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Electrical properties of rapid thermal oxides on $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ films

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The electrical characteristics of rapid thermal oxides on $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ layers are reported. X-ray photoelectron spectroscopy results indicate segregation of Ge at the $\text{SiO}_2/\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ interface, a thin GeO_2 layer at the oxide surface, and elemental Ge at the interface and in the oxide. The interface state density of the samples ranges from 3.0×10^{11} to $3.6 \times 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$. All the samples show electron trapping behavior and the trap generation rate decreases with increasing C concentration. The charge-to-breakdown value and the oxide breakdown field are higher for $\text{Si}_{0.887}\text{Ge}_{0.113}$ than for $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ samples, and these values decrease with increasing C concentration. © 2000 American Institute of Physics. [S0003-6951(00)01928-8]

Heterojunction bipolar transistors,¹ field effect transistors,² and photodetectors³ based on $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ layers have been fabricated recently. In the realization of Si and Si-based heterojunction field effect transistors, oxidation is one of the most crucial process steps. Research in thermal oxide on $\text{Si}_{1-x}\text{Ge}_x$ showed that Ge segregation at the $\text{SiO}_2/\text{Si}_{1-x}\text{Ge}_x$ interface leading to high negative fixed oxide charge (Q_f) and interface state density (D_{it}).⁴ Rapid thermal process has been suggested⁴⁻⁶ to be suitable for $\text{Si}_{1-x}\text{Ge}_x$ strained layer as it creates less misfit dislocations. In this letter, we examine the effects of Ge segregation and the role of C on the electrical properties of rapid thermal oxides (RTO) on $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ films.

The $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ samples were grown on *n*-type (100) Si substrates in a rapid thermal chemical vapor deposition (RTCVD) system. RTO was carried out at 1000 °C in dry oxygen ambient for 270 s for all the samples. The oxide thickness was found to be between 10 and 16 nm. Details of the growth procedure and RTO process can be found in Refs. 7 and 8, respectively. The electrical properties of the oxides were obtained from the capacitance–voltage, conductance–voltage, current–voltage, and constant current stressing characteristics of an aluminum gate metal–oxide–semiconductor (MOS) capacitor structure.

Figure 1 shows an x-ray photoelectron spectroscopy (XPS) result of a RTO $\text{Si}_{0.8686}\text{Ge}_{0.113}\text{C}_{0.0184}$ sample. The peaks at the surface of the oxide correspond to the O 2s peak at 25.0 eV and the smaller and broader GeO_2 peak at 33.7 eV.⁹ The thin GeO_2 layer at the oxide surface has been identified previously at 1221.43 eV.⁸ By focusing on the Ge 3d peak (29.2 eV), one can see from Fig. 1 that elemental Ge is present throughout the oxide layer. This is not observable with the Ge 2p peak.⁸ The Ge 3d intensity peaks at the oxide surface and reduces as oxide thickness increases. The strong Ge 3d peak at the $\text{SiO}_2/\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ interface (at profile time 1250–1500 s) confirmed the segregation of Ge at the interface. Riley and Hall⁹ reported a small amount of elemental Ge in anodized oxide on $\text{Si}_{0.84}\text{Ge}_{0.16}$ alloy film. In

contrast, Fig. 1 shows a significantly higher elemental Ge concentration at the bulk and surface of SiO_2 .

Figure 2 shows the high frequency (1 MHz) capacitance versus voltage characteristics of all the RTO samples. The inversion capacitance values (C_i) are higher for the $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ than $\text{Si}_{0.887}\text{Ge}_{0.113}$ samples. C_i of the $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ samples increases with increasing C concentration. As C_i can be increased with an increase in donor concentration in the semiconductor of a MOS capacitor, the increase in C_i of the $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ samples may be due to an increase of donor-like centers in these films. This is possible as donor-like centers could be formed with the introduction of carbon into the SiGe network and the concentration of such centers increases with increasing C concentration.¹⁰ Q_f is calculated from the flatband voltage of Fig. 2 to be: -9.53×10^{10} , -1.4×10^{12} , -2.2×10^{12} , and $-9.5 \times 10^{11} \text{ cm}^{-2}$ for samples $\text{Si}_{0.887}\text{Ge}_{0.113}$, $\text{Si}_{0.8811}\text{Ge}_{0.113}\text{C}_{0.0059}$, $\text{Si}_{0.8738}\text{Ge}_{0.113}\text{C}_{0.0132}$, and $\text{Si}_{0.8686}\text{Ge}_{0.113}\text{C}_{0.0184}$, respectively. Q_f therefore increases with C in $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ films. Ahn *et al.*¹¹ suggested that Si–O–Si and Si–O–Ge bonds can form during oxidation of the SiGe layer. The Ge–O bond is weaker and can be broken leaving a Si–O–dangling bond structure. If such dangling bond does not subsequently bond with another Si atom, it

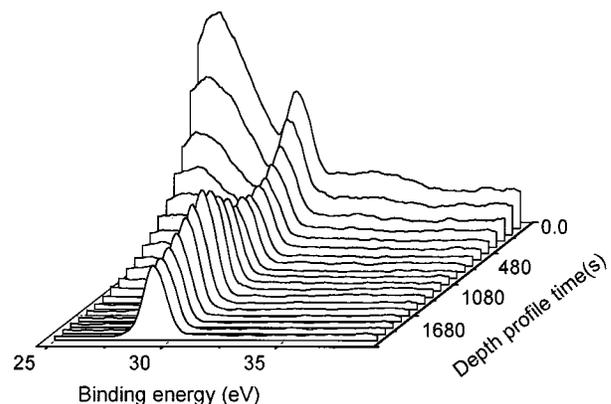


FIG. 1. XPS spectra of the rapid thermal oxide grown on $\text{Si}_{0.8686}\text{Ge}_{0.113}\text{C}_{0.0184}$ film at 1000 °C for 270 s. Note that the SiO_2 region covers from profile time 0 to 1250 s.

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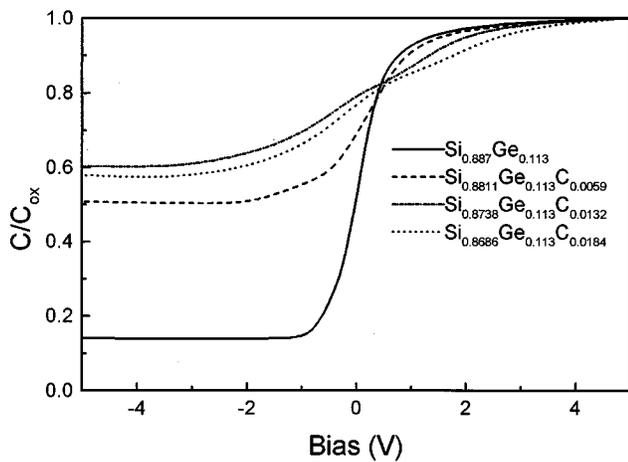


FIG. 2. High frequency (1 MHz) capacitance–voltage characteristics of Al–SiO₂–Si_{1–x–y}Ge_xC_y and Al–SiO₂–Si_{1–x}Ge_x capacitors.

can trap an electron and becomes negatively charged. Our XPS results show that the Ge 3d peak intensity is lower for RTO Si_{0.887}Ge_{0.113} than for Si_{1–x–y}Ge_xC_y samples. This means that the elemental Ge content in the oxide and in the SiO₂/substrate interface is lower in Si_{0.887}Ge_{0.113} than the Si_{1–x–y}Ge_xC_y samples. If the elemental Ge originates from Ge atom detached from the Si–O–Ge bond, then the elemental Ge concentration should be related to Q_f . This agrees with our Q_f results presented in Fig. 2.

The D_{it} values of samples Si_{0.887}Ge_{0.113}, Si_{0.8811}Ge_{0.113}C_{0.0059}, Si_{0.8738}Ge_{0.113}C_{0.0132}, and Si_{0.8686}Ge_{0.113}C_{0.0184} are calculated¹² to be: 3.0×10^{11} , 1.1×10^{12} , 1.6×10^{12} , and 3.6×10^{12} eV⁻¹ cm⁻², respectively. D_{it} is higher for Si_{1–x–y}Ge_xC_y samples compared to Si_{0.887}Ge_{0.113} and increases with an increase in C concentration in the films. As the increase in the Ge pileup at the SiO₂/Si_{1–x–y}Ge_xC_y interface will increase the misfit dislocation, D_{it} is therefore directly related to the peak Ge concentration at the SiO₂/Si_{1–x–y}Ge_xC_y interface.

Figure 3 shows the current versus field characteristics of the MOS capacitors measured under a positive gate bias condition. The breakdown field strength of oxide grown on Si_{1–x–y}Ge_xC_y films was found to be in the range of 10–14

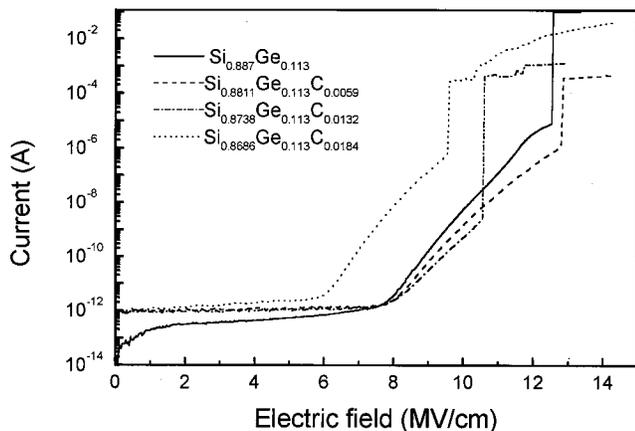


FIG. 3. Current vs electric field characteristics of Al–SiO₂–Si_{1–x–y}Ge_xC_y and Al–SiO₂–Si_{1–x}Ge_x capacitors. Note that the Al contact area is 3.14×10^{-4} cm².

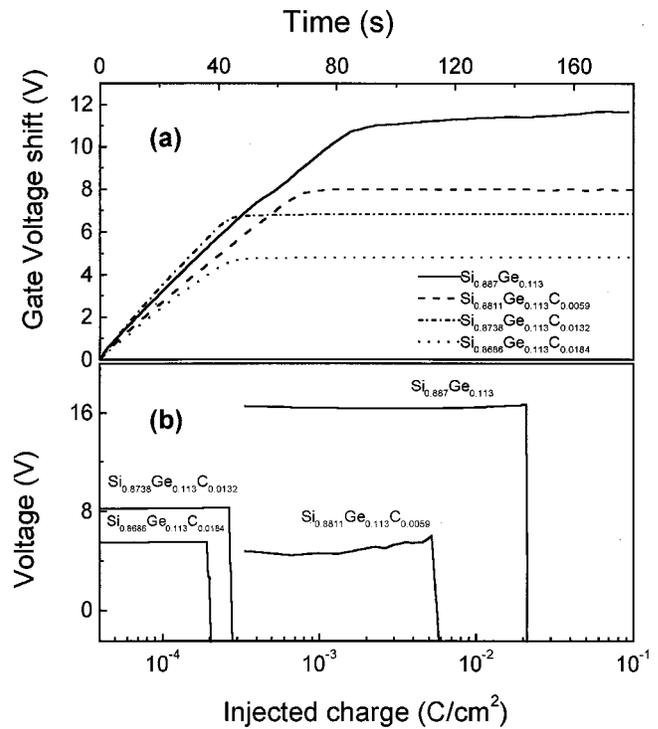


FIG. 4. (a) Gate voltage shift vs stress time characteristics of RTO on Si_{1–x–y}Ge_xC_y and Si_{1–x}Ge_x films. The samples were under a constant current stress of 30 nA/cm². (b) Charge-to-breakdown characteristics of RTO on Si_{1–x–y}Ge_xC_y and Si_{1–x}Ge_x films. Note that the initial voltage value (at time zero) is set by the oxide thickness.

MV/cm. The oxide breakdown field reduces as the C concentration in the Si_{1–x–y}Ge_xC_y substrate increases. The SiO₂/Si_{1–x–y}Ge_xC_y barrier heights extracted from Fig. 3 were found to be 3.48, 3.07, 2.72, and 2.82 eV for samples Si_{0.887}Ge_{0.113}, Si_{0.8811}Ge_{0.113}C_{0.0059}, Si_{0.8738}Ge_{0.113}C_{0.0132}, and Si_{0.8686}Ge_{0.113}C_{0.0184}, respectively. Cross-sectional transmission electron microscope results of the RTO Si_{1–x–y}Ge_xC_y samples show the rough SiO₂/Si_{1–x–y}Ge_xC_y interface for higher C content samples.¹³ We believe this roughen interface results in higher electric field and thus a lower effective barrier height.¹⁴

We monitored the change of gate voltage (ΔV_G) of the MOS capacitors for a constant current 30 nA/cm² with positive bias to the Al gate. The positive ΔV_G shift for all the samples in Fig. 4(a) shows electron trapping characteristics. The electron trap generation is higher for Si_{0.887}Ge_{0.113} than the Si_{1–x–y}Ge_xC_y samples, and the trap generation rate decreases with increasing C concentration in the films. Our secondary ion mass spectroscopy results⁸ showed that during RTO of Si_{1–x–y}Ge_xC_y samples, some of the C is consumed via formation of CO₂ or CO and the rest remains in the oxide. Carbon atoms in the oxide have been reported¹⁵ to act as positive charges. All these nonsubstitutional C contributes to hole traps, and hence, decreases electron trap generation.¹⁶ Figure 4(b) shows that the charge to breakdown value of Si_{0.887}Ge_{0.113} sample is higher compared to Si_{1–x–y}Ge_xC_y samples. For the Si_{1–x–y}Ge_xC_y samples, the charge to breakdown value decreases with an increase in the C concentration. During oxidation the outdiffusion of C atoms may cause conducting path between the interfaces to be formed via randomly generated traps in the oxide. Such conducting path will reduce the charge to breakdown value of the film.

Also the probability of forming conducting path increases with increase in the C concentration in the film.

In conclusion, our XPS results revealed that elemental Ge exist in the oxide and oxide/alloy interface. Q_f and D_{it} increase, but the breakdown field, effective barrier height, and charge-to-breakdown values decrease, with increasing C concentration in the $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ films. The oxides exhibit electron trapping behavior and the trap generation rate decreases with an increase in C concentration in the film.

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