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Radiation damage of Ge-on-Si devices

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ABSTRACT

The radiation damage induced by 2-MeV electrons and 70-MeV protons in p$^+$n diodes and p-channel MOS transistors, fabricated in epitaxial Ge-on-Si substrates is reported for the first time. For irradiation above 5×10^{15} e/cm^2, it is noted that both the reverse and forward current increase, and that the forward current is lower after irradiation for a forward voltage larger than about 0.5 V. The reason for this might be an increased resistivity of the Ge-on-Si substrate. For p-MOSFETs, for a 1×10^{16} e/cm^2 dose, a slight negative shift of the threshold voltage and a decrease of the drain current for input and output characteristics have been observed. In addition, g_m decreases after irradiation. The degradation of the transistor performance is thought to be due to irradiation-induced positive charges in the high-κ gate dielectric. The induced lattice defects are also mainly responsible for the leakage current increase of the irradiated diodes.

With the 90 nm CMOS technology node, the scale of semiconductor devices has decreased into the nano-size. At the same time, the physical thickness of the gate oxide has become smaller than the limit for electron tunneling (~3 nm) so that the gate leakage current density in the channel region becomes unacceptably high. In order to permit low-voltage, low-power operation of nano-scale circuits, the traditional silicon dioxide film has to be replaced by a high-κ dielectric layer such as HfO_2, ZrO_2, etc. However, the use of high-κ gate oxides is confronted with some serious problems. One of them is the quality of the layer and its interface from a viewpoint of charges and traps present there. For this reason, there is a strong interest in high-mobility channel materials, replacing Si for high-speed logic applications. One of the most promising materials is Ge together with SiGe, which has a bulk electron and hole mobility that is approximately two and four times higher than for Si, respectively [1]. Some studies on the radiation damage of Ge device have been performed so far [2,3], however few reports are available on the radiation source dependence and the detailed performance degradation mechanisms. In this paper, the radiation damage induced by 2-MeV electrons and 70-MeV protons in p$^+$n diodes and state-of-the-art p-channel MOS transistors, fabricated in epitaxial Ge-on-Si substrates is reported for the first time.

Device fabrication has been performed in the Si pilot line at IMEC. The starting material used in this study is ~2 μm epitaxial Ge layers, deposited on 200 mm (1 0 0) Si wafers, which have a threading dislocation density of approximately 10^8 cm^{-2}. The epitaxial Ge is nominally undoped. Active areas have been defined by etching

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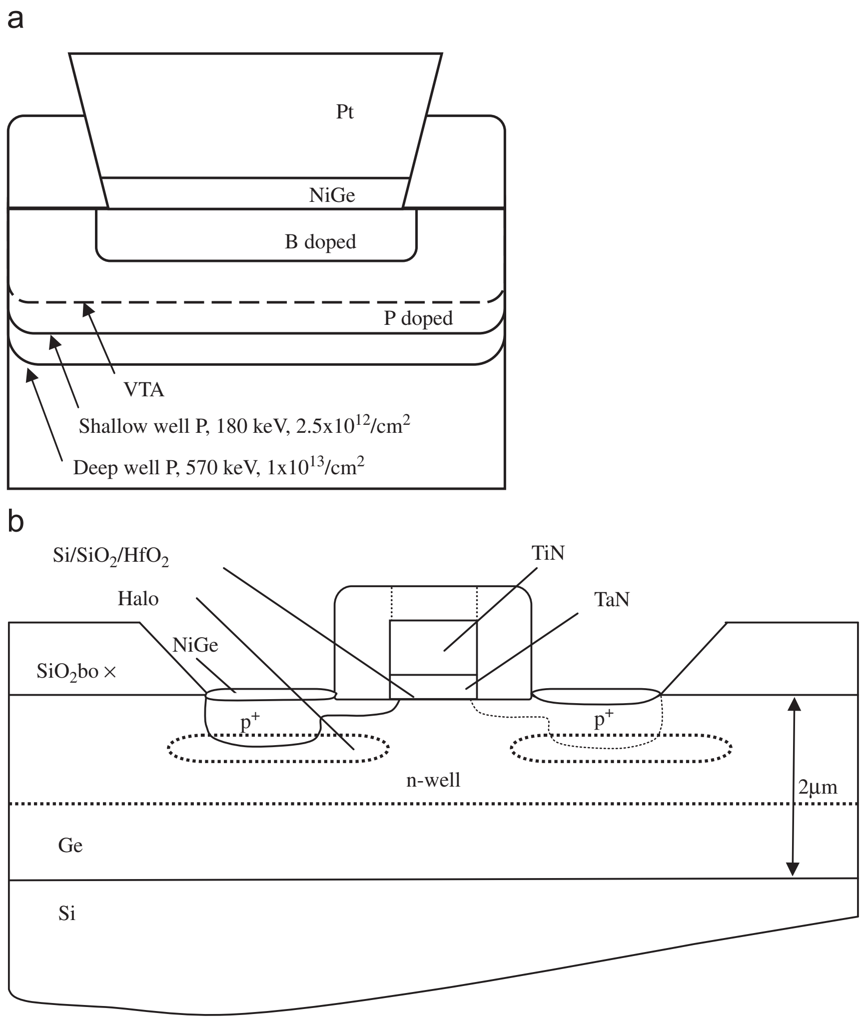

Fig. 1. The cross-section view of a Ge diode (a) and a p-MOSFET (b).

windows in a 200 nm thick deposited oxide. The wafers first receive ^{31}P implants to form the n-well, through a 30 nm deposited SiO_2 layer. Full wafers receive deep well and shallow well implants, and each wafer quadrant receives a different 90 keV threshold voltage adjust (VTA) implant dose. The studied devices correspond to a $4\times10^{12}\,cm^{-2}$ dose. In addition, a 60 keV P halo was implanted under an angle of 25° to a dose of 4×10^{13} at/cm^2. For Ge-on-Si p-MOSFETs, the Ge surface is passivated by 6 ML of Si, which is partially oxidized and subsequently capped with 4 nm atomic layer deposition (ALD) HfO_2, followed by ex-situ physical vapor deposition of 10 nm TaN for the metal gate. A junction anneal at 500 °C for 5 min in N_2 is performed prior to processing with either TiN or TiN/Ti/Al/TiN contact pads. For FETs, the typical gate length and width is 0.5 and 9.8 μm, respectively. In addition to transistors, different geometry junctions have been processed on the same wafers, using the same procedure as for the source/drain junctions of the p-MOSFETs. Diodes with an area between 10^2 and $10^4\,\mu m^2$, and a perimeter between 10^2 and $10^3\,\mu m$ are used in this study. Fig. 1(a and b) shows the cross-sectional view of the used p$^+$n diodes and p-channel MOS FETs, respectively. The detailed fabrication procedure is described in Ref. [4].

Devices are irradiated unbiased by 2-MeV electrons for a fluence of 1×10^{13}–1×10^{17} e/cm^2 at room temperature using the electron accelerator at Takasaki Japan Atomic Energy Agency. Also 70-MeV proton exposures to a fluence of 1×10^{11}–2×10^{12} p/cm^2 have been carried out in the heavy ion medical accelerator synchrotron at the National Institute of Radiological Science. Before and after irradiation, the current/voltage (I/V) and capacitance/voltage (C/V) characteristics of the diodes were measured with applied voltages ranging from −2 to 2 V. Likewise, the pre- and post-irradiation input (I_{DS}–V_{GS}) and output (I_{DS}–V_{DS}) current/voltage characteristics were measured with a parameter analyzer (HP-4156). The maximum transconductance (g_m) and hole mobility (μ_h) as a function of width have been derived from the input curves in linear operation.

Fig. 2 shows typical I/V characteristics for area diode before and after electron irradiation. From this figure, it is noted that for irradiation above 5×10^{15} e/cm^2 both

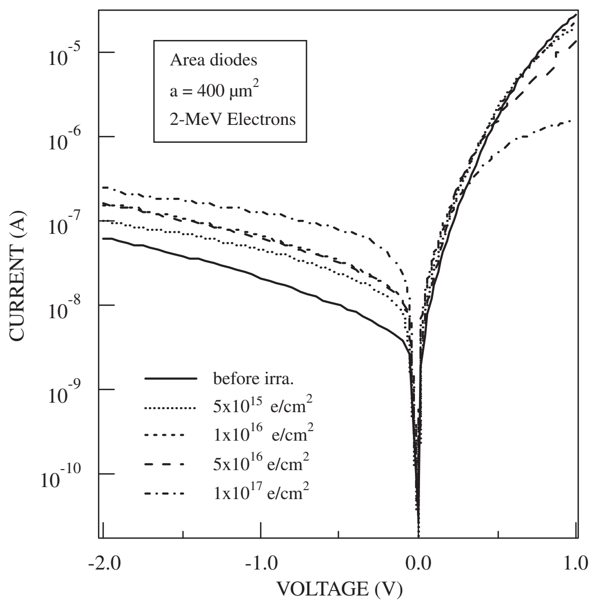

Fig. 2. *I*/*V* characteristics for an area diode before and after electron irradiation.

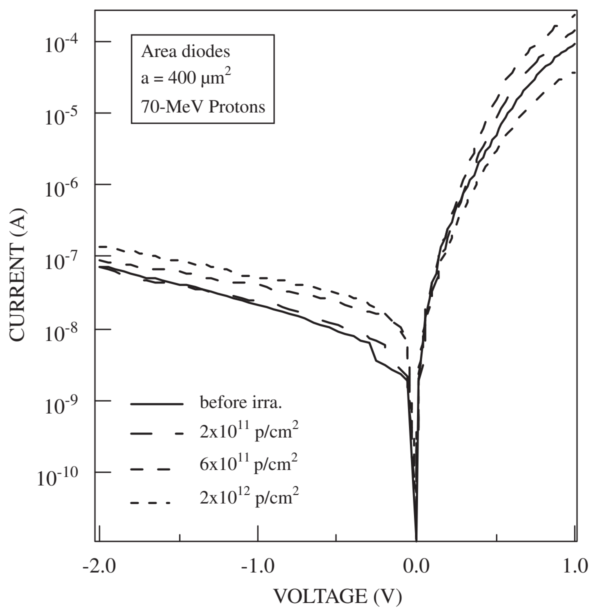

Fig. 3. *I*/*V* characteristics for an area diode before and after proton irradiation.

the reverse and forward current increase and that the forward current is lower after irradiation for a forward voltage larger than about 0.5 V. The ideality factor of the diodes before irradiation is 1.05, while it is 1.67 after a 1×10^{17} e/cm^2 irradiation. The reason for this current decrease might be an increased resistivity of the Ge-on-Si substrate by dopant deactivation. The same tendency is observed for irradiated perimeter diodes. Fig. 3 shows typical *I*/*V* characteristics for an area diode before and

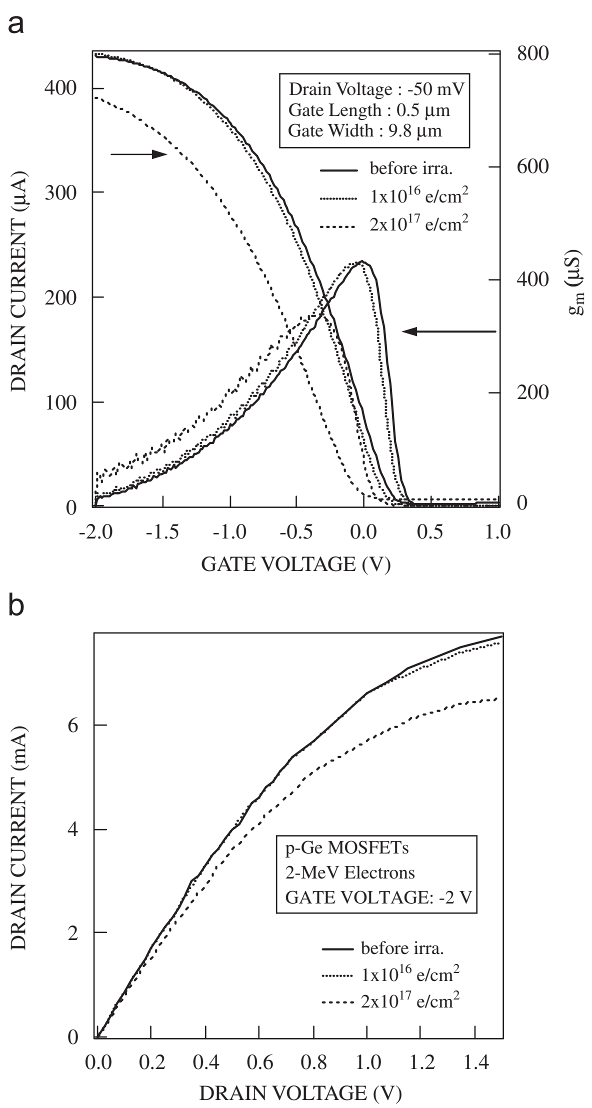

Fig. 4. Input (a) and output (b) characteristic together with g_m for p-MOSFETs before and after electron irradiation.

after proton irradiation. The degradation behavior exhibits some differences compared to the electron irradiation case. The radiation source dependence of the performance degradation has been reported before for SiGe diodes [5]. According to these results, the damage coefficient as defined below is about three orders of magnitude larger for protons than for electrons due to the difference in particle mass and probability for collision to induce lattice defects in the Ge-on-Si substrate. It is also concluded from Fig. 3 that a proton irradiation for a fluence below 2×10^{11} p/cm^2 is too low for performance degradation of the Ge-on-Si diodes studied and that probably the resistivity increase is too small.

Fig. 4(a and b) shows typical input and output characteristics together with g_m for p-MOSFETs before and after electron irradiation, respectively. In those

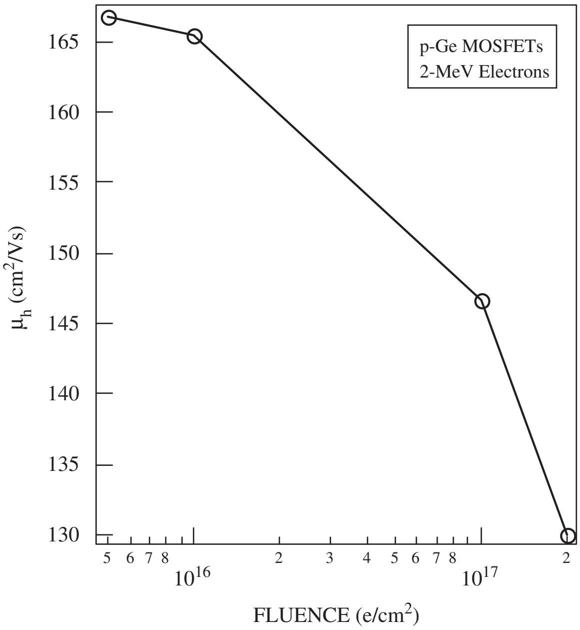

Fig. 5. Hole mobility as a function of electron fluence.

figures, a slight negative shift of the threshold voltage and a decrease of the drain current for input and output characteristics is found above a fluence of 1×10^{16} e/cm^2. Fig. 5 shows μ_h as a function of electron fluence. For 1×10^{17} e/cm^2, μ_h decreases by about 30% below the pre-rad value. In addition, g_m decreases after irradiation as shown in Fig. 4(a). The degradation of the transistor performance is thought to be mainly due to irradiation-induced positive charges in the high-κ gate dielectric.

Assuming a linear relationship between damage increase and fluence, one can calculate a damage coefficient of current (K), which can be defined by the following equation:

$$I(\phi) = I(0) + K\phi \tag{1}$$

where Φ is the electron or proton fluence.

Using this expression, K is calculated to be 4.9×10^{-23} e^{-1} A cm^2 and 5.5×10^{-20} p^{-1} A cm^2, respectively. The difference of K is mainly due to the difference of radiation source such as mass and displacement probability as mentioned above.

Finally, to examine the effect of interface and bulk substrate on the leakage current of the irradiated diodes, the leakage current of area and perimeter diodes is compared in Fig. 6. From this figure, it is noted that until 1×10^{16} e/cm^2, no clear linear relationship between reverse current and area/perimeter is observed. This proves that for low fluences the bulk generation current is not dominant for the leakage current in irradiated Ge-on-Si diodes. The deep levels associated with the radiation-induced defects which cause the leakage current increase will be studied further using DLTS.

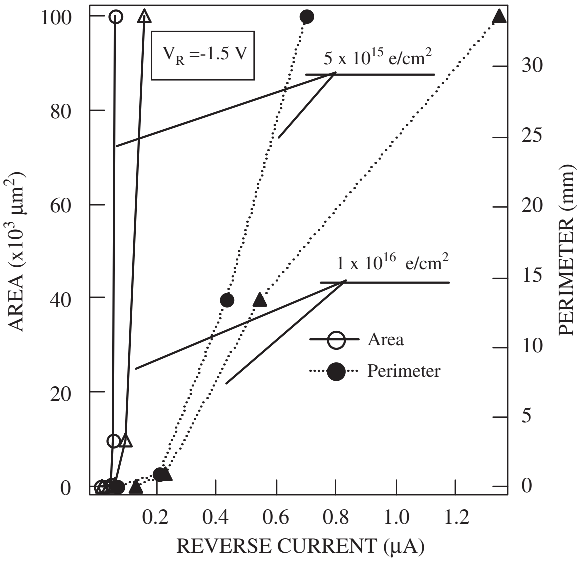

Fig. 6. Leakage current as a function of diode area and perimeter.

In conclusion, for irradiations above 5×10^{15} e/cm^2, it is noted that both the reverse and forward current increase, and that the forward current is lower after irradiation for a forward voltage larger than about 0.5 V. The reason for this might be an increased resistivity of the Ge-on-Si substrate. For p-MOSFETs, for a 1×10^{16} e/cm^2 dose, a slight negative shift of the threshold voltage and a decrease of the drain current for input and output characteristics have been observed. In addition, g_m decreases after irradiation. The degradation of the transistor performance is thought to be due to irradiation-induced positive charges in the gate dielectric. The induced lattice defects, most likely E centers (P–V) are thought responsible for the leakage current of irradiated diode. Future Deep Level Transient Spectroscopy studies should investigate this hypothesis in more detail.

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