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Charge Enhancement Effects in 6H-SiC MOSFETs Induced by Heavy Ion Strike

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35-WORD ABSTRACT:
A transient current following an ion strike in 6H-SiC MOSFETs was measured under the various bias configuration. The charge enhancement by parasitic bipolar transistor was evaluated by using 18MeV-O and 50MeV-Cu microbeam.

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1. INTRODUCTION

Metal Oxide Semiconductor Field Effect Transistor (MOSFET) made of Silicon Carbide (SiC) is regarded as a promising candidate for high-power and high-frequency electronic devices because of its excellent electrical and thermal properties. The benefit to using SiC material instead of other more established materials such as Silicon (Si) or Gallium Arsenide (GaAs) is that compact, lightweight, and, highly energy efficient devices operating at high temperature can be developed. Moreover, it is well known that the SiC material is extremely radiation resistant. Therefore, it is expected that the SiC devices will be particularly useful in terrestrial applications as well as in space applications. To use SiC devices in space radiation environments, it is important to understand the effect of various types of irradiation on their electrical characteristics.

Space radiation causes destructive or non-destructive events such as Total Ionizing Dose (TID) effect, Displacement Damage Dose (DDD) effect, and Single Event Effect (SEE). We have studied the TID effects on 6H-SiC MOSFETs as well as MOS capacitors over several years [1, 2]. After high dose irradiation (several MGy) of the MOSFETs at high dose rate (several thousands of Gy/h), the channel mobility decreases and the threshold voltage shifts due to interface traps and trapped charges in gate oxide. However, the degradation was extremely low compared to that in gamma-ray irradiated Si MOSFETs. For MOS capacitors fabricated on 4H- and 6H-SiC wafers, the capacitance-voltage curve shifts due to interface traps and trapped charges, in the same manner as MOSFETs [3-5]. More noteworthy is that the degradation of the electrical properties strongly depends on the oxidation process of MOSFETs and MOS capacitors. On the other hand, the DDD effects on SiC diodes have been the subject of controversy from the point of view of radiation-hard detectors. As a result of electron and gamma-ray irradiations, it was found that the Charge Collection Efficiency (CCE) decreases with increasing fluence [6, 7]. CCE is one of the most important physical parameters indicating the performance of particle detectors. At the same time, the forward current of Schottky Barrier Diodes (SBD) and pn junction diodes in high injection region dramatically decreases with increasing fluence. This is due to the decrease of the effective carrier concentration in the epitaxial layer. In contrast to the TID and DDD effects, few attempts have so far been made to study the transient response when an ion strikes a SiC device.

For Si bulk and Silicon-on-Insulator (SOI) MOSFETs, the effects of charge amplification following an ion strike have been discussed in the literature [8]. Similar mechanisms are reported also in 4H-SiC and GaAs Metal Semiconductor Field Effect Transistors (MESFETs) [9, 10]. Recently Lee et al. have reported the enhanced charge collection of 6H-SiC MOSFETs [11]. These transistors are devices with an inherent parasitic bipolar structure resulting in charge amplification. The purpose of this paper is to further highlight the charge collection phenomena including charge amplification, occurring when an ion strikes SiC MOSFETs.

2. EXPERIMENTAL

2.1. Sample fabrication

Fig. 1 shows the cross-sectional structure of the N-channel MOSFETs (NMOSFETs) used in this study. NMOSFETs were fabricated on a p-type 6H-SiC epitaxial layer (50 μm thick) with a net acceptor concentration of 2.3×10^{15} cm^{-3}. The epitaxial layer was grown on a 6H-SiC substrate (CREE, 3.5^{o} off, Si-face) by a hot-wall chemical vapor deposition system at the National Institute of Advanced Industrial Science and Technology (AIST). The source and drain region of the MOSFETs were formed by implanting a phosphorus (P) box profile (E_{impl} =60, 90, 140 keV) at 800 ^{o}C followed by an annealing step at 1650 ^{o}C for 3 min in Ar atmosphere. This process resulted in a P mean concentration of 5×10^{19} cm^{-3}. To avoid degradation of the surface morphology, the sample surfaces were covered with a carbon film during the annealing. After the annealing, the carbon films were removed by oxidation at 800 ^{o}C for 30 min in dry oxygen. The gate oxide was fabricated using both dry and pyrogenic oxidation

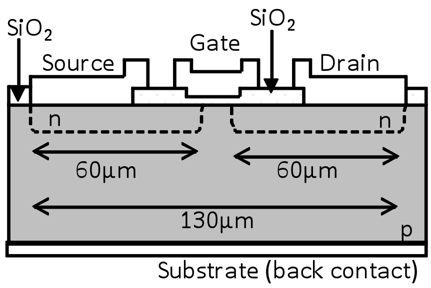


Fig. 1: Cross sectional schematic of MOSFETs.

processes to decrease the interface traps and trapped charges in the oxide layer. First the dry oxidation (O_2 at 1180 ^oC for 140 min) was performed. After the first oxidation, the post oxidation annealing was performed at 900 ^oC in Ar atmosphere for 60 min. Next; the pyrogenic oxidation (H_2:O_2 = 1:1 at 900 ^oC for 15 min) was performed. The thickness of the gate oxide was about 30 nm. Al electrodes were formed by a lift-off method. The gate length and width of MOSFETs are 10 and 200 μm, respectively. Finally, each sample was mounted on a ceramic chip carrier with microstriplines to facilitate high bandwidth measurements.

2. 2. Ion irradiation

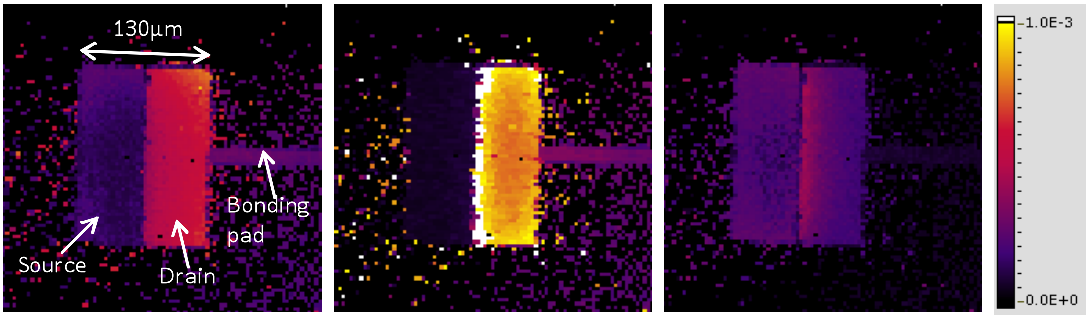
The devices were irradiated at normal incidence with a focused microbeam using either 15 or 18 MeV O ions at Japan Atomic Energy Agency (JAEA) Takasaki. The bias tees were used for sample biasing. During irradiation, the gate was biased ranging from 0 to 15V and the drain was biased ranging from 0 to 20V. The source and substrate (back side of the chip) were grounded. Fast current amplifiers (Picosecond Pulse Lab. 5840A) were connected to all electrodes for amplification. The microbeam was scanned over the source, gate and drain region. The signal induced by a single ion was recorded together with the strike location by using the 3GHz digital storage oscilloscope (Tektronix Model TDS694C). The collected charge was estimated from the integration of the transient current signals. To evaluate the Linear Energy Transfer (LET) dependence of charge collection, similar experiments were performed using 50 MeV Copper (Cu) ions at Sandia National Laboratories (SNL). The setup at SNL was almost the same as the setup at JAEA except for the oscilloscope. In these experiments, a 20GHz digital phosphor oscilloscope (Tektronix Model DPO72004) was used.

3. RESULTS AND DISCUSSION

3.1. Bipolar amplification

Two dimensional maps of transient currents characterized by the peak currents are shown in Figs. 2 (a, b, c), when the 15MeV-O ion strikes the 6H-SiC NMOSFETs. During the irradiation, the drain was biased at 10V and the other electrodes were grounded (OFF state). The powerful advantage of mapping is the ability to determine the position dependence of the event due to an ion incidence. When an ion strikes the source, no signal is observed from the drain, and signals are detected from the substrate and the source contacts. Although not shown here the transient currents have the typical shape of charge collection in a non-biased np junction diode. Since the source was not biased, the amplitudes of these transient currents are very small. When an ion strikes the bonding pad of the drain contact, small signals are detected from the substrate and the drain contacts. No signal is observed at source contact. The shape of the signal from the gate is almost the same as that from the drain except for the polarity. Since the bonding pad was fabricated on the field oxide layer, it can be assumed that the transient current on parasitic capacitance is detected.

Fig. 3 (a) shows the transient currents measured at the source, drain and substrate contacts, when an ion strikes the drain region. In the previous studies, little attention has been given to the substrate current. The substrate and drain currents have the typical shape of charge collection in a reverse biased np junction diode. At first there is a prompt component due to the drift of injected carriers along the ion track, and then there is a slower component due to the diffusion. However the amplitude of the substrate current is smaller



(a) Substrate current (b) Drain current (c) Source current

Fig. 2: Typical TIBIC peak images observed from the substrate , the drain and the source contact of 6H-SiC MOSFETs induced by 15MeV-O ions. The drain contact was biased with 10V, and other contacts were grounded.

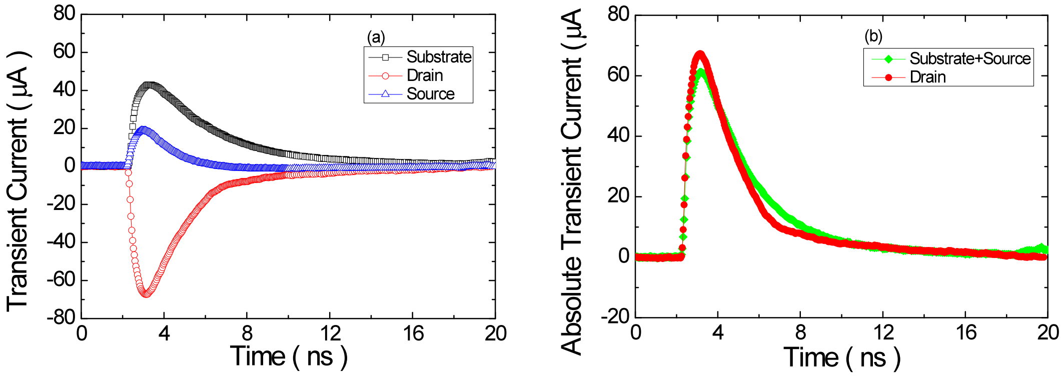


Fig. 3: Transient currents observed from the substrate, the drain, and the source contacts when 15MeV O ion strikes in drain region with following bias conditions (a) ; drain bias was 10V, and other contacts were grounded. The absolute drain current and the sum of substrate and source currents are represented in (b).

than the drain current. The reason for the difference in shape is the current provided from the source due to bipolar action. The bipolar gain is calculated to be about 2. The bipolar gain is obtained from the ratio between the total collected charge and the deposited charge [12]. The collected charge is calculated by the integration of the transient current of the drain contact. As shown in Fig. 3 (a), the source current is positive for several nanoseconds. This fact suggests that the source provides some charge to the drain. After about 5ns, the source current becomes slightly negative, indicating that bipolar amplification is over. The source current is only diffusion current, just like the drain current. Fig. 3 (b) shows the absolute values of the drain current and the sum of the source and the substrate currents. A close look at waveforms will reveal that these transient currents slightly differ from each other in shape. The most likely reason for the difference can be assumed that the gate current contributes to the charge collection.

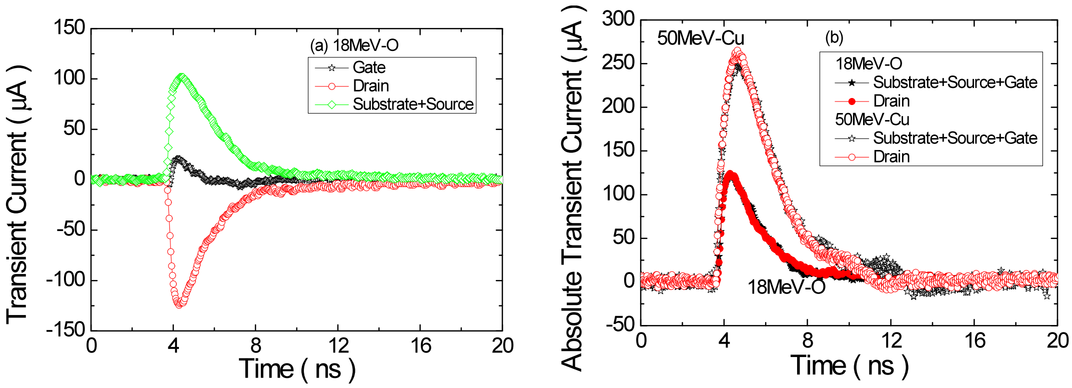


Fig. 4: Transient currents observed from substrate, drain, and source contacts when 18MeV-O ion strikes in drain region with following bias conditions (a) ; gate bias was 5V, drain bias was 20V, and other contacts were grounded. The absolute drain current and the sum of substrate, source and gate currents are shown in (b). The data observed when 50MeV-Cu strikes in drain region are also shown in (b).

3.2. Gate currents

For the reasons mentioned above, these transient currents were measured under different bias conditions. The gate was biased at 5V and the drain was biased at 20V. The source was connected together with substrate contacts, and was grounded. Fig. 4 (a) shows the transient currents when 18MeV-O ion strikes the drain region. The gate current is positive for several nanoseconds (about 2ns). After that, the gate current becomes slightly negative. This fact suggests that mainly the displacement current contributes to the gate current [13]. As shown in Fig. 4 (b), good agreement between the drain current and the sum of other currents is observed. The LET dependence of transient current is estimated by using 18MeV-O and 50MeV-Cu ions. The projected ranges of these ions are 7.97 and 7.68 μm, the LETs are 7.02 and 32.5 MeVcm^2/mg, respectively. In much the same manner as for the 18MeV-O ion strike, the drain current is very close to the sum of the other currents. The bipolar gains are estimated to be 2.7 for 18MeV-O and 1.5 for 50MeV-Cu. Although not shown here, it is found that the gate current depends on the ion strike location such as the drain and the gate, and that the gate current is independent of the gate bias.

4. CONCLUSION

Transient currents were measured for 6H-SiC MOSFETs using 15MeV-O microbeam. As a result, the typical bipolar amplification was observed from OFF-mode MOSFETs. The good agreement between the absolute drain current and the sum of source, gate, and substrate currents is observed. To evaluate LET dependence of the bipolar gain, we performed experiments with 18MeV-O and 50MeV-Cu ions. The projected ranges of these ions were approximately the same. The LET of 18MeV-O is about five times smaller than the LET of 50MeV-Cu. In the final paper, we will discuss the position dependence of the bipolar gain and the transient currents observed from all electrodes as well as the LET dependence of bipolar gain.

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