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High Gamma Ray Tolerance for 4H-SiC Bipolar Circuits

Sethu Saveda Suvanam^{1, a}, Shin-Ichiro Kuroki², Luigia Lanni¹, Raheleh Hedayati¹, Takeshi Ohshima³, Takahiro Makino³, Anders Hallén^{1, b}, Carl-Mikael Zetterling^{1, c}

¹ KTH Royal Institute of Technology, SE 164 40 Kista, Sweden

² Research Institute for Nanodevice and Bio Systems, Hiroshima University, Higashi-Hiroshima, Japan

³ National Institutes for Quantum and Radiological Science and Technology (QST), Takasaki, Japan

^asuvanam@kth.se, ^bahallen@kth.se, ^cbellman@kth.se

ABSTRACT- A high gamma radiation hardness of 4H-SiC circuits is performed. The OR NOR circuits are based on emitter coupled logic (ECL), using integrated bipolar NPN transistors. Gain degradation in individual bipolar junction transistors (BJT) is minimal up to a dose of 38 Mrad (SiO₂), but for the dose of 332 Mrad (SiO₂) a degradation of 52% is observed. The SiC BJTs show higher radiation hardness than existing Si-technology and high stability under temperature stress. It is proposed that the oxide charge-dominated recombination is the key base current recombination mechanism contributing to gain degradation. An improvement in the gain is seen after annealing at 400 °C for 1800 s due to the possible annealing of some of the oxide defects contributing to the oxide charge.

Index term- 4H-SiC, Bipolar Junction Transistors, Gamma rays, Logic Circuits, Ionization radiation

I. Introduction

Advances in space and nuclear technologies are limited by the capabilities of the conventional silicon (Si) electronics. Hence, there is a need to explore materials beyond Si with enhanced properties to operate in extreme environments. For such applications, many material technologies have been explored [1-5]. Among them, the wide bandgap semiconductor 4H-SiC is a promising candidate for high temperature and radiation applications due to its relatively high atomic displacement energy (20-35 eV), three times larger bandgap, and higher temperature conductivity compared to Si [5,6].

4H-SiC devices and integrated circuits with different design configurations have been shown to operate in extreme high temperature up to 600 °C [7-10]. Apart from exhibiting an ability to operate at high temperatures, these devices are also able to function under high radiation environments (in Mrad range) for space and nuclear applications. Various device types of 4H-SiC, such as diodes, MOSFETs, BJTs and JFETs have been tested under different radiation environments like protons, neutrons and gamma ray [11-17]. Among these

Figure 1. Cross section and top view of bipolar junction transistor in SiC. The shaded area indicates the surface passivation around the base-emitter junction proposed to dominate the degradation seen for high doses.

devices BJTs are generally considered to be the most radiation hard.

In our previous publication on 4H-SiC NPN BJTs exposed to 3 MeV protons, it was proposed that the ionization effects in the dielectric due to proton irradiation was the key gain degradation mechanism [15]. While protons create both the displacement and ionization damage, it is known that gamma radiation mainly creates ionization damage in electronic devices. Previous studies on 4H-SiC Schottky diodes irradiated up to 1 Mrad gamma ray dose have shown no degradation in forward current-voltage characteristics, but an increase in reverse breakdown voltage is observed due to negative charge build-up in the passivation oxide [18]. On the other hand, commercially available 4H-SiC power MOSFETs irradiated up to 1.5 Mrad of gamma ray at room temperature show a large negative threshold voltage shift and becomes inoperative after a dose of only 300 krad [19].

However, there is very sparse literature available on gamma ray studies on 4H-SiC BJTs, and in this paper, we investigate 4H-SiC BJTs and OR-NOR integrated logic circuits irradiated with extremely high dose (up to 332 Mrad) of gamma rays from a ⁶⁰Co source. Forward current gain degradation up to 38 Mrad (SiO₂) was found negligible, but for the dose of 332 Mrad (SiO₂), a degradation of 52% is seen. Results have shown that the 4H-SiC bipolar technology is exceptionally

Figure 2. Collector current (I_C) versus collector voltage (V_{CE}) for different gamma ray doses at a base current of 0.2 mA.

radiation hard, about 2 orders of magnitude higher than Si technology.

II. Experiment

A) Sample fabrication

Bipolar transistors and OR-NOR gates were fabricated in an in-house bipolar SiC technology on 100 mm wafers. The process is ion-implantation free, and all regions of the transistors are defined by etching out regions in a six layer epitaxially grown stack on 4H-SiC wafers. After etching, sacrificial oxidation is performed to remove surface damage, and then a passivation oxide is deposited and annealed in N_2O . Ohmic contacts to n- and p-type regions are made with Ni and Ni/Ti/Al respectively. For process details see [7] and references therein. Resistors are etched in the collector layer. All devices are junction isolated from each other, see cross section in figure 1. The shaded area indicates the sensitive region of the emitter-base mesa passivation.

B) Irradiation

Gamma-ray irradiation testing is carried out at the facilities of National Institutes for Quantum and Radiological Science and Technology (QST), Takasaki, Japan. Four chips, as described above, are used for radiation testing. The free standing chips are irradiated by gamma rays from a ^{60}Co source with a dose rate of 278 rad (SiO_2)/s and at room temperature (RT) with zero biasing. The total accumulated dose was 1, 3, 9, 38, 108 and 332 Mrad (SiO_2), respectively. There is about 5% chip to chip variations in the forward current gain characteristics for the unirradiated samples and is attributed to the variation in the doping of the epitaxial layer along the wafer. To remove the influence from this variation, a same chip was used

Figure 3. Base current (I_B) and collector current (I_C), as a function of base voltage (V_B) for different gamma ray doses.

to irradiate at relatively lower doses of 1, 3 and 9 Mrad (SiO_2).

C) Electrical Measurements

Static DC measurements on the BJTs (forward Gummel and output characteristics) and voltage transfer characteristics on OR-NOR logic circuits were performed before and after irradiation. In accordance with Method 1019 of MIL-STD-883 testing protocol [20], both the logic gates and transistors were measured within 1 hour after the irradiation. Additionally, transistors were measured at 2, 4, 8 and 12 hours after the irradiation to validate the recovery from the transient effects. Samples were measured at various time over a period of three months from the time of irradiation to investigate the recovery from the self-annealing at room temperature. Furthermore, high temperature annealing measurements were performed on the sample irradiated with a dose of 38 Mrad (SiO_2). For these measurements, the chip was annealed at the temperatures of 250, 300, 350, 400 and 425 °C for 1800 s at each annealing step. In situ static measurements were performed on the transistors at 60, 300, 600, 1200 and 1800 s while annealing at each temperature. Note that it takes about 150 s to

Table 1: shows the variations in the radiation induced gain degradation (β_{post}/β_{pre}) for three different emitter-base mesa passivation areas.

Dose	108 Mrad (SiO_2)	332 Mrad (SiO_2)
Emitter-Base passivation area		
600 μm^2	77.9%	53.3%
750 μm^2	76%	50.8%
1050 μm^2	74.4%	48.6%

Figure 4. Forward current gain as a function of collector current for different irradiation doses. From a total dose of 38 Mrad (SiO_2), gain strongly decreases with dose.

perform a full static DC measurement. After each annealing step the chip is cooled to room temperature and the static DC measurement is performed again to assess the post annealing recovery of the transistor.

It should also be noticed that no change could be measured in the specific contact resistance for emitter, base and collector contacts before and after irradiation. Also for specific contact resistance measurements after the 425 °C annealing, no change could be seen compared to the contact resistance measured before the annealing started. The results shown below should therefore not be related to the metallization or contact layers.

III. Results

A) DC measurements at room temperature

Figure 2 shows the collector current (I_C) versus collector voltage (V_{CE}) at a base current (I_B) of 0.2 mA of a representative BJT measured at different total doses. It is observed that collector saturation current (I_{CS}) decreases with radiation dose, particularly from 38 Mrad (SiO_2). A reduction of 45% and 65% in the I_{CS} for the dose of 108 and 332 Mrad (SiO_2), respectively, is observed, compared to non-irradiated device. Even at the highest dose, the device is still functioning, although the amplification has been reduced by 55%.

Figure 3 shows the base current (I_B) and collector current (I_C) respectively as a function of base voltage (V_B) for different irradiations. It can be observed that I_B at low injection levels increases as

Figure 5. Forward current gain measured at different times after the gamma ray exposure. A slight improvement in gain for a dose of 332 Mrad (SiO_2) is seen due to self-annealing after 12 hours of exposure.

the dose increases. On the other hand, no influence of radiation is seen in I_C for the V_B in the range of 2.5 to 2.75 V. This is a typical phenomenon in the BJTs exposed to ionizing radiation [4]. The increase in base current can be caused by an increase in surface states along the emitter-base mesa, or the build-up of charges in the passivation oxide, or a combination. Both these effects will be discussed in Section IV. Collector leakage current increase with dose can be attributed to the leakage due to the surface/oxide traps formed at the base-collector passivation.

Figure 4 shows the forward current gain ($\beta = I_C/I_B$) versus I_C for various irradiation doses. The sharp drop in gain at high collector currents is due to forward biasing of the base collector junction and high injection in the low doped collector [21]. For doses up to 9 Mrad (SiO_2), β degradation is minimal, measured at $I_C=20$ mA. From a total dose of 38 Mrad (SiO_2) and higher, β strongly degrades. For the total dose of 332 Mrad (SiO_2) 53% degradation in β at $I_C=20$ mA can be observed, in agreement with results presented in Fig. 3. The gain degradation as function of dose is a result of an increase in base current for the low injection levels, as described above. Table 1 shows the variations in the radiation induced gain degradation for three BJTs with different emitter-base mesa passivation areas. Gain degradation scales with the mesa passivation area due to the increase in the oxide passivation area exposed to the ionizing radiation, creating more oxide/interface defects.

B) Annealing effects on irradiated devices

Figure 6. Reduction in forward current gain measured in situ as a function of post annealing temperature comparing 38 Mrad (SiO₂) and virgin sample.

In this section annealing effects on the irradiated BJT are presented. Figure 5 shows the forward current gain measured at room temperature at different times after the gamma ray exposure for three different total doses. It can be observed that for doses up to 108 Mrad (SiO₂), β remain constant after the gamma ray exposure. Only for the device radiated with the dose of 332 Mrad (SiO₂) gain was found to improve slightly by 7% after 4 hours self-annealing at room temperature. The small improvement in β for the highest dose could possibly be because of the annealing of a smaller amount of oxide charges, only seen in the highest dose sample. All the devices have been measured several times during the span of three months after the gamma ray exposure and the gain was found to be unchanged after the initial self-annealing for the highest dose case.

Following the three month room temperature self-annealing, the samples were annealed at higher temperatures and DC measurements were done at the various annealing stages, as mentioned in Section II.c. Figure 6 shows the relative reduction in gain, measured in situ (while annealing), versus the annealing temperature after 60 s annealing stress time for 38 Mrad (SiO₂) and non-irradiated samples. The gain is seen to be monotonically reduced for higher temperatures, but this temperature dependence of β is well known for 4H SiC BJTs [7] and is mainly due to reduced carrier mobilities. The point with Fig. 6 is to show that both the non-irradiated reference and 38 Mrad (SiO₂) sample show very similar gain reduction as a function of annealing temperature. It appears that the gamma dose of 38 Mrad (SiO₂) does not change this dependence. Figure 7 shows the change in gain as a function of annealing time at different post-irradiation annealing temperatures for the total dose of 38 Mrad (SiO₂). At each of the temperatures, the samples were measured 4 times during the 1800 s

Figure 7. Forward current gain as a function of annealing stress time for 38 Mrad (SiO₂) irradiated sample measured in situ at different annealing temperature for 38 Mrad (SiO₂) sample.

Figure 8. Increase in the forward current gain measured at room temperature after various post irradiation annealing temperature for the 38 Mrad (SiO₂) sample.

long annealing and very small changes in β are recorded. A similar trend was observed for the sample irradiated with a dose of 332 Mrad (SiO₂) with gain remaining constant as a function of annealing stress time.

Figure 8 shows the current gain measured at room temperature after different post irradiation annealing temperatures after 1800 s for the sample with a total dose of 38 Mrad (SiO₂). The gain is normalized to the value before radiation. Previous investigations on the annealing effects of 4H-SiC bipolar devices irradiated with gamma rays dose of 42 Mrad have showed a full recovery of the Gummel characteristics after an 420 °C anneal for 1800 seconds [22]. In contrast, our sample did not show a full recovery of the gain and instead appears to saturate after the annealing of 425 °C.

C) Measurements on integrated circuits

Figure 9. Voltage transfer characteristics of a) OR output b) NOR output of OR-NOR logic gates at different irradiation doses.

The chips also contained a number of integrated circuits and the operation of these are also monitored as a function of the gamma ray exposure to be able to extrapolate the behaviour of individual transistors to more complex systems. Figure 9 a and b show the voltage transfer characteristics (VTC) for the OR and NOR output of the OR-NOR circuit respectively. The centre intersect point of the VTC, known as the logic threshold, was observed to be approximately constant over the entire gamma dose range for both the OR and NOR circuits. A marginal change (~ 0.4 V) in the logic swing, defined as the difference between logic high and low signal, was observed for a dose of 108 Mrad (SiO_2). Logic swing for the highest dose decreased by 1 V compared to the non-irradiated circuit. One of the figures of merit for the digital circuits is the noise margin for high and low logic level (NM_{high} and NM_{low}). The NM_{high} is defined as the difference between the high output voltage level and the high input voltage level, and vice versa for the NM_{low} . Noise margins can be extracted by plotting VTC characteristics and its inverse as shown figure 10. From figure 10 it can

Figure 10. Voltage transfer characteristics (VTC) of NOR output for different radiation dose. For each dose, VTC is plotted with its inverse to graphically extract noise margin.

be seen (for the NOR output of the gate) that both the NM_{high} and NM_{low} is reduced for 108 Mrad (SiO_2) compared to 0 Mrad and that no NM_{low} could be extracted for the 332 Mrad (SiO_2) irradiated sample. However, the BJTs in the OR-NOR logic gate are still functional.

IV. Discussions

Figure 11 compares the forward current gain degradation for various technologies, involving different semiconductors, as a function of gamma radiation dose. Radiation effects on the devices strongly depend on the design and structure of the devices, dose rates of the radiation and an absolute comparison of different technologies is very difficult. In Fig. 11 we have compiled the degradation trend under ^{60}Co gamma radiation for bipolar transistors manufactured with different radiation hard technologies available in the literature. The selection is somewhat arbitrary and does not claim to be extensive. However, the results presented for the SiGe [24] and 4H-SiC power BJT [22] is the best radiation hard device (in terms of gain degradation) under gamma ray authors have found in the literature. It can be clearly observed that our device with 4H-SiC technology has a superior tolerance to gamma radiation. BJT devices made in a Si technology [25] show 40% degradation in gain for a dose of 2 Mrad, whereas our 4H-SiC BJTs show a degradation of 45% for a dose of 332 Mrad (SiO_2). While devices with SiGe technology [24] and the previously reported 4H-SiC power BJT showed a much better tolerance in comparison with Si technology, they were still one order of magnitude lower than our 4H-SiC technology. It can be seen that our 4H SiC BJTs show a very high tolerance for ionizing radiation. In addition, these devices also show an extreme thermal stability, as shown in Figs. 5 and 6. This could open up application areas for electronics in extremely harsh environments, where no other

Figure 11. Comparison of forward current gain degradation for various technologies as function of gamma radiation dose. Devices with 4H-SiC technology show superior tolerance to gamma radiation in comparison to other technologies.

semiconductor technology have been able to operate.

In radiation tests with MeV gamma rays from ^{60}Co it is also possible to induce displacement damage in the semiconductor bulk due to Compton scattering. The probability for such events is relatively small, but considering the high doses used in this experiment, this possibility is maybe not negligible. On the chips various integrated resistors are also included, where the resistance is given by the semiconductor resistivity, and the geometry of the structure. Displacement damage will create point defects that compensate for the doping, thereby increasing the resistivity. However, no increase in resistance of the integrated resistors is observed, even for the highest gamma dose. We then conclude that the effect of displacement damage in the semiconductor bulk can be neglected and only ionizing effects are considered for the interpretation of the results of this investigations. For power devices this may not be the case, since the lowest doping levels can be orders of magnitude lower for these devices than in these integrated BJTs, and compensation effects will be seen for lower levels of displacement damage.

Irradiating bipolar devices with ionizing radiation induces two major effects that influence the BJT operation: (i) increase in the surface states along the passivation oxide and semiconductor interface, and (ii) build-up of positive charges in the oxide [26]. The former effect (i) increases the surface recombination velocities (SRV) while the latter (ii) results in an increase in the emitter-base junction space-charge region. Both of these effects results in an increase in the base current. Therefore, excess base current, i.e. the difference between the base current after and before gamma exposure ($\Delta I_B = I_{B\text{post}} - I_{B\text{pre}}$), is an important parameter that helps to understand the effects of ionizing radiation on bipolar devices. It is possible to determine which of the recombination processes are more dominant in influencing the excess base current due

Figure 12. Excess base current versus base voltage for four doses. All the doses have an ideality factor greater than 2 indicating oxide charges to be dominant recombination mechanism.

to radiation [27]. This can be achieved by plotting ΔI_B versus base voltage (V_B) and extracting the ideality factor (n). If the ideality factor for low injection levels is between 1 and 2 the recombination is dominated by the surface states. If the ideality factor is greater than 2 ($n > 2$) the recombination is dominated by the oxide charge.

Figure 12 shows the ΔI_B as a function of base voltage, calculated from Fig. 3 at low injection level, for four different gamma doses. It can be seen that all the four devices exposed to different total dose levels have the same slope with the ideality factor greater than 2. This indicates that the oxide charge is main cause for the recombination at the emitter-base mesa and the key contributor to the current gain degradation. In Si BJT devices, exposed to dose rate of 10 rad (Si)/s it is reported that the excess base current up to a total dose of 1 Mrad has two distinct ideality factors [25]. Initially, at low base voltages, the recombination is also influenced by the surface recombination, for doses above 1 Mrad, the increase in base current is primarily due to oxide charge recombination.

Figure 13. Excess base current versus base voltage comparing the variations post 400 °C annealing for a dose of 38 Mrad (SiO_2).

Figure 13 shows the ΔI_B as a function of base voltage for 38 Mrad (SiO_2) sample after 400 °C post irradiation annealing. The ΔI_B after 400 °C annealing decreases by a factor of 2-3 for a base voltage of 2.5 V and it remains constant for further annealing at 425 °C. No significant change in the ideality factor was found after annealing i.e $n > 2$; implying that the oxide charge is still the main contributor to the recombination mechanism. Thus, the improvement in the gain after annealing (Fig. 8)

can be attributed to the possible annealing of some of the oxide defects contributing to oxide charge.

Figure 14 shows the noise margin (NM) extracted from the VTC of OR-NOR gate as a function of gamma irradiation dose. It can be observed there is no significant change in the high NMs for the OR and NOR gates respectively. Whereas, the low NMs for both the outputs rapidly degraded from the total dose of 38 Mrad (SiO_2). This is attributed to the reduction in the low logic level. This effect can be overcome by designing the circuits for higher logic swing, or by shifting the logic threshold, resulting in logic circuits capable of operating in radiation fields in excess of 100 Mrad.

V. Conclusion

We have demonstrated the radiation hardness of 4H-SiC logic circuits exposed to extremely high doses (332 Mrad (SiO_2)) of gamma radiation. Up to a total dose of 38 Mrad (SiO_2), current gain

Figure 14. Noise margin extracted from the VTC curves of OR-NOR gate as a function of irradiation dose.

degradation is minimal and, for the total dose of 332 Mrad (SiO_2), around 50% degradation in current gain is observed. By analysing the excess base current at low voltage levels, it is found that the oxide charge dominated recombination at the emitter-base mesa and is the key contributor for current gain degradation. It is also seen that, for the chip irradiated with 38 Mrad (SiO_2), a 92% recovery in gain is possible by annealing at 400 °C

for 1800 s. Finally, it is concluded that noise margins extracted from the VTC of the OR-NOR gate are stable up to a dose of about 10 Mrad (SiO_2), but by redesigning the circuits for higher logic swing, logic gates based on 4H-SiC BJTs could continue to operate above doses of 100 Mrad.

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