Effects of 5 MeV Proton Irradiation on 1200 V 4H-SiC VDMOSFETs ON-State Characteristics

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ABSTRACT The effects of 5 MeV proton irradiation on ON-state characteristics of 1200 V 4H-SiC VDMOSFETs are investigated in this paper, and related mechanisms have been revealed by the analysis of their test structure of ohmic contacts, lateral nMOSFETs and MOS capacitors simultaneously fabricated on same wafer. The results show that the threshold voltage ($V_{TH}$) decreases obviously with increasing irradiation doses because the dominant hole traps induced by nitrogen passivation might capture more holes produced by the ionization effect of proton irradiation, resulting in the generation of net positive charges nearby the SiO$_2$/4H-SiC interface. The interface trap density ($D_{it}$) extracted by subthreshold swing increases but field effective mobility ($\mu_{FE}$) is improved with increasing irradiation doses. The un-trapped near interface electron traps (NIETs) are reduced by the ionization effect of proton irradiation, which could be beneficial to the improvement of $\mu_{FE}$. And after the maximum irradiation dose of $1 \times 10^{14}$ p/cm$^2$ the VDMOSFET fails in the ON-state capability. Before it fails, the ON-state resistivity ($R_{ON}$) firstly decreases and then increases with the increase of irradiation dose. The deterioration of the resistance of lightly doped drift region ($R_D$) and the resistance of JFET region ($R_{JFET}$) caused by the displacement effect of proton irradiation covers up the improvement of the channel resistance ($R_{CH}$) with increasing irradiation doses, finally leading to the failure of the VDMOSFET at the maximum proton irradiation dose.

INDEX TERMS 4H-SiC power MOSFETs, mobility, ON-state characteristics, proton irradiation, SiO$_2$/SiC interface.

I. INTRODUCTION

Silicon Carbide (SiC) is an attractive wide-bandgap semiconductor material in the rapidly increased demands of the power, high temperature and space electronic fields due to its excellent electrical and thermal properties [1], [2]. Electronic components, such as metal–oxide–semiconductor field-effect transistors (MOSFETs), are often exposed to different types of radiation, changing their electrical performance, or even making the permanent failures of devices. Because of the high displacement threshold energy and the wide bandgap of SiC, the devices based on SiC are expected to exhibit high radiation hardness. Since 2011, with the improvement of the quality of the SiC/SiO$_2$ interface, high voltage power MOSFET are available in the commercial market, and then the research interests are turned to the radiation effect of the power MOSFET. The previous studies focus on the ionization effects of $\gamma$-ray and X-ray irradiation [3]–[6]. The negative shift of threshold voltage is the main degradation due to the positive charges generated in the gate oxide during irradiation. But displacement effect of irradiation on the devices is rarely reported. The effect of electron irradiation on commercial power MOSFET has been investigated [7], [8]. When electron dose reaches 200 kGy, the ON-state resistance increases. Because the experiment is only based on the commercial devices, the irradiation effect on the key structure of
the devices such as the ohmic contact, the channel, the JFET region and the low doped drift region cannot be differentiated in detail.

Proton irradiation has both the ionization effect and displacement effect. Since energetic proton is one of the main particles in space environment, it is needful to study the effects of proton irradiation on power MOSFET for space application [9]. The previous report of proton irradiation was only based on the lateral MOSFETs [10]. Improvements of $\mu_{FE}$ extracted at same gate voltage ($V_{GS}$) were observed, which is connected with the proton irradiation improving the SiC/SiO$_2$ interface quality. But considering the irradiation induced largely negative shift of $V_{TH}$, the calculation of $\mu_{FE}$ should be at the same $V_{GS} - V_{TH}$ for ensuring the comparison of $\mu_{FE}$ at the same vertical electric field. And it must be considered that the $\mu_{FE}$ is not only affected by the interface quality but also the status of near interface [11]–[14]. In this paper the effects of 5 MeV proton irradiation on 1200 V 4H-SiC VDMOSFETs ON-state characteristics are investigated. And related mechanisms have been revealed by the analysis of their test structure of ohmic contacts, lateral nMOSFETs and MOS capacitors simultaneously fabricated on same wafer, whose results are beneficial to the improvement of the hardness of the devices against proton irradiation.

![FIGURE 1. Micrograph of the devices under test.](image)

**II. EXPERIMENTAL DETAILS**

**A. TEST DEVICES**

Devices under test are 1200 V VDMOSFETs with their test structure of ohmic contacts, lateral nMOSFETs and MOS capacitors fabricated simultaneously on same wafer, as shown in Fig. 1. The VDMOSFETs were fabricated on a 4H-SiC epilayer with thickness of 10 $\mu$m and nitrogen doped concentration of $5.8 \times 10^{13}$ cm$^{-3}$, grown on a 4$^\circ$ off-axis N$^+$ type 4H-SiC substrate with thickness of 350 $\mu$m. The doping concentration of P-well formed by aluminum ion implantation is $3.9 \times 10^{17}$ cm$^{-3}$. The gate oxide layer was formed by dry O$_2$ oxidation with post oxidation annealing in NO, and the thickness of the gate oxide is about 75 nm, obtained from the high frequency (100 kHz) capacitance-voltage (C-V) measurements. An aluminum layer was deposited and patterned to form gate electrode. The ohmic contacts to the drain and the source were formed by Nickel with the thickness of 200 nm. The schematic cross-section of the VDMOSFET is shown in Fig. 2. Both the channel length and JFET width of the VDMOSFETs are 2 $\mu$m. The channel length of the lateral nMOSFET is also 2 $\mu$m. The test structure of lateral NDMOSFETs and MOS capacitors simultaneously fabricated on same wafer, whose results are beneficial to the improvement of the hardness of the devices against proton irradiation.

![FIGURE 2. Schematic cross-section of the VDMOSFET.](image)

**B. HIGH ENERGY PROTON IRRADIATION**

The proton irradiation experiment was carried out using the EN2 $\times$ 6 Serial Electrostatic Accelerator (High Voltage Engineering Europa B.V.) with 5 MeV proton energy. The irradiation was performed in vacuum atmosphere at room temperature with the proton fluence of $5 \times 10^{12}$ p/cm$^2$, $5 \times 10^{13}$ p/cm$^2$ and $1 \times 10^{14}$ p/cm$^2$ under the same proton fluence rate of $1.39 \times 10^{10}$ p/(cm$^2$.s) and the irradiation time was 6 mins, 60 mins and 120 mins, respectively. The proton energy was chosen from the energy range of protons in space environment, which is similar to the previous report on the irradiation effects of protons on 4H-SiC epilayers and devices [10], [15]. The irradiation dose was chosen based on our previous study of 4H-SiC NMOS capacitors, in which the doses have remarkable effects on flat-band voltage, Dit and free carrier concentration ($n_p$) in the epilayer of the samples and the devices are failed after the proton dose of $1 \times 10^{14}$ p/cm$^2$. The devices have not been biased during irradiation. The injected proton beam was vertical to surface of the samples and the samples are without packaging. The maximum incident depth is approximately 150 $\mu$m located in the substrate, which is determined by performing the Monte Carlo simulations using the SRIM software [16], as shown in Fig. 3. According to the SRIM simulation of the ionization energy loss and the number of target vacancies versus the depth, the ionization
effect and displacement effect of proton irradiation occur along the path of the injected protons during the proton irradiation. The regions which can significantly affect the electrical characteristics are gate oxide, near interface, interface and epilayer at depths of 5.5 \( \mu \text{m} \) to 15.5 \( \mu \text{m} \) (the shaded region in Fig. 3). The I-V characteristics and C-V characteristics of these devices were re-measured at room temperature after each proton irradiation.

### III. RESULT AND DISCUSSION

#### A. OHMIC CONTACTS

The TLM test of ohmic contact was implemented with applied different doses for 5 MeV proton irradiation measured at room temperature and the results are shown in Fig. 4. It can be seen that the ohmic contact resistance \( R_C \) is nearly unchanged for all dose ranges up to \( 1 \times 10^{14} \text{ p/cm}^2 \). The specific contact resistance and the sheet resistance are extracted and shown in Table 1. Both of them are nearly unchanged. It means that \( R_C \) should not contribute to the variation of \( R_{\text{ON}} \) of the lateral nMOSFETs and the VDMOSFETs in all dose ranges for proton irradiation.

#### B. THE LATERAL NMOSFETS

The gate-source leakage current \( I_{\text{GS}} \) after 5 MeV proton irradiation doses measured by the nMOSFET has been shown in Fig. 5. It can be seen that \( I_{\text{GS}} \) is nearly unchanged. It means that the displacement effect on gate oxide does not significantly affect the gate oxide integrity of the device.

| Dose (\( \text{p/cm}^2 \)) | Sheet Resistance (\( \Omega \)) | Specific Contact Resistance (\( \Omega \cdot \text{cm}^2 \)) |
|---------------------------|-------------------------------|----------------------------------|
| 0 (Pre)                   | 2.90 \times 10^{4}           | 2.26 \times 10^{3}              |
| 5 \times 10^{12}          | 1.99 \times 10^{4}           | 2.55 \times 10^{3}              |
| 5 \times 10^{13}          | 1.98 \times 10^{4}           | 2.63 \times 10^{3}              |
| 1 \times 10^{14}          | 1.97 \times 10^{4}           | 2.38 \times 10^{3}              |

The effects of the 5 MeV proton irradiation in the all dose ranges on output characteristics at \( V_{\text{GS}} \) of 20 V and transfer characteristics at drain voltage \( V_{\text{DS}} \) of 0.5 V of the lateral nMOSFETs are shown in Fig. 6 and Fig. 7, respectively. The variation of \( V_{\text{TH}} \) with applied different doses of 5 MeV protons is shown in Fig. 8, in which \( V_{\text{TH}} \) is defined to be equal to the \( V_{\text{GS}} \) when the drain current \( I_{\text{DS}} \) is 1 \( \mu \text{A} \) at \( V_{\text{DS}} = 0.5 \text{ V} \). It can be seen that the \( V_{\text{TH}} \) of the lateral nMOSFETs decreases obviously with the increase of radiation dose, which means a significant increment of the net positive charges nearby the \( \text{SiO}_2/4\text{H-SiC} \) interface (including the gate oxide layer, near interface and interface of the \( \text{SiO}_2/4\text{H-SiC} \)) during irradiation. The schematic diagram of main
traps affecting $V_{TH}$ during irradiation nearby the SiO$_2$/4H-SiC interface is shown in Fig. 9. The nitrogen passivation not only reduces the numbers of the NIETs but also generates large numbers of the near interface hole traps locate at energy level of 0.5 eV from the valence band edge of SiC [17], [18], leading to the dominant hole traps nearby the SiO$_2$/4H-SiC interface. The obvious decrease of $V_{TH}$ with increasing irradiation doses is similar to the previous studies of $\gamma$-ray and X-ray irradiation which have only ionization effects [3]–[6]. It can be inferred that the dominant hole traps nearby the SiO$_2$/4H-SiC interface is not significantly affected by the displacement effect of proton irradiation, so the effect of proton irradiation on $V_{TH}$ is mainly affected by the ionization effect of the proton irradiation. When the protons penetrate though the devices the ionization effect of proton irradiation creates electron-hole pairs along the path of the injected proton during the proton irradiation. The dominant hole traps capture more holes in this event, resulting in the generation of net positive charges nearby the SiO$_2$/4H-SiC interface. This is the reason for the largely negative shift of $V_{TH}$ after proton irradiation. It can induce that the MOSFETs could not be turned off normally.

Variation of the subthreshold characteristics with applied doses for 5MeV proton irradiation is shown in Fig. 10.
TABLE 2. The changes of subthreshold swing induced by proton radiation.

| Dose (p/cm²) | Subthreshold Swing (V/decA) | Calculated Dit (cm⁻³) |
|--------------|-----------------------------|-----------------------|
| 0 (Pre)      | 0.373                       | 1.5×10¹⁴              |
| 5×10¹²       | 0.775                       | 3.5×10¹²              |
| 5×10¹³       | 2.642                       | 1.2×10¹³              |
| 1×10¹⁴       | 3.386                       | 1.6×10¹³              |

The energy level of NIET is near the 4H-SiC conduction band [19]. In subthreshold state the Fermi level (Ef) is below the energy level of the NIET, so the NIET cannot capture carrier in that state and affects the subthreshold current. Therefore, the Dit can be extracted by the subthreshold swing. And the free carrier concentration (p_A) of the P-well region extracted by high frequency C-V characteristics of the test structure of PMOS capacitors is nearly unchanged after irradiation. The changes of subthreshold swing induced by proton radiation and the calculated Dit are shown in Table 2. It can be seen that the subthreshold swing increases with the increasing irradiation dose, which means there is a significant increase of Dit after proton irradiation. The displacement effect of the proton irradiation causes various types broken bonds between atoms, especially the passivated bonds, when the protons penetrate though the interface. The nitrogen de-passivation and the generation of defects at the interface could be the reason for the increase of Dit. But μ_FE is improved with the increasing irradiation dose, which is shown in Fig. 11. The μ_FE is extracted from the transconductance at the same VGS−V_TH in order to avoid the influence of largely negative shift of V_TH induced by irradiation for ensuring the comparison of μ_FE in the same vertical electric field. The μ_FE is much smaller than the Hall mobility because of greater trapping of inversion electrons with the gate voltage [12]. The μ_FE is affected by the interface traps located close to the conduction band and the NIETs near the conduction band, and the effect of the latter one on μ_FE is more significant [11]–[13]. The electrons in the inversion layer can directly tunnel or tunnel via interface traps to the un-trapped NIETs whose energy levels are near the conduction band, which reduce the number of channel conducting electrons resulting in the effective reduction of μ_FE. The proton irradiation effects on NIETs and interface traps are shown in Fig. 12. Because the ionization effect of proton irradiation creates electron-hole pairs along the path of the injected proton, un-trapped NIETs will capture electrons during the proton irradiation. The trapped electron could not be released in a short time, which reduces the number of trapping of inversion electrons when the device is turned on. Therefore, the reduction of the un-trapped NIETs by the ionization effect of proton irradiation could be the reason for the improvement of μ_FE with increasing irradiation dose.

C. VDMOSFETS

The effects of the 5 MeV proton irradiation in all dose ranges on output characteristics at V_GS = 20 V and transfer characteristics at V_DS = 0.5 V of the VDMOSFETs are respectively shown in Fig. 13 and Fig. 14. It can be seen that the VDMOSFETs lose ON-state capability after maximum irradiation dose of 1×10¹⁴ p/cm², which is different from the lateral nMOSFETs. The V_TH and R_ON versus the irradiation doses before the failure of the device is shown in Fig. 15. It can be observed that V_TH decreases obviously with the increase of irradiation dose, which is similar to the tested lateral nMOSFETs. And the reason is same to the lateral nMOSFETs discussed previously.
From Fig. 15, it is found that $R_{ON}$ firstly decreases and then increases with the increasing irradiation dose before the failure of the devices. Because of $\rho_C$ is nearly unchanged during irradiation, the variation of the $R_{CH}$, the $R_{JFET}$ and the $R_D$ lead to the variation of the $R_{ON}$. The $R_D$ is determined by the bulk resistivity of the epilayer ($\rho_C$), which is affected by two factors, i.e. the free carrier concentration ($n_D$) and electron mobility in the epilayer. The $n_D$ of the epilayer versus 5 MeV proton fluence extracted by high frequency (100 kHz) C-V characteristics of the test structure of NMOS capacitors is shown in Fig. 16, which shows that the $n_D$ is reduced with increasing irradiation dose and especially its value is significantly decreased by two orders of magnitude at the proton fluence of $1 \times 10^{14}$ p/cm$^2$. This is connected with the formation of radiation defects in the epilayer. The previous experiment of deep-level transient spectroscopy (DLTS) measured on the 6.5 MeV proton irradiated 4H-SiC epilayer, which is similar energy and range of doses to our experiment, shows the displacement effect of the proton irradiation introduces several electron traps and their energy levels are locate at 0.18 eV, 0.2 eV, 0.4 eV, 0.72 eV, 0.76 eV and 1.09 eV below the conduction-band edge [15]. The concentrations of the defects are linearly related to irradiation dose and the introduction rates are separately 0.3 cm$^{-1}$, 3.2 cm$^{-1}$, 4.1 cm$^{-1}$, 11 cm$^{-1}$, 3.5 cm$^{-1}$ and 2.4 cm$^{-1}$. These electron traps capture free carrier, resulting in the $n_D$ reduced as carrier removal effect. When the proton dose is up to $1 \times 10^{14}$ p/cm$^2$, the concentration of these defects is relatively high compared to the doping concentration of the epilayer. This can explain the significant decrease of $n_D$ after the maximum irradiation dose of $1 \times 10^{14}$ p/cm$^2$. And these defect trap charges also can decrease electron mobility in the epilayer because of coulomb scattering [20]. The two reasons above lead to the $\rho_C$ increases with increasing irradiation dose, making the $R_D$ worsened. The $R_{JFET}$ is mainly affected by the $\rho_C$ and the depletion width between P-well and drift layer ($W_0$), and the effect of the latter one on $R_{JFET}$ is more significant at the proton fluence of $1 \times 10^{14}$ p/cm$^2$ because the $W_0$
increases with the decrease of \(n_D\) and the JFET region is pinched off when the \(n_D\) decreases to \(1 \times 10^{15}\ \text{cm}^{-3}\), which calculated by the structure parameter of the device. Thus, the \(R_{\text{JFET}}\) is also increased with increasing irradiation dose. In addition, the \(R_{\text{CH}}\) decreases with increasing irradiation dose, as mentioned previously. These are the reasons that \(R_{\text{ON}}\) firstly decreases and then increases with increasing dose. The deterioration of \(R_{\text{D}}\) and \(R_{\text{JFET}}\) covers up the improvement of the \(R_{\text{CH}}\) after the dose of \(5 \times 10^{13} \ \text{p/cm}^2\). Considering the un-failure of the lateral nMOSFETs at the maximum irradiation dose of \(1 \times 10^{14} \ \text{p/cm}^2\), it is considered that the deterioration of \(R_{\text{D}}\) and \(R_{\text{JFET}}\) caused by the displacement effect of the proton irradiation finally makes the device failed after the maximum irradiation dose.

### IV. Conclusion

The effects of 5 MeV proton irradiation on ON-state characteristics of 1200 V 4H-SiC VDMOSFETs are investigated in this paper, in which the VDMOSFETs were fabricated with their test structure of ohmic contacts, lateral nMOSFETs and MOS capacitors simultaneously on same wafer. And related mechanisms have been fully revealed by the analysis of their test structure. The results show that the threshold voltage (\(V_{\text{TH}}\)) decreases obviously with increasing irradiation doses because the dominant hole traps induced by nitrogen passivation might capture more holes produced by the ionization effect of proton irradiation, resulting in the generation of net positive charges nearby the SiO\(_2\)/4H-SiC interface. It can be seen that the largely negative shift of \(V_{\text{TH}}\) after proton irradiation is also one of the main problems in the application of proton environment which can induce the devices could not be turned off normally. The interface trap density (Dit) extracted by subthreshold swing increases but field effective mobility (\(\mu_{\text{FE}}\)) is improved with increasing irradiation doses according to the analysis of the lateral MOSFETs. The un-trapped NIETs are reduced by the ionization effect of proton irradiation, which could be beneficial to the improvement of \(\mu_{\text{FE}}\). And after the maximum irradiation dose of \(1 \times 10^{14} \ \text{p/cm}^2\), the VDMOSFET fails in the ON-state capability. Before it fails, the ON-state resistivity (\(R_{\text{ON}}\)) firstly decreases and then increases with the increasing of irradiation dose. \(R_{\text{C}}\) is nearly unchanged in all dose ranges up to \(1 \times 10^{14} \ \text{p/cm}^2\) and \(R_{\text{CH}}\) is decreased with the increasing of irradiation dose. The increase of \(R_{\text{D}}\) and \(R_{\text{JFET}}\) made by the displacement effect of proton irradiation covers up the improvement of the \(R_{\text{CH}}\) with increasing irradiation doses, finally leading to the failure of the VDMOSFET at the maximum proton irradiation dose. It can be seen the deterioration of \(R_{\text{D}}\) and \(R_{\text{JFET}}\) made by the displacement effect of proton irradiation is the most critical problem in the application of proton environment. The value of deterioration of \(R_{\text{D}}\) and \(R_{\text{JFET}}\) is separately related to the doping concentration of the drift region and the JFET region, which can be considered as the ideas to improve the hardness of the devices against proton irradiation in future.

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