Model, design, and fabrication of antenna coupled metal-insulator-metal diodes for IR sensing

Mesut Inac*[a], Atia Shafique[a], Meric Ozcan[a], Yasar Gurbuz[a]
[a]Sabanci University, 34956, Orhanlı, Tuzla, Istanbul, TURKEY
yasar@sabanciuniv.edu
+90 216 483 9533

ABSTRACT

There is increasing demand for devices operating at room temperature for IR sensing and imaging. Antenna coupled metal-insulator-metal (MIM) diodes are potential candidates in this field. The reasons are miniaturizing features and femtosecond operation of these devices: smaller sizes lead to more pixels in limited areas and quantum tunneling phenomenon leads to faster operation. In this work, it is aimed to design and develop a device that can act as IR detector at room temperature.

Keywords: Metal-Insulator-Metal (MIM) diodes, tunneling, IR sensing, rectennas.

1. INTRODUCTION

Demand for the inexpensive devices operating at room temperature for infrared (IR) sensing and imaging are increasing in the last years as well as the energy harvesters in the IR-range. Due to the small sizes and the integration capabilities, antenna coupled metal-insulator-metal (MIM) diodes are one of the potential candidates in the field of IR sensing, imaging and energy harvesting. The antenna coupled diodes are already illustrated in the literature for energy harvesting applications[1], wireless power transmission[2] and IR detection[3]. The miniaturizing feature and ease of integration with infrared focal plane array makes antenna-coupled-MIM diode an attractive alternative for IR sensing and imaging applications alongside IR energy harvesters. As matter of fact, the functionality of MIM diode is based on quantum tunneling leads to device time constant as lower as few femtoseconds. The smaller sizes of these devices can enable more pixels in detectors and harvesters. In general, conventional IR detectors are classified based on two mechanisms: thermal detectors and photon detectors[4]. Due to the inevitable limitations of the both types, antenna-coupled diode is thought to be a better choice as an ultrafast and highly responsive IR detector. Also, these devices can be an alternative to low efficiency energy harvesters: photovoltaic (PV) and thermo-photovoltaic (TPV) devices.

In this work, it is aimed to design and develop a device that can detect in the IR regime of light spectrum. The MIM diodes model formation is based on electron tunneling. First the preliminary DC characterization of individual MIM diodes have been carried out, afterwards, joint characterization of antenna along with diode has been performed. Device characteristics such as responsivity, resistance and I-V results are reported.

2. METHODOLOGY

Metal-insulator-metal diodes were fabricated on to 100 nm SiO_2 coated Si substrates. Three layers of device were patterned by Vistec / EBPG500plusES Electron Beam Lithography system. The exposure current was 12 nA. The masks can be seen in the Figure 1. Bi-layer resist was used in lithography. The bottom layer was 495K polymethyl-methacrylate (PMMA). The top layer was 950K PMMA. Both of the resists were spin coated at 5000 rpm and baked at 175 °C for 5 minutes. The exposure dose was 700 $\mu C/cm^2$. After exposure, the resist was developed in three steps. The first development step was 60 seconds in 1 : 3 mixture of methyl-isobutyl ketone : isopropanol (MIBK : IPA). Instantly the second step was applied for 5 seconds in 1 : 1 mixture of MIBK : IPA, immediately followed by last step to stop the further development of resist in IPA.

After the patterning, first electrode of MIM device which is also a bowtie arm was deposited in Physical Vapor Deposition (PVD) system. The first electrode and the insulator layer were deposited in the first step. 65 nm thick Aluminum (Al) was deposited by thermal evaporation method with 1.5 A/s rate under $7x10^{-6}$ Torr pressure. Immediately without breaking the vacuum Al_2O_3 layer was deposited by e-beam evaporation with 0.2 A/s rate, 26 mA filament

Infrared Technology and Applications XLI, edited by Bjørn F. Andresen,
Gabor F. Fulop, Charles M. Hanson, Paul R. Norton, Proc. of SPIE Vol. 9451,
94511L · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2177385

current and 5.92 kV accelerator voltage. A lift-off process took place in acetone (ACE) to have pattern on the substrates. Different thicknesses of Al_2O_3 were deposited in order to investigate the thickness dependence of the characteristics of the devices. In the second electrode, 5 nm of Chromium (Cr) followed by 65 nm thick Gold (Au) were deposited using thermal evaporation. The evaporation rates were 0.3 A/s and 2 A/s respectively under $5x10^{-6}$ Torr pressure. Following deposition, a lift-off process carried out in order to finalize the pattern on substrates.

The I-V characteristics of the fabricated MIM diodes were measured at room temperature inside a black box using an Agilent B1500A semiconductor parameter analyzer. The cross-section of the fabricated MIM diodes are illustrated in Figure 2, Optical microscopy image is shown in Figure 3.

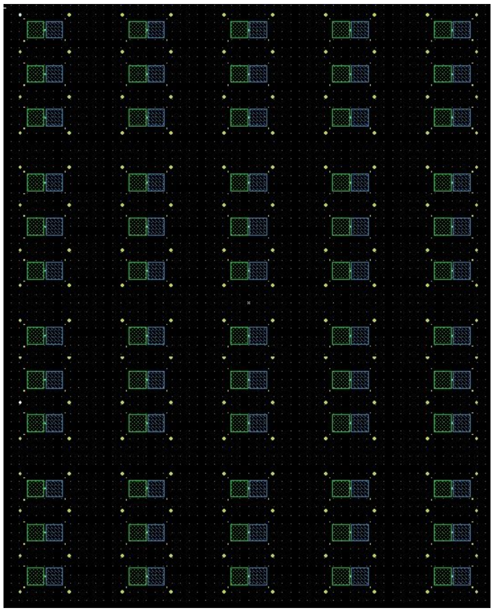

Figure 1 - The mask which was used in the fabrication

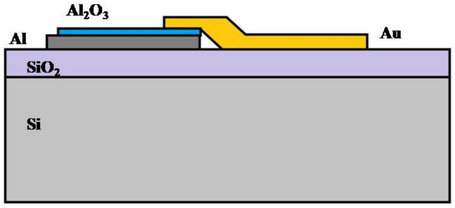

Figure 2 - Illustration of cross-section of the diodes

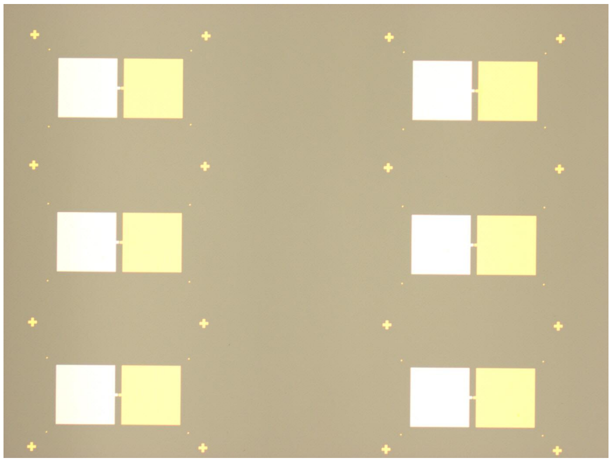

Figure 3 - Optical microscopy images of the fabricated diodes.

3. RESULTS

Fabricated MIM diodes were measured by Agilent B1500A Semiconductor Parameter Analyzer and probed in black box probe station. The Current – Voltage characteristics of the fabricated MIM diodes were extracted and fitted to 9th order polynomial function for further analysis of the fabricated MIM diodes and extracting other characteristics of the diodes. The fitted Current – Voltage characteristics of the fabricated MIM diodes can be seen in the Figure 4. According to (1) differential resistances of the fabricated MIM diodes were extracted.

$$\mathrm{R} = \frac{dV}{dI} \tag{1}$$

The resulting resistance was used in calculation of responsivity. The capacitances of fabricated MIM diodes can be estimated according to (2) assuming that they are parallel plate capacitors.

$$\mathrm{C_D} = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{2}$$

The fabricated MIM diodes under 0.6 V applied bias had 100 kΩ resistance and 30 fF. The non-linearity[5] of the fabricated MIM didoes was extracted according to (3). These values were used to calculate responsivity of the fabricated MIM diodes that is stated in (4).

$$\text{Non-Linearity } (I'') = \frac{d^2 I}{dV^2} \tag{3}$$

$$\text{Responsivity } (\beta) = \frac{\left(\frac{d^2 I}{dV^2}\right)}{\left(\frac{dI}{dV}\right)} = RI'' \tag{4}$$

After the calculations, the maximum non-linearity value of 14.46 A/W was achieved by fabricated MIM diodes. The quantum efficiency of the diodes calculated as 29% at 60 THz operation.

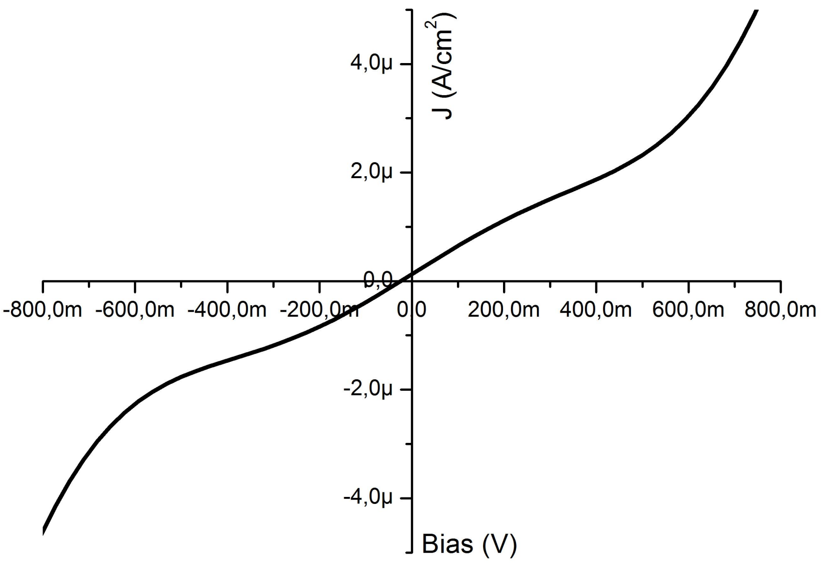

Figure 4 - J-V charactics of fabricated MIM diodes

4. CONCLUSION

Metal-Insulator-Metal diodes have high response time and low area. In this work, highly responsive nm^2 scaled fabricated MIM diodes is shown. Moreover, the fabricated Al-Al_2O_3-Au MIM diodes have high responsivity and non-linearity. These results show that they are capable of being used in the IR detection applications. Additionally, the material selection of these diodes enables to be integrated into modern ICs. Coupling with bowtie antennas allows wide bandwidth operation of these devices.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support from Lockheed Martin University Research Agreement.

REFERENCES

[1] G. Moddel, "Will Rectenna Solar Cells Be Practical?," in [Rectenna Solar Cells], New York, USA: Springer, 2013, ch. 1, pp. 3-24.
[2] W. C. Brown and R. H. George, “Rectification of Microwave Power,” IEEE Spectrum, pp. 92-97, Oct. 1964.
[3] Z. Zhu and G. Moddel, “High Performance Room Temperature Rectenna IR Detectors Using Graphene Geometric Diodes”, IEEE Journal of Selected Topics in Quantum Electronics, vol. 20, no. 6, 3801409, 2014.
[4] Rogalsky, A., “Infrared Detectors: Status and Trends” Progress in Quantum Electronics, vol. 27, pp. 59-210, 2003.
[5] F. Yesilkoy et al., “A Mid-IR Antenna Integrated with a Geometrically Asymmetrical Metal-Insulator-Metal Rectifying Diode,” in Rectenna Solar Cells. New York, USA: Springer, 2013, ch. 8, pp. 163-188