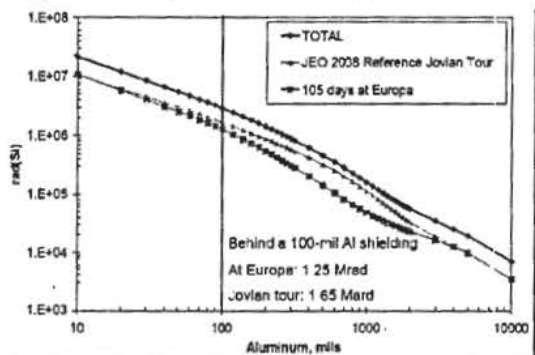

Fig. 1. Total ionizing dose as a function of aluminum shielding thickness for the entire JEO mission, as well as for the Jovian tour and the Europa orbit [1].
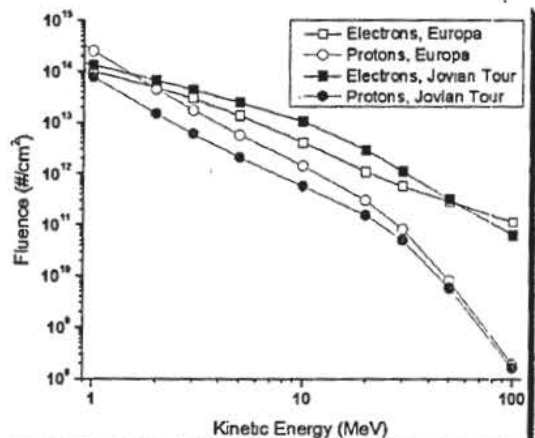

Fig. 2. Electron and proton fluences as a function of energy [2].

instrument design and heavy use of localized shielding are necessary. The harsh radiation environment, combined with severe mass restrictions and distributed instrument architecture, may make it impossible to propose heritage instrument designs.

Roughly half of the anticipated ionizing dose comes from high-energy electrons trapped within the Jovian radiation belts, which further complicates the issue of JEO's high radiation environment. This can be seen in Figure 2. These electrons have energies and mission fluences orders of magnitude higher than seen in the Earth's trapped radiation belts. While the use of graded-Z shielding for electrons is well understood, the instruments proposing to JEO will be mass- and cost-constrained. The work discussed in this paper was undertaken in an effort to identify whether the additional time and expense of electron testing is required, or whether Cobalt-60 (^{60}Co) γ-ray testing would be sufficient for most circumstances, other than cases where parts have shown considerable displacement damage dose (DDD) response.

Test Facilities and Techniques

We conducted electron DD and TID tests at Rensselaer Polytechnic Institute's (RPI) Gaerttner Linear Accelerator Laboratory with 17 MeV electrons, unless specified otherwise.

^{60}Co TID tests were performed at NASA's Goddard Space Flight Center. Because of the high total doses required, all irradiations were performed at high dose rate. Some of the parts tested may be susceptible to Enhanced Low Dose Rate Sensitivity (ELDRS), but it was infeasible to irradiate at an appropriately low dose rate due to the time that would have been required to complete these tests. Efforts were made to bound ELDRS with accelerated testing by elevated temperature irradiation [3], alternating high dose rate irradiations and elevated temperature anneals [4], switched dose rate irradiations [5, 6], and by exposing the parts to molecular hydrogen [7].
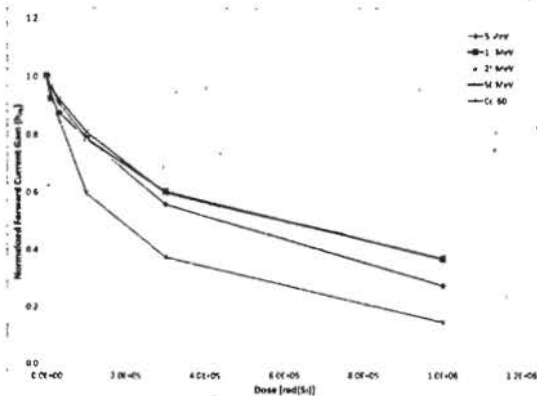
Fig. 3. The average h_{FE} for Semicoa 2N2222 PNP BJTs (averaged over three parts for each test condition – electron energy and gamma irradiation) after the parts are irradiated with normalized to the pre-rad value as a function of dose.
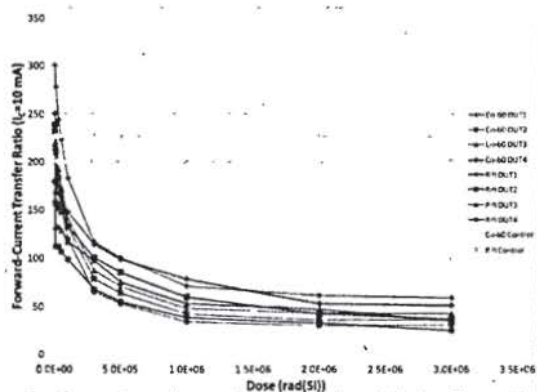

Fig. 4. Output frequency of the QTech MCM2760-4M after each dose step for control parts, parts irradiated with 17 MeV electrons at RPI, and parts irradiated with gammas at GSFC's Co-60 facility.
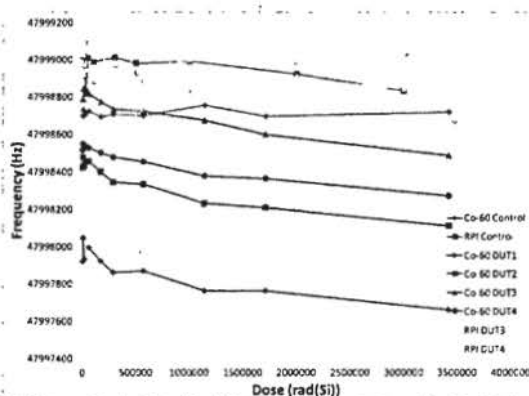

Fig. 5. Output frequency of the QTech MCM2760-4M after each dose step for control parts, parts irradiated with 17 MeV electrons at RPI, and parts irradiated with gammas at GSFC's Co-60 facility.

Test Results

Presented in this paper are a summary of the test results. The full test reports are available online at http://radhome.gsfc.nasa.gov [8].

Semicoa 2N2222 Silicon NPN Transistor

Semicoa's 2N2222 is a general purpose, low power silicon NPN transistor. These parts were not procured to a specification that included radiation tolerance. Three parts were irradiated for each test. The tests included ^{60}Co γ-rays and electrons with energies of 5, 17, 25, and 50 MeV. There were also control parts that were measured at each dose step.

Traditionally, bipolar components are particularly susceptible to displacement damage, suggesting that the parts irradiated with electrons might show a greater decrease in forward current gain (h_{FE}); however, for these particular parts, the opposite was found to be true. Figure 3 shows the normalized forward current gain as a function of dose for the average of the three parts irradiated in each test. Of all parameters measured, only h_{FE} went out of specification. For the electron energies, h_{FE} dropped below specification between 300 krad(Si) and 1 Mrad(Si) for all electron energies, and between 100 and 300 krad(Si) for the ^{60}Co experiment. There was little difference in the effect of electron energy except at 1 Mrad(Si). The parts irradiated with 50 MeV electrons showed a greater change at that dose step than the others.

Microsemi 2N2907 PNP Silicon Switching Transistor

The 2N2907s used in this experiment are PNP BJTs manufactured by Microsemi. These parts are complementary to the 2N2222s, and were also not procured to a radiation radiation specification.

The 2N2907s were irradiated to 3 Mrad (Si), and saw substantial degradation in the h_{FE} for all collector currents measured (Figure 4.) However, there was no significant difference in the degradation of the parts irradiated with ^{60}Co and electrons.

QTech MCM2760-4M Crystal Oscillator

The MCM2760-4M is a hybrid crystal oscillator manufactured by QTech to operate at 48 MHz. These parts were designed using 100 krad(Si) logic and a quartz crystal. The concern was that the electrons could damage the crystal, and would have a worse radiation response than with ^{60}Co irradiation.

Both sets of irradiations stayed within specification to the final dose step (3 Mrad(Si) for the electrons and 3.5 Mrad(Si) for the ^{60}Co). Again, the greater decrease in frequency was evident in the parts irradiated with ^{60}Co than the parts irradiated with electrons; this can be seen in Figure 5. The bias current also decreased proportionally to the frequency in both cases, though it stayed within specification.
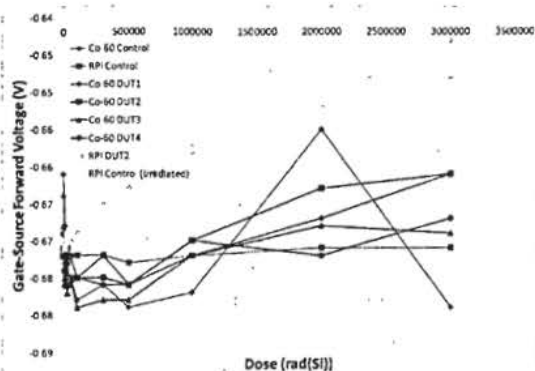
Fig. 6. Vgs(f) increases with TID in Vishay's 2N5116 JFET. The magnitude of the parts irradiated with electrons changed at a faster rate than the magnitude of the parts irradiated using Co-60.
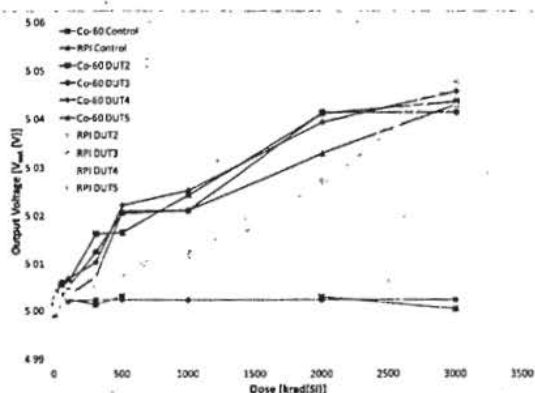

Fig. 7. In the Linear Technology RH1021, the outputvoltage increases with increasing TID. In the both the Co-60 and electron irradiations, the parts went out of specification at 30 krad(Si).

Fig. 8. In the Linear Technology RH1021, the outputvoltage increases with increasing TID. In the both the Co-60 and electron irradiations, the parts went out of specification at 30 krad(Si).
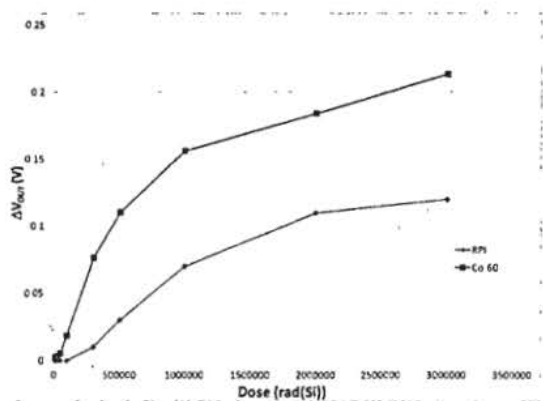
Vishay 2N5116 P-Channel JFET

Vishay's 2N5116 is a p-channel junction field effect transistor (JFET) analog switch. It is not a rad-hard part, but JFETs are known to be inherently tolerant to TID due to their construction and operational device physics.

All parameters that began in specification stayed within specification through 3 Mrad(Si). However, the gate-source forward voltage ($V_{gs(f)}$) did show an increase with dose, and this can be seen in Figure 6. This increase was more pronounced in the parts irradiated with electrons than in the parts irradiated with the ^{60}Co source.

Linear Technology RH1021 Voltage Reference

The RH1021 is a rad-hard 5 V reference and is designed in a bipolar process. The radiation response of this part is provided by the manufacturer, Linear Technology, for doses up to 200 krad(Si).

These parts showed very interesting responses to the two types of radiation. As can be seen in Figure 7, the parts irradiated in the ^{60}Co chamber exceed the specification for the output voltage (V_{out}) as early as 30 krad(Si), as did the parts irradiated with electrons. However, the overall degradation trends are very different. The ^{60}Co parts appear to degrade very quickly and look as though they are beginning to plateau between 2 and 3 Mrad(Si), while the degradation in the electron parts is slower and shaped more like a polynomial.

International Rectifier LS2805S Radiation-Hardened DC/DC Converter

International Rectifier's LS2805S is space-qualified DC/DC converter with a 28 V input and 5 V output and a maximum output power of 30 W. This part is a hybrid, and does come with a guaranteed radiation tolerance of greater than 100 krad(Si).

Each part was taken to a total dose of 3 Mrad(Si). However, for this experiment, only one part was irradiated for each test, so there would be substantial error bars on all the results. That being said, the converter irradiated with ^{60}Co showed a greater degradation in output voltage (V_{out}) than the part irradiated with electrons as shown in Figure 8. The electron irradiated part stayed within specification until the 2 Mrad(Si) dose point, while the ^{60}Co irradiated part remained in specification until the 300 krad(Si) dose point.

Summary

Presented here are a number of parts from a variety of technologies, including bipolar discretes and integrated circuits, JFETs, and hybrids. Generally, the difference in response with respect to total ionizing dose between irradiating with high-energy electrons and γ-rays from a ^{60}Co source is not so large as to necessitate the additional expense of irradiating with electrons in all cases. Exceptions to this generalization may include optical components or any other part where displacement damage would be a major concern. More investigation using

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4

linear bipolar integrated circuits is recommended.

Acknowledgment

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5