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# Impact of Neutron-Induced Displacement Damage on Electrical Characteristics of 4H-SiC SBDs and MOSFETs

Der-Sheng Chao[1], Hua-Yu Shih[2], Jheng-Yi Jiang[2], Chih-Fang Huang[2], Ching-Yu Chiang[3], Ching-Shun Ku[3], Kung-Yen Lee[4]

[1] Nuclear Science and Technology Development Center, National Tsing Hua University
No. 101, Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan, ROC
Phone: +886-3-5742866 E-mail: dschao@mx.nthu.edu.tw
[2] Institute of Electronics Engineering, National Tsing Hua University
[3] National Synchrotron Radiation Research Center, Taiwan, ROC
[4] Department of Engineering Science and Ocean Engineering, National Taiwan University

## Abstract

**In this study, the fission neutron source and Co-60 gamma rays were employed to investigate the radiation effects on 4H-SiC SBDs and MOSFETs. The results revealed that the displacement damage caused by fission neutrons disturbed the carrier concentration in SiC, thus contributing to undesirable electrical characteristics of the SiC-based devices.**

## 1. Introduction

Owing to the distinctive features of high blocking voltage, low on-state resistance, fast switching speed, and high thermal conductivity, Silicon Carbide (SiC) power devices have become the next generation of energy-saving electronic components. Moreover, the robust radiation hardness arising from high atomic displacement energy of SiC material also allows the SiC power devices being the suitable components for harsh radiation environments such as space, high-energy accelerator facilities, and nuclear power plants [1]. However, the studies concerning the radiation effects on SiC-based devices are relatively limited, especially for the displacement damage in SiC caused by fast neutrons [2]. For this reason, the purpose of this study is to investigate the neutron-induced radiation effects on 4H-SiC Schottky barrier diodes (SBDs) and MOSFETs using fission neutron source.

## 2. Experimental Procedures

In this study, the test devices used for neutron irradiation experiments are commercially available 4H-SiC SBDs and MOSFETs supplied by a domestic SiC power device manufacturer. The ratings of forward current and reverse voltage for the SBDs are 20 A and 650 V, and those of on-state resistance, drain current, and blocking voltage for the MOSFETs are 120 mΩ, 20 A, and 1200 V. In addition, the n-type 4H-SiC bulk crystals were also adopted to characterize the material property change induced by neutron irradiation. The neutron irradiation experiments were carried out in the Tsing Hua Open-pool Reactor (THOR) under an operating power of 1.5 MW. The detailed irradiation conditions of THOR neutron source are listed in Table I. Since the irradiation experiments were proceeded in a fission reactor core, it is unavoidable to accompany the emission of gamma rays from fission products during irradiation. In order to identify the influence of neutron radiation, the test devices were also independently irradiated by a Co-60 gamma-ray source for comparison.

## 3. Results and Discussion

Figs. 1 and 2 show the forward current-voltage (I-V) curves of the SiC SBD and MOSFET by neutron irradiation at a fluence of $1.0\times10^{13}$ #/cm$^2$. As can be seen, no obvious degradation in electrical performance can be found in SiC SBD and MOSFET, but the output current of SiC MOSFET slightly increased due to a shift in threshold voltage ($V_{th}$). The drift of $V_{th}$ can be mainly attributed to the charge trapping of gate oxide resulting from the ionizing by gamma rays accompanying with fission [3]. This inference can be further evidenced by the results of Co-60 gamma-ray irradiation at a dose of 300 krad as shown in Figs. 3 and 4. Since the neutron-induced displacement damage can be neglected at such a moderate neutron fluence, it can be expected that the SBDs should be more robust against neutron irradiation than the MOSFET with a MOS-like structure whose insulator is susceptible to damage by ionizing radiation.

In order to assess the impact of neutron-induced displacement damage, the fast neutron fluence was highly raised to $1.3\times10^{15}$ #/cm$^2$. Fig. 5 shows the measured I-V curves of the SiC SBD. It is clear that the forward I-V curve exhibited an anomalous change by a high-fluence neutron irradiation. The ideality factor of the SBD greatly increased from 1.05 to 1.86, implying a large number of defects formed in SiC. Moreover, a significant reduction in blocking voltage can be found in the reverse I-V curve. Otherwise, the SiC MOSFET also appeared an inoperable failure by this high-fluence neutron irradiation. Thus the neutron-induced displacement damage would introduce considerable electrically active defects in SiC, which could greatly vary the effective carrier density and impact the electrical operation of SiC-based devices.

Figs. 6 and 7 show the capacitance-voltage (C-V) curves of the SiC SBD and MOS capacitor irradiated by fast neutron fluences of $1.0\times10^{13}$ and $1.3\times10^{15}$ #/cm$^2$. The trend of the C-V curves for both the SBD and MOS capacitor almost remained unchanged at low neutron fluence, while a great decrease in capacitance was observed at high neutron fluence. Also, the method of the C-V profiling was implemented to determine the doping density in SiC. The effective bulk doping densities derived from the C-V curves of the SiC SBD and MOS capacitor are listed in Table II. A pronounced drop in doping density due to high neutron fluence suggests that the defects originating from neutron-induced displacement damage indeed disturbed the carrier concentration in SiC. Further analysis of the displacement damage in 4H-SiC was also done by X-ray Laue diffraction from a high-brilliance synchrotron radiation source. As shown in Fig. 8, the arc-shaped diffraction spots revealed from the neutron-irradiated 4H-SiC manifested the production of atomic displacements along the (1, -1, L) lattice plane in SiC.

## 4. Conclusions

The influence of neutron-induced displacement damage on SiC SBDs and MOSFETs were investigated in this study. At a moderate neutron fluence ($1\times10^{13}$ #/cm$^2$), only SiC MOSFET exhibited a $V_{th}$ drift due to the charge trapping of gate oxide by ionizing radiation. At a high neutron fluence ($1.3\times10^{15}$ #/cm$^2$), a significant degradation in electrical characteristics can be found in both SiC SBDs and MOSFETs, which can be attributed to the modification of doping density caused by neutron-induced displacement damage.


## Acknowledgements

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## References


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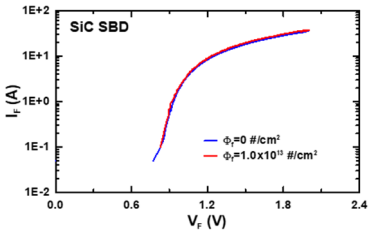


Fig. 1 Measured forward I-V curves of SiC SBD irradiated by a fast neutron fluence of $1.0\times10^{13}$ #/cm$^2$.

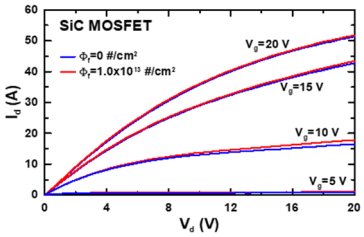


Fig. 2 Measured $I_d$-$V_d$ curves of SiC MOSFET irradiated by a fast neutron fluence of $1.0\times10^{13}$ #/cm$^2$.

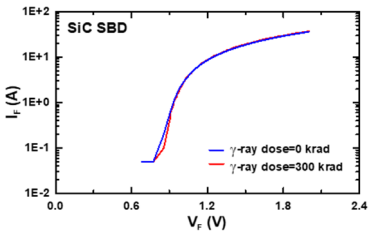


Fig. 3 Measured forward I-V curves of SiC SBD irradiated by a Co-60 gamma-ray dose of 300 krad.

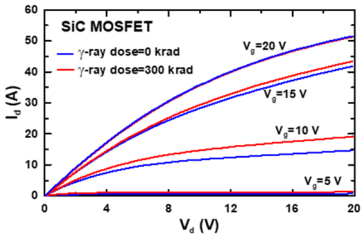


Fig. 4 Measured $I_d$-$V_d$ curves of SiC MOSFET irradiated by a Co-60 gamma-ray dose of 300 krad.

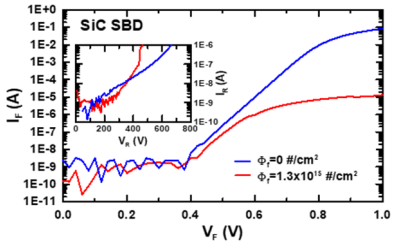


Fig. 5 Measured forward I-V curves of SiC SBD irradiated by a fast neutron fluence of $1.3\times10^{15}$ #/cm$^2$. The inset is the reverse I-V curves.

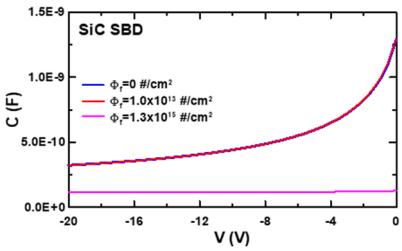


Fig. 6 Measured C-V curves of SiC SBD irradiated by fast neutron fluences of $1.0\times10^{13}$ #/cm$^2$ and $1.3\times10^{15}$ #/cm$^2$.

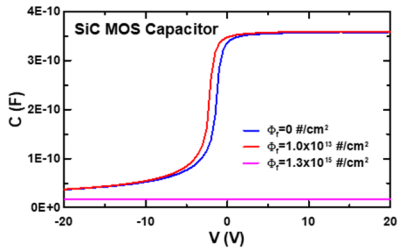


Fig. 7 Measured C-V curves of SiC MOS Capacitor irradiated by fast neutron fluences of $1.0\times10^{13}$ #/cm$^2$ and $1.3\times10^{15}$ #/cm$^2$.

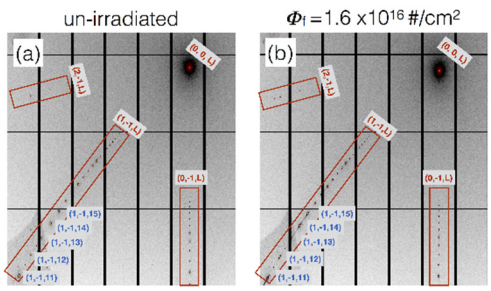


Fig. 8 X-ray Laue diffraction patterns of 4H-SiC by a high-brilliance synchrotron radiation: (a) un-irradiated and (b) $\Phi_f=1.6\times10^{16}$ #/cm$^2$.

Table I Neutron irradiation conditions of SiC devices and crystals

| | THOR Tube | $t_{irradiation}$ | $\Phi_t$ (#/cm$^2$) | $\Phi_f$ (#/cm$^2$) |
|---|---|---|---|---|
| Devices | VT-6 | 50 s | $4.9\times10^{13}$ | $1.0\times10^{13}$ |
| | VT-4 | 1 h | $4.4\times10^{15}$ | $1.3\times10^{15}$ |
| Crystals | VT-4 | 12 h | $5.3\times10^{16}$ | $1.6\times10^{16}$ |

*$\Phi_t$: thermal neutron fluence; $\Phi_f$: fast neutron fluence

Table II Effective bulk doping density ($N_B$) of SiC SBD and MOS capacitor irradiated by various fast neutron fluence ($\Phi_f$)

| $\Phi_f$ (#/cm$^2$) | $N_{B,\ SiC\ SBD}$ (#/cm$^3$) | $N_{B,\ SiC\ MOS\ Capacitor}$ (#/cm$^3$) |
|---|---|---|
| 0 | $1.0\times10^{16}$ | $6.5\times10^{15}$ |
| $1.0\times10^{13}$ | $1.0\times10^{16}$ | $6.4\times10^{15}$ |
| $1.3\times10^{15}$ | $6.7\times10^{14}$ | $7.2\times10^{14}$ |