Evaluation of the Radiation Tolerance of SiGe Heterojunction Bipolar Transistors Under 24GeV Proton Exposure

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Advantages of SiGe Bipolar Over CMOS for Silicon Strip Detectors

- A key element in the design of low noise, fast shaping, charge amplifiers is high transconductance in the first stage.
- With CMOS technologies, this requires relatively larger bias currents than with bipolar technologies.
- The changes that make SiGe Bipolar technology operate at 100 GHz for the wireless industry coincide with the features that enhance performance in high energy particle physics applications.
  - Small feature size increases radiation tolerance.
  - Extremely small base resistance (of order 10-100 Ω) affords low noise designs at very low bias currents.
- These design features are important for applications with:
  - Large capacitive loads (e.g. 5-15 pF silicon strip detectors)
  - Fast shaping times (e.g. accelerator experiments with beam crossing times of tens of nanoseconds in order to identify individual beam crossing events)
The LHC upgrade will increase the luminosity by a factor of 10! Fluences in the inner detector will reach as high as $10^{16} \text{ n}_{eq}/\text{cm}^2$!

The challenge is to find front-end electronics resistant to radiation damage that will also reduce power consumption with acceptable noise.

Our efforts focus on fluences achieved in the mid to outer radii of silicon strip detectors.
Silicon Germanium (SiGe) Heterojunction Bipolar Transistors (HBTs)
(First Generation IBM Process)

Origin of radiation tolerance:
• Small active volume of the transistor
• Thin emitter-base spacer oxide (weakest spot)

Irradiation Procedure:
• Devices were sent to CERN and exposed to a 24GeV proton source with the highest fluence taking 5 days to accumulate.
• The leads were grounded during irradiation --> worst case scenario.
• The transistors were annealed to improve performance.
• Special thanks to the RD50 collaboration, especially, Michael Moll and Maurice Glaser.

<table>
<thead>
<tr>
<th>Device Sizes:</th>
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<tbody>
<tr>
<td>0.5x1 μm²</td>
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<tr>
<td>0.5x2.5 μm²</td>
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<tr>
<td>0.5x10 μm²</td>
</tr>
<tr>
<td>0.5x20 μm²</td>
</tr>
<tr>
<td>4x5 μm²</td>
</tr>
</tbody>
</table>
The Effects of Proton Irradiation

Pre-rad

1.15 x 10^{13}

4.15 x 10^{13}

3.50 x 10^{14}

1.34 x 10^{15}

3.58 x 10^{15}

1.05 x 10^{16}

ATLAS Upgrade

Outer Radius

Mid Radius

Inner Radius
Radiation Damage Mechanisms

Forward Gummel Plot for 0.5x2.5 μm²

I_c, I_b vs. V_{be} Pre-rad and After 1x10^{15} p/cm² & Anneal Steps

Radiation damage increases base current causing the gain of the device to degrade.

Gain=I_c/I_b (collector current/base current)

Ionization Damage (in the spacer oxide layers)
- The charged nature of the particle creates oxide trapped charges and interface states in the emitter-base spacer increasing the base current.

Displacement Damage (in the oxide and bulk)
- The incident mass of the particle knocks out atoms in the lattice structure shortening hole lifetime, which is inversely proportional to the base current.
We studied the effects of annealing. The performance improves appreciably. In the case above, the gain is now over 50 at 10µA entering into the region where an efficient chip design may be implemented with this technology. The annealing effects are expected to be sensitive to the biasing conditions. We plan to study this in the future.
Initial Results:

After irradiation, the gain decreases as the fluence level increases. Performance is still very good at a fluence level of $1 \times 10^{15}$ p/cm². A typical $I_c$ for transistor operation might be around $10 \, \mu A$ where a $\beta$ of around 50 is required for a chip design. At $3 \times 10^{15}$, operation is still acceptable for certain applications.
Universality of Results:

Universal behavior independent of transistor geometry when compared at the same current density $J_c$. For a given current density $\Delta(1/\beta)$ scales linearly with the log of the fluence. This precise relation allows the gain after irradiation to be predicted for other SiGe HBTs. Note there is little dependence on the initial gain value.
Qualifications for a good transistor:

- A gain of 50 is a good figure of merit for a transistor to use in a front-end circuit design.
- Low currents translate into increased power savings.

<table>
<thead>
<tr>
<th>Transistor Size $\mu m^2$</th>
<th>$I_c$ irrad</th>
<th>$I_c$ anneal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5x1</td>
<td>2.E-06</td>
<td></td>
</tr>
<tr>
<td>0.5x2.5</td>
<td>4.E-06</td>
<td>5.E-08</td>
</tr>
<tr>
<td>0.5x10</td>
<td>3.E-05</td>
<td>8.E-07</td>
</tr>
<tr>
<td>0.5x20</td>
<td>5.E-05</td>
<td>2.E-06</td>
</tr>
<tr>
<td>4x5</td>
<td>9.E-06</td>
<td>5.E-07</td>
</tr>
</tbody>
</table>

At 3.5x10^{14} in the outer region (60 cm), where long (10 cm) silicon strip detectors with capacitances around 15pF will be used, the collector current $I_c$ is low enough for substantial power savings over CMOS!

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<th>Transistor Size $\mu m^2$</th>
<th>$I_c$ irrad</th>
<th>$I_c$ anneal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5x1</td>
<td>3.E-05</td>
<td>1.E-07</td>
</tr>
<tr>
<td>0.5x2.5</td>
<td>7.E-05</td>
<td>4.E-06</td>
</tr>
<tr>
<td>0.5x10</td>
<td>4.E-04</td>
<td>9.E-06</td>
</tr>
<tr>
<td>0.5x20</td>
<td>6.E-05</td>
<td></td>
</tr>
<tr>
<td>4x5</td>
<td>1.E-04</td>
<td>1.E-05</td>
</tr>
</tbody>
</table>

At 1.34x10^{15} closer to the mid radius (20 cm), where short (3 cm) silicon strip detectors with capacitance around 5pF will be used, the collector current $I_c$ is still good for a front transistor, which requires a larger current while minimizing noise. We expect better results from 3rd generation IBM SiGe HBTs.
Conclusions

• We extended the radiation testing of SiGe Bipolar transistors by a factor 100 in fluence thanks to the RD50 radiation program.

• The 5HP technology we examined is far superior to that used for the current ATLAS silicon strip detectors.

• The 5HP demonstrates utility--power savings and low noise--for the entire analog front-end in the outer region and for the front transistor in the mid radius of ATLAS Upgrade.

• Future generations (smaller sizes) of SiGe HBTs show huge potential for power savings with low noise at extreme radiation levels.

• Investigation is currently under way to determine the benefits of the next generations of SiGe HBTs in future collider experiments (i.e. sLHC).