Component irradiation studies with the 72 MeV OPTIS proton beam: Low dose-rate irradiation of UHF1X transistors

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***Abstract*—Having to design electronics for high-energy physics experiment such as the Electromagnetic CALorimer (ECAL) of the Compact Muon Solenoid (CMS) experiment leads to the study of components under irradiation. We are designing a radhard readout system. This paper will present the facility we are using to study and validate the radiation hardness of our system. This is a proton beam located at the Paul Scherrer Institute (PSI). The results of a low dose-rate irradiation of some transistors from the UHF1X bipolar technology will be used as an example of the tests made using this facility.**

***Index Terms*—Bipolar transistor, irradiation, low dose-rate, proton beam facility, UHF-1X.**

I. INTRODUCTION

For the next generation of high-luminosity proton collider experiments being built for the Large Hadron Collider (LHC) at CERN in Geneva, radiation levels near the interaction region can be as high as 30 Mrad (Si) along with $10^{15}\ n/cm^2$ (1 MeV equivalent) over the lifetime of the experiments. We are developing custom readout electronics for the Electromagnetic Calorimeter (ECAL) of the Compact Muon Solenoid (CMS) detector, where radiation levels are roughly one tenth of the levels given above. In order to assess the performance and reliability of all of the components, we have been conducting tests for several years at the *OPTIS* proton beam at the Paul Scherrer Institute (PSI) located at Villigen in Switzerland.

II. THE CMS ECAL.

The CMS experiment is one of the two main experiments that will be installed on the LHC. This new accelerator will produce two proton beams of 7 TeV that will collide inside the experiment. The detector has to analyze the products of these collisions and thus must be as hermetic as possible. It is made of several sub-detectors, each of them having a dedicated function in the particle analysis and identification process.

The ECAL has to measure the energy of charged particles as well as photons. To obtain a closed volume, the ECAL is made of three parts: the barrel and two endcaps closing it on its two ends.

The calorimeter is made of 80000 lead tungstate crystals that are converting the energy of incoming particles into light. They are followed by an Avalanche photodiode (APD) in the barrel or Vacuum Photodiode (VPT) in the endcaps, which convert light into current. This current is then processed by the electronic readout system.

One of the main goals of the LHC is the discovery of a particle predicted by the standard model used in physics but not yet observed. This particle is named the Higgs boson and it needs a challenging detector to be found. Since the events where it should appear will be rare, the collision rate of protons is 40 MHz and thus, all the acquisition electronic has to work at least at that speed. It has also to have a high dynamic range: around 15-bit. This is why our system is made of an custom circuit designed using the UHF1-X process described later in this paper, which has to fit the whole dynamic range into a commercial 12-bit ADC. This later is followed by a serializer (custom chip currently designed in the Honeywell CHFET GaAs process [1]) which feeds the acquired data in an optical fiber to send it out of the detector.

Due to the requested performances, the electronics have to be placed close to the crystals in a zone where, because of the high energy of the proton beam, there is a high level of radiation. To increase to difficulty, once the detector will be built, the electronics will become non-accessible for at least 10 years. This means that during this time, it has to cope with the following levels of radiation [2]:

- In the barrel : $1\ Mrad\ (Si)\ \oplus\ 2\times10^{12}\ n/cm^2$
- In the endcaps : $2.5\ Mrad\ (Si)\ \oplus\ 5\times10^{13}\ n/cm^2$

The $\oplus$ sign means that we have at the same time ionizing radiation and displacement damages caused by neutrons.

There are no heavy ions as in space environment because the crystals are acting as a particle filter.

To ensure the proper operation of the electronics over this lifetime, the radiation hardness of the components has to be checked and thus require the use of an irradiation facility,

III. PROTON IRRADIATION FACILITY AT PSI

The Paul Scherrer institute houses research in nuclear physics. It has an accelerator which, starting with a proton

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beam, is able to produce various particles such as protons, neutrons and pions.

For our irradiation studies, we are using the 72 MeV proton beam coming from the first injector and designed for medical applications (treatment of eye tumors). This beam is available in two areas: OPTIS, which is the place where patients are cured and a zone named “area B”.

The fact that this beam was designed for medical application implies two useful characteristics for our field of applications:

1. The beam is well collimated and this allows us to put non-radhard components near to the device under test (e.g. FPGA’s). In OPTIS, the beam diameter is around 3 cm while in “area B” it is 10 cm. This size is useful to proceed to multiple chip irradiation. But, it is quite simple to reduce the size of the beam by using a collimator. To reduce the risks coming along with activated materials, we are using some polyethylene or Plexiglas. A piece of 5cm thickness is enough to stop the beam.
2. The beam intensity is quite stable.

With a beam energy of 72 MeV, protons are roughly 5 times minimum ionizing in silicon, and one proton creates the equivalent displacement damage of two 1 MeV neutrons. Measurements are carried out with a flux of $1.25\times10^{9}\ p/cm^{2}/s$, which means that in two hours a sample has received 1 MRad(Si) along with $1.8x10^{13}\,1\,MeV\ n/cm^{2}$. This combination of ionization and displacement damage is quite similar to what is expected in the CMS ECAL during 10 years of LHC operation for components located between the end of the barrel and the beginning of the endcap.

Since this beam simulates well our final environment, we are using it to test and develop the radiation hardness of our readout system. We are irradiating all components that should be used in the final design. The following is a list of all devices that were irradiated using the PSI facility:

- Test structure : transistors, resistor and capacitors from different technologies : bipolar UHF1X, BiCMOS DMILL and CHFET GaAs)
- Complete ASIC’s designed for the CMS ECAL readout made using the above technologies. The tests made include total dose measurements and Single Event Upset (SEU) sensitivity analysis.
- Discrete and passive components: resistors, capacitors, power transistors.
- Commercial IC’s: voltage regulators, optical link circuit (GLINK transmitter from Agilent (formerly Hewlett-Packard)) and the ADC that will be used in the final electronic readout system (AD9042 from Analog Devices [3]).
- Optical fibers.
- Optical connectors: complete connector and basic connector building elements such as lenses and plastic housing.
- Thermal grease.

We developed a multi-purpose test bench that we are using to perform tests in the lab and to do the irradiation. There is a motherboard that can house up to 32 current or voltage generators. These are programmable generators that can be set remotely from the control-room. The motherboard is communicating with a computer using a custom made bi-directional interface based on three optical fibers. There is two connectors accepting a daughter-board. This later can be something built for a special or complex irradiation or this can be a general-purpose board. This look like a prototype board customizable using for example a wire-wrap technique.

IV. LOW DOSE-RATE IRRADIATION OF UHF1X TRANSISTORS

A. *The UHF1X process*

The UHF1X process is made by Intersil (formerly Harris) this is a full complementary bipolar process. It uses a bonded wafer technology that, along with trench isolation makes it radiation hard. A cross section of a NPN transistor can be seen on fig. 1.

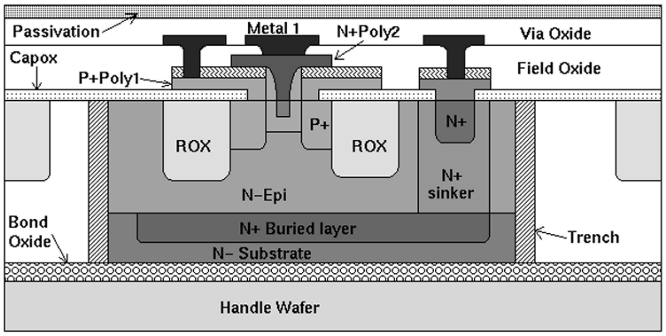

Fig. 1. UHF1X NPN transistor cross section

This process is suitable to build analog radhard functions as well as small digital circuits. Along with NPN and PNP transistors, the following devices are available:

- Resistors: nickel-chrome and diffused
- Capacitor
- Inductors

This process is used in our front-end circuit that is a mixed mode device. We already irradiated single transistors and circuit prototypes but it was at the maximum flux: 140 rad/s (Si).

B. *Low dose-rate irradiation*

In list of publications dealing with component irradiation, there is a lot of articles showing that for many commercial components, the performance degradation is much higher if the irradiation is made at a low dose-rate (e.g. see [4],[5]). Around 150 rad/s (Si) is often referred as a high dose-rate while a value of less than 0.1 rad/s (Si) is presented as a low dose-rate.

The performance degradation at low dose-rate is often seen for lateral devices such as lateral PNP transistors [6]. Although, there is some evidences of effects in vertical devices. Since there was no low dose-rate data for the UHF1-X process, we had to do some irradiation to check the its behavior under such conditions.

At PSI, it is possible to change the proton beam current and thus the dose-rate is adjustable. But, there are some limitations due to the regulation system that allows a maximum ratio of 50 between the high dose-rate and the low dose-rate. Going further makes the beam unstable and requires an additional dose-rate monitoring system close to the irradiated device.

So, in our case, the low dose-rate will correspond to:

$$\sim 2.5\times10^{9}\ 70\,MeV\ \ p/cm^{2}/s$$

Which, in our environment, produces the same effects as:

$$\sim 5\times10^{7}\ 1\,MeV\ n/cm^{2}/s \quad \oplus \quad \sim 3\ rad/s\,(Si)$$

The irradiation was done in “area B” using test chips containing several transistors in a DIL18 ceramic package. Table I list the type of devices that were irradiated.

Table 1: Geometry and quantity of UHF-1X transistors irradiated at low dose-rate.

Type	Geometry [μm] $W_E \times L_E \times N_E$	Quantity
NPN	1.3 x 5 x 1	6
	1.3 x 10 x 1	2
	1.3 x 25 x 1	2
	1.3 x 50 x 3	2
	1.3 x 20 x 1	10
PNP	1.3 x 5 x 1	6
	1.3 x 10 x 1	2
	3.3 x 20 x 1	2
	1.3 x 20 x 1	10
	1.3 x 50 x 3	2

W_E is the emitter width, L_E is its length and N_E is the number of emitters.

The sizes used for this test correspond to the transistors that are used in our front-end circuit. All devices were biased during irradiation. $I_c = f(V_{BE})$ curves were recorded simultaneously for each transistor before, during and after the beam operation. The test started with a particle flux corresponding to the low dose-rate. The device under test was irradiated with this flux during two hours. The beam was then switched to its maximum intensity for two more hours.

By this way we have for each devices, data about the low and the high dose-rate behavior and we are able to make comparisons.

V. IRRADIATION RESULTS

The data analysis of the results corresponds to the spice parameter extraction of each transistor. During this process, we are making the following assumptions:

1. Early effects are ignored ($V_{AF} = V_{AR} = 0$).
2. Only forward biased effects are modeled because of the test setup limitation. The system has a dynamic range of 1000 and it is not possible to measure reverse currents (of the order of some nano-amperes) and forward currents (up to several mili-amperes) without changing some hardware settings.
3. I_{KF} / I_S scales with W_E. This is because the setup also limit the maximum current. The limiting value of 5mA is too low to allow the extraction of I_{KF} for large transistors. It has to be calculated from the data of smaller ones and should then be scaled to match with what we should expect for a large device.

Based on the effects of radiation, an obvious model is to represent the excess base current as the current flowing in a parasitic diode connected in parallel with the base emitter junction as shown in fig. 2.

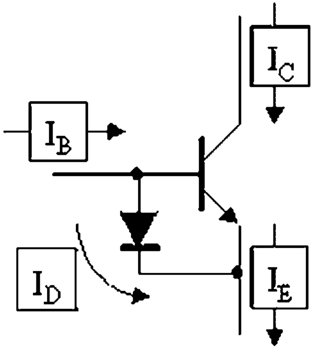

Fig. 2. Radiation effects modeling

The diode current obeys to the following equation:

$$I_D = I_{SRAD}\ \exp(V_{BE}\ /(n_{RAD}\ V_T))$$

Where the saturation current I_{SRAD} and ideality factor n_{RAD} will characterize the radiation sensitivity of the device and will have to be extracted from the $I_c = f(V_{BE})$ curves. This model reflects well the behavior of this bipolar transistor under irradiation. For a given operating point, the collector current remains unchanged while the base and thus the emitter current are increasing. This effect is often described as the degradation of the current gain β .

The value of the extracted spice parameters was used to check the analysis program as well as the irradiation data quality.

A. *Thermal effects.*

Looking at a typical result as the one visible on fig. 3 shows that there is a thermal effect. This is not a surprising behavior because the interaction of the beam with test chip package is producing some heat. There is also some self-heating because the device is biased. Since we need to compensate the effects of temperature to extract the contribution of radiation, we choose to use the collector current as a thermometer since it is not affected by radiation. The extracted temperature change was correlated with an estimation of the amount of heat created by the beam in the package. The two results are in good agreement and fig. 4 and fig. 5 present some typical temperature compensated results obtained on $1.3\mu m \times 50\mu m \times 3$ transistors.

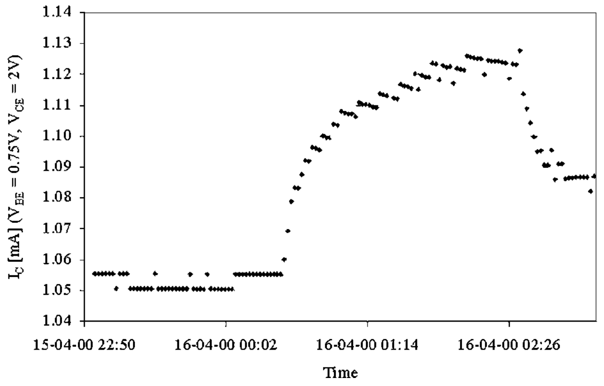

Fig. 3. Measured collector current for a $1.3\mu m \times 50\mu m \times 3$ NPN transistor. Raw data without any correction. $V_{BE} = 0.75\,V, V_{CE} = 2V$.

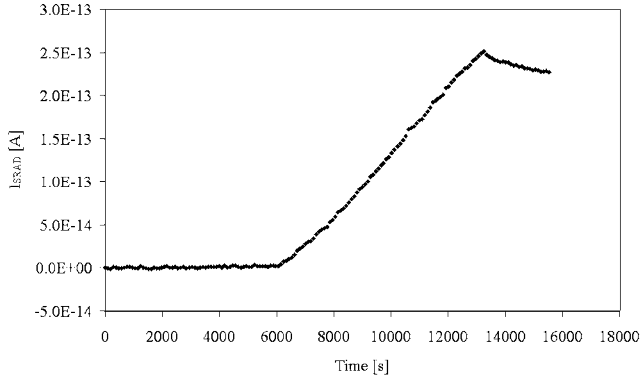

Fig. 4. I_{SRAD} parameter extracted after temperature compensation for a $1.3\mu m \times 50\mu m \times 3$ PNP transistor biased such that $I_E = 1\,mA$ and $V_{CE} = 2\,V$.

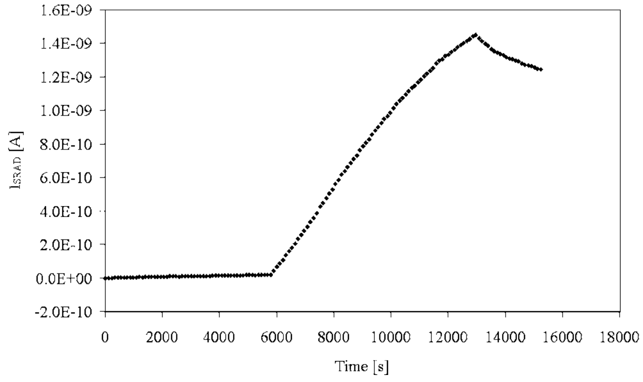

Fig. 5. I_{SRAD} parameter extracted after temperature compensation for a $1.3\mu m \times 50\mu m \times 3$ NPN transistor biased such that $I_E = 1\,mA$ and $V_{CE} = 2\,V$.

B. Radiation effects.

On fig. 4 and fig. 5, the points between 0 and 6000s correspond to the low dose-rate irradiation. Between 6000s and 13000s the high dose-rate irradiation took place. The last points show the annealing after the beam shutdown.

Radiation damages occur at the interface between silicon and oxide over the base-emitter junction of the transistor [6][7]. Thus, they should scale with the emitter perimeter. Since most of the transistors we tested have the same emitter length, the effects should scale with the width W_E. On fig. 6 and 7, we plotted I_B for two different sizes of transistor. To show the scaling, we are not using the extracted $I_{SRAD} = f(t)$ curve because this is the result of a fit. Since we are also extracting the n_{SRAD} parameter, all the physical effects may be spanned between I_{SRAD} and n_{SRAD}. The scaling is clearly visible on the total base current over time curve.

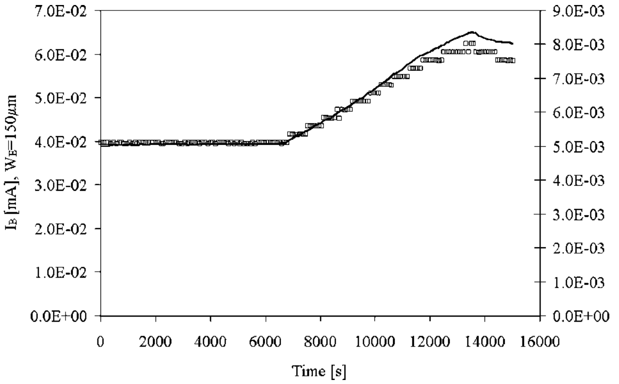

Fig. 6. Base current function of time for two different sizes of PNP transistors. Solid line: $W_E = 150\mu m$, left Y-axis. Open boxes: $W_E = 20\mu m$, right Y-axis.

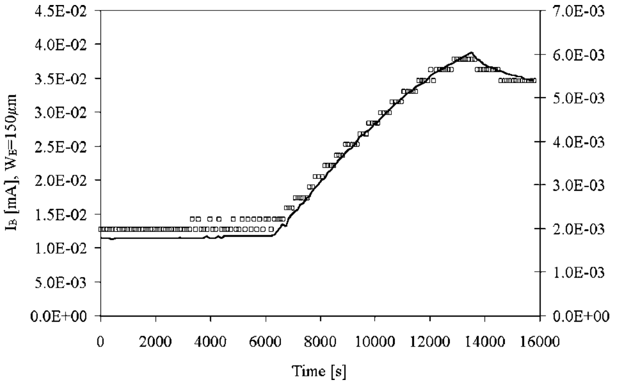

Fig. 6. Base current function of time for two different sizes of NPN transistors. Solid line: $W_E = 150\mu m$, left Y-axis. Open boxes: $W_E = 25\mu m$, right Y-axis.

Fig. 5 shows that the NPN transistor exhibits a kind of saturation in the high dose-rate region since the curve is not as linear as it is with the PNP. By the way, the effects are roughly proportional to the total dose and it is possible to extract the slope of the two periods of irradiation. For the NPN we will use the slope of the linear part of the curve.

During low dose-rate irradiation, the slopes are the following (these numbers are coming from fig. 4 and fig. 5):

NPN: $dI_{SRAD} / dt = 3.16 \times 10^{-15}\ A/s$

PNP: $dI_{SRAD} / dt = 4 \times 10^{-19}\ A/s$

While during high dose-rate, they become:

NPN: $dI_{S\ RAD} / dt = 2.21 \times 10^{-13}\ A/s$

PNP: $dI_{SRAD} / dt = 4 \times 10^{-17}\ A/s$

To check if a low dose-rate effect exists, we are taking the ratio of the slope during high dose-rate irradiation over the slope during the low dose-rate period. We obtain 61 for the NPN transistor and 100 for the PNP. These numbers have to be compared with the ratio of the beam intensity during the two periods of irradiation: 50. We can see that, within errors, the radios of effects are close to the ratio of the cause. The differences can be explained by:

- The beam stability during low dose-rate irradiation. We know that we were at the limit of the regulation system.
- The measuring errors during the low dose period. The effects seen during this time are small and the accuracy of the data is not as good as during the high dose-rate irradiation due to the test setup limitations.

Hence, there is no evidence of a low dose-rate effect.

VI. CONCLUSION

We presented the PSI proton irradiation facility. This is a good benchmark to check the components that should be used in the environment of the CMS electromagnetic calorimeter. This is because the beam used produces the same ionizing radiation and displacement damages, as there will be in the normal operation of the detector.

Using this facility, we did a low dose-rate irradiation of some UHF1-X transistors. We presented the steps of the data analysis that brought us to the conclusion that this complementary bipolar process does not exhibit any low dose-rate sensitivity.

VII. ACKNOWLEDGMENT

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