Development of wide-bandgap semiconductor-based dosimeter for LET distribution measurement in carbon therapy field

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Abstract. This paper presents a proof of concept of silicon carbide (SiC), a type of wideband semiconductor, based dosimeter for linear energy transfer (LET) distribution measurement at clinical carbon beam therapy field. SiC Schottky barrier diode (SBD), which has been designed for ionization detector, was utilized for spectroscopy of pristine 290 MeV/u 12C heavy ion therapy beams at Gunma University Heavy Ion Medical Centre (GHMC) facility, Japan. Measurement of LET distribution was successfully demonstrated at different depth with developed SiC SBD dosimeter. Also SiC SBD was exposed with clinical carbon beam with high intensity condition. Through CCE and deep level defect evaluation, sufficient radiation tolerance was examined for SiC SBD for futuristic usage in clinical carbons. Those results suggested that preliminary evaluation of SiC SBD was successful as energy-dispersive dosimeter for heavy ion therapy field.

1. Introduction

As technologies of carbon cancer therapy progresses, it would be an urgent matter to measure not only physical dose distribution but also factors of linear energy deposition (LET) distributions for the estimation of relative biological effectiveness (RBE) for further precise quality control and quality assurance (QA/QC) [1,2]. For such conditions, dosimeter should equip micrometre scaled spatial resolution with high accuracy of energy resolution [3,4]. It would be also practically important that dosimeter survives and stays stable in charge collection efficiency during continuous irradiation of high-energy carbons. Several type of dosimeters/radiation detectors have been developed and studied including semiconductor on insulators (SOIs) or silicon-based devices [5,6]. Silicon is reliable semiconductor in many aspects; however, its radiation tolerance is limited, and energy response of low energy carbon or protons are nonlinear if it compared with water equivalent targets.

To meet such demand, there are many re-search and development on dosimeters based on further radiation-tolerant semiconductors including SiC or diamond, where ideal detection response with
promising radiation hardness is expected. In this study, we have developed and utilized 4H-SiC Schottky barrier diode-based radiation detector for the measurement LET distributions of pristine clinical carbon for proof of concept of futuristic QA/QC by rad-hard semiconductor-based dosimeter.

2. Materials and Methods

2.1. Dosimeter preparation
Detector body of SiC Schottky Barrier Diode (SBD) was fabricated at Central Research Institute of Electric Power Industry (CRIEPI). Homoepitaxial layer was grown on 4H SiC substrate with several different thickness of epitaxial layers from 25, 69, and 170 μm were grown on different substrate for evaluation of its function. Schottky barrier contact was formed on the top side of SiC by evaporation of nickel (Ni) through a square-shaped metal shadow mask, while ohmic contacts were formed on the backside of the substrate by nickel sintering at 950 °C in Argon atmosphere. The fundamental electrical properties of SiC SBDs were investigated by current-voltage (I-V) and capacitance-voltage (C-V) characteristics. Although it would not be an extraordinary compared with recent SiC substrate, limited leakage current below 10 nA was observed from each SiC SBD with reverse bias voltage up to 200 V.

Figure 1. Picture and schematic illustration of SiC SBD detector utilized for LET measurement.

2.2. Irradiation facility and measurement setup
Pristine-carbon beam of 290 MeV/u with scanning size of 2 cm x 2 cm was irradiated at GHMC, Japan [7]. Physical dose distribution of the beam was evaluated prior to the irradiation with Advanced Markus chamber (PTW). In order to avoid pileup of the detector, the beam intensity was reduced to approximately about 5.0 × 10^6 pps or less. As illustrated in Fig. 3, thickness-tuneable water phantom was installed upstream of the detector with a precision of sub-millimetre in beam axis, and the LET distribution was measured at an arbitrary depth.

Figure 2. (a) current-voltage and (b) capacitance-voltage characteristics of SiC SBD detector.

Figure 3. Illustration and picture of irradiation and measurement condition of SiC SBD for LET measurement of 290 MeV/u clinical carbon beam at GHMC.
For the measurement of the LET distribution, signals from the SiC SBD were processed using a complex of preamplifier and a linear / shaping amplifier, $\mu^+$ probe produced at University of Wollongong, Australia. Then signal was processed by a commercially available multi-channel analyser (MCA; MCA8000D, Amptek Co., Ltd.).

2.3. Post-irradiation analysis
Detector was further irradiated with clinical carbon beam with total dose up to 10 Gy and those degradation in charge collection efficiency was evaluated. Evaluation of radiation tolerance of SiC SBD was demonstrated at same beam line with a pencil beam condition using clinical beam fluence of approximately 10$^9$ pps of pristine carbon pencil beam of 290 MeV/u. Three different doses-equivalence of 1, 10, and 100 GyE were exposed to three SiC SBDs with different exposure time of 10 seconds, 1 minutes, and 10 minutes, respectively. The maximum dose is approximately equivalent to the monthly exposure of radiation, if the operation is demonstrated in clinical dose condition. While there are no particular regulation on semiconductor-based dosimetry at this research and development phase. However, it would practically be considered to be operated in reductant beam fluence such as 10$^6$ pps. Therefore, those irradiations are enough high to investigate the lifetime of the probe.

After the exposure, detector responses of SiC SBDs were examined by checking charge collection efficiency (CCE) utilizing $^{241}\text{Am}$ alpha checking source. Bias voltage dependencies of CCE was compared between virgin and irradiated samples for the investigation of CCE degradation caused by radiation induced damages in SBDs. In addition to CCE evaluation, deep level transient spectroscopy (DLTS) was performed to investigate electrically active defects in damaged SiC samples after clinical carbon exposure.

3. Results and Discussion

3.1. LET measurement
Figure 4 illustrates water-equivalent LET spectra obtained by SiC SBD at four different depth in water tank (phantom), with physical dose distribution measured by ionization chamber. As seen in figure, it was confirmed that the LET distribution obtained by the measurement shifted to the high LET side as the water depth increased from the plateau region to the Bragg peak region. Each spectrum had multiple peaks corresponding to carbon ions and its fragments. Unfortunately, current energy resolutions and dynamic range of measurement system is not ideally optimized for SiC SBD and contributions of light elements i.e. proton or helium are not well defined to perform precise consideration of energy deposition by different species of fragments. Therefore, dose averaged LET delivery and RBE estimation based on those measurement, as shown in Fig. 5, should contains over- and under-estimation at this moment. Beside of these facts, estimation of alpha and beta parameters for RBE delivery from conventional Japanese model using averaged LET measurement [8] was fundamentally functionated as seen from the changes in those parameters at different dose deposition at plateau and Bragg Peak points.

![Graph showing LET measurement](image)

**Figure 4.** (left) Physical dose distribution measured by ionization chamber and (right) four LET spectra obtained by SiC SBD at particular point from (a) to (d).
3.2. Evaluation of radiation tolerance
Figure 6 indicates differences in charge collections for carbon-irradiated SiC SBDs. Through the bias voltage dependencies of CCE, degradation of SiC SBD was not significantly observed and almost negligible until the exposure reaches 100 GyE. Creation of new defect levels is able to be investigated by DLTS analysis as shown in Fig. 7. At 300K each sample including virgin SiC SBD had a peak, however, there are no significant reduction or generation of DLTS peaks with different carbon radiation exposure. Through the activation energy analysis, the peaks ($E_a=0.65-0.69$ eV) fall into well-known $Z_{1,2}$ centres residential in SiC substrate [9]. These results of two different analytical approach evidentially suggested SiC SBD are not strongly degraded by clinical carbon exposure up to 100 GyE.

4. Conclusions
As a proof of concept, 4H SiC SBD was utilized for LET measurement at clinical carbon beam irradiation field at GHMC, Japan. Differences in LET spectra were successfully obtained as well as those radiation hardness test with continuously irradiated with clinical carbon beams up to 100 GyE. Results suggested that SiC is promising candidate of semiconductor-based dosimetry at clinical carbon field with desirable radiation tolerance. For futuristic application in the clinical field, further improvements are necessary including three-dimensional process on substrate for defined detection volume to adapt updated biological model such as micodosimetric kinetic model (MKM) [10], as well as optimization of peripheral circuit and system for wide dynamic range and low LET fragment detection.
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