Post deposition annealing effect on properties of Y$_2$O$_3$/Al$_2$O$_3$ stacking gate dielectric on 4H-SiC

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**Article info**

Article history:
Received 6 January 2019
Received in revised form 4 March 2019
Accepted 5 March 2019
Available online 6 March 2019

Keywords:
Y$_2$O$_3$/Al$_2$O$_3$ stacking dielectric
Post-deposition anneal
XRD
XPS
HRTEM

**Abstract**

In this paper, the effect of post deposition annealing (PDA) on the chemical, structural, and electrical properties of the high-k Y$_2$O$_3$/Al$_2$O$_3$ stacking dielectric on p-type 4H-SiC were studied. High-k dielectric provides a physically thicker film with equivalent capacitance, therefore better exploits the high breakdown strength of 4H-SiC in its MOSFET devices. The Y$_2$O$_3$/Al$_2$O$_3$ stacking films were deposited using RF magnetron sputtering, with PDA in Ar ambient at 400 °C, 600 °C, 800 °C and 1000 °C. X-ray diffraction (XRD) and angle resolved X-ray photoelectron spectroscopy (XPS) results show that an Al$_5$O$_{12}$Y$_3$ crystal layer was formed in between Y$_2$O$_3$ and Al$_2$O$_3$ films after annealing above 600 °C. High resolution transmission electron microscope (HRTEM) was used to investigate the atomic structure and measure the thickness of each layer. Charges and dielectric strength of the stacking films were characterized by high frequency capacitance-voltage (C-V) and current-voltage (I-V) measurements. The lower charge density and higher dielectric strength were found after PDA at 800 °C and 1000 °C.

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1. Introduction

Due to the high breakdown strength, high electron drift velocity, and high thermal conductivity, 4H-SiC is suitable for high power devices. Although 4H-SiC power MOSFETs have been commercially available, research on its gate dielectric still attracts significant efforts. The gate dielectric is essentially critical in 4H-SiC MOSFET devices, since it needs to sustain the high electric field and low gate leakage current. Thermally grown SiO$_2$ on 4H-SiC followed by NO, N$_2$O or POCI$_3$ annealing has been identified promising [1,2]. High-k dielectric is another potential candidate. Compared to the relatively low dielectric constant of SiO$_2$ (k = 3.9), high-k dielectric provides a physically thicker film with equivalent capacitance, therefore better exploits the high breakdown strength of 4H-SiC.

Numerous high-k dielectrics such as Al$_2$O$_3$, CeO$_2$, La$_2$O$_3$, HfO$_2$, and Y$_2$O$_3$ have been investigated on Si [3–7] and as well as on SiC [8–12]. Among them, Al$_2$O$_3$ and Y$_2$O$_3$ have high k values of 8 and 15–18, large band gap energies of 7 eV and 5.5 eV, respectively. The electrical properties of Y$_2$O$_3$ gate oxide on n-type 4H-SiC by pulsed laser deposition and annealing have been investigated [12], with low interface trap density and high dielectric breakdown field. Single Al$_2$O$_3$ layer [8] and Al$_2$O$_3$/SiO$_2$ stacking film [13] as gate dielectric on 4H-SiC have also been investigated. However, the stacking of Y$_2$O$_3$ and Al$_2$O$_3$ oxides on p-type 4H-SiC has yet been investigated. Y$_2$O$_3$/Al$_2$O$_3$ stack is an important building block that can be used as a gate oxide for MOS-based power devices since it has potential to take the advantageous material properties of both Y$_2$O$_3$ and Al$_2$O$_3$. Most studies on gate dielectric have been performed on n-type 4H-SiC [8–13] but not p-type 4H-SiC which the material used in n-channel MOSFET. Therefore, Y$_2$O$_3$/Al$_2$O$_3$ stacking films on p-type 4H-SiC is being studied and reported for the first time in this paper. RF sputtering followed by annealing in Ar ambient at different temperatures were applied to form the high-k stacking dielectric. The effect of PDA on the chemical, structural, and electrical properties of the Y$_2$O$_3$/Al$_2$O$_3$ bilayer films were studied by XRD, XPS, HRTEM, C-V and I-V measurements.

2. Experimental procedure

A 4° off-axis 4H-SiC wafer with 6 μm-thick p-type epilayer (5 × 10$^{15}$ cm$^{-3}$, aluminum) were diced into 1 × 1 cm$^2$ pieces and
used as the starting materials. Standard acetone/IPA and then RCA cleaning processes were applied to clean the substrates, followed by BOE (1:10) to etch the native oxide on the samples. Al$_2$O$_3$ (5 nm) and then Y$_2$O$_3$ (60 nm) films were deposited on each substrate by RF magnetron sputtering. PDA was performed in a horizontal tube furnace for 30 min at 400, 600, 800, and 1000 °C in Ar ambient for comparison. The heating and cooling rates were maintained at 10 °C/min. After PDA, the phases of the Y$_2$O$_3$/Al$_2$O$_3$ stacking films were investigated by XRD, and their chemical configuration by angle resolved XPS. Atomic structure and layer thickness were imaged by HRTEM. In order to study the electrical properties, an array of Al contacts was patterned by lift-off processes to form MOS capacitors which were tested with I-V and C-V measurements by a semiconductor parameter analyzer.

3. Results and discussion

High frequency C-V measurements (at 1 MHz) on the as-deposited and PDA samples are shown in Fig. 1(a). Compared to the values in accumulation for as-deposited and 400 °C annealed samples, capacitances increased after annealing at 600–1000 °C. The flat-band voltages $V_{FB}$ shifted to more negative after 400 °C annealing compared to as-deposited, indicating that there are high density positive charges in the 400 °C samples. After PDA at 600–1000 °C, the density of the positive charges reduced therefore $V_{FB}$ shifted less negative. Previous studies \[12\] of Y$_2$O$_3$ film on n-type 4H-SiC show that such positive charges might be due to oxygen vacancies, which are commonly found in high-k dielectrics \[14\]. I-V curves showing the leakage current density versus electric field (J-E) of the as-deposited and annealed films are demonstrated in Fig. 1(b). With the increase of annealing temperature, the breakdown electrical field increases, and the 800 °C and 1000 °C PDA
films exhibit the lowest leakage currents and the highest dielectric strength close to 10 MV/cm. This is attributed to the low charge density in the films due to high temperature Ar annealing. Such high strength is essentially important for this high-k film stack to be applied as gate dielectric for 4H-SiC MOSFETs.

The Y$_2$O$_3$/Al$_2$O$_3$ stacking high-k films after PDA were also studied by XRD with data presented in Fig. 2. The diffraction peak corresponding to the SiC substrate is clearly shown. After PDA at 400 °C, no peak was visible except SiC, indicating that Y$_2$O$_3$ and Al$_2$O$_3$ films are still in amorphous phase. Upon annealing at 600 °C, polycrystalline structure was formed with the emergence of a sharp (2 1 1)-oriented Al$_2$O$_3$Y$_3$ peak. Further increasing to 800 °C, the intensity of the (2 1 1)-oriented Al$_2$O$_3$Y$_3$ peak is also increased. In addition, another sharp (3 2 1)-oriented Al$_2$O$_3$Y$_3$ peak started to show up, and its intensity increased when the annealing temperature increased to 1000 °C as shown in the inset graphs. The increment in the intensity of both Al$_2$O$_3$Y$_3$ (2 1 1) and (2 1 1) peaks as the PDA temperature increases indicated that a better crystallized Al$_2$O$_3$Y$_3$ film had been obtained. By comparing the peak intensity, it is shown that the (2 1 1) plane is the preferred orientation for the Al$_2$O$_3$Y$_3$ crystalline film.

Chemical configuration of the Y$_2$O$_3$/Al$_2$O$_3$ bilayer film after PDA at 800 °C was analyzed by angle resolved XPS with results shown in Fig. 3. By changing the tilt angles of the sample, surface sensitivity can be increased by reducing the XPS information depth. The measured peaks (dotted line) were deconvoluted using a non-linear Gaussian-Lorentzian function (solid lines) with the assistance of CasaXPS software (version 2.3.15). The de-convoluted spectra disclosed the different chemical bonds in the dielectric film. The obtained elemental composition in atomic percentage (at %) are: Si-7.7%, Al-4.6%, Y-18.82%, and O-68.88%. The Y 3d spectra are well fitted by Y-O and Y-Al-O components at their respective binding energies, Al 2p spectra are well fitted by Al-O and Y-Al-O at their respective binding energies, and O 1s spectra are also well fitted by Y-O, Al-O, and Y-Al-O at their respective binding energies. It is observed that all spectra are complimentary to each other. As the tilt angles increases, a progressive chemical shift of Y-O, Al-O, and Y-Al-O peaks towards lower or higher binding energies. This is attributed to the different oxygen concentrations in the layer towards a deeper region.

The Y$_2$O$_3$/Al$_2$O$_3$ high-k films after PDA at 800 °C was also characterized by HRTEM to investigate their atomic structures and layer thickness. A representative image is shown in Fig. 4. Crystalline p-SiC is clearly shown, together with three layers above it, and their thicknesses are labeled respectively. Combined with XRD and XPS results, we concluded that the 38.4 nm-thick film

![XPS-Y](image1.png)

![XPS-Al](image2.png)

![XPS-O](image3.png)

**Fig. 3.** Angle resolved XPS spectra with Y 3d, O 1s, and Al 2p core levels of the Y$_2$O$_3$/Al$_2$O$_3$ stacking films after PDA at 800 °C in Ar ambient.

**Fig. 4.** HRTEM image of the Y$_2$O$_3$/Al$_2$O$_3$ stacking films after PDA at 800 °C.
corresponds to the Y-Al-O layer, which is mainly Al$_5$O$_{12}$Y$_3$ (2 1 1) crystalline structure. As for Y$_2$O$_3$ and Al$_2$O$_3$ layers, they are dominantly amorphous or minor crystalline embedded in the amorphous structures as shown in Fig. 4. This agrees with the XRD results as no Y$_2$O$_3$ or Al$_2$O$_3$ peak was found in Fig. 2(c).

4. Conclusion

Chemical, structure and electrical properties of Y$_2$O$_3$/Al$_2$O$_3$ high-k stacking thin films on p-type 4H-SiC after PDA in Ar ambient at 400–1000 °C were investigated. After annealing above 600 °C, an Al$_5$O$_{12}$Y$_3$ crystalline layer was formed in between Y$_2$O$_3$ and Al$_2$O$_3$ layers based on XRD, XPS and HRTEM results. C-V and I-V measurements showed that, when PDA at 800 and 1000 °C, lower charge density and leakage current, and higher dielectric strength were demonstrated by this high-k film stack.

Declaration of interest

None.

Acknowledgements

F. Zhao and C.F. Huang thank the WSU Vancouver External Mentoring Program for its support of this work.

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