Dose Estimation for X-ray Irradiation of Insulated Gate Bipolar Transistor

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1. Introduction

A previous study was conducted on the effect of gamma irradiation on MOS-based devices such as Insulated Gate Bipolar Transistor (IGBT) [1]. The study on kilo-voltage X-ray induced change in the electrical characteristics of IGBT has been followed. To study the effect of X-ray irradiation on an IGBT, an evaluation of the total ionizing dose (TID) delivered to the IGBT has been required. In a fixed irradiation condition, the dose rate delivered to the target is determined by the target's physical properties. However, the dose rate of the irradiation facility is calibrated by using a specific dosimeter. Thus the dose rate delivered to the IGBT for X-ray irradiation should be estimated separately.

In the present study, we simulated the IGBT X-ray irradiation experiment using the Monte Carlo code. The energy deposition rates in the dosimeter's sensitive layer and IGBT's inner layers were calculated to compare the dose delivery characteristics of them. Finally, the dose estimation factors were suggested to estimate the dose in the IGBT layers.

2. Methods and Results

2.1 Specification of X-ray irradiator and IGBT device

A trench-gate NPT IGBT with an n-channel was considered the target sample. The IGBT device was fabricated on a six-inch n-type Si wafer involving six different masks in the fabrication process [1]. The schematic vertical structure of the IGBT device used in the present study is shown in fig. 1. The total thickness of the device was about 107.15 μm including a 4 μm thick front electrode and a 0.45 μm thick back electrode. The thickness of the p^+ collector and gate oxide was 0.2 μm and 1.5 μm, respectively.

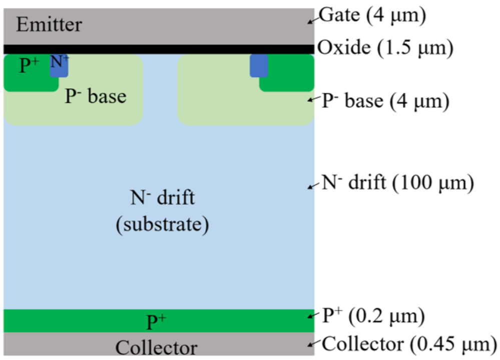

Fig. 1 A schematic vertical structure of the IGBT device.

A hard X-ray irradiation facility in Radiation Bioengineering Laboratory (RadBio Lab) at Seoul National University (SNU) was considered the X-ray irradiator [2]. Fig. 2 shows a schematic of the X-ray irradiation system. The facility consists of an X-ray beam tube (450-D08, YXLON, Germany), a high voltage power supply, a target cooler, a system control unit, and shielding systems. The maximum operating anode voltage is 450 kV and the tube current is limited to 10 or 20 mA depending on the operating anode voltage. The solid angle of the beam outlet is 40° and the beam of energy below 20 keV is removed by a 3 mm-thick aluminum filter. The dose delivered to samples can be measured by using gafchromic EBT film (ISP, USA) [3]. Gafchromic EBT film changes its color in response to radiation exposure on the 28 μm thick sensitive layer.

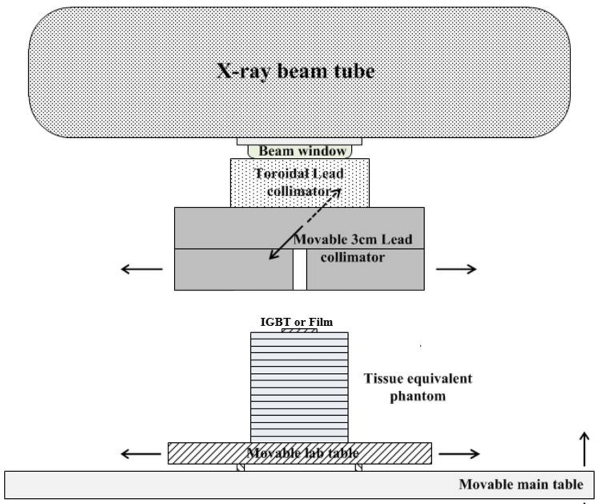

Fig. 2 A schematic of the X-ray irradiation system.

2.2 Monte Carlo simulation

The IGBT X-ray irradiation was simulated using the MCNP 6.1 code [4]. Each structure of the X-ray irradiation facility, the gafchromic EBT film, and the IGBT device was simulated in the MCNP geometry. The simulation was conducted at 150, 250, 350, and 450 kV anode voltages of the X-ray beam tube. The anode voltage determines the maximum energy of the bremsstrahlung X-ray spectra. The bremsstrahlung X-ray spectra were calculated by using the MCNP X-ray beam tube model [2]. The distance between the beam window and the target was assumed to be 40 cm. The total energy deposition in the gafchromic EBT film's sensitive layer and the IGBT's inner layers (substrate, oxide, and total) were calculated using the *F8 tally. Photon-induced ionization damage is initiated when electron-hole-pairs are generated along the track of secondary electrons emitted via photon-material interaction [5]. The *F8 tally can track secondary electrons and calculate the total energy deposition in a cell. The simulation was done for 10^8 particles and relative error was decreased by using variance reduction techniques.

2.3 Ratio of IGBT's dose rate to dosimeter's dose rate

The calculated energy deposition was converted into dose by dividing the mass within the cell and converting the units from mega electron volts (MeV) to joules (J). To compare the dose delivery characteristics between the gafchromic EBT film and the IGBT, the ratios of the IGBT inner layers' dose rate to the gafchromic EBT film's dose rate at 150, 250, 350, and 450 kV anode voltage are presented in fig. 3.

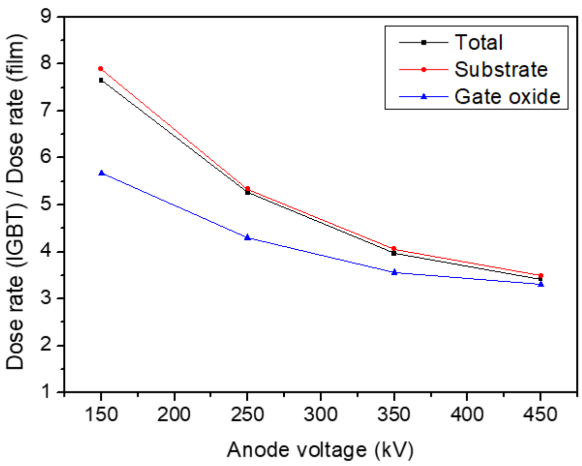

Fig. 3. The ratios of the IGBT inner layers' dose rate to the gafchromic EBT film's dose rate at 150, 250, 350, and 450 kV anode voltage.

At the anode voltage of 150kV, the ratios for the total layers (107.15 μm thick), the substrate (100 μm thick), and the gate oxide (1.5 μm thick) were 7.65, 7.89, and 5.67, respectively. The dose rate in the IGBT was higher than the dose rate in the gafchromic EBT film because the effective atomic number and density of the IGBT are higher than those of the film. In the energy region of tens kilo-electron volts (keV), the photoelectric effect is the dominant interaction of photons with the target atoms. And the probability of photoelectric effect mainly depends on the atomic number of the material. Therefore, the photons interact more in the IGBT than in the film. As the anode voltage increased, the dose rate ratios for the IGBT decreased because the Compton effect became dominant. At the anode voltage of 450kV, the ratios for the total layers (107.15 μm thick), the substrate (100 μm thick), and the gate oxide (1.5 μm thick) were 3.42, 3.49, and 3.31, respectively.

The dose rate in the oxide layer was lower than the dose rate in the substrate layer because the atomic number of elements in the oxide layer was lower than those in the substrate. The difference between the dose rate ratio of oxide and substrate decreased as the anode voltage increased. Also, the secondary electrons did not lose all energy and escape the oxide layer because the thickness of the layer was very thin. However, the effect of secondary electrons' loss was not significant due to charge compensation from other layers.

The ratios of the IGBT layers' dose rate to the gafchromic EBT film's dose rate were referred to as dose estimation factors. These factors can be used to estimate the dose of IGBT layers only for the X-ray irradiation facility at SNU RadBio laboratory.

3. Conclusions

The energy deposition in the IGBT by X-ray irradiation was simulated using the MCNP 6.1 code. The ratios of the IGBT layers' dose rate to the film's dose rate were presented and referred to as dose estimation factors for the IGBT. These factors can be used to estimate the dose of the IGBT layers only for the X-ray irradiation facility at SNU RadBio laboratory.

Acknowledgements

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