Oxidation Studies of Silicon Germanium (SiGe) using In-Situ Steam Generated (ISSG) and Plasma Enhanced Atomic Layer Deposited (PEALD) Oxides

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SiGe is a versatile material for the semiconductor industry for sub-7 nm node technology development; it can be used as a high mobility channel material in FinFET, and as multiple sacrificial layers to form channel regions in gate all around (GAA) nanosheet device architecture. Understanding SiGe film oxidation is important for matching oxidation rates between SiGe layers with different Ge% in nanosheet applications [1]. In this paper, a study of ISSG (800 ^{o}C) and PEALD (room temperature to 300 ^{o}C) oxidation processes is performed on blanket $Si_{1-x}Ge_x$ films ranging from $x = 0.25$ to 0.80. We establish the boundaries of three distinct regions of oxidation behavior for the ISSG process (Region I: $0 < x < 0.5$, Region II: $0.5 < x < 0.67$, and Region III: $x > 0.67$). Historically, low Ge oxidation has been extensively studied [2-4]. Here, we show for Region I, the ISSG oxidation rate is very small (1.7 nm of oxide growth in 5 sec). The oxidation rate rapidly increases in Region II as x increases, where it reaches a maximum (13.8 nm in 5 sec) at the Region II/Region III boundary, then abruptly drops in Region III as x increases due to complete sublimation of Ge (see Figure 1). The abrupt increase in the ISSG oxidation rate between Regions I and II makes it difficult to match oxide thicknesses for the wide range of Ge% utilized by nanosheet device architecture. Therefore, we studied a lower temperature oxidation process (PEALD) which has a lower oxidation rate. We found that PEALD oxidation rates are unchanged across the Region I/II boundary, even for higher temperatures up to 300 ^{o}C as shown in Figure 2. This enables oxide thickness matching for a wide range of Ge%. These results are applicable to the development of various nanotechnologies such as nanosheet and high mobility channel FinFET devices.

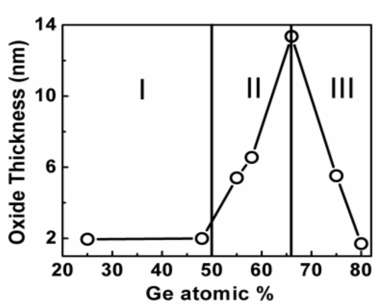

Figure 1. ISSG oxidation of SiGe films exhibits three types of behavior: (I) slow oxidation, (II) fast oxidation with condensation, and (III) sublimation. We can explain this behavior with a binary mixing model [5].

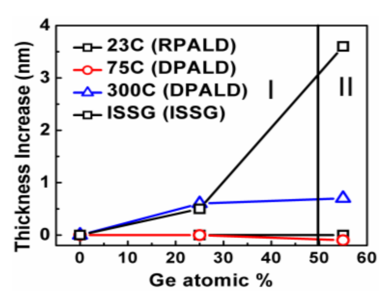

Figure 2. ISSG exhibits a stronger oxidation with increasing Ge concentration than ALD. ALD also shows enhanced oxidation at higher temperature (> 300 ºC). 75 ºC PEALD has minimal oxidation with good quality oxide.

Reference: [1] N. Loubet *et al.*, VLSI 2017, T230-231; [2] S. Siddiqui *et al.*, ECS Trans. 2013, vol. 53, issue 3, 137-146; [3] P.-E. Hellberg *et al.*, J. Appl. Phys. 82, 5773 (1997); [4] F. K. Legous *et al.*, J. Appl. Phys. 65, 1724 (1989); [5] H. K. Liou *et al.*, Appl. Phys. Lett. 59, 1200 (1991).

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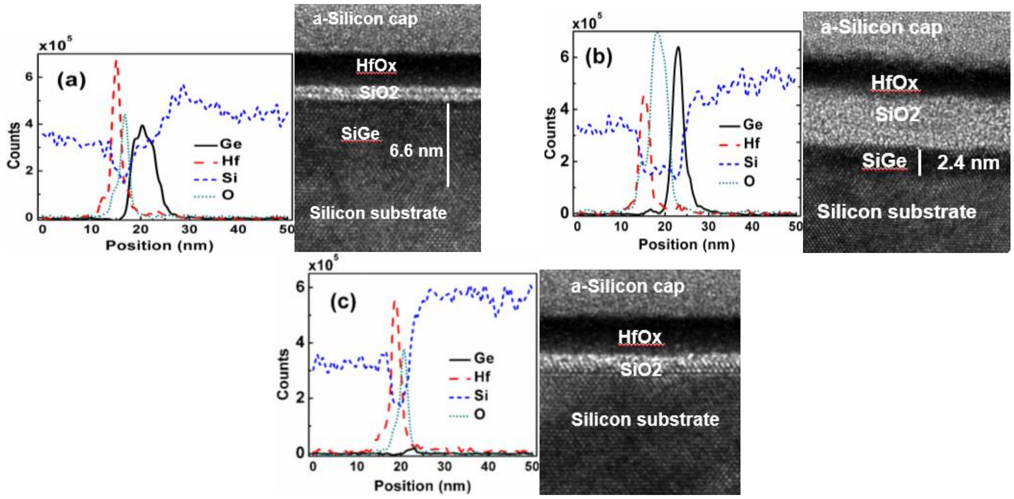

Figure S1. Electron Energy Loss Spectroscopy (EELS) and Transmission Electron Microscopy (TEM) for $Si_{1-x}Ge_x$ films post ISSG oxidation, where x = (a) 0.25, (b) 0.55 and (c) 0.80. **(a)** For x = 0.25, EELS shows some Ge condensation at the SiGe/oxide interface. **(b)** For x = 0.55, there is a sharp increase in the Ge signal at the SiGe/oxide interface, accompanied by a very high oxidation rate, which leads to thicker oxide. **(c)** For x = 0.80, EELS/TEM results show Ge is completely sublimed and ISSG forms SiO_y.

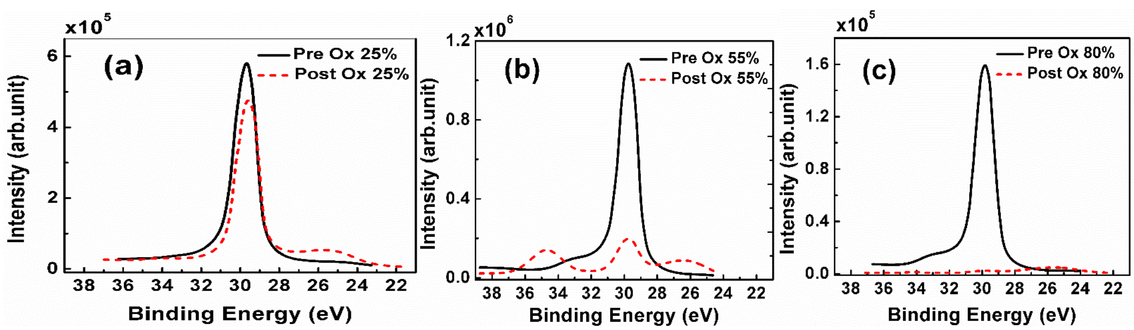

Figure S2. Ge^{3d} spectra using X-ray Photoelectron Spectroscopy (XPS) for $Si_{1-x}Ge_x$ films post ISSG oxidation, where x = (a) 0.25, (b) 0.55 and (c) 0.80. **(a)** For x = 0.25, there is a small amount of elemental Ge loss, while there is no GeO_y formation. **(b)** For x = 0.55, there is significant elemental Ge loss at 29.8 eV indicating Ge sublimation, while there is GeO_y formation at 34.8 eV. **(c)** For x = 0.80, all Ge atoms are fully sublimated, indicated by the lack of elemental and oxide peaks, which is consistent with TEM data from Figure S1(c).

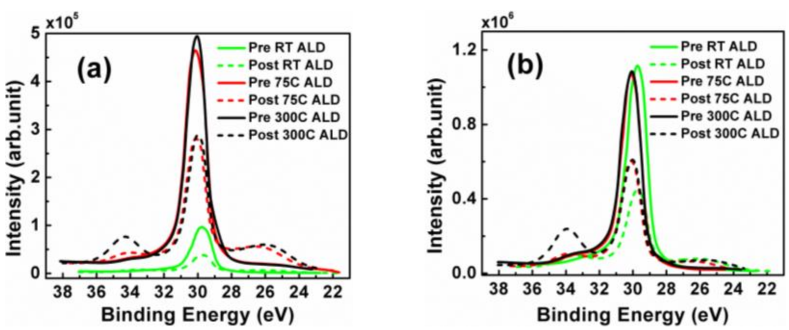

Figure S3. Ge^{3d} spectra using XPS for (a) x = 0.25 and (b) x = 0.55 $Si_{1-x}Ge_x$ films before and after PEALD oxide deposition at room temperature, 75 ºC and 300 ºC. For both x = 0.25 and 0.55, a GeO_y peak is observed at ~34 eV, which increases with temperature. Interestingly, GeO_y can be formed with low temperature PEALD processes [2]. This behavior is not observed with ISSG processes at x = 0.25 (see Figure S2(a)).