Measurement of Dose Rate Dependence of Radiation Induced Damage to the Current Gain in Bipolar Transistors

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Abstract
We report the study of radiation induced change in the current gain of bipolar transistors for three different gamma dose rates. The dose rates differed by a factor of 60 with the lowest close to that anticipated for the LHC, and the highest at a rate we have been routinely using for radiation damage tests. The maximum dose attained was 200kRad, which is high enough to compare with other measurements. The importance of annealing high dose rate data is demonstrated.

I. INTRODUCTION
One of the major challenges for High Energy Physics experimentation at the future Large Hadron Collider (LHC) at CERN is the expected radiation damage to electronic devices. For example, the front-end electronics (FEE) of the silicon tracking device SCT in the ATLAS experiment is expected to accumulate a total dose of approximately 10 MRad over an anticipated lifetime of 10 years [1]. Previous studies have examined the effect of total irradiation dose on bipolar transistors and electronics, and found lowered current gain for increased doses [2,3]. Recently, new results have shown that for a given dose, more damage is induced if the irradiation is performed at a lower dose rate [4-10]. This effect may have a significant impact on electronics being developed for the readout of the silicon tracking detectors for use at the LHC.

Radiation damage to bipolar transistors is characterized by a rapid decrease of the current gain in the first few hundred kRad, with a leveling off at much larger total doses. While it has been demonstrated that the transistors will still operate adequately after 10 MRad when irradiated at a dose rate of 3Rad/s, (yielding a current gain of about 50 in typical npn transistors [3]), there is concern that the low irradiation rate at the LHC of about 0.05Rad/s may lead to increased damage such that the electronics are no longer functional for their anticipated lifetime of 10 years [1]. Previous studies have shown that a large fraction of the damage occurs early in the irradiation. It should be pointed out that in Refs. [4-10], the radiation damage was investigated at extremely low currents and correspondingly small V_{BE}. In this investigation, we will concentrate on damage at constant collector current I_C, which tends to be kept stable in bipolar circuits, and determine the change in current gain at realistic collector currents I_C.

In this study we have irradiated 32 transistors from the Maxim CB2 process identical to those which are currently being used in the prototype CAFE-M bipolar chip designed for the silicon tracker of the ATLAS experiment [13]. We have exposed these transistors to three different rates of gamma's from a 60Co source at the Santa Cruz Institute for Particle Physics (SCIPP), including the expected dose rate for the LHC of 0.05Rad/s, and at the highest dose rate of the source (3Rad/s), employed in previous measurements [2,3]. Measurements of induced damage to the current gain of the transistors were performed at regular intervals throughout the irradiation to a total dose of 200 kRad. In addition, careful studies of the effect of annealing under controlled conditions were obtained.

II. TEST STRUCTURES AND IRRADIATION
The Maxim CB2 was developed by Maxim as an enhancement to the Tektronix SHPi process by adding vertical pnp structures. The process is a fully complementary bipolar process which uses oxide isolation. The typical p+ isolation is replaced with a recessed oxide isolation to reduce the collector area. This process is designed for superior performance and flexibility. The CB2 process uses polysilicon emitters in both the pnp and npn transistors and typically shows dc gains (h FE) of about 90. The various size transistors are arranged in standard test keys included on the wafers of CAFE-M VLSI chips. Table 1 summarizes the various transistors used in this study. The reference current listed in the table is the nominal current at which the transistor is run in the CAFE-M chip.

To characterize the transistors we performed forward Gummel plots following the specifications of the CB2 process published by Maxim in their design documentation to extract the dc parameters and characteristics of the various BJT’s under test [14].
Table 1
Summary of MAXIM CB2 Transistors.

<table>
<thead>
<tr>
<th>Device</th>
<th>Emitter size</th>
<th>Emitter #</th>
<th>Ref. current</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPN1</td>
<td>1.0x3.2 µm²</td>
<td>1</td>
<td>5 µA</td>
</tr>
<tr>
<td>NPN2</td>
<td>1.0x7.2 µm²</td>
<td>1</td>
<td>10 µA</td>
</tr>
<tr>
<td>NPN8</td>
<td>1.0x7.2 µm²</td>
<td>4</td>
<td>40 µA</td>
</tr>
<tr>
<td>NPN32</td>
<td>1.0x31.2 µm²</td>
<td>4</td>
<td>160 µA</td>
</tr>
<tr>
<td>PNP1</td>
<td>1.0x3.2 µm²</td>
<td>1</td>
<td>5 µA</td>
</tr>
<tr>
<td>PNP2</td>
<td>1.0x7.2 µm²</td>
<td>1</td>
<td>10 µA</td>
</tr>
<tr>
<td>PNP8</td>
<td>1.0x31.2 µm²</td>
<td>1</td>
<td>40 µA</td>
</tr>
<tr>
<td>PNP16</td>
<td>1.0x31.2 µm²</td>
<td>2</td>
<td>80 µA</td>
</tr>
</tbody>
</table>

The photon irradiation took place at the $^{60}$Co source at UC Santa Cruz. The devices were irradiated to a total dose of 200 kRad at three different rates: 3, 0.1 and 0.05Rad/s. Two opti-chromic dosimeters [15] were used to calibrate the dose rate at each of the three different device and exposure positions. The measured dose rate at the different positions agreed to better than 5%. We estimate the relative error on the dose between different dose rates to be 5%.

In all cases the transistors were biased with an emitter current of approximately 100 µA during the irradiation at a temperature of 20°C. During the annealing period, the devices were stored in the same location to eliminate temperature effects to skew the data, but without applied bias. Forward Gummel plots were obtained periodically throughout the irradiation for the lower dose rates. Table 2 summarizes the irradiation and annealing history of the devices under test.

### III. RESULTS

#### A. Annealing

During the measurements taken throughout the irradiation, as indicated in Table 2, we looked carefully for room temperature annealing of 1 week, 2 weeks and 3 weeks respectively. The data shows appreciable detrimental post-radiation annealing, with the radiation damage increasing by a large factor within the first week after the exposure for structures irradiated with high dose rate, but with very little change afterwards. However, for the test structures irradiated with the lower dose rates, little change appears between measurements taken directly after the irradiation, and those performed a week later.

Thus we can conclude that for exposures lasting much longer than one week, the radiation damage in low rate exposures will have annealed out during the irradiation time and the measurements taken immediately after the final irradiation will reflect the stable radiation damage. For the 10Mrad irradiation of Ref. 3 at 3Rad/s, the exposure time was 5.5 weeks, so the error was less than 20%, assuming an anneal time of less than one week. The data taken during the irradiation, on the other hand, would have systematically underestimated the damage. In the following, we will compare data of low and high dose rate exposures after annealing times of up to 13 weeks.

#### B. Change of Current gain as a function of Dose

During irradiation, we measured the current gain $h_{FE}$ as a function of collector current for all eight of the transistors at the dose and anneal points listed in Table 2. They correspond to values of $V_{BE} >= 0.7V$. They were fit with a second order polynomial in $\log(I_C)$, which describes the data very well:

$$h_{FE} = A + B*\log(I_C) + C*\log(I_C)^2.$$  

For comparison of the radiation induced damage between different transistors and differing rates of irradiation, the data for different transistors could not be compared directly because of the difference in pre-rad current gains. Instead we compared the percent change form the pre-irradiation current gain at the nominal collector currents specified in Table 1.
Figure 1: Relative change in transistor current gain vs. dose for different dose rates for the four npn transistor at scaled collector currents $I_c$.

Figure 2: Relative change in transistor current gain vs. dose for different dose rates for the four pnp transistor at scaled collector currents $I_c$. 
Figures 1 and 2 summarize the results for 8 transistor sizes. Each figure contains data from all three dose rates for a given size transistor. For data corresponding to the same total dose, the one with the longest anneal time is displayed. Error bars representing our estimate of the relative dose uncertainties (5%) are shown. The error bars in the vertical scale are of the order 1%. The smallest transistors (npn1, pnp1) show similar trends as the other 6 transistor sizes, but have special features which we will investigate further in the future.

The npn transistors show a larger initial gain than the pnp transistor, however, the relative damage in the npn transistors appears larger, especially at the lower collector currents. These trends are common across the 32 transistors tested. The increased radiation hardness of the pnp transistors has not been seen in previous Maxim C-Pi or SHPi processes. For the pnp transistors, we observe for low dose an initial increase in the current gain, followed by the expected decrease for larger doses.

C. Dose Rate Dependence

In Figures 1 and 2, a line connecting the origin with the 200kRad dose point for the 3.0 Rad/s dose rate is displayed. A deviation from this line for the data with lower dose rates will indicate a dose rate dependence of the radiation damage. We can first compare the points of the two test structures irradiated with the high dose rate of 3Rad/s, which had different histories of irradiation and annealing, as listed in table 2. At a total dose of 220kRad, they agree with each to 30% for the npn (Fig. 1) and much better for the pnp transistors (Fig. 2). This level of agreement is a measure of the sensitivity of our test. Since the low dose rate data deviate from the high dose rate data at 200kRad by about the same amount, we can state that the maximal dose rate effect is less or of the order of 30%.

In general, the initial low dose points deviate more from the expectation than the final point. The npn and the pnp show different trends, with the pnp's generally lying above the expectation. We attribute this to the fact that the data taken at early times did not have time to anneal out completely. For a given radiation dose, it is apparent that the induced damage for a pnp transistor is roughly half that of a npn transistor, as mentioned before. This makes the use of pnp's more attractive for applications where the current gain is affected by radiation.

A comparison of the dose rate dependence at the highest total dose point and more than 10 weeks of annealing is shown in Figs. 5 and 6. Here the relative change in current gain is

\[
\Delta h_{FE}/h_{FE} = [h_{FE}(220kRad)-h_{FE}(0kRad)]/h_{FE}(0kRad)
\]

shown as a function of the collector current. The curves are calculated using the fits to the forward Gummel plots mentioned above [eq. (1)]. The values for the two lower dose rates are scaled linearly by 10% to account for the different total dose. The conclusions from these plots are the same as from the figures showing the dose dependence (Figs. 1 and 2): the radiation damage in the pnp is about half of that in the npn, and the scatter of the two high dose rate curves are as large as between the high and the low dose rate sets, of about 30%.

IV. CONCLUSIONS

We have investigated the dose rate dependence of radiation induced damage to the current gain of bipolar Maxim CB2 transistors at realistic collector currents. Test structures were irradiated with gamma’s from a $^{60}$Co source at dose rates differing by a factor 60 up to a total dose of 200kRad.
No evidence for rate dependence was found in the region of 0.05Rad/s to 3Rad/s. The significance of the latter is that it is at the anticipated dose rate at the LHC, and the one of the former is that it is the dose rate of our Co source, used before frequently for our radiation damage studies. We find that for higher dose rates the total damage to the transistor current gain is not apparent until an annealing period of about a week at room temperature has elapsed. Measurement taken directly after irradiation would yield reduced damage effects for these higher rate exposures [12]. Earlier long-term studies of several weeks [2,3] are thus only marginally affected. To a level of 30%, the total induced damage appears to be dependent on dose received, at least for the dose rates employed in this study.

A direct comparison with previous measurements indicating dose rate dependence of the radiation damage in bipolar circuits [4-10] is difficult because they were determined in very different current regimes, i.e. at very much lower currents where the radiation damage is much larger and surface effects are large and possibly technology dependent.

V. REFERENCES