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Radiation Hardness Measurements on Maxim Full Custom Bipolar Processes C-Pi and CB2

A. Grillo, C. Jordan, T. Nissen, W. Rowe, E. Spencer,
R. Wichmann

Santa Cruz Institute for Particle Physics,
University of California, Santa Cruz, CA 95064

We compare the radiation hardness of the two bipolar processes C-Pi and CB2 by Maxim to evaluate the characteristics of the newer CB2 process over the older C-Pi process. The transistors manufactured in the Maxim CB2 process will be used to design a low-power, low-noise front-end amplifier chip for silicon microstrip detectors used for the Semi-Conductor Tracker (SCT) in the ATLAS detector being built for the Large Hadron Collider (LHC) at CERN. We tested both NPN and PNP transistors of various sizes by measuring dc characteristics before and after irradiating the devices with photons and protons which enables us to investigate the sensitivity of the dc parameters to both ionization and displacement effects, respectively. The photon irradiation was carried out in a ^{60}Co *source using a total dose of up to 10 Mrad in a few steps. For the proton irradiation, the devices were exposed to a beam of 55 MeV protons with a total fluence of* 5×10^{13} cm^{-2}*. After proton irradiation two chips were stored at* $100^{\circ}C$ *and retested to determine the influence of annealing effects on the dc parameters. The most significant effects observed are the decrease in the dc current gain* h_{FE} *and the increase of the reverse collector leakage current after irradiation. Due to annealing, these parameters improve over time depending on the temperature of operation.*

1 Introduction

The particle fluence in the silicon tracker SCT [1] of the ATLAS [2] detector at CERN is expected to be of the order of 10^{13} to 10^{14} particles/cm^2 during 10 years of operation. A fluence this high has a considerable impact on the semiconductor material and will therefore significantly change the performance of the front-end readout electronics which will be exposed to it. In designing the bipolar amplifier chips, the change in the dc parameter of the transistor devices needs to be taken into account to ensure proper functioning of the detector readout even after 10 years of operation in this high radiation environment. The studies undertaken here with protons and photons will supply important information for the designers of the front-end electronics.

A similar study of irradiated bipolar devices was conducted several years ago [3] using transistors from the Tektronix SHPi process. That study showed that the NPN structures had an acceptable performance after irradiation but the PNP devices with a lateral structure did not. The C-Pi and the newer CB2 process use vertical PNP structures which are believed to be more radiation tolerant. An important goal of this study was to verify that.

2 Test Structures

The Maxim C-Pi process was developed by Tektronix as an enhancement to their SHPi process by adding verticle PNP structures. The process is a fully complementary bipolar process which uses oxide isolation. The typical p$^+$ isolation is here replaced with a recessed oxide isolation to reduce the collector area. This process is designed for superior performance and flexibility. The emitter size of a vertical size 2 transistor is 1.0 $\mu m \times$ 7.2 μm with one emitter. The typical dc current gain h_{FE} for these transistors is about 120 for all NPN sizes and about 30 for PNP transistors.

The Maxim CB2 process has similar manufacturing features but uses polysilicon emitters in both the PNP and the NPN transistors. It shows a typical dc gain h_{FE} of about 100 for NPN and about 80 for PNP transistors. The emitter size in this process is the same as in the older C-Pi process.

A summary of the tested transistors including emitter sizes and emitter numbers is given in table 1. Note that the PNP8 in the CB2 process has one emitter of 4 times the area as compared to the one manufactured in the

C-Pi process which has 4 emitters. Also a PNP32 was not available in the CB2 process and a PNP16 was used instead. In addition to those available in C-Pi, size 1 transistors were included in the characterization of the CB2 process.

	C-Pi Process		CB2 Process	
device	emitter size	emitter number	emitter size	emitter number
NPN1	-	-	$1.0{\times}3.2\ \mu m^2$	1
NPN2	$1.0{\times}7.2\ \mu m^2$	1	$1.0{\times}7.2\ \mu m^2$	1
NPN8	$1.0{\times}7.2\ \mu m^2$	4	$1.0{\times}7.2\ \mu m^2$	4
NPN32	$1.0{\times}31.2\ \mu m^2$	4	$1.0{\times}31.2\ \mu m^2$	4
PNP1	-	-	$1.0{\times}3.2\ \mu m^2$	1
PNP2	$1.0{\times}7.2\ \mu m^2$	1	$1.0{\times}7.2\ \mu m^2$	1
PNP8	$1.0{\times}7.2\ \mu m^2$	4	$1.0{\times}31.2\ \mu m^2$	1
PNP16	-	-	$1.0{\times}31.2\ \mu m^2$	2
PNP32	$1.0{\times}31.2\ \mu m^2$	4	-	-

Table 1: Table of the tested devices in both processes with emitter size and emitter number

3 Characteristics and Irradiation

We performed common emitter characteristics and forward gummel plots following the specifications of the C-Pi process published by Maxim in their design documentation [4] to extract the dc parameters and characteristics of the various BJT's under test. The common emitter characteristic is a measurement of the collector current I_C as a function of the collector-emitter voltage V_{CE} for a fixed set of base currents I_B. For the forward gummel plot, the collector current I_C and the base current I_B were monitored as a function of V_{BE}, the base emitter voltage. The limits on the currents were given by the specification that the minimum collector current I_C for a size 2 transistor was assumed to be 1 μA and the maximum collector current I_C for a size 32 transistor 10 mA. For each individual device the currents were then scaled with the total emitter size.
The dc parameters were measured using a HP 4145B semiconductor parameter analyzer which was read out with a MacIntosh computer via GPIB [5].

The photon irradiation took place at the ^{60}Co source at UC Santa Cruz. The devices were irradiated at a rate of 12 krad/hr slightly below room temperature. The structures were retested after a total dose of 0 krad (pre-rad), 200 krad, 1 Mrad, 5 Mrad and 10 Mrad. The proton irradiation was performed at the 88" cyclotron at the Lawrence Berkeley Laboratory (LBL) with a 55 MeV proton beam up to a total fluence of 5×10^{13} cm^{-2} which corresponds to 1×10^{14} minimum ionizing particles (MIPs) per cm^2 equivalent to a dose of 2.7 Mrad accumulated during ionization processes. Immediately after the proton irradiation, the devices were stored at -20°C to freeze out annealing processes. Since 2 chips for each process were irradiated with protons, one set was kept at -20°C while the other set was stored at 100° C and remeasured after 100 hours, 200 hours and 300 hours to investigate the influence of annealing and reverse annealing on the dc parameters of the test structures.
All devices were biased with a emitter current of 100 μA during the irradiation and heating procedure.

4 Results

4.1 NPN Transistors

The measurements of the NPN transistors of both processes show as the most significant effects a decrease in the dc current gain h_{FE} and an increase in the leakage current through the reverse biased base collector junction.
Figure 1 shows the dc current gain h_{FE} as a function of the collector current obtained from the forward gummel plot for a NPN8 transistor manufactured in the C-Pi process before irradiation and after a total photon dose of 200 krad, 1 Mrad, 5 Mrad and 10 Mrad. The maximum value for the dc current gain h_{FE} is about 118 reached at a collector current of I_C = 100 μA. After a total dose of 200 krad this value for h_{FE} dropped down to approximately 105 at a collector current of I_C = 500 μA, 90 at I_C = 1.5 mA after 1 Mrad, 65 at I_C = 1 mA after 5 Mrad and 50 at I_C = 600 μA after 10 Mrad in the measured collector current range.

Figure 2 shows the same plot for the NPN8 transistor manufactured in the CB2 process. The initial maximum dc current gain h_{FE} before irradiation is with 100 about 15% lower than for the C-Pi process but is almost flat over the

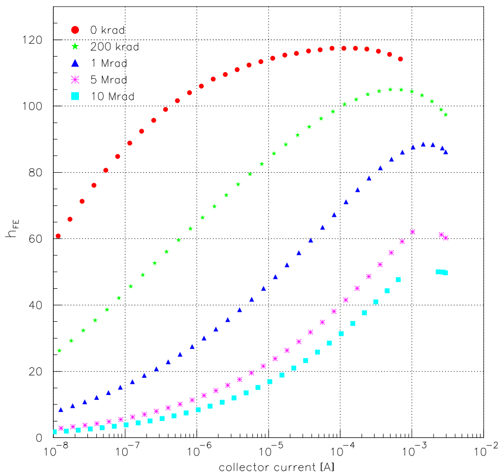

Figure 1: The dc current gain h_{FE} vs collector current for the NPN8 C-Pi transistor before irradiation and after total ^{60}Co doses of 200 krad, 1 Mrad, 5 Mrad and 10 Mrad.

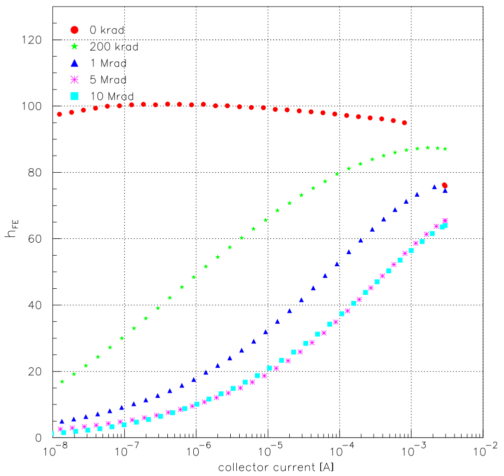

Figure 2: The dc current gain h_{FE} vs collector current for the NPN8 CB2 transistor before irradiation and after total ^{60}Co doses of 200 krad, 1 Mrad, 5 Mrad and 10 Mrad.

measured collector current range. For a total dose of 200 krad the maximum value for h_{FE} is about 88 at a collector current I_C = 2 mA and 75 at I_C = 2 mA for 1 Mrad total dose. Since the compliance limit of the semiconductor parameter analyzer was set to 3 mA, the maximum value for the two highest doses is not the absolute maximum because the necessary collector current for this value would have exceeded the compliance limit due to the increase in leakage current after irradiation. The maximum value observed for a total dose of 5 Mrad is about 66. The curves for 5 Mrad and 10 Mrad are again almost identical over the measured current range. This feature was observed for all size transistors measured in the CB2 process.

The transistors manufactured in the C-Pi process have a higher initial gain than the ones manufactured in the CB2 process, but this disadvantage gets canceled out after irradiation due to the smaller proportional decrease of the gain as a function of total dose.

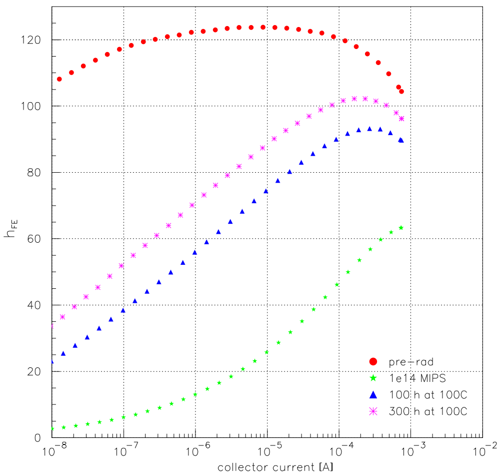

Figure 3: The dc current gain h_{FE} vs collector current for the NPN2 C-Pi transistor before irradiation, after a fluence of 1×10^{14} MIPs/cm^2, after annealing for 100h and 300h at 100°C.

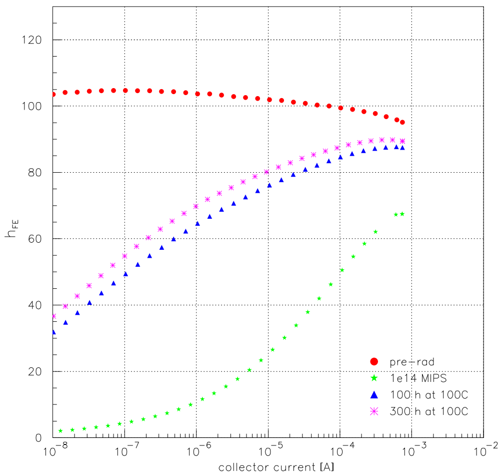

Figure 4: The dc current gain h_{FE} vs collector current for the NPN2 CB2 transistor before irradiation, after a fluence of 1×10^{14} MIPs/cm^2, after annealing for 100h and 300h at 100°C.

Figure 3 shows the dc current gain h_{FE} as a function of the collector current I_C for the C-Pi NPN2 transistor before irradiation, after a total fluence of 1×10^{14} MIPs/cm^2, after 100 hours and 300 hours of annealing at 100°C.
The maximum initial dc current gain reached 125 at a collector current of 10 μA and dropped down to about 65 at I_C = 800 μA immediately after the irradiation in the measured collector current range. After storing the devices for 100 hours at 100°C, their performance improved drastically and the maximum dc current gain increased to a value of about 90 accompanied by a simultaneous decrease in the collector current to 200 μA due to annealing effects in the semiconductor material. The material seems still to anneal after 300 hours storage at 100°C since the dc current gain was then larger than 100 at a slightly smaller collector current.

The results of the proton irradiation and the following annealing for the CB2 NPN2 transistor are shown in figure 4. The initial dc current gain

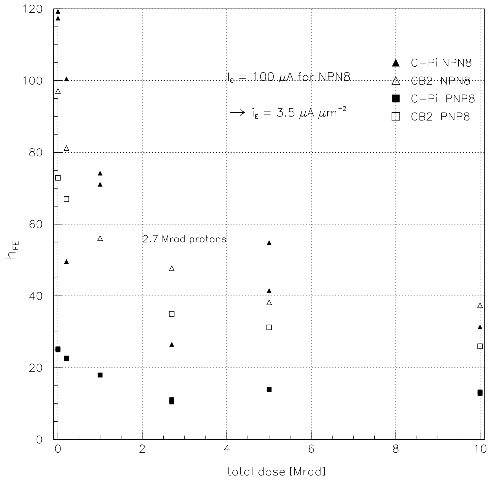

Figure 5: The dc current gain h_{FE} vs total dose for NPN and PNP transistors in both the C-Pi and the CB2 process for the same emitter current density corresponding to $I_C = 100\ \mu$A for a size 8 transistor. The proton fluence was converted to a total dose of 2.7 Mrad and is included in this plot.

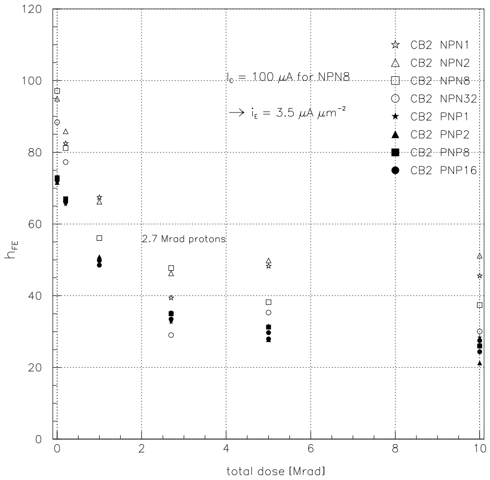

Figure 6: The dc current gain h_{FE} vs total dose for NPN and PNP transistors in the CB2 process for the same emitter current density corresponding to $I_C = 100\ \mu$A for various size transistors. The proton fluence was converted to a total dose of 2.7 Mrad and is included in this plot.

h_{FE} is an almost flat function of the collector current I_C in the measured current range and has a value between 100 and 105. Before annealing, the current gain decreased dramatically to a maximum value of roughly 70 at a collector current of 800 μA. After annealing the semiconductor material at 100°C for 100 and 300 hours, the current gain h_{FE} recovered to a maximum value of about 90 for a collector current of about 500 μA. The fact, that the curve for the longer annealing time almost coincides with the one for 100 hours suggests, that the desirable annealing is still in progress while there is no anti-annealing process strong enough to affect the behavior of the transistors.

In figure 5, we plot the dc current gain h_{FE} as a function of the total dose for an emitter current density of 3.5 $\mu A/\mu m^2$ which corresponds to a collector current of I_C = 100 μA. Scaling the currents with the total emitter area gives the same results for all device sizes as can be seen from figure 6. For clarity, only results for size 8 transistors are shown in most plots. The fluence of 1×10^{14} MIPs/cm^2 corresponds to an equivalent dose of 2.7 Mrad concerning ionization and displacement effects and the results are included in the plots of figure 5 and 6.
For the C-Pi NPN transistors, the current gain after proton irradiation is considerably smaller than one would expect from the same total dose after a gamma irradiation. This indicates, that besides the damage caused by ionization we also see a significant displacement effect. The CB2 NPN transistors seem to be more resistant against displacement effects since the point corresponding to the proton dose is in the region one would expect from an equivalent photon dose and might even permit a slightly larger dc current gain.
The results for the PNP transistor will be discussed in section 4.2.

4.2 PNP Transistors

The PNP transistors available in the Maxim C-Pi process have a relatively low initial maximum dc current gain h_{FE} of about 28 for a collector current $I_C \approx 1\mu$A with a more or less flat dependence on the collector current before irradiation. Figure 7 shows the dc current gain h_{FE} as a function of the collector current I_C for a C-Pi PNP8 transistor for different total doses of 0 krad (pre-rad), 200 krad, 1 Mrad, 5 Mrad and 10 Mrad. Again, we observe a decrease in h_{FE} and an increase in I_C shifting the maximum dc current gain to higher collector currents for increasing total dose. For a total dose of 200 krad, a maximum value of 23 was reached at I_C = 100 μA, for a total dose of 1 Mrad, we found h_{FE} = 18 at I_C = 500 μA. The curve after 10 Mrad total dose was almost identical to the one obtained after 5 Mrad.

Figure 8 shows the dc current gain h_{FE} as a function of the collector current I_C for a PNP8 transistor manufactured in the Maxim CB2 process. The initial dc current gain h_{FE} for this process is considerably larger than for a C-Pi PNP transistor and reaches 77 at I_C of about 1 μA. After irradiating the device with a total photon dose of 200 krad, the maximum value for h_{FE} was about 67 at a collector current of I_C = 100 μA, after a total dose

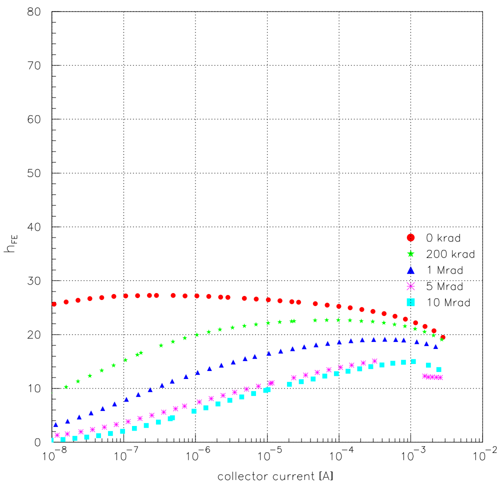

Figure 7: The dc current gain h_{FE} vs collector current for the PNP8 C-Pi transistor before irradiation and after total ^{60}Co doses of 200 krad, 1 Mrad, 5 Mrad and 10 Mrad.

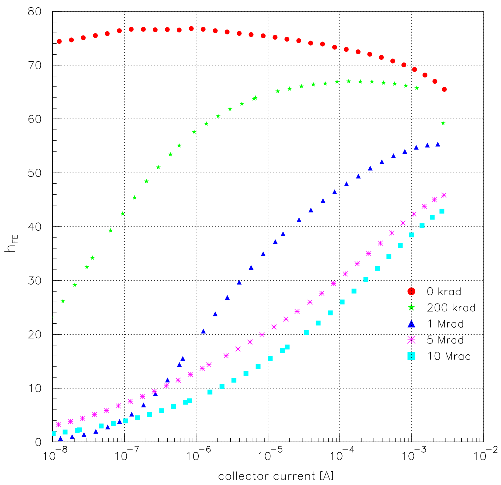

Figure 8: The dc current gain h_{FE} vs collector current for the PNP8 CB2 transistor before irradiation and after total ^{60}Co doses of 200 krad, 1 Mrad, 5 Mrad and 10 Mrad.

of 1 Mrad the dc current gain dropped down to 55 at a collector current of about 2 mA. For a total ^{60}Co dose of 1 Mrad, the maximum for h_{FE} in the used collector current range is about 45 at I_C = 2 mA. After a total dose of 5 Mrad, a maximum value for h_{FE} of about 47 is reached at a collector current of 2 mA, while the gain after 10 Mrad was with 45 slightly less at the same current. After irradiation, the available dc current gain of a PNP transistor manufactured in the CB2 process is comparable to the gain of the equivalent NPN transistor.

The results of the proton irradiation of the C-Pi PNP2 transistor are shown in figure 9. The initial dc current gain h_{FE} reaches a maximum value of 26 with only a slight dependence on the collector current in the used current range with a decrease for high collector currents. After irradiating the device with 1×10^{14} MIPs/cm^2, the maximum value of h_{FE} was about 14 at a collector current I_C of about 400 μA. As for the NPN structures, we

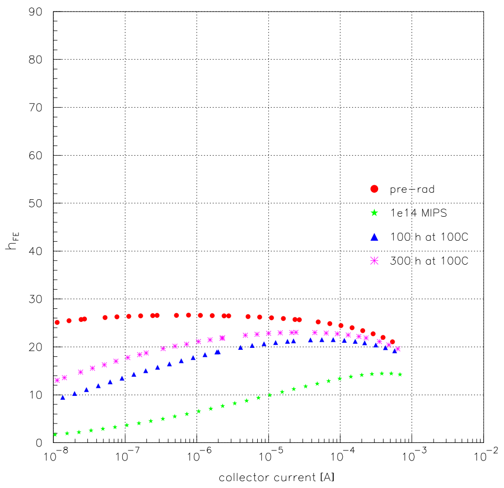

Figure 9: The dc current gain h_{FE} vs collector current for the PNP2 C-Pi transistor before irradiation, after a fluence of 1×10^{14} MIPs/cm^2, after annealing for 100h and 300h at 100°C.

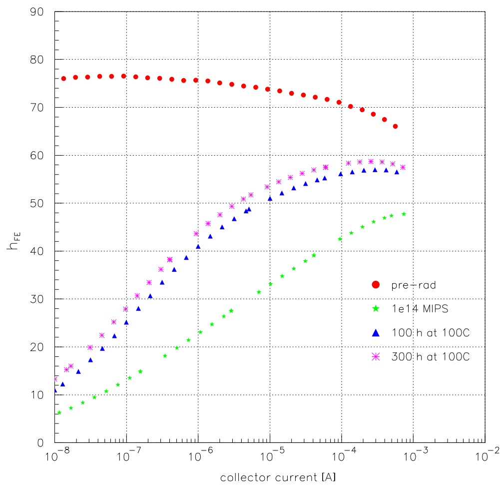

Figure 10: The dc current gain h_{FE} vs collector current for the PNP2 CB2 transistor before irradiation, after a fluence of 1×10^{14} MIPs/cm^2, after annealing for 100h and 300h at 100°C.

also see an increase in the dc current gain to values of about 22 to 24 and a shift of the curves to smaller collector currents I_C. The maximum value was reached at a current of $I_C \approx 400$ μA with no big difference between 100 and 300 hours of annealing.

The results for the CB2 PNP2 transistor irradiation are shown in figure 10. The overall behavior is comparable to the older C-Pi process. The initial dc current gain at about 76 is much higher for the CB2 than for the C-Pi process and is essentially a flat function of the collector current with a decrease for higher collector currents. After a fluence of 1×10^{14} MIPs/cm^2 the current gain h_{FE} dropped down to a maximum value of 48 at a collector current of about 600 μA. After annealing the devices for 100 and 300 hours at 100°C, the maximum dc current gain h_{FE} increased to a value of 56 to 58 at a collector current of approximately 200 μA. Again the two curves are almost identical.

Referring back to figure 5 we see the dc current gain h_{FE} as a function of

the total dose for a emitter current density of $i_E = 3.5\ \mu A/\mu m^2$ corresponding to $I_C = 100\ \mu A$ for a PNP8 transistor. Since the currents scale with the total emitter area, only the data for size 8 transistors are shown in both the C-Pi and the CB2 process.
As we have seen for the NPN transistors, we find that the proton irradiation caused a significant damage due to displacement effects in the C-Pi transistor since the proton point equivalent to 2.7 Mrad lies well below the current gain one would estimate from the photon data alone. Again the data point for the CB2 device seems to suggest, that the CB2 process is more resistant towards displacement effects than the C-Pi process. The dc current gain h_{FE} measured for this device fits well into the overall decrease due to gamma irradiation.

5 Conclusion

The radiation tolerance of the NPN transistors of the C-Pi process looks very similar to the results obtained earlier with the SHPi process and the verticle PNP structures are much improved over the laterals. We observe a decrease in the dc current gain h_{FE} and an increase in the leakage current through the reverse biased base collector junction but the devices show sufficient radiation hardness for the design of fast, low power front-end electronics for silicon microstrip detectors in a high radiation environment.
The newer manufacturing process by Maxim called CB2 shows the same decrease in dc current gain and increase in the leakage current as a result of irradiation as the C-Pi process. The initial lower gain of the CB2 process for the NPN transistors is canceled out after irradiation due to the lower proportional decrease in dc current gain after high doses. However, it is difficult to say whether these differences are systematic or due to lot variations given our small sample size. The dc current gain of the PNP transistors was improved by a factor of approximately 3 over the old C-Pi process. With a similar response to radiation damage, the gain after high doses of radiation was comparable to the one measured for the NPN structures.
Comparing the data obtained from the proton irradiation with the photon data, the CB2 process seems to be less vulnerable to displacement damage than the transistors manufactured in the older C-Pi process.
Since the meaurements taken after 5 Mrad and 10 Mrad total photon dose

only differ by a small amount for both processes, it seems that not much further damage beyond 5 Mrad is done to the transistor material to reduce the gain and increase the leakage current.
Annealing works in our favour, since only the desirable short term effect plays a role for the bipolar transistors while anti-annealing effects don't influence the performance of these devices.
Overall, the new CB2 process offers the same radiation hardness as the C-Pi process and shows a better performance for the PNP transistors so that it can replace the C-Pi process.

References

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