Device characteristics of antenna-coupled metal-insulator-metal diodes (rectenna) using Al_2O_3, TiO_2 and Cr_2O_3 as insulator layer for energy harvesting applications

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ABSTRACT

Antenna-coupled metal-insulator-metal devices are most potent candidate for future energy harvesting devices. The reason for that they are ultra-high speed devices that can rectify the electromagnetic radiation at high frequencies. In addition to their speed, they are also small devices that can have more number of devices in unit area. In this work, it is aimed design and develop a device which can harvest and detect IR radiation.

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

1. INTRODUCTION

Demand for the inexpensive devices operating at room temperature for broadband sensing and imaging applications are increasing in the last years. Due to the small sizes and the integration capabilities, antenna coupled metal-insulator-metal (MIM) diodes are one of the potential candidates for sensing, imaging and energy harvesting in IR and solar range of spectrum. The antenna coupled diodes are already illustrated in the literature for energy harvesting applications[1], wireless power transmission[2] and detection[3]. As matter of fact, functionality of MIM diodes based on quantum tunneling leads to device time constant in the order of femtoseconds. The smaller sizes of these devices enable to place more pixels in detectors and harvesters. Due to speed and size of these devices, antenna-coupled MIM diode is thought to be a better choice as an ultrafast and highly responsive harvesting device; 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 operate in the IR regime of light spectrum. The model formation is based on electron tunneling in MIM diode devices. It includes three different insulators (Al2O3, Cr2O3 and TiO2) and different sizes of devices. 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 and I-V results are reported.

2. METHODOLOGY

MIM diodes were fabricated on SiO_2 coated Si substrate. Vistec / EBPG500plusES Electron Beam Lithography system was used for patterning layers of device. In the Figure 1, the mask that is used in the lithography is presented. Double layer PMMA resist (495K and 950K PMMA) is spin coated and patterned under 750 $\mu C/cm^2$ electron dose. Development was carried out in methyl-isobutyl ketone: isopropanol (MIBK:IPA) solution

The first electrode of the MIM device is one of the bowtie arms which were deposited with Physical Vapor Deposition (PVD) system. As a first step, electrode and the insulator layer were deposited. Metal layer-1 were deposited below $7x10^{-6}$ Torr pressure around 2 A/s rate with thermal evaporation method and then insulator layer was deposited by e-beam evaporation. In this study, Gold (Au) was used as a metal layer - 1 which its thickness was 65 nm and Al_2O_3, TiO_2, and Cr_2O_3 were used as insulator layer. To pattern the substrates lift-off process was performed in acetone (ACE). Insulator layers had been deposited 5 nm of thicknesses. Thermal evaporation method was used for deposition of the metals as a second electrode. Those metals were Chromium (Cr), Aluminum (Al) and Titanium (Ti) at thicknesses of 65 nm. In order to finish the patterning process of the substrates lift-off process was used.

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By using Agilent B1500A semiconductor analyzer, the I-V characteristics of the MIM diodes were performed at room temperature in a black box. In Figure 2 the cross section of the structure is demonstrated and in Figure 3 optical microscopy image is presented.

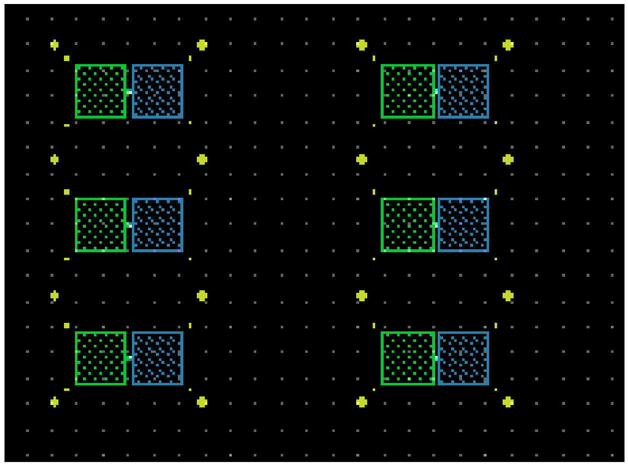


Figure 1 - The mask which was used in the fabrication

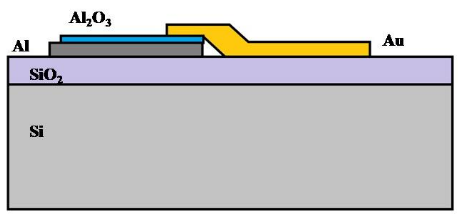


Figure 2 - Illustration of cross-section of the diodes fom Al-Al2O3-Au diode

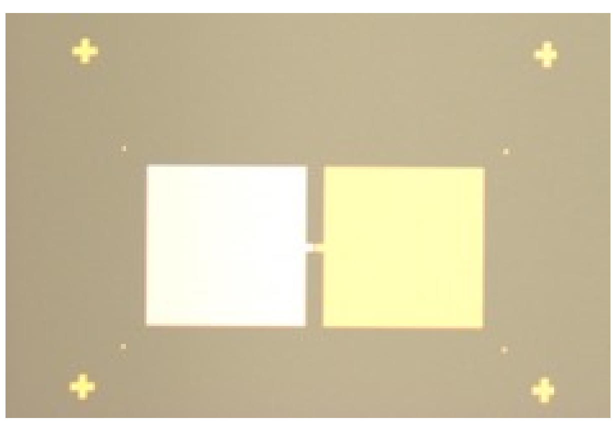


Figure 3 - Optical microscopy images of the fabricated diodes.

3. RESULTS

By using Agilent B1500A Semiconductor Parameter Analyzer and probed in black box probe station the I-V charactersitics of the MIM diodes were measured. The I-V cahacateristics of the MIM diodes subtracted and fitted to 9^{th} order polynomial function for further analysis of the fabricated MIM diodes and extracting other characteristics of the diodes. In Figure 4 I-V characteristics of the diodes are shown. According to (1) differential resistances of the MIM diodes were extracted.

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

Resistances of fabricated diodes vary from 6 kΩ to 3 GΩ with different insulators. Lowest resistance was acquired form TiO_2 diode. To calculate the responsivity, the resulting resistance was used. The capacitances of MIM diodes can be estimated by (2) assuming that they are parallel plate capacitors.

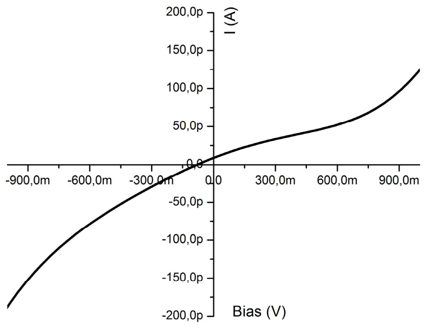
$$\mathrm{C_D} = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{2}$$

The fabricated MIM diodes have approximately 30 fF, 35 fF and 60 fF (Al_2O_3, Cr_2O_3 and TiO_2 respectively) capacitance. The non-linearity[4] of the MIM didoes was extracted regarding to (3). These values were used to calculate responsivity of the fabricated MIM diodes that is stated in (4).

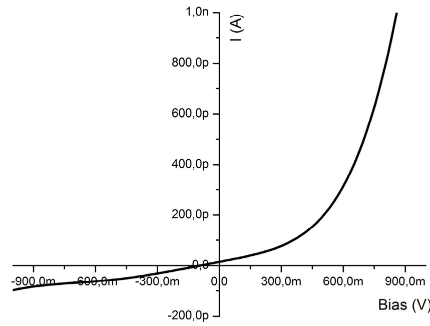
$$\text{Non-Linearity } (I'') = \frac{d^2 I}{dV^2} \tag{3}$$

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

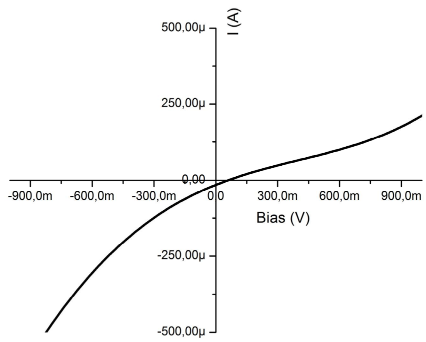
The maximum responsivity value of 14.46 A/W was achieved form Al_2O_3 MIM diodes by using these calculations. In Cr_2O_3 and TiO_2 diodes have 8 A/W and 2 A/W responsivities respectively.



(a)



(b)



(c)

Figure 4 - I-V characteristics of fabricated MIM diodes. (a) Au-Al_2O_3-Al (b) Au-Cr_2O_3-Cr (c) Au-TiO_2-Ti diodes.

4. CONCLUSION

MIM diodes have many properties such as ultra-high speed, small dimension and so on. In this study, high speed, nm^2 size MIM diodes are presented. According the results that we experimented these diodes are useful and advantageous for IR harvesting applications. Furthermore, the material selection for the diodes allows to integration of the diodes for modern ICs. By coupling the MIM diodes with bowtie antennas enables wide bandwidth operation for these devices.

ACKNOWLEDGMENT

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