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Fabrication and Characterization of Vanadium/Vanadium Pentoxide/Vanadium ($V/V_2O_5/V$) Tunnel Junction Diodes

M.F. Zia[a], M.R. Abdel-Rahman[a,*], N.F. Al-Khalli[b], N.A. Debbar[b]

[a]Prince Sultan Advanced Technologies Research Institute (PSATRI), College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia

[b]Electrical Engineering Department, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia

A metal/insulator/metal (MIM) diode is a structure in which a thin oxide layer is sandwiched between two metal layers. Metal/insulator/metal (MIM) diodes coupled to antennas have been widely investigated as detectors for millimeter wave and infrared radiation for imaging and spectroscopic applications. In this work, we report on the fabrication and characterization of MIM tunnel junction diodes by using a new material combination, vanadium-vanadium pentoxide-vanadium ($V/V_2O_5/V$), with contact areas of 2×2 μm^2. The $V/V_2O_5/V$ MIM was fabricated using electron-beam lithography, sputter deposition and conventional liftoff methods. The fabricated $V/V_2O_5/V$ MIM diodes showed a maximum absolute sensitivity of 2.35 V^{-1}. In addition, noise spectra for the fabricated MIM diodes were measured and analyzed.

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1. Introduction

A metal/insulator/metal (MIM) diode is a device having a thin oxide layer sandwiched between two metal layers, where electrons pass from first metal layer to second metal layer through a thin oxide layer by quantum tunneling process [1]. Quantum tunneling occurs only if the oxide layer is less than or equal to 4 nm [2]. Metal-insulator-metal diodes are usually designed to have small contact areas, compared to the wavelengths of the incident radiation, in order to satisfy required cut-off frequencies. Due to the compulsory small contact areas of MIM diodes, antennas are usually coupled to the MIM diodes in order collect incident electromagnetic radiation. Antenna-coupled MIM diodes have been widely investigated for millimeter wave and infrared detection [3–5] due to several inherent advantages of the structure: fast response, easy fabrication compared to other millimeter wave and infrared detectors, low power consumption, easy to integrate to read-out integrated circuits (ROICs), and uncooled operation [6]. So far many material combinations such as Ni/NiO/Ni [3, 4], $Al/Al_2O_3/Pt$ [5], $Al/Al_2O_3/Al$ [6], Ni/NiO/Au [7], Cu/CuO/Cu [8], Cu/CuO/Au [9], and others have been studied aiming at MIM diodes with highly nonlinear current-voltage (I-V) behavior to achieve high sensitivities.

In this work, we fabricate and characterize thin film based MIM tunnel junction diodes using a novel material combination, vanadium-vanadium pentoxide-vanadium ($V/V_2O_5/V$). The MIM diodes are manufactured using electron-beam lithography (e-beam) and liftoff techniques. The diode junction is fabricated using direct current (DC) sputtering for the deposition of the metal electrodes and radiofrequency (RF) diode sputtering for the deposition of the thin oxide layer. I-V characteristics were measured in order to study the dynamic resistance and sensitivity of diode. The theoretical Simmons equation for tunneling current was employed to analyze the experimental results and quantify the MIM diode parameters. In addition, noise spectrum of the fabricated MIM diode was measured and analyzed.

2. Device fabrication

The $V/V_2O_5/V$ MIM diodes were fabricated on silicon (Si) substrate with 300 nm of silicon dioxide (SiO_2) layer thermally grown on top of it for the purpose of electrical isolation. Electron-beam lithography was used for patterning the MIM diodes. The e-beam resist processing parameters, exposure and development processes parameters, liftoff process and contact pad patterning are in detail described in [8] for Cu/CuO/Cu MIM diodes; the same process was applied in this work for fabricating $V/V_2O_5/V$ MIM diodes. The first V electrode of the structure, 100 nm thick, was deposited using DC sputtering at 150 W of power, a chamber base pressure of 2×10^{-6} Torr and Argon (Ar) pressure of 3 mTorr. Vanadium pentoxide was RF diode sputtered for 3 minutes on top of the first V electrode at 150 W of RF power, a chamber base pressure of 2×10^{-6} Torr and Argon (Ar) pressure of 3 mTorr. Liftoff process was performed overnight to remove V and V_2O_5 layers deposited on unexposed regions to get patterned first electrode. The second electrode was deposited under the same conditions as the first electrode. Figure 1 shows a scanning electron microscope (SEM) image of a fabricated $V/V_2O_5/V$ MIM diode with 2×2 μm^2 contact area.

*corresponding author; e-mail: mabdelrahman@ksu.edu.sa

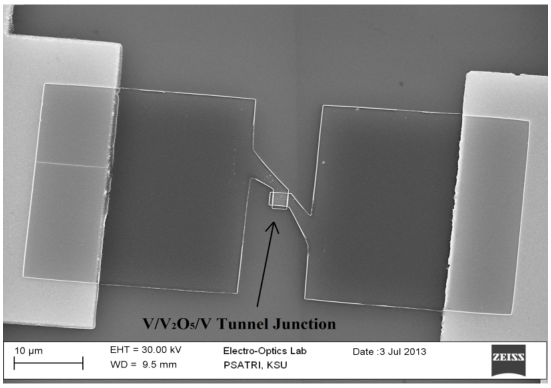

Fig. 1. Scanning electron microscope (SEM) image of $V/V_2O_5/V$ MIM diode showing 2×2 μm^2 contact area.

3. Measurements and results

The room temperature I-V characteristics of the fabricated MIM diodes were measured with HP B1500 semiconductor parameter analyzer with cascade probe station setup. Simmons equation [10] was used to fit measured I-V characteristics, and is given by:

$$J = \frac{e}{2\pi h(\beta\Delta s)^2} \times \left\{\left(\phi_o + \frac{eV}{2}\right)\exp\left[-A\sqrt{\left(\phi_o - \frac{eV}{2}\right)}\right] - \left(\phi_o + \frac{eV}{2}\right)\exp\left[-A\sqrt{\phi_o + \left(\frac{eV}{2}\right)}\right]\right\} \quad (1)$$

where J is the current, h is Plank's constant, e is electronic charge, φ_o is the barrier height between insulating layer and metal electrode, Δs is the oxide thickness, β is correction factor which has value ≈ 1 and A is given by: $A = \frac{4\pi\beta\Delta s}{h}(2m)^{1/2}$ where m is the electron mass.

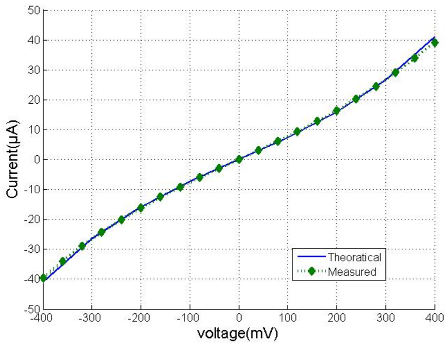

Fig. 2. Theoretical and measured I-V characteristic of $V/V_2O_5/V$ MIM diode.

Figure 2 shows the theoretically fitted curve using Simmons equation and measured I-V characteristics of a fabricated $V/V_2O_5/V$ MIM diode. A barrier height $\varphi_o = 0.89$ eV is used in the above equation which is extracted from the electron affinity of V_2O_5 used in [11]. Oxide thickness extracted from theoretical fitted curve is 1.45 nm. Nonlinearity of measured I-V characteristics confirms their applicability in millimeter wave and infrared applications.

Figure 3 shows dynamic resistance of fabricated thin film based $V/V_2O_5/V$ MIM and Fig. 4 shows the sensitivity S of the $V/V_2O_5/V$ MIM diode versus the bias voltage. Sensitivity S of an MIM diode is given by:

$$S = \frac{(d^2I/dV^2)}{(dI/dV)} \quad (2)$$

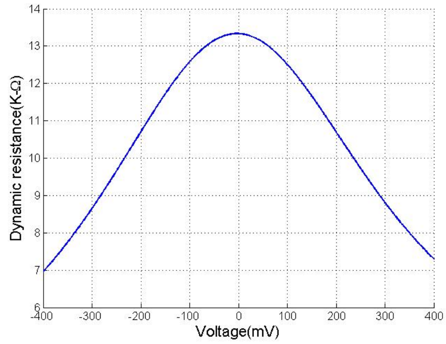

Fig. 3. Dynamic resistance curve of $V/V_2O_5/V$ MIM diode.

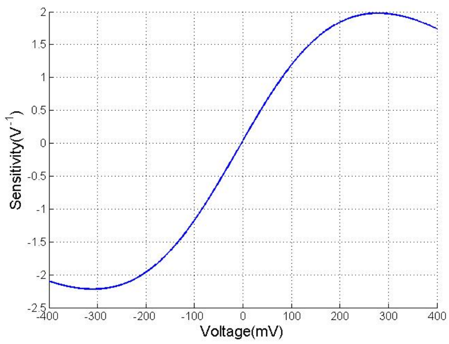

Fig. 4. Sensitivity curve of $V/V_2O_5/V$ MIM diode.

High sensitivity value can be achieved by large nonlinearity of I-V characteristics. Maximum sensitivity obtained for our fabricated $V/V_2O_5/V$ MIM diode is approximately -2.35 V^{-1} at bias voltage of -310 mV.

For noise measurements, a low noise bias source was used to bias the MIM diode at a bias voltage of 270 mV. The MIM diode signal was preamplified by a $1\times$ amplification stage. The amplified signal is then input into high pass filter with a cutoff frequency of 0.15 Hz. The signal was then amplified using a $952\times$ amplifier. The total amplification factor of the MIM diode was made to be 952 and so to yield an MIM diode signal level above the level of inherent noise of the signal analyzer. The signal was then input and measured using Agilent 3567A signal analyzer. Further, the noise spectrum of a 962 Ω resistor, corresponding approximately to the resistance of the MIM diode at 270 mV, was captured at the same above conditions. The captured noise spectrum, which corresponds to the Johnson noise level of the MIM diode and the noise of the electronic circuit, was then subtracted in quadrature from the noise spectrum of the MIM diode yielding the pure $1/f$ noise spectrum of the $V/V_2O_5/V$

MIM diode, Fig. 5. The resultant spectrum confirms the typical dominant $1/f$ noise behavior in MIM diodes.

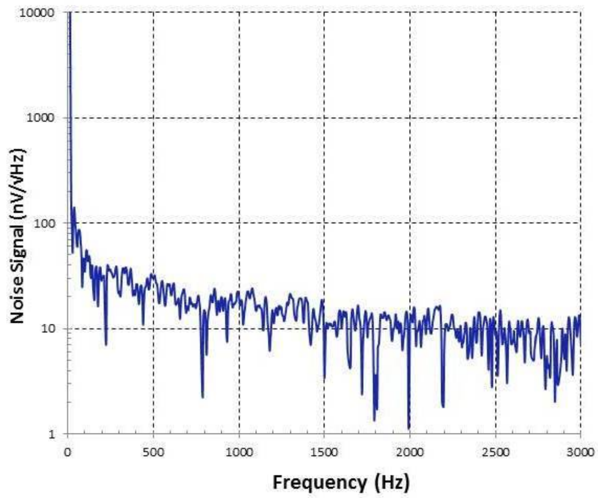

Fig. 5. Measured $1/f$ noise spectrum of $V/V_2O_5/V$ MIM diode.

4. Conclusion

Thin film $V/V_2O_5/V$ MIM junctions have been experimentally realized and characterized to demonstrate their feasibility in millimeter wave and infrared detection applications. The MIM diode was patterned by e-beam lithography, liftoff and conventional sputtering techniques. The thin insulating V_2O_5layer was deposited by RF diode sputtering. The I-V characteristics of the junctions were measured, showing nonlinear behavior, a zero bias resistance of 13.4 kΩ and a maximum absolute sensitivity of 2.35 V^{-1} at a bias voltage of –310 mV. Moreover, the noise spectrum of the $V/V_2O_5/V$ MIM diode was measured and analyzed showing a typical dominant $1/f$ noise behavior.

Acknowledgments

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