Radiation damage of $Si_{1-y}C_y$ Source/Drain n-MOSFETs with different carbon concentrations

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Abstract

The 2-MeV electron radiation damage of $Si_{1-y}C_y$ S/D n-type MOSFETs with different C concentrations is studied. Before irradiation, an enhancement of the electron mobility with C concentration of the S/D stressors is clearly observed. On the other hand, both the threshold voltage shift and the maximum electron mobility degradation are independent on the C concentration for all electron fluences. These results indicate that the strain induced electron mobility enhancement due to C concentration is retained after irradiation in the studied devices.

1. Introduction

The scaling of CMOS technologies leads to an intrinsic hardening against certain radiation effects, so that the development of ULSI components and circuits for harsh environments is becoming more popular [1].This has been driven by multiple factors, including the implementation of microelectronics components and circuits in nuclear plants, high-energy particle accelerators and artificial satellites. On the other hand, in the frame of high mobility substrates, new channel materials and promising methods to create strained channels are being explored [2-4].The potential of local compressive strain, based on the embedded or recessed silicon–germanium (SiGe) source/drain (S/D) method in p-type metal oxide semiconductor field effect transistors (p-MOSFETs) has been demonstrated at the 22 nm node and beyond [5]. For n-type MOSFET (n-MOSFETs), tensile strain is required for electron mobility and drive current enhancement. The embedded SiC S/D regions can be formed by using epitaxial silicon–carbon(SiC) $Si_{1-y}C_y$($0.01 \leqq y \leqq 0.02$) stressors [6, 7].However, it is not clear whether the strain will be maintained in a radiation-harsh environment due, for example, to a possible is placement damage in the stressors. In the present paper, we have investigated the degradation of the device performance of $Si_{1-y}C_y$ S/D n-MOSFETs irradiated by 2-MeV electrons. This leads to a better understanding of the reliability of $Si_{1-y}C_y$ S/D n-MOSFETs in a radiation harsh environment.

2. Experimental details

2.1 Sample preparation

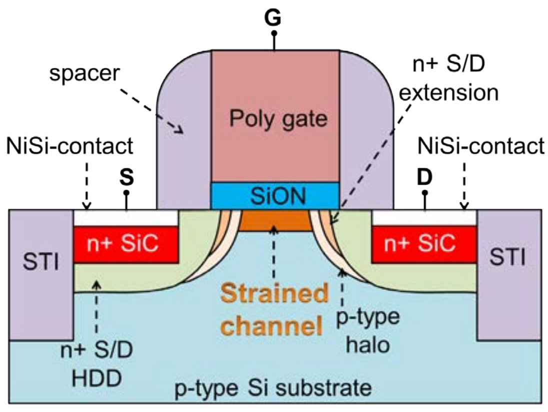

Fig. 1. Schematic cross-sectional view of the $Si_{1-y}C_y$ S/D n-MOSFETs

Figure 1 shows a schematic cross-sectional view of the $Si_{1-y}C_y$ (y = 0, 0.01, 0.015) S/D n-MOSFETs fabricated on 200 mm p-type silicon wafers at imec. Active diode regions are defined by shallow trench isolation (STI), followed by boron (B) p-well implantations. Extension and halo implantations were also performed. Subsequently, a highly-doped drain (HDD) implantation of 4keV phosphorus (P) ions at a dose of 5 x 10^{15} cm^{-2} was carried out. The trenches of the S/D regions were dry-etched to a depth of 90 nm and were refilled by *in-situ* highly P doped SiC epitaxial layers with C concentrations y = 0.01and 0.015, using an Epsilon®chemical vapor deposition (CVD) tool manufactured by ASM. Unstressed reference Si transistors were also processed in order to allow comparison. Dopant activation was achieved by a 950°C spike anneal. The studied transistors were fabricated with a 1.5 nm SiON/poly-Si gate stack, 10μm gate width and 0.25μmgate length.

2.2 Experimental conditions

These devices were irradiated by 2-MeV electrons for a fluence of 1 x 10^{16}and1 x 10^{17} e/cm^2 at room temperature without applied bias. The electrons were irradiated using the electron accelerator at Takasaki Japan Atomic Energy Agency (JAEA). The fluence rate was fixed at 4.68 x 10^{13} e/cm^2・s. The degradation of the device performance of $Si_{1-y}C_y$ S/D n-MOSFETs has been evaluated by the input (I_{DS}-V_{GS}) characteristic with a drain voltage (V_{DS}) at 0.5V and gate voltages (V_{GS}) ranging from -0.5 to 1.2 V. The threshold voltage (V_{TH}) was extracted from linear extrapolation of the input characteristics. In addition, the electron mobility (μ_n) was calculated according to equation (1), where L, W and C_{OX} represent the gate length, the gate width, and the capacitance of the gate oxide, respectively.

$$\mu_n = \frac{\partial I_{DS}}{\partial V_{GS}} \cdot \frac{L}{W \cdot C_{OX}} \cdot \frac{1}{V_{DS}} \qquad \text{(Eq. 1)}$$

3. Results and discussion

3.1Carbondoping effect

First, the effect of the tensile strain in the Si-channel of $Si_{1-y}C_y$ S/D n-MOSFETs induced by different C concentrations was evaluated. Figure 2 (a) and (b) show the input characteristics, the maximum electron mobility and the threshold voltage of $Si_{1-y}C_y$ S/D n-MOSFET, as a function of C concentration (y = 0, 0.01 and 0.015), respectively. Before irradiation, the drain current and the maximum electron mobility increase with increasing the C concentration. In addition, the threshold voltages exhibit a limited tensile strain induced V_{TH} change with C concentration in line with literature observations [8]. These results suggest that the change of the drain current with C concentration can be mainly attributed to the increase of electron mobility due to the tensile strain in the Si-channel.

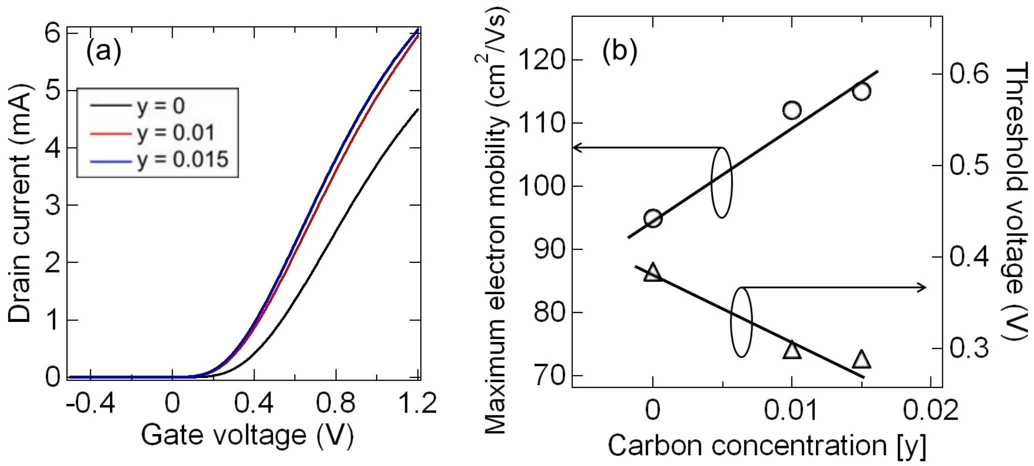

Fig. 2. Input characteristics (a), maximum electron mobility and threshold voltage (b) of $Si_{1-y}C_y$ S/D n-MOSFETs before electron irradiation.

3.2Electron irradiation effect

Next, the effect of electron irradiation on the electrical performance of $Si_{1-y}C_y$ S/D n-MOSFETs was evaluated. Figure 3 shows the input characteristics of 2-MeV electron irradiated $Si_{1-y}C_y$ S/D n-MOSFETs corresponding to different C concentrations. After 2-MeV electron irradiation, the gradient of the drain current significantly decreases with increasing electron fluence for all the C concentrations. The decrease of the drain current due to electron irradiation has two important causes. In the following, we will discuss separately the two causes.

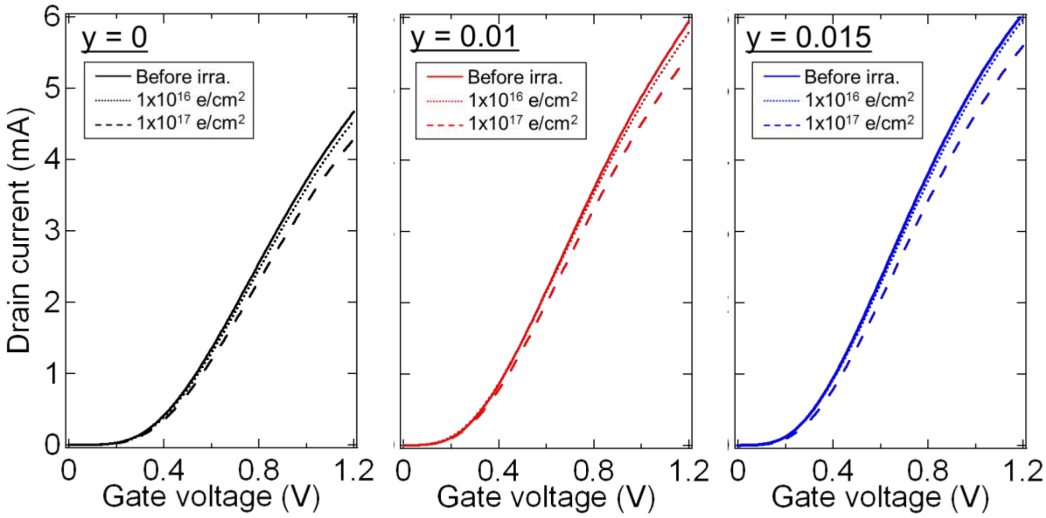

Fig. 3. Input characteristics of 2-MeV electron irradiated $Si_{1-y}C_y$ S/D n-MOSFETs.

One cause is a negative shift of the threshold voltage due to the generation of positive charge trapping in the gate dielectrics by electron irradiation. The threshold voltage corresponding with different electron fluences is summarized in Fig. 4 as a function of the C concentration. It is shown that the threshold voltage variations with electron fluence did not change markedly between the studied C concentrations. This result indicates that the generation of positive charge trapping in the gate dielectrics due to electron irradiation does not depend on the C concentration in the case of the studied electron fluence range.

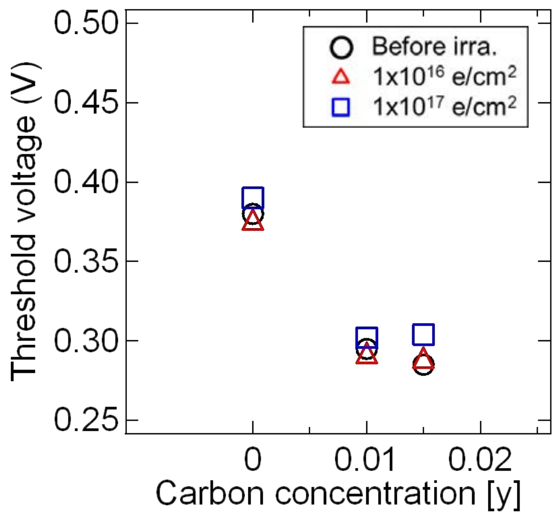

Fig. 4. Threshold voltage of 2-MeV electron irradiated $Si_{1-y}C_y$ S/D n-MOSFETs.

The second cause is electron irradiation induced displacement damage in the Si channel and at the interface between the SiON and the Si channel [9].Figure 5 shows the maximum electron mobility of 2-MeV electron irradiated$Si_{1-y}C_y$ S/D n-MOSFETs as a function of C concentration. It is observed that the maximum electron mobility decreases with increasing electron fluence. This result suggests that the series resistance in the Si channel region increased due to lattice defects created by 2-MeV electron irradiation. On the other hand, no clear relationship between the reduction of the maximum electron mobility and the C concentration can be noted in Fig. 5. This result indicates that the strain induced electron mobility enhancement due to the C concentration has been retained after electron irradiation in the studied C concentration and electron fluence range.

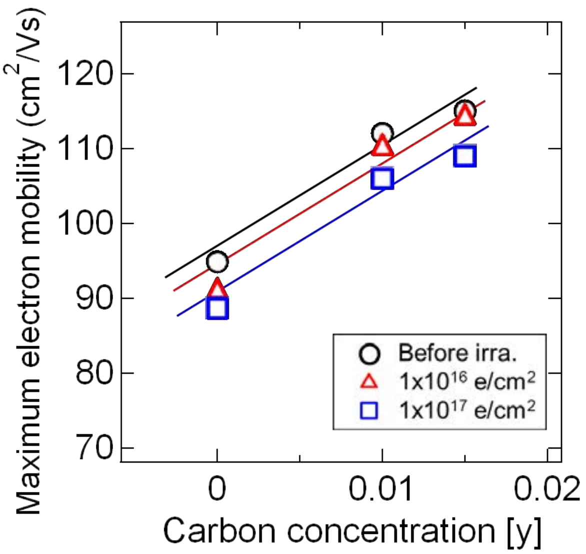

Fig. 5. Maximum electron mobility of 2-MeV electron irradiated $Si_{1-y}C_y$ S/D n-MOSFETs.

4. Conclusion

We have investigated the effect of 2-MeV electron irradiation on the input characteristics of $Si_{1-y}C_y$ S/D n-MOSFETs with different C concentrations and for different electron fluences. It has been shown that after electron irradiation, the drain current decreases with increasing electron fluence for all C concentrations. This can be attributed to two different factors which take place after electron irradiation. The first factor is a negative shift of the threshold voltage due to the generation of positive charge trapping in the gate dielectric. The second factor is the reduction of the maximum electron mobility because of lattice defects created in the Si channel. Both the threshold voltage shifts and the maximum electron mobility degradation are independent on the C concentration for all electron fluences. These results indicate that the tensile strain in the Si channel is maintained after electron irradiation in the studied devices.

Acknowledgments

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