Present status and prospects of R&D of radiation-resistant semiconductor devices at JAEA

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ABSTRACT

Research and development of radiation resistant semiconductor devices have been performed at Japan Atomic Energy Agency (JAEA) for their application to electronic system used in harsh environments like space, accelerator and nuclear facilities. Such devices are also indispensable for robots and equipment necessary for decommissioning of the damaged reactors at Fukushima Daiichi Nuclear Power Plants. For this purpose, we have fabricated transistors based on a wide band-gap semiconductor SiC and examined their radiation degradation. As a result, SiC-based transistors exhibited no significant degradation up to 1MGy, indicating their excellent radiation resistance. Recent our R&Ds of radiation resistant devices based on SiC are summarized and reviewed.

Keywords: radiation resistant devices, SiC semiconductors, electronic system used in harsh environment

1. INTRODUCTION

Japan Atomic Energy Agency (JAEA)[1] was established in October, 2005 by merging Japan Atomic Energy Research Institute (JAERI) and Japan Nuclear Cycle Development Institute (JNC). At JAEA, we are making basic and applied research of nuclear energy as well as R&Ds of nuclear fuel cycle technology such as fast breeder reactor (FBR), nuclear fuel for FBR, reprocessing, and treatment and disposal of high level wastes. To perform such R&Ds, we have eight research directorates, i.e., nuclear safety research center, advanced science research center, nuclear science and engineering directorate, quantum beam science directorate (QuBS), fusion research and development directorate, advanced nuclear system research and development directorate, geological isolation research and development directorate, and nuclear cycle backend directorate. Especially at the QuBS, we promote R&Ds for “quantum beam science and technology”, which will bring innovation not only to nuclear energy field but also the other wide technology fields, as described below.

Quantum beams, which involve electromagnetic waves like lasers, X-rays, γ-rays, etc. and energetic particles like electrons, protons, neutrons, ions, etc., possess both wave and particle characteristics. Quantum beams allow us to make material processing in nanometer level (atomic or molecular level) because they interact with constituent atoms of a material to change their configuration, composition, and electronic state. It means that quantum beams have “function of processing”. Such quantum beam interactions also cause changes in the beams themselves, e.g., the beam direction and energy, and sometimes generate different types of quantum beams. Thus we can get the atomic or molecular level information by observing alternation of the beam parameters, indicating that quantum beams have “function of probe”.

At the QuBS, we are performing R&Ds of advanced beam technology using neutrons, ions, electrons, γ-rays, lasers and synchrotron X-rays available in our quantum beam facility complex involving research reactors, accelerators and so on. By utilizing the “functions of processing and probe” of quantum beams, we are making fundamental and applied researches in the wide fields[2], i.e., (1) materials science, (2) environment and energy, and (3) life science, advanced medical treatment, and biotechnology fields, along the ’Science and Technology Basic Plan’[3] of Japan. We are intensively promoting these R&Ds for contributing the progress in science and technology as well as the promotion of industry.

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As an important part of R&Ds in the environment and energy field, we have studied radiation effects on semiconductors for developing radiation resistant devices in connection with their application to electronic system used in harsh environments like space, accelerator and nuclear facilities. Radiation hard electronic components are useful for detection and control system in nuclear reactors and related facilities of which environmental information[4] is denoted in Tables 1 and 2. Such radiation resistant devices are also indispensable for robots and other remote-controlled equipment necessary for inspection of internal reactor pressure vessel as well as removal of fuel debris at Fukushima Daiichi Nuclear Power Plants, which were severely damaged owing to the earthquake and following tsunami disaster on March 11, 2011. In this R&D, we are focusing on wide band-gap semiconductor silicon carbide (SiC) because of its high temperature stability, excellent electrical properties, and high radiation tolerance[5-7]. So far, we have fabricated SiC-based transistors and examined their radiation response by using Co-60 γ-rays and high energy charged particles like electrons and ions. In this paper, our recent R&Ds of radiation resistant semiconductor devices based on SiC are reviewed.

Table 1. Reactor environments[4].

Reactor Type	In Core (Gy/h)	In Containment (MGy)	
		Normal Operation	Accidents
Pressurized Water Reactor (PWR)	10^3-10^8	0.5 (40 years)	1.5
Boiling Water Reactor (BWR)	10^3-10^8	0.5 (40 years)	0.26
Fast Breeder Reactor (FBR)	10^3-10^8	0.1 (30 years)	100

Table 2. Radiation environment in various nuclear facilities[4].

Nuclear Facilities	Common Dose Rates (Gy/h)	Radiation Tolerance Requirement (Gy)
Fuel Fabrication	0.001	10^1
Cell Decontamination	10^1	10^5
Reactor Decommissioning	0.3	$3x10^3$
Fuel Processing	10^1	10^5
Fuel Handling	10^2	10^6
Underground Storage	10^1	10^5
Reactor Incident Inspection (TMI recommendation)		$3x10^6$

2. TEST PROCEDURES

For investigating radiation degradation of SiC-based semiconductor devices, we have prepared several types of transistors, i.e., Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs), Metal-Semiconductor Field Effect Transistors (MESFETs)[8], and Static Induction Transistors (SITs)[9,10] using 6H- or 4H-SiC. Different oxidation processes of dry oxidation and pyrogenic oxidation were adopted to fabricate SiC-MOSFETs, which are referred to as MOSFETs(dry) and MOSFETs(pyro), respectively. Details of the fabrication process are described elsewhere[11,12].

These device samples were irradiated with Co-60 γ-rays at Takasaki Advanced Radiation Research Institute[13] of JAEA. Our γ-ray irradiation facilities, in which Co-60 sources of approximately 30PBq are installed, consist of three buildings equipped with eight irradiation cells. Figure 1 shows the schematic view of experimental setup. The Co-60 source stored in water pool of 6m in depth is lifted up with a conveyer for γ-ray irradiation to samples into the cell surrounded with 1.3m thick heavy concrete shield walls. The exposed dose rate can be changed from 0.04Gy/h to 20kGy/h by selecting the source intensity and the distance of a sample from the source. In our experiments, the dose of γ-rays to device samples was measured with alanine dosimeter. The device samples were mounted on the control board connected with the equipment outside via sleeve tube for supplying appropriate power to the samples, controlling the sample temperature, and examining the device performance during irradiation.

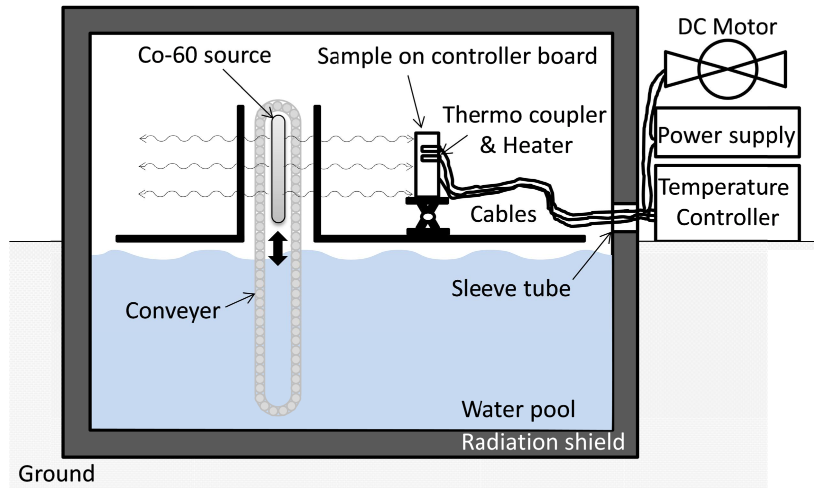

Figure 1. Schematic view of experimental setup of Co-60 γ-ray irradiation to semiconductor device samples for examining their radiation resistance.

3. TEST RESULTS OF RADIATION RESISTANCE OF SiC DEVICES

3.1 Radiation response for SiC field effect transistors

Electron-hole pairs are known to be induced in oxide layers of MOSFETs by irradiation of γ-rays, and a part of them are trapped in oxide and near the interface between oxide and semiconductor to form oxide trapped charge and interface traps, respectively. Since such oxide trapped charge and interface traps have harmful influences to carrier transport properties of semiconductors, the electrical characteristics of MOSFETs are degraded by their generation[14,15], which is called the total ionization dose (TID) effect. For example of the TID effect, the threshold voltage (V_T) shifts and/or the channel mobility (μ_{ch}) decreases due to irradiation to MOSFETs.

Irradiation of γ-rays was carried out at room temperature (RT) for SiC-MOSFETs(dry), SiC-MOSFETs(pyro), SiC-MESFETs, and SiC-SITs. During γ-ray irradiation, no bias was applied to any electrodes of the transistors. Figure 2 shows the shift of the threshold voltage (ΔV_T) for all the SiC transistors as a function of absorbed dose. For comparison, the results reported for Si-MOSFETs are also plotted in the figure[14]. No significant change in ΔV_T was observed up to

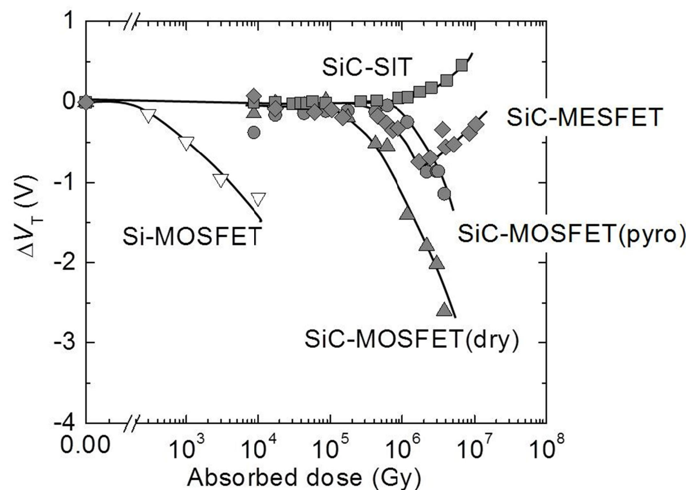

Figure 2. Change in ΔV_T for SiC-MOSFETs(dry) , SiC-MOSFETs(pyro), SiC-MESFETs, and SiC-SITs as a function of absorbed dose.

10^5Gy for all the SiC transistors whereas the Si-MOSFETs showed obvious degradation in ΔV_T. This result indicates that SiC-MOSFETs and the other SiC-transistors have extremely high radiation resistance in comparison with Si-MOSFETs. The value of ΔV_T for both the SiC-MOSFETs shifted to the negative voltage side by γ-ray irradiation above 10^5Gy, and the shift for the MOSFETs(dry) was larger than that for the MOSFETs(pyro). It means that radiation resistance of SiC-MOSFETs(pyro) is higher than that of the SiC-MOSFETs(dry). It is also suggested that radiation degradation of SiC-MOSFETs depends strongly on the gate oxidation process of SiC.

For the SiC-MESFETs[16], the value of ΔV_T shifted to the negative voltage side by γ-ray irradiation in an absorbed dose range from 4×10^5 to 2×10^6Gy, and the maximum shift of -0.75V was observed at 2×10^6Gy. On the other hand, the negative shift became smaller with increasing absorbed dose above 2×10^6Gy and the value of ΔV_T became -0.27V after irradiation at 10^7Gy. For the SiC-SITs[17], although the positive shift of ΔV_T was observed above 10^6Gy, the value was relatively small (0.45V at 7×10^6Gy) compared to the other SiC transistors. Thus, it can be concluded that radiation hardness of SiC-SITs and SiC-MESFETs is higher than that of SiC-MOSFETs. Since SITs and MESFETs do not have gate oxide, such high radiation resistance to γ-rays is attributable to the structural difference from MOSFETs. However, it should be noted that the electrical characteristics of SITs and MESFETs are affected by TID effects because they are also covered with an insulating oxide for the surface termination, and radiation induced charge is trapped in such oxide layers. In addition, in such a high absorbed dose range, the displacement damage effect due to Compton electrons should be taken into consideration.

3.2 Radiation degradation of power devices based on SiC and Si

Next, radiation effects on the device performance of power transistors based on SiC and Si were investigated. As the device samples for γ-ray irradiation experiments, we used SiC-SITs exhibiting an on-resistance of 0.15Ω and a blocking voltage of 900 V at a gate voltage (V_G) of -10 V[9,10]. The SiC-SITs mounted in TO220 packages were irradiated with γ-rays at a dose rate of 8.8kGy/h at RT. No bias was applied to every electrode during irradiation. For comparison, two Si power devices with similar current and voltage ratings, Si-MOSFET (17N80C3) and Si-IGBT (5J301), were also prepared and irradiated. Figure 3(a) shows the shift of the breakdown voltage for the SiC-SITs, the Si-MOSFETs, and the Si-IGBT as a function of absorbed dose. The blocking characteristics for the SiC-SITs and the Si power transistors (IGBTs and MOSFETs) were measured at V_G of 10V and 0V, respectively. Whereas no obvious change in the breakdown voltage was obtained up to 10^7Gy for the SiC-SITs and the Si-IGBTs, the breakdown voltage shift for the Si-MOSFETs increases above 4×10^5Gy and reaches to -500V at 10^7Gy. It was also found that after irradiation at 10^7Gy, the leakage current for the SiC-SITs was kept low values of the order of 10^{-6}A though it drastically increased to 10^{-4}A level for the Si-MOSFETs[14].

The on-state characteristics were examined for the SiC-SITs at V_G of +2.5V and for the Si transistors (IGBTs and MOSFETs) at V_G of +15V. Then, the on-voltage was defined as the value of drain voltage (V_D) at drain current (I_D) of

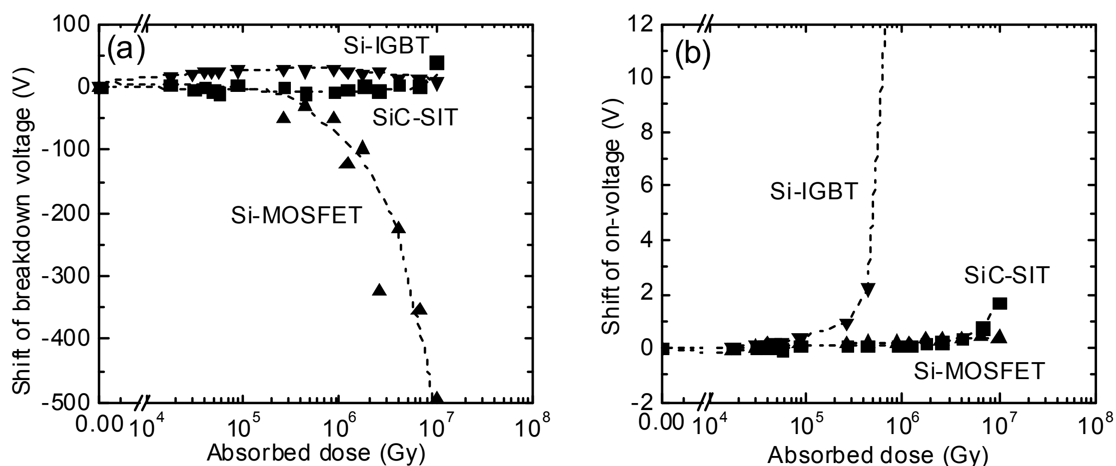

Figure 3. Shifts of the breakdown voltage (a) and the on-voltage (b) due to Co-60 γ-ray irradiation for SiC-SITs, Si-MOSFETs, and Si-IGBTs.

10A. Figure 3(b) shows the absorbed dose dependence of the shift of the on-voltage for the SiC-SITs, the Si-MOSFETs, and the Si-IGBTs. The on-voltages for the SiC-SITs and the Si-MOSFETs were found to show very stable behavior up to 10^7Gy, whereas that for the Si-IGBTs remarkably increased from 2.3V to more than 20V after irradiation at 8×10^5Gy. It was reported that the displacement damage effect induced by Compton electrons degraded the gain for Si bipolar transistors[18]. Similarly to the reported case, the remarkable increase in the on-voltage for Si-IGBTs can be interpreted in terms of the majority carrier removal in the drift region (low doping region) due to the displacement damage effect. On the other hand, for the SiC-SITs and the Si-MOSFETs, the doping concentration in the drift region is not so low compared with Si-IGBTs, suggesting that generated displacement damage has little effect on their on-voltage. All the results show that SiC-based power devices like SITs have superior radiation resistance (up to 10MGy) to Si-based devices.

3.3 Radiation tolerance of electronic circuits composed of SiC power devices

In order to demonstrate high radiation resistance of electronic circuits composed of SiC devices, a chopper circuit was designed and fabricated with SiC-SIT for driving a DC motor (Tusima Electric, BF4-080H1U) with a rating output of 1.0kW and a rating rotation speed of 2500/min. The chopper circuit was placed inside an irradiation cell and the other components such as the DC motor, the power supply, and the temperature controller were set outside of the cell (Fig.1) for performing γ-ray irradiation to the test circuit only. Temperature of the SiC-SIT was monitored with thermo couplers, and raised up to 150ºC by using a heater and control apparatus for examining the device performance under such high temperatures.

In-situ tests of the DC motor rotation driven with the chopper circuit irradiated with γ-rays were performed and the results obtained are shown in figure 4. The rotation speed of the motor became to approximately 2300/min soon after starting it, and it was kept almost constant value during irradiation up to an absorbed dose of 2.5MGy. Temperature of the SiC-SIT was also raised up to 85ºC by self-heating due to normal transistor operation. No apparent change in the device temperature was observed during γ-ray irradiation. Moreover, the rotation speed did not change even when the SiC device was heated up to 150ºC, as shown in the figure. Thus, electronic circuits composed of SiC-based devices are demonstrated to work normally at extremely high radiation doses around 3MGy as well as at high temperatures up to 150ºC, giving us the feasibility of SiC-device application to electronic system used in severe radiation environments like nuclear facilities.

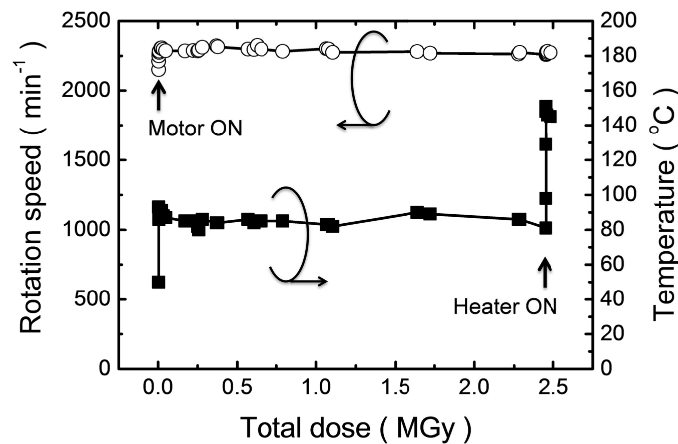

Figure 4. In-situ test results of DC motor rotation driven with SiC-SIT irradiated with γ-rays. Temperature of the SiC-SIT was monitored during irradiation, and raised up using a heater at the final stage in order to examine the influence of device temperature on the motor rotation.

4. SUMMARY

We have performed R&Ds on radiation resistant devices based on SiC semiconductors at JAEA for their application to electronic system operated in severe radiation environments such as space, accelerator and nuclear facilities. Two types of SiC-MOSFETs, i.e., MOSFETs(dry) and MOSFETs(pyro) of which gate oxide layers were fabricated with dry and pyrogenic oxidation processes respectively, and SiC-MESFETs were irradiated at RT with Co-60 γ-rays, and the shift of

the threshold voltage ΔV_T for each transistor was examined. As a result, no significant change in ΔV_T was observed up to 10^5Gy for SiC-MOSFETs(dry), 10^6Gy for SiC-MOSFETs(pyro), and $4x10^5$Gy for SiC-MESFETs, whereas large values of ΔV_T were reported for Si-MOSFETs at doses around 10^3Gy. The breakdown voltage and the on-voltage of power transistors based on SiC and Si, i.e., SiC-SITs, Si-MOSFETs, and Si-IGBTs, were also evaluated after γ-ray irradiation at RT up to 10^7Gy. For SiC-SITs, both the breakdown and on-voltages were found to be very stable even after irradiation at 10^7Gy. On the other hand, remarkable change was observed above 10^5Gy in the breakdown voltage for Si-MOSFETs and the on-voltage for Si-IGBTs. It is derived from all the results that SiC-based devices have excellent radiation resistance compared with Si-based ones. In addition, electronic circuits composed of SiC-SITs were fabricated as a DC motor drive, and their performance was tested by monitoring the rotation speed of the DC motor under γ-ray irradiation at RT and 150ºC. The motor rotation was shown to be almost constant during irradiation up to $2.5x10^6$Gy, and this behavior did not change by raising device temperature up to 150ºC. Thus, it is demonstrated that electronic circuits composed of SiC-based devices have extremely high radiation resistance (approximately $3x10^6$Gy), which corresponds to the TMI-model recommended value of radiation tolerance required for reactor incident inspection. Such radiation hard SiC-devices are expected to be applied for robots and other remote-controlled equipment used for inspection of internal reactor pressure vessel as well as removal of fuel debris at Fukushima Daiichi Nuclear Power Plants. On the basis of the test results, further investigations are necessary for realizing radiation resistant devices used for the reactor decommissioning.

ACKNOWLEDGMENTS

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