Surface & Coatings Technology 206 (2011) 864–868

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Charge generated in 6H–SiC n$^+$p diodes by MeV range heavy ions

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ARTICLE INFO

Available online 29 March 2011

Keywords:
Silicon Carbide
Transient Ion Beam Induced Current
Heavy ion incidence
Charge Collection Efficiency

ABSTRACT

Charge induced in 6H–SiC diodes by heavy ions, oxygen (O), silicon (Si), nickel (Ni), and gold (Au), at energies from 6 to 18 MeV was evaluated using a Transient Ion Beam Induced Current (TIBIC) measurement system. In the case of heavy ions with relatively light mass, such as O and Si, the high Charge Collection Efficiency (CCE) was obtained, although the CCE decreased with increasing atomic numbers. The CCE of 6H–SiC n$^+$p diodes irradiated with Au ions was approximately 40%. From the calculation using the modified Kobetich and Katz (KK) model, it is found that dense electron–hole (e–h) pairs were generated in SiC by irradiation of ions with heavy mass, such as Ni and Au, and the density was much higher than that in SiC irradiated with O ions. The decrease in the CCE due to ion irradiation with heavy mass, such as Ni and Au can be interpreted in terms of the annihilation of e–h pairs in plasma due to the Auger recombination.

1. Introduction

Accelerators with high luminosity, such as J-PARC and Super-LHC, are planed/constructed for high energy physics. For these projects, particle detectors with superior radiation hardness (Rad-Hard) are expected to be developed [1,2]. In addition, energetic particles such as protons and heavy ions are used for material modifications/creations [3,4]. In such studies, the development of Rad-Hard particle detectors is also expected for checking exact number and energy of particles into target materials. On the other hand, researchers involved in space applications make a strong effort to develop Rad-Hard electronic devices for realizing artificial satellites with high reliability and long lifetime. Since electronic devices show failure, degradation or/and break down due to charge generated by even single heavy ion incidence (Single Event Effects, SEEs), ion irradiation effects, especially heavy ions, on semiconductor devices are one of the most major issues for space applications.

Silicon Carbide (SiC) is regarded as a promising candidate for electronic devices used in harsh radiation environments because of its high radiation tolerance [5,6]. For the development of Rad-Hard particle detectors as well as Rad-Hard devices for space applications based on SiC, it is important to understand the behavior of charge generated in SiC by particle incidence. In a previous study [2], Nava et al. reported that the Charge Collection Efficiency (CCE) obtained from 4H–SiC Schottky diodes irradiated with alpha particles was 100%. It was also reported that X-rays from radio isotopes could be detected by 4H–SiC Schottky diodes [7,8]. Furthermore, the neutron detection using SiC diodes was discussed in Refs. [9] and [10]. As for light ions and X-ray irradiations into SiC, relatively large number of results has been already reported, however, in the case of heavy ion incidence, only a few studies have been reported before. From Transient Ion Beam Induced Current (TIBIC) measurements using 15 MeV oxygen (O) ions, Ohshima et al. [11] reported that almost of all charge generated in 6H–SiC pn diodes was collected. A decrease in the CCE in the case of gold (Au) ion incidence was also reported [12]. These reported results suggest that the value of charge collected by SiC diodes is affected by mass and energy of incident ions. This information is very important to develop SiC particle detectors and to understand SEEs in SiC devices. However, the sufficient information on heavy ion irradiation effects on the CCE of SiC detectors has not been obtained yet.

In this article, we will evaluate charge induced in 6H–SiC n$^+$p diodes by heavy ions, such as O, Silicon (Si), Nickel (Ni) and Au, at energy ranges between 6 and 18 MeV using a TIBIC measurement system, which is a very useful tool for the evaluation of currents generated in devices with minimizing the influence of damage, because a high-speed transient current generated by only one incident ion can be measured.

2. Experimental

The 6H–SiC n$^+$p diodes with 100–300 μm diameters were fabricated on p-type substrates (3.5° off, Si-face, CREE Inc.) with p-type epitaxial layers. In this study, two kinds of epi-layers were used. The substrates with an epi-layer at a thickness of 10 μm, in which the net acceptor concentration is $3.5 \times 10^{15}/cm^3$, were purchased from CREE Inc. On the other hand, the epi-layer at a thickness of 30 μm was grown by chemical vapor deposition at the Institute of Crystal Growth, Berlin. The net

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0257-8972/$ – see front matter
doi:10.1016/j.surfcoat.2011.03.097

acceptor concentration of the epi-layer is 8×10^{14}–1×10^{15}/cm^3. The n^+ region was formed by three-fold implantation (60, 90, and 140 keV) of phosphorus (P) ions at 800 °C and subsequent annealing at 1650 °C for 3 min in argon (Ar) atmosphere. The thickness and a mean P concentration of the implanted layer are ≈100 nm and 5×10^{19}/cm^3, respectively. During the annealing, the sample surface was covered with a carbon coat to avoid the degradation of the surface morphology [13]. For the surface termination, the filed oxide of approximately 100 nm thick was formed on the surface by pyrogenic oxidation at 1100 °C (O_2:H_2 = 1:1). The aluminum (Al) electrodes at a thickness of 25 nm were formed using lift-off technique on the n^+ region. For the backside electrodes, Al onto p-type substrates was sintered at 850 °C for 5 min in Ar, and Al at 70 nm thick was re-evaporated onto the sintered areas.

The diodes were irradiated with O, Si, Ni, and Au microbeams at energies between 6 and 18 MeV under applied reverse biases up to 150 V. Transient currents generated by irradiation of these heavy ions were measured using the TIBIC collection system at JAEA Takasaki. In the TIBIC collection system, a single event triggering system in combination with a fast switch beam shutter is installed. The transient current signals were measured using a 3 GHz Tektronix TDS694C oscilloscope, and the data were collected in real time. The details of the single ion hit TIBIC collection system are described in Ref. [14]. Before and after the TIBIC measurements, the current–voltage (*I–V*) characteristics of the diodes were measured at room temperature (RT) in a shielded and dark prove box to minimize noises. The leakage currents of the diodes were in order of 10^{-11} A at applied reverse bias of 150 V, and no significant differences in the *I–V* characteristics between before and after TIBIC measurements were observed. The degradation of the IBIC signals due to radiation damage was reported [15]. However, since the electrical characteristics of the diodes were not degraded after the TIBIC measurements in this study, it can be concluded that the single-ion hit TIBIC is a useful tool for the evaluation of the CCE with minimizing the influence of radiation damage.

3. Results and discussion

Fig. 1 shows the TIBIC signals obtained for the n^+p 6H–SiC diodes by 12 MeV–Si ion microbeam irradiation. The values of the applied reverse bias during the TIBIC measurement are described in the figure. The peak current of the transient signal increases with increasing applied bias. For the fall-time, which is defined as the time from 90% to 10% of the current transient, the value becomes smaller with increasing applied reverse bias. The applied bias dependence of the peak current and the fall time of TIBIC signals are summarized in Fig. 2. The value of the peak current monotonically increases from 0.19 to 0.50 mA at applied biases from 30 to 150 V. The value of the fall-time decreases from 0.98 to 0.48 ns at applied biases up to 150 V. These results can be interpreted in terms of an increase of the electric field in the depletion layer due to increasing applied bias.

Fig. 3 shows the TIBIC signals observed for the 6H–SiC n^+p diodes by Si ion irradiation at energies between 6 and 18 MeV. The reverse bias of 150 V was applied to the SiC diodes during the TIBIC measurement. The energies of incident Si ions are described in the figure. The peak currents of the transient signals increase with increasing the energies of Si ions. The length of the depletion layer for the SiC diodes at a reverse bias of 150 V is estimated to be longer than the projection range of 18 MeV Si ions. Thus, the charge generated in the SiC diodes is collected by the electric field in the depletion layer, although Si ions at higher energies create electron–hole pairs (charge) in deeper region. Therefore, the results shown in Fig. 3 indicate that the amount of charge collected by the SiC diodes increases with increasing Si ion energy. The amount of charge collected by 6H–SiC n^+p diodes (Q_{exp}) at a bias of 150 V can be estimated by the integration of TIBIC signals. Fig. 4 shows the charge collected in the 6H–SiC diodes as a function of the energy of Si ions (squares). For comparison, the ideal values of charge generated in 6H–SiC (Q_{ideal}) are also shown as a broken line in the figure. In this estimation, the energy loss in the top Al electrode, in the n^+ region and in the measurement system, and by non-ionizing collisions is not considered. Thus, the value of Q_{ideal} is obtained by the following equation.

$$Q_{ideal} = (E_{ion} / E_{e-h}) \text{x } e, \quad (1)$$

where E_{ion}, E_{e-h} and e are the energy of incident ions, the generation energy of an electron–hole (e–h) pair and electron charge, respectively.

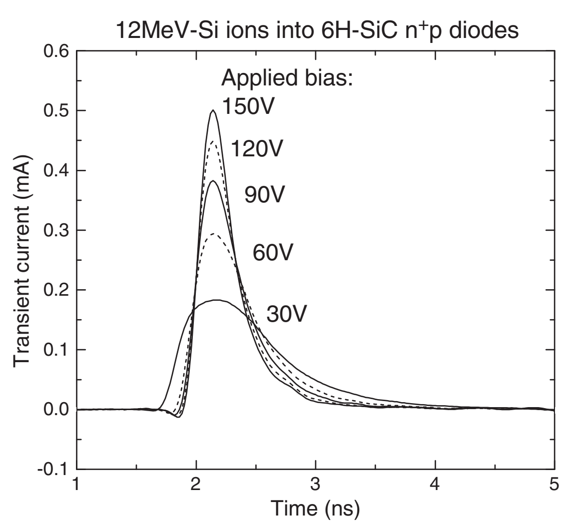

Fig. 1. TIBIC signals obtained for n^+p 6H–SiC diodes by 12 MeV Si ion microbeams. The values of the applied reverse bias during the TIBIC measurement are described in the figure.

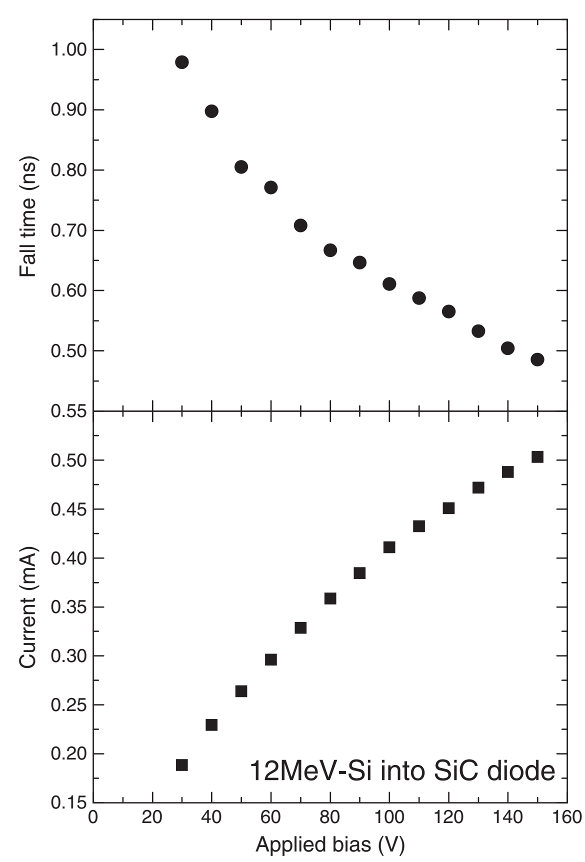

Fig. 2. Applied bias dependence of the peak current and the fall time of TIBIC signals for n^+p 6H–SiC diodes irradiated with 12 MeV–Si ions.