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Novel GeO_x Interface Layer Engineering by Ultra Low Power Microwave Plasma Oxidation

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Abstract

Novel low power microwave plasma (NLPMP) oxidation and its application in growing thin GeO_x interface layer are presented. The combination of NLPMP oxidation with a lower temperature realizes both precise thickness control for a GeO_x interface layer and a lower gate leakage current. The NLPMP oxidation at 50°C through 1nm Al_2O_3 forms 0.19nm GeO_x interface layer, and the D_{it} at E_i-0.2eV is $4\times10^{11}cm^{-2}eV^{-1}$. The thermal stability of Ge interface is investigated, and the GeO_x formation by NLPMP oxidation improves the interface thermal stability.

1. Introduction

Germanium (Ge) is particularly attractive for use as a channel material in future CMOS technology because of the higher hole and electron mobility compared to a Si channel device as well as its compatibility with Si VLSI high volume manufacturing. One of the biggest challenges in Ge channel based MOSFET devices is the gate stack formation, especially high quality Ge interface layer (IL) formation[1 ~5].

Post plasma oxidation through a thin atomic layer deposition (ALD) Al_2O_3 was proposed to achieve thin GeO_x IL and low D_{it} [6~8]. Higher quality ultra-thin GeO_x IL in the Ge gate stack is required, with the equivalent oxide thickness (EOT) scaling to 1nm and below. However, the controllability of GeO_x IL is a considerable challenge.

In this paper, we report on the NLPMP oxidation technique to form the ultrathin GeO_x IL. To realize the ultrathin GeO_x formation with more precise control, low temperature oxidation with NLPMP source is applied. The thickness dependence of the ultrathin GeO_x on the thermal stability is investigated to understand the thinning limit of GeO_x IL thickness.

2. Experiments

The fabrication processes of Ge MOSCAPs are shown in Fig.1. After the pre-cleaning of the Ge wafers, a thin Al_2O_3 layer with 1nm thickness was deposited by ALD. Thereafter, NLPMP oxidation was carried out at temperature raging from 50°C to 300°C. An additional 4nm of the ALD Al_2O_3 layer was deposited after the NLPMP oxidation, followed by PVD TiN deposition. Finally, forming gas anneal (FGA) was processed to complete the device fabrication. To investigate the thermal stability of the Ge interface, varied times and temperatures were applied for FGA.

The schematic of the NLPMP unit which was applied in this work is shown in Fig. 2. The wafer temperature was controlled ranging from 50°C to 300°C. Low power microwave of 210W at the minimum was introduced from the top.

3. Results and discussion

Figure 3 shows the Ge 3d XPS spectra of the Ge (100) substrate which received NLPMP oxidation through 1nm thickness ALD Al_2O_3. The stoichiometry of the IL improves with increasing oxidation time, regardless of the oxidation temperature with utilizing NLPMP. By lowering the oxidation temperature from 300°C to 50°C, the GeO_x growth rate is clearly reduced, as shown in Fig. 4(a). NLPMP oxidation power dependence of GeO_x growth was investigated as well, as shown in Fig. 4(b) and lower power oxidation forms a lesser amount of GeO_x. Combining NLPMP oxidation with a lower temperature realizes a more precise GeO_x thickness control. Figure 5 illustrates the cross section TEM of the TiN/A_2lO_3/GeO_x/Ge gate stack. A clear and smooth Ge/GeO_x interface is observed in Fig. 5.

The EOT of the TiN/Al_2O_3/GeO_x/Ge stack as a function of the oxidation time is plotted in Fig 6. The EOT with 50°C oxidation for 30sec is reduced by approximately 0.1nm, and the EOT is increased with further oxidation time. GeO_x formation is confirmed even for 30sec oxidation, as shown in Fig. 3(a) therefore the EOT reduction is considered to be related to the stoichiometry improvement of the bottom Al_2O_3 resulting in a permittivity increase of the Al_2O_3. NLPMP oxidation at 50°C provides an extremely mild oxidation process and the EOT reduction occurs at the early stage of the oxidation process. As for 300°C oxidation, the EOT regrowth rate is much faster than that at 50°C, and the EOT reduction is not observed at the early stage. As confirmed in Fig.7, the gate leakage current of the stack with GeO_x IL formed by NLPMP oxidation at 50°C is lower than that at 300°C. Figure 8 shows D_{it} of TiN/Al_2O_3/Ge stack or TiN/Al_2O_3/GeO_x/Ge stack. The D_{it} is improved by the NLPMP oxidation. The D_{it} value with 50°C NLPMP oxidation is smaller than that with 300°C. The reason for the lower leakage current by 50°C NLPMP oxidation is related to the smoother and high quality interface resulting in lower D_{it}. It was reported that the D_{it} of Al_2O_3/GeO_x/Ge MOS degraded as the GeO_x thinned, and a significant degradation of the D_{it} started around 0.5nm GeO_x. [7,8]. The NLPMP oxidation at 50°C formed 0.19nm GeO_x, and the D_{it} at E_i -0.2eV is $4\times10^{11}cm^{-2}eV^{-1}$ which is smaller than the reported D_{it} such as $8\times10^{11}cm^{-2}eV^{-1}$ at 0.23nm GeO_x [7].

To investigate NLPMP oxidation effect on the thermal stability of CV, FGA at 400°C was processed at varied anneal time. The resulting C-V is plotted in Fig. 9. C-V for w/o NLPMP oxidation is clearly degraded as FGA time is increased from 10min to 100min. The degradation is thought to be related to poor thermal stability of the Ge/Al_2O_3 interface. C-V shape for with 30sec NLPMP oxidation does not change with increasing annealing time, however the flatband voltage (V_{fb}) shift occurs. The V_{fb} instability suggests that the GeO_x formed by 30sec NLPMP oxidation is too thin for Ge interface passivation. As for C-V with 120sec and 360sec NLPMP oxidation, they do not show any shape change or shift in C-V, indicating Ge interface thermal stability is improved by GeO_x formed by NLPMP oxidation. The FGA temperature effect from 250°C to 500°C on the C-V was also investigated. The C-V shape w/o NLPMP oxidation degraded even at 400°C FGA. Meanwhile, C-V with NLPMP oxidation shows no significant degradation up to 500°C FGA without increasing EOT, as shown in Fig. 10.

4. Conclusion

We have demonstrated ultrathin GeO_x IL formation by NLPMP oxidation. The thickness controllability of the GeO_x formation and the GeO_x/Ge interface quality are improved by lowering the oxidation temperature. The thermal stability of the GeO_x/Ge interface formed by NLPMP oxidation is also improved up to 500°C thermal processing.

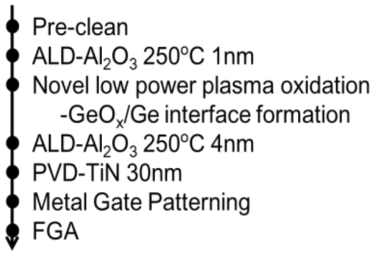

Fig. 1 Process flow of MOSCAPs using pGe (100) substrate.

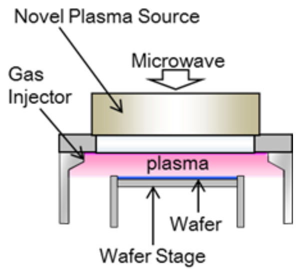

Fig. 2 Schematic of the NLPMP oxidation system

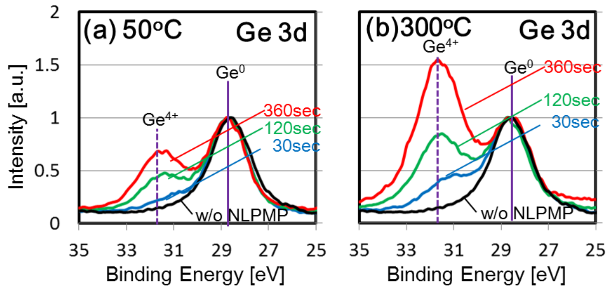

Fig. 3 AR-XPS spectra of Ge 3d normalized by Ge^0 peak intensity. The samples are Al_2O_3(1nm)/Ge before or after NLPMP oxidation with 210W power. (a): NLPMP at 50°C (b): NLPMP at 300°C. GeO_x peak increases with the oxidation time. GeO_x growth rate at 50°C is slower than that at 300°C.

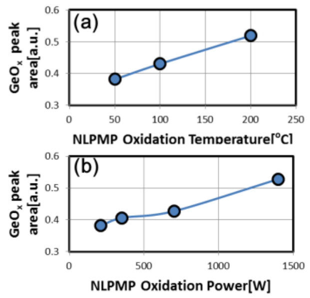

Fig. 4 GeO_x peak area is calculated from each AR-XPS spectrum of Ge 3d. (a): NLPMP oxidation temperature dependence for 30sec with 210W power. (b): NLPMP oxidation power dependence at 50°C for 30sec.

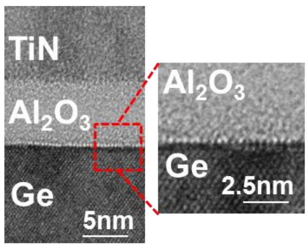

Fig. 5 Cross section TEM picture of the TiN/Al_2O_3/GeO_x/Ge stack formed by 50°C 30sec NLPMP oxidation with 210W. The GeO_x/Ge interface is smooth atomically.

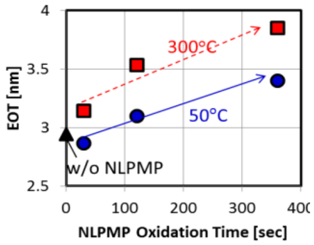

Fig. 6 NLPMP oxidation time dependence of EOT. EOT of GeO_x formed by 50°C NLPMP with 210W increases more slowly than that of 300°C.

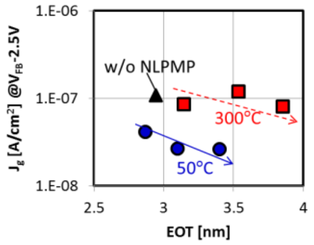

Fig. 7 EOT-Jg. Jg of GeO_x formed by 50°C NLPMP with 210W power is lower than that of 300°C.

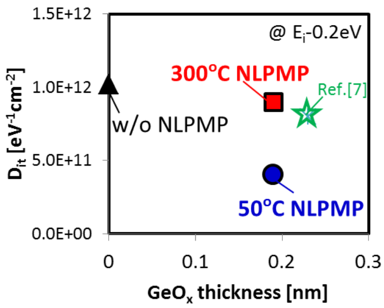

Fig. 8 D_{it} of GeO_x/Ge interface at E_i-0.2eV as a function of GeO_x IL thickness, compared with a reported result. The D_{it} was extracted by the conductance method at room temperature, and is related to the sub-threshold MOSFET characteristic.

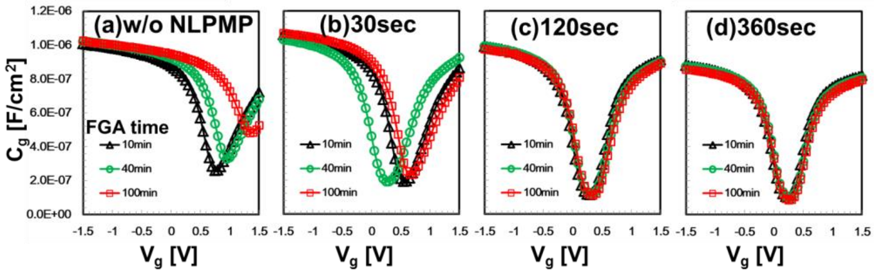

Fig. 9 FGA(400 °C) time dependence of CV curve (10kHz). (a): w/o NLPMP (b): with 30sec NLPMP oxidation (c): with 120sec NLPMP oxidation (d): with 360sec NLPMP oxidation at 50°C with 210W power. The thermal stability is improved by 120sec or beyond NLPMP oxidation time.

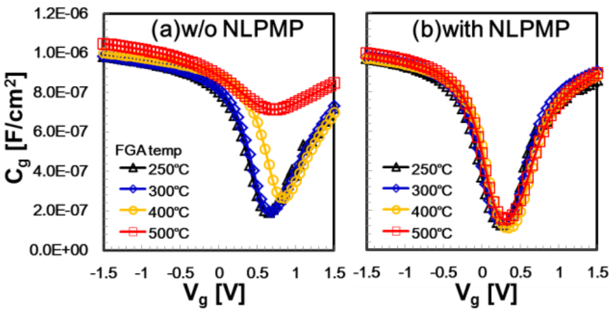

Fig. 10 FGA temperature dependence of C-V curve (10kHz). (a): w/o NLPMP oxidation (b): with 300°C 30sec NLPMP oxidation with 210W power. The NLPMP oxidation improves thermal stability of CV.

Acknowledgment

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