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Fabrication and Electrical Properties of Metal/Double-Insulator/Metal Diode

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ABSTRACT

We have fabricated two metal/double insulator/metal diodes using a sputtering system and atomic layer deposition. Here, we show metal/double insulator/metal diode applied as a switch element. The diode exhibits good rectifying characteristics at room temperature. We used the electrode material with Pt and insulators were HfO_2/ZrO_2 and NiO/ZnO each. The devices were fabricated using the lithographic system and top electrode sizes were 30 µm x30 µm. The double insulator diode produces an enhanced nonlinearity by incorporating two adjacent oxides instead of the single oxide layer of the MIM diode. In the double insulator diode the mode of tunneling under positive applied biases can be made different from that under negative applied biases resulting in improved asymmetry.

INTRODUCTION

Silicon based transistor have been the most popularly used switch element. However, silicon based transistor do not conform to high density, nonvolatile memories with three dimensional(3D) stack structures due to their high processing temperatures and the difficulty of growing high quality epitaxial silicon over metals. MIM (Metal Insulator Metal) diodes may provide a suitable rectifying element. MIM diodes are rectifying electron devices made out of metals and insulators [1-3]. The advantage of the MIM diode over semiconductor rectifiers is its extremely fast response time and wide bandwidth. These attributes make possible the promise of higher speed detection and mixing of optical radiation. Despite this conceptual simplicity fabricating functional and reliable MIM diodes is challenging. However, MIM diodes show less asymmetry and nonlinearity than desired. We would like a diode with increased asymmetry for linear rectification and increased nonlinearity. Most MIM diodes follow Fowler-Nordheim and direct tunneling mechanisms [4-5]. Moreover, a third possibility is resonant tunneling [6]. Increased asymmetry may be achieved by making the electrons traverse the oxide by resonant tunneling under one polarity of bias and standard tunneling under the other polarity. This situation can be realized by using a multilayer structure between the electrodes instead of the single oxide layer.

EXPERIMENTAL DETAILS

NiO/ZnO films were deposited 10 nm and 30 nm thicknesses each using RF Magnetron sputtering system onto Pt deposited SiO_2 substrate. The deposition pressure during sputtering was maintained at 5mTorr, and the base pressure was kept at ~10^{-6} Torr. Then top electrode Pt was deposited by DC sputter. HfO_2 and ZrO_2 films were fabricated through atomic layer deposition (ALD). Terarkis (dimethlylamido) hafnium ($Hf(NM_2)_4$) was used as a precursor of Hafnium and terakis (dimethlylamido) zirconium ($Zr(NM_2)_4$) was also used as a precursor of Zirconium. Moreover distillated water was a precursor of oxygen each. Initial vacuum pressure was under 1 mTorr and working pressure was 5 Torr. HfO_2/ZnO_2 thin films prepared for electrical characterization were deposited at a deposition temperature of 150ºC. Then Pt top electrode was also deposited by sputter. Each metal/double oxide/metal devices were annealed up to 600ºC . Measurement of electrical properties was done by depositing a top Pt layer of 30 μm x 30 μm using a photolithographic mask. Electrical characterization was done by Agilent 4156C Semiconductor Parameter analyzer.

DISCUSSION

To investigation symmetric dependence of thickness, I-V characteristics with various double oxides thickness were shown in Figure 1. The experiments were performed with different deposition time, which correspond to the double oxide thickness from 200 Å to 600 Å, respectively. Voltages and fields are plotted with respect to the sign of the voltage on the top electrode. The terms "forward" and "reverse" bias refer to positive and negative voltages on the top electrode, respectively. Figure 1 shows I-V characteristics of Pt/NiO/ZnO/Pt and Pt/HfO_2/ZrO_2/Pt structure for different thicknesses. As shown in Figure 1, we observed the lowest leakage currents in thick films and the voltage sign had less effect on the leakage current than it did for thin films. Therefore, we confirmed that the thicker film is more effective for Poole-Frenkel emission. In order to improve I-V symmetric characteristics of MIM diodes, we suggested high temperature deposition conditions MIM diode. Figure 2 shows I-V characteristics of HfO_2(10 nm)/ZrO_2(10 nm) thin film. Each layer was deposited various temperatures. The leakage current density showed a strong dependence on the deposition temperature. As shown in Figure 2, an I-V characteristic of room temperature deposited HfO_2/ZrO_2 film has a large asymmetric characteristic and the lowest leakage currents. I-V symmetric characteristics were improved and the leakage currents increased with increasing deposition temperature as shown in Figure 2. Annealing temperature at 300ºC, I-V characteristics show good symmetry and exhibited an acceptable leakage current density (~10^{-4} A/cm^2 at 1 MV/cm), a reasonable breakdown voltage (~5 MV/cm). In general, for the application of switching devices, symmetric characteristics of current-flow behavior are more important factor than any other characteristics.

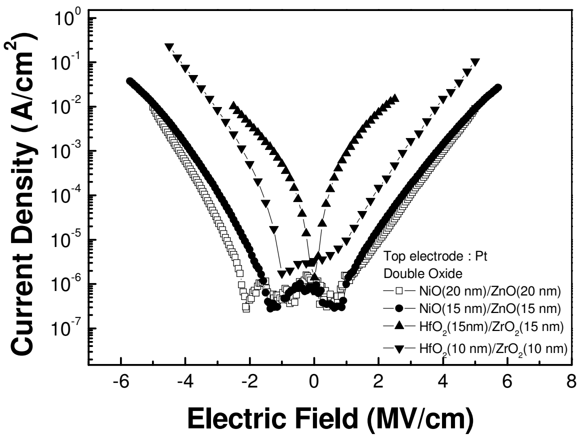

Figure 1. I-V characteristics of double insulator diodes with various insulator thicknesses for insulator layers of NiO/ZnO and HfO_2/ZrO_2.

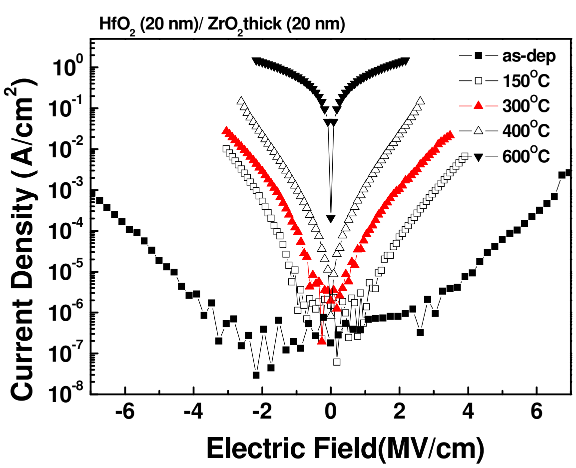

Figure 2. I-V characteristics of double insulator diode with a various annealing temperature for insulator layer of HfO_2/ZrO_2.

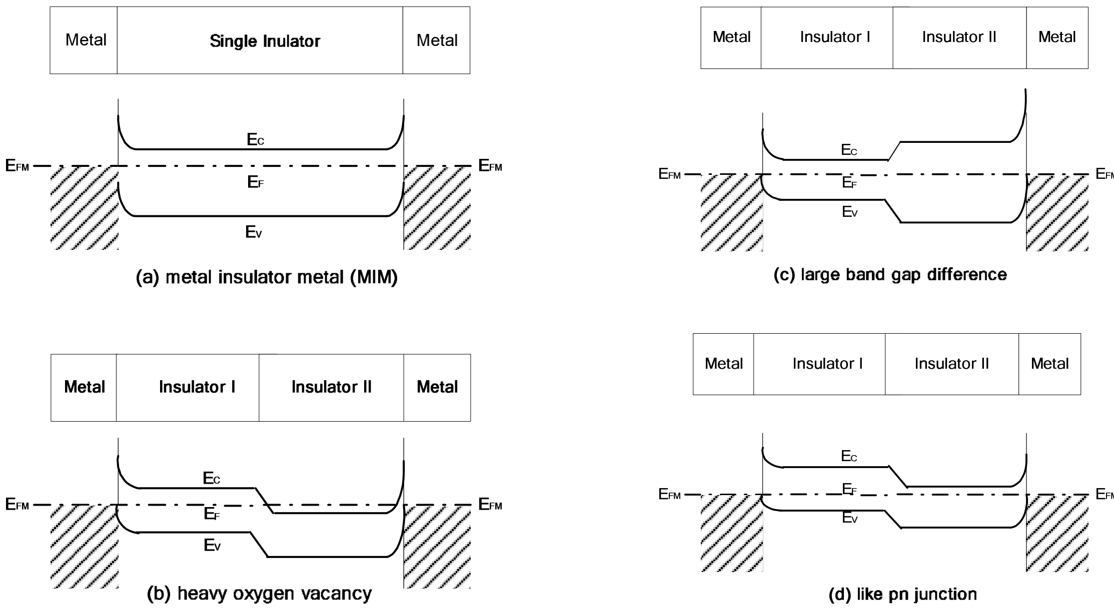

Figure 3. Energy band diagrams of MIM diode: (a) MIM diode, (b) double insulator with heavy oxygen vacancy, (c) large band gap difference and (d) likely pn junction double insulator

Figure 3 show the MIM and double insulator structure diode's energy band diagram. (a) is normal MIM energy band diagram, (b) shows double insulator with heavy oxygen defect at right side, (c) shows double insulator with large different energy band gap and (d) is likely pn junction layer energy band gap diagram. When the devices is annealed, the insulator adjacent to metal region is increasing oxygen defects and sufficient to generate a defect band which makes the potential barrier steep, thereby reducing its width and then resulting in more tunneling of electrons. Figure 3 (b) shows heavy oxygen vacancy that is, after annealing process in vacuum, oxygen diffused the insulator II thin film region. We believe the decrease of the thickness of pure insulator II films has an effect on the conduction mechanism of metal double insulator metal diodes. Figure 3(b) insulator II region's Fermi level is located within the conduction band and this region is considered to be degenerate. For MIM diodes, barrier heights between the metal and oxide are typically less than 2 eV. The energy band diagram of an MIM diode with barrier height is less than 2 eV [5]. This MIM diode, with an equivalent applied bias of positive and negative 2.5 V, enters the Fowler-Nordheim tunneling regime.

CONCLUSIONS

In summary, we have developed double insulator MIM diode with good symmetry. Annealing temperature at 300ºC, I-V characteristics show good symmetry and exhibited an acceptable leakage current density (~10^{-4} A/cm^2 at 1 MV/cm) and a reasonable breakdown voltage (~5 MV/cm) to the HfO_2/ZrO_2 thin film. Annealing may affect to the Fowler-Nordheim tunneling due to the oxygen vacancy of the insulator layer. The double insulator diode produces an enhanced nonlinearity by incorporating two adjacent oxides instead of the single oxide layer of the MIM diode.

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