Radiation performance of commercial SiGe HBT BiCMOS high speed operational amplifiers

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Abstract—We present results on heavy-ion and proton irradiations for commercial SiGe BiCMOS operational amplifiers: LTC6400-20 from Linear Technology and THS4304 from Texas Instruments. We found that the devices are susceptible to heavy-ion-induced SETs. The SET cross-sections increase with increasing operating frequency. The LTC6400 exhibits a $LET_{th} < 7.4$ MeV·cm^2/mg for frequencies ranging from 10 to 1000 MHz. The THS4304 exhibits a $LET_{th} < 4.4$ MeV·cm^2/mg at 200 MHz; the LET_{th} decreases with increasing frequency. The significance of the SETs also increases with frequency. The SETs at 1000 MHz can erase several signal cycles. We also found that the LTC6400 is relatively robust against 198 and 54 MeV protons. We did not observe angular sensitivity from the proton irradiations.

Index Terms—Silicon Germanium, Single event transients, heavy-ions, protons, COTS, high speed operational amplifiers,

I. INTRODUCTION

Silicon-germanium (SiGe) heterojunction-bipolar-transistors (HBTs) are well suited for high speed microelectronic applications. SiGe HBTs utilize bandgap engineering to achieve similar performance as III-V compound semiconductors, while maintaining the same Si CMOS fabrication processes. Therefore we benefit from the high performance, while keeping the manufacturing costs down.

Although flight systems desire radiation hardened parts, these components are often more expensive and remain several technology generations behind their commercial counterparts. As a result, space systems are utilizing more commercial-off-the-shelf (COTS) parts, especially in missions with relatively lower radiation requirements. The SiGe HBT technology is attractive for space applications due to its intrinsic tolerance to both ionizing and non-ionizing irradiation effects [1]–[3]. However SiGe HBT-based circuits

are sensitive to single event effects (SEE), such as single event upsets (SEU) and transients (SET) [4]. Furthermore, since SiGe HBT technology is often designed for high speed applications, the high operating frequency further enhances the significance of the SEUs and SETs [5], [6].

Furthermore these high speed devices typically have low linear energy transfer (LET) upset thresholds, which can lead to vulnerability to proton irradiations [7]. Proton-induced SEEs can be a concern for orbits in proton rich environments, like the Van Allen Belt. The SEUs/SETs from protons can also exhibit angular dependence, which increases in significance as geometries become smaller [6].

Here we investigate the SEE sensitivities of commercial SiGe HBT BiCMOS operational amplifiers from different manufacturers with heavy-ion and proton irradiations.

II. DEVICE DESCRIPTION

The devices in this experiment include the LTC6400 differential output amplifier from Linear Technology and the THS4304 wideband amplifier from Texas Instruments. Table I. shows the device information, including the process technology, lot date code, and part function.

The LTC6400 is fabricated with the JAZZ-TOWER 0.35 µm SiGe BiCMOS process. The process comes with a 3.3 V CMOS with deep trench isolations, and lateral PNP transistors. Additional options include a 5 V CMOS, vertical PNP transistor, and triple-well isolation.

The THS4304 is developed in Texas Instrument's BiCom3 Silicon-Germanium BiCMOS process. The process contains complementary SiGe PNP and NPN transistors, 5 V 0.35 µm SOI CMOS logic, and trench isolation.

Table I. Device information.

	LTC6400	THS4304
Manufacturer	Linear Technology	Texas Instrument
Process	JAZZ-TOWER 0.35 µm SiGe BiCMOS	TI BiCom3SiGe BiCMOS
Lot date code	0746 and 0705	October, 2004

III. EXPERIMENTAL DETAILS

We conducted the heavy-ion irradiations at the Texas A&M Cyclotron SEE Test Facility. The beam energy was 15 MeV/amu. The flux varied from 1×10^4 to 1×10^5 particles/cm^2/s. Table II lists the ion species used in the experiments, with their respective values for energy, linear energy transfer (LET), and penetration range in silicon. The
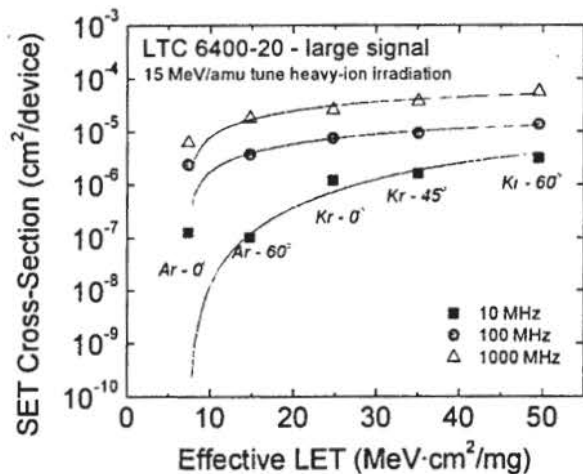
Figure 1. Heavy-ion-induced SET cross-sections vs. effective LET for the LTC6400 with V_{IN} = 140 mV at 10, 100, and 1000 MHz.
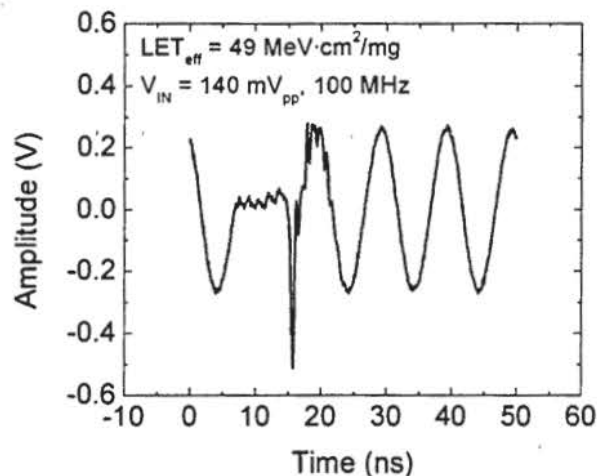

Figure 2. SET characteristics of the LTC6400 operating with frequency = 100 MHz for LET_{eff} = 49 MeV·cm^2/mg.
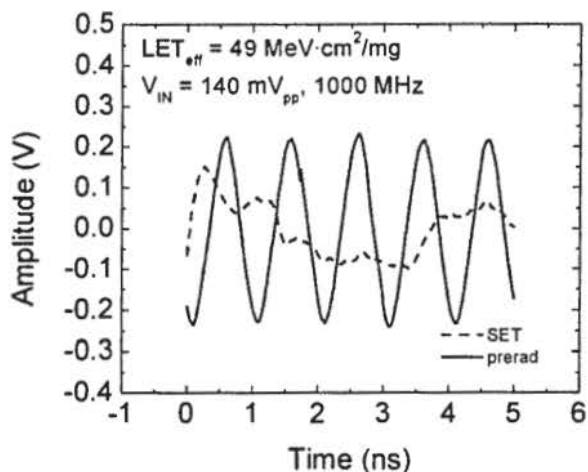

Figure 3. SET characteristics of the LTC6400 operating with frequency = 1000 MHz for LET_{eff} = 49 MeV·cm^2/mg.
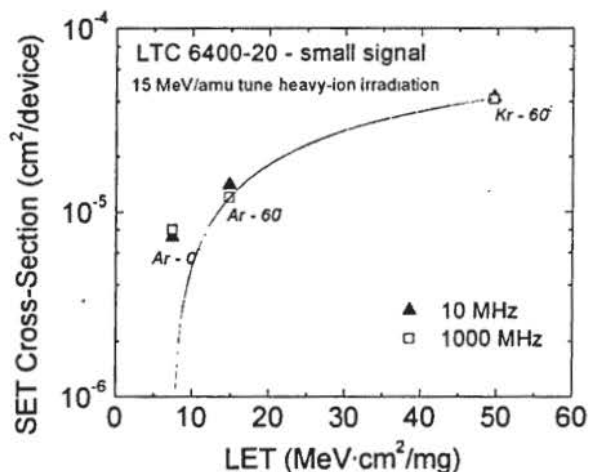

Figure 4. Heavy-ion-induced SET cross-sections vs. effective LET for the LTC6400 with V_{IN} = 2 mV at 10, 100, and 1000 MHz.

heavy-ion irradiations were carried out until 100 transients are observed and acquired, or up to a fluence of 2×10^7 particles/cm^2. The proton experiment was conducted at the Indiana University Cyclotron Test Facility. The beam energy was 198 MeV/amu. Various angles were used during the irradiations.

During the irradiation runs, an RF generator provides a high frequency sinusoidal signal to the device input. A digital oscilloscope monitors the output. A computer controls the test setup, including the device operating conditions and transient trigger levels, via LabVIEW program.

Table II. Heavy-ion specifications.

Ion	Peak Energy (MeV)	LET (MeV·cm^2/mg)	Range in Si (µm)
Ne	300	2.5	316
Ar	29	7.4	229
Cu	944	17.8	172
Kr	152	24.8	170
Ag	1634	38.5	156

HEAVY-IONS

A. LTC6400

We tested the LTC6400-20 for single-ended operation. Two LTC6400 parts were irradiated at room temperature with the devices operating at V_{CC} = 3 V, V_{CM} = 1.25 V, sinusoidal inputs of 140 mV$_{pp}$ (large signal) or 2 mV$_{pp}$ (small signal), at frequencies of 10, 100, and 1000 MHz. Two ion species were used for this experiment: Ar and Kr.

Figure 1 shows the SET cross-sections from large signals at 10, 100, and 1000 MHz. We observed SET LET_{th} < 7.4 MeV·cm^2/mg for all frequencies of operation. The SET cross-section increases linearly with increasing frequency, partly due to reduced noise-margins and an increasing proportion of clock edges [4]. The SET LET threshold may also exhibit frequency dependence at smaller LET values.

The SET characteristics also depend on the device's operating frequency. SETs at 10 MHz appeared as small glitches. The majority of SETs at 100 MHz are positive- or negative-going voltage spikes, which disrupt 1 to 2 bits of the
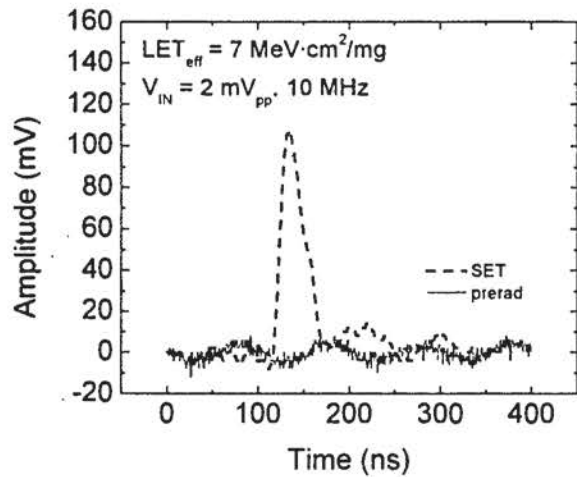
Figure 5. SET characteristics of the LTC6400 operating with V_{IN} = 2 mV$_{PP}$ and 10 MHz, for LET$_{eff}$ = 7 MeV·cm^2/mg.

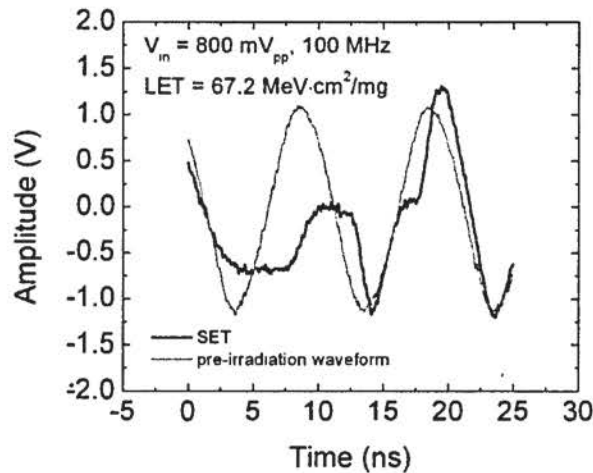Figure 6. Heavy-ion-induced SET cross-sections vs. effective LET for the THS4304 at different operating conditions.

Figure 7. SET characteristics of the THS4304 operating with V_{IN} = 800 mV and 100 MHz, for LET$_{eff}$ = 7 MeV·cm^2/mg.

signal, as shown in Figure 2. Figure 3 shows a typical SET at 1000 MHz. A few of the SETs at 100 MHz and most of the SETs at 1000 MHz erases several signal cycles, which can significantly impact device performance.

We also evaluated the small signal performance. Unlike the large signal response, the SET cross-sections are similar for different frequencies, as shown in Figure 5. The SET characteristics are also similar for the different frequencies. Figure 6 shows a worst case SET at 1000 MHz. The SET has a voltage spike of ~ 110 mV, which is approximately 20× the output's amplitude. The signal recovers from the large voltage spike after 1 cycle, but remains unstable for several cycles.

No latchup events were observed. The supply current values remained relatively unchanged, at ~ 85 – 90 mA, throughout irradiation. The parts were exposed to approximately 100 krad(Si) total ionizing dose for the duration of the heavy-ion irradiation, with no significant effect on the SET cross-section.
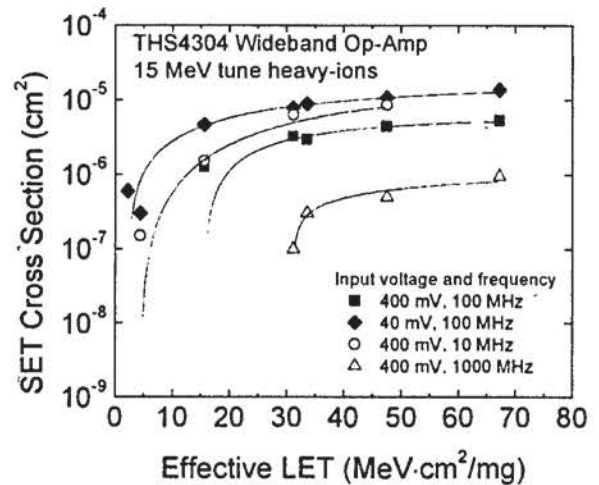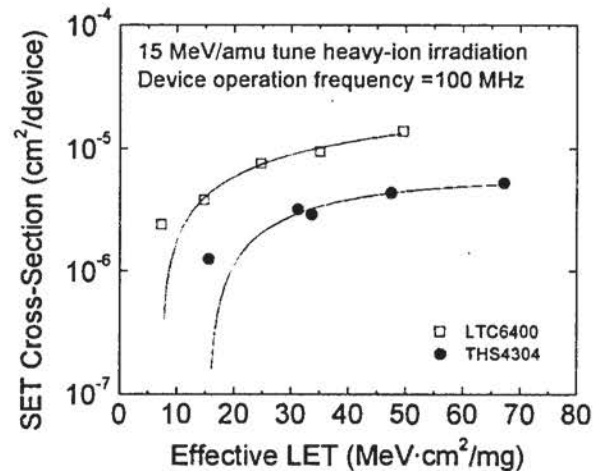
B. THS4304

Two THS4304 parts were irradiated with the devices operating with V_{CC+} = 2.5 V, V_{CC-} = -2.5 V, sinusoidal V_{in} = 800 mV$_{pp}$ or 100 mV$_{pp}$, 10, 100, and 200 MHz. Three ion species were used for this experiment: Ne, Cu, and Ag. Figure 7 shows the SET cross-sections vs. LET, with the devices operating in various conditions. The SET LET$_{th}$ and error cross-sections vary with the LET, the operating frequency, and the input signal.

The SET LET$_{th}$ decreased while the SET cross-section increased, with increasing frequency for large signals (1 V$_{pp}$). The SET LET$_{th}$ and cross-sections for the small signal (100 mV$_{pp}$) showed negligible frequency dependence, similar to the LTC6400 part. The SET LET$_{th}$ is less than 4.4 MeV·cm^2/mg at 200 MHz. Figure 8 shows a typical SET from a large signal at 100 MHz. Approximately 1 – 2 data bits are affected by an SET at this frequency, similar to the LTC6400.

Figure 9 shows the SET cross-sections for the THS4304 and LTC6400, with both devices operating at 100 MHz. We note that there are differences in the operation conditions. The magnitudes of the input signals and signal gains from the application circuits were V_{IN} = 140 mV$_{pp}$, 20 dB and V_{IN} = 800 mV$_{pp}$, 6 dB for the LTC6400 and THS4304, respectively.

The SET cross-section for the LTC6400 is about half of one magnitude larger than that of the THS4304. The SET

LET$_{th}$ for the THS4304 (< 15.6 MeV·cm^2/mg) is also higher than that of the LTC6400 (< 7.4 MeV·cm^2/mg) at 100 MHz.

Figure 9 offers a quick comparison of the relative SEE performances of the state-of-the-art SiGe operational amplifiers of similar technology node. The LTC6400 and the THS4304 have considerable differences in their processes, designs, and functions, which may lead to the differences in their radiation performance. For example the THS4304 utilizes SOI CMOS, which is known to be more robust against SEEs relative to Bulk CMOS. The SET susceptibility also depends on many other elements. As described previously, the different operation conditions for the input signals may also influence the SEE sensitivity.

IV. PROTONS

We also examined the SEE susceptibility of the LTC6400 with high energy protons. We tested 3 parts throughout two separate proton tests. The parts operated at 200 MHz during the irradiations. We irradiated the first part (DUT3) with 198 MeV protons, at 0°, 60°, 90°, and again at 0° incident angles, up to a total proton fluence of ~ 4.3 × 10^{12} cm^{-2}. The proton fluence for each run was 1 × 10^{12} cm^{-2}. The initial 0° incident run produced 3 SETs. The following runs at 60° and 90°, produced 8 SETs each. The final run at 0° produced 15 SETs. Figure 10 shows the cross-sections vs. accumulated proton fluence, with noted incident angles.

The increase in SET error cross-sections from 0° to 60° is unlikely due to angular effects that result from nuclear elastic scattering or spallation reactions, since the final 0° incident run produced a larger cross-section than the angular irradiations and the initial normal incident run. The data trend suggests that the increase in error cross-section is possibly due to increases in accumulated TID and/or displacement damage.

We irradiated a second part (DUT4) with 198 MeV protons at normal incidence up to a total fluence of 2.5 × 10^{13} cm^{-2} to examine the effect of increasing proton dose. As shown in Figure 10, the cross-section increases notably from a proton fluence of approximately 5 × 10^{13} cm^{-2} to 8.2 × 10^{13} cm^{-2}, but then decreases. The dataset here is consistent with a Poisson distribution with allowable error deviations. The increases in cross-section early in the irradiation may be bounded by the error deviations, as the SET counts are relatively sparse. For example the first data point is based on 1 SET.

The notable difference in the magnitudes of the SET cross-sections between the two parts may also be the result of the error deviations and/or part-to-part variations, as the parts have different lot-date-codes.

Figure 11 shows a typical proton-induced SET. The SET characteristics are similar to the heavy-ion-induced SETs, with the device running at similar frequency.

We also irradiated a third part with 54 MeV protons at 0°, 60° and 90° incident angles. We observed a maximum of 1 SET up to 2 × 10^{12} cm^{-2} proton fluence at each angle. So the part is very robust against 54 MeV protons, with no signature of angular sensitivity.

V. CONCLUSION

We have evaluated the performance of two state-of-the-art commercial SiGe HBT-based operational amplifiers in heavy-ion and proton radiation environments. The devices were sensitive to heavy-ion-induced SETs, with relatively low LET thresholds. The SET cross-sections increased with increasing frequency, similar to previous studies [ ]. The significance of the SETs also increased with increasing frequency. The most significant transients at 1 GHz for the LTC6400 erased several cycles of the output signal. The small signal response did not exhibit frequency dependence for either of the devices.

Additionally the LTC6400 was robust against high energy protons, with relatively low SET cross-sections. We observed sharp increases in the cross-section at early stages of irradiation for each of the two parts. The increase in cross-section may be due to the increase in degradation from accumulated TID/DD. However the significant scatter in the dataset suggests that the SET cross-sections more likely follow a Poisson distribution, and do not correlate strongly with accumulated dose. The significant difference in the SET cross-sections for the two parts is also consistent with the large data scatter. In addition the different lot date codes of the parts may also contribute to the variability of their radiation response.

VI. ACKNOWLEDGEMENT

VII. REFERENCES

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