

# Growth of Epitaxial Beryllium Oxide on Ge (111) by Molecular Beam Epitaxy

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## 1. Introduction

Ge is a competitive candidate to replace Si for the post-14nm technique node because of its high mobility. However, the thermodynamic instable and water soluble nature of its oxides on Ge becomes a big obstacle against its development [1]. To realize high-quality high-k/Ge stack with low  $J_g$  and low EOT, inserting a stable interfacial layer with large bandgap to suppress gate leakage and the formation of  $GeO_x$  is a promising way. Recently, by applying atomic layer deposition (ALD) method, epitaxial BeO has been demonstrated to be a good choice for GaAs passivation because of its advantageous properties in the lattice (domain) match, large band gap (10.6 eV), thermal stability and thermal conductivity [2]. Since Ge has almost the same lattice constant with GaAs, BeO is presumably regarded as an ideal interface passivation layer (IPL) on Ge. However, ALD-BeO precursor ( $Be(CH_3)_2$ ) is highly toxic to harm researchers seriously, so in this paper, we introduce a novel way for BeO epitaxially grown on Ge(111) with less security risk that may open a wide prospect for Ge surface passivation.

## 2. Experimental

As shown in Fig. 1, MOS capacitor was fabricated on p-type Ge (111) substrate. After a HF-last cleaning process, the wafer was immediately transferred into the load-lock of rf-MBE system. Then, the substrate was thermal cleaned in high vacuum at 650 °C for 30s to remove the residual Ge oxide. Deposition of a few nanometers thick Be layer was performed on Ge (111)-1x1 surface at 200 °C, followed by *in situ* radical oxidation process at the same temperature. Consequently, 10nm-thick  $Al_2O_3$  was deposited on the top of BeO using atomic layer deposition (ALD). In these devices, evaporated Ni/Au was used as electrodes. The thickness of the BeO film is confirmed to be 3.8 nm by grazing incidence x-ray reflectometer (GIXR) analysis.

## 3. Results and discussion

Reflection high-energy electron diffraction (RHEED) technique was efficiently utilized to *in situ* monitor the whole growth process. On Ge (111)-1x1 clean surface [Fig. 2(a)], a thin Be layer was first deposited onto the surface. It is found that the Be layer has a 30° in-plane rotation of its lattice with respect to the substrate by a

3:1 domain matching [Fig. 2(b)]. In this way the in-plane lattice misfit can be lowered to ~0.8%, which benefits the formation of high-quality Be film. Oxidation with active oxygen radicals was then performed, and a thin single-crystalline BeO layer formed [Fig. 2(c)]. Theoretically, as shown in Fig. 3, BeO displays relatively lower reaction constant than other candidate oxides, implying the better thermal stability of BeO on Ge. This is also presumably attributed to the strong Be-O bond and compact structure of BeO film. To examine whether BeO is fully oxidized or not, x-ray photoelectron spectroscopy (XPS) measurement were carried out. As illustrated in Fig. 4(a), the Be 1s core-level spectrum shows only one peak at around 113.8 eV, which is attributed to the  $Be^{2+}$  state, whereas no  $Be^{0+}$  exists, indicating that metallic Be is totally oxidized. Moreover, on the basis of the Ge 3d spectrum (Fig. 4(b)), the peak located at the lower binding energy side is assigned to the  $Ge^{0+}$  state, which is in good accordance with the results in other literature [3], indicating that almost no Ge oxide was formed after O-radical treatment. This result suggests that metallic Be epitaxy followed by O-radical oxidation at 200 °C is a good way to fabricate the oxide-free interface so as to meet the needs of EOT scaling down. To further confirm the structure of the BeO film, x-ray diffraction measurement was performed under  $\theta$ -2 $\theta$  mode. As depicted in Fig. 5, according to other reference, we infer that the film is dominated by wurtzite BeO (002) under tensile stress. Fig. 6 shows the  $J_g$ -V characteristics of the MOSCAPs with BeO IPL and 10nm- $Al_2O_3$  dielectric and the one with 15nm- $Al_2O_3$  dielectric. Compared with  $Al_2O_3$ -only case, by inserting the BeO IPL,  $J_g$  was effectively reduced even with a relatively thin dielectric, demonstrating that BeO is superior in Ge surface passivation.

## 4. Conclusions

In summary, wurtzite BeO film has been successfully epitaxially grown on Ge (111) by plasma-assisted MBE method. The BeO film has been confirmed to be an effective IPL with high thermal stability to form germanium oxide free interface as well as reduce gate leakage current. The introduction of BeO IPL into Ge may open a new prospect for the realization of high-performance Ge MOSFETs.

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## References

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- ◆ Ge (111) substrate
- ◆ HF-last chemical cleaning
- ◆ UHV annealing at 650 °C for 1min
- ◆ Metallic beryllium deposition @  $T_{\text{sub}}=200$  °C
- ◆ O-radical oxidation @  $T_{\text{sub}}=200$  °C
- ◆ ALD- $\text{Al}_2\text{O}_3$  deposition @  $T_{\text{sub}}=300$  °C
- ◆ Au electrodes evaporation

Fig. 1 Process flow of BeO/Ge (111) / Au MOS Capacitors

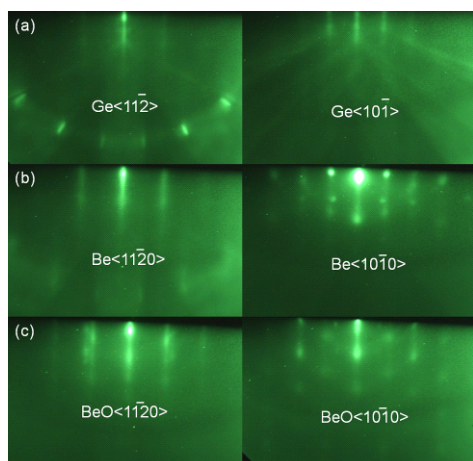


Fig. 2 RHEED pattern of (a) as-cleaned Ge (111) surface; (b) after 650 °C annealing, (1x1) reconstruction is obtained; (c) after metallic beryllium deposition; (d) after O-radical oxidation that forms BeO

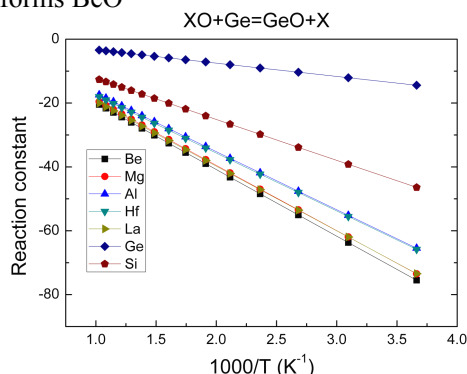


Fig.3 Calculated reaction constant (red-ox reaction) for various candidate dielectric oxides on Ge. Here X refers to Be, Mg, Al, Hf, La, Ge, and Si.

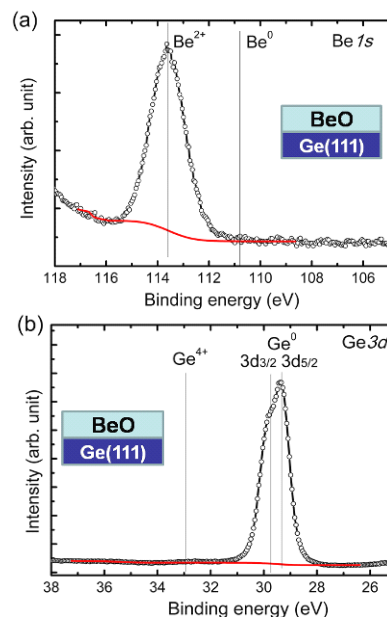


Fig. 4 (a) Be 1s and (b) Ge 3d XPS spectra of as-prepared BeO/Ge (111) stack after a Shirley background subtraction (red line). Note the peak at around 113.8 eV is assigned to  $\text{Be}^{2+}$ , whereas the metallic  $\text{Be}^0$  is undetectable in Fig. 4(a), indicating that Be is totally oxidized.. In Fig. 4(b), only  $\text{Ge}^0$  peak is observed, suggesting that there is no interfacial Ge oxide layer exists.

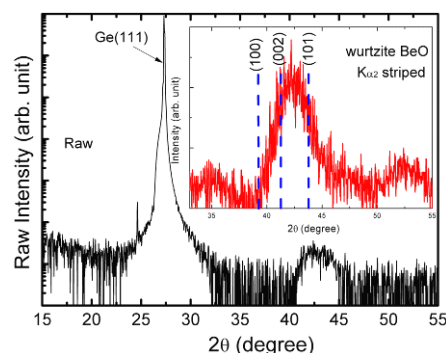


Fig. 5 XRD spectrum of as-deposited BeO on Ge (111) substrate. The peak at around 42° is assigned to wurtzite BeO (002) with tensile stress [4].

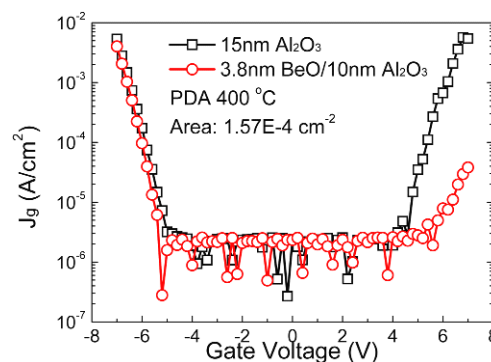


Fig. 6  $J_g$ -V characteristics of Au/Ni/ $\text{Al}_2\text{O}_3$ (10nm)/BeO(3.8nm)/Ge and Au/Ni/ $\text{Al}_2\text{O}_3$ (15nm)/Ge MOSCAPs.