High-Frequency Metal-Insulator-Metal (MIM) Diodes for Thermal Radiation Harvesting

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***Abstract*—The fabrication of low-cost metal-insulator-metal (MIM) diodes using a self-assembled monolayer as the insulating layer is presented. DC and AC analysis show that the diodes have excellent non-linear current voltage characteristics compared to those typically reported, with a zero-bias curvature coefficient ranging from 0.5 V^{-1} to 5.4 V^{-1}, voltage responsivity of 1.9 kV/W at a frequency of 1 GHz. The process developed for fabricating these diodes is simple, cost effective, and can potentially be used in the roll-to-roll manufacturing of MIM diodes. Reliability tests performed on the fabricated OTS diodes shows that the OTS layer of the diodes remains unaffected by high temperature up to approximately 450 °C which is significant in thermal energy harvesting applications, where the diode may be exposed to high temperatures.**

I. Introduction

The metal-insulator-metal (MIM) diode is a quantum device wherein a thin dielectric is sandwiched between two metal electrodes. This device can operate at very high frequencies, well into the terahertz range, a promise first highlighted over thirty years ago [1]. The different work functions of the metal electrodes provide an asymmetric tunneling barrier, which results in a diode-like current-voltage *(J-V)* characteristic. By selecting a careful combination of metals and insulating material, this characteristic can be further optimised to operate the diode as a detector without the need for an externally applied bias [2]. MIM diodes have been fabricated using different fabrication techniques, with the most critical part of the fabrication being the definition of the insulating layer, with metal oxides being a popular choice.

This work presents the fabrication of novel high-frequency low-cost MIM diodes where the dielectric layer is formed using a self-assembled monolayer (SAM). Octadecyltrichlorosilane (OTS), which is commonly used to functionalise the surface of silicon dioxide (SiO_2) in thin-film devices, and has a typical thickness of approximately 2 nm [3], was deposited in between titanium and platinum, which have a work function difference of 1.4 eV thereby resulting in MIM diodes with strong non-linear current-voltage *(J-V)* characteristics.

The diodes were fabricated using the basic process as in [4] with the major difference being the use of OTS as the dielectric layer rather than TiO_x. Rather than using the more aggressive techniques typical of the semiconductor industry, the process for OTS deposition on top of a metal was carried out at low temperature, using chemistry which is compatible with flexible polymer substrates, and which can be potentially used in the manufacturing of MIM diodes on a large scale using a roll-to-roll process. This device is thus a useful component in a wide range of applications, including non-contact charging, radio frequency identification (RFID) tags, high frequency detectors, mixers, and electromagnetic energy harvesting [5].

II. Electrical Characterization

DC measurement was carried out on the fabricated diodes using a parameter analyzer. The bias voltage range was kept within ±0.2 V in order to avoid damaging the diode junctions, as they were found to have a breakdown voltage of ±0.35 V. Analysis shows that the diodes have strong non-linear *J-V* characteristics with a typical zero-bias curvature coefficient (γ_{ZB}) of up to 5.4 V^{-1}, calculated by;

$$\gamma_{ZB} = \frac{d^2I}{dV^2} / \frac{dI}{dV}\bigg|_{V=0} \quad (1)$$

which compares favourably with those available in the literature [6]. The zero-bias curvature coefficient is a major figure of merit for MIM diodes in applications such as energy harvesting. A scanning electron microscopy (SEM) image of a fabricated device can be seen in Fig. 1, with the crossover region of the arms at the center (in the SEM image) which defines the MIM junction. A sketch of the device cross-section can be seen in the inset of Fig. 2, where the OTS layer is sandwiched between the two metal layers (platinum and titanium). The nominal feature size of the fabricated diode junction is 2 X 2 µm.

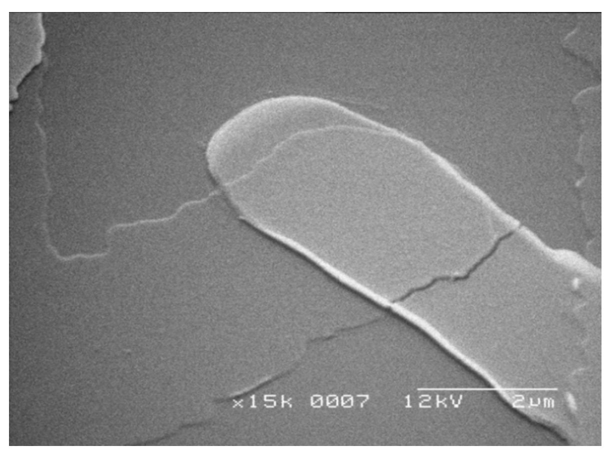

Fig. 1. Scanning electron micrograph of a typical OTS-based MIM diode. The bottom and top layers consist of titanium and platinum, respectively. The diode is embedded in a coplanar waveguide for high-frequency

Characterisation at high frequencies, from 1 MHz to 3 GHz, was carried out on the diodes using a vector network analyser (VNA). To enable high frequency testing, the diodes were embedded within a coplanar waveguides with a characteristic impedance of 50 Ω, and matched to the characteristic impedance of the VNA probes, thus minimising unwanted reflections from the layout as well as reducing radiation losses. All measurements were carried at room temperature, and the input power compensated at different frequencies to account for the measured losses in the cables, probes and coplanar waveguides.

Figure 2 shows a typical rectified output voltage of the diode as a function of power injected into the coplanar waveguide at a frequency of 1 GHz. The diode voltage responsivity R_V is defined as [7];

$$R_V = P_{HF}\left(\frac{d^2V}{dI^2} / \frac{dV}{dI}\right) \quad (2)$$

where P_{HF} is HF power injected by the VNA into the coplanar waveguide. Its value was determined by a linear fitting of the rectified output voltage as a function of the input power, shown in Fig. 2, and had an absolute value of approximately 1.9 kV/W at a frequency of 1 GHz, comparable to state-of-art Schottky diode detectors [5].

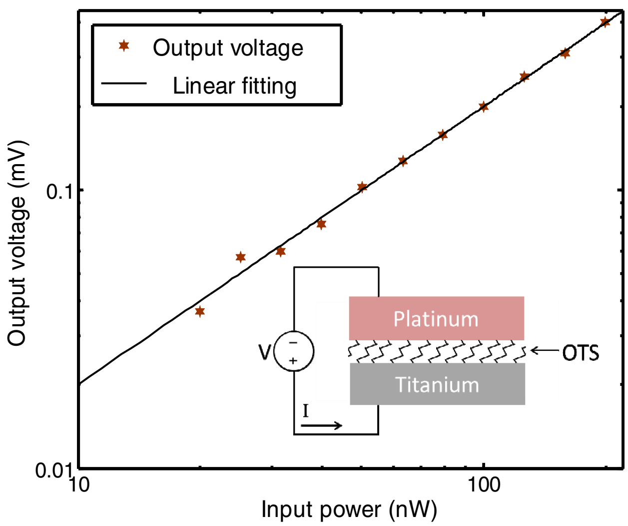

Fig. 2. Rectified voltage as a function of input HF power at a frequency of 1 GHz characterization. In the inset is a sketch of the device cross-section.

III. RELIABILITY TEST

Temperature reliability test performed on the fabricated OTS diodes shows that the OTS layer of the diodes remains unaffected by high temperatures up to approximately 450 °C, when the (OTS) layers starts to degrade and the device typical zero bias curvature coefficients significantly decreases with increasing temperature, as it can be seen in Fig. 3, where the zero bias curvature coefficient (γ_{ZB}) of the diode was plotted as a function of temperature.

For comparison, the curvature coefficient of MIM diodes fabricated with a TiO_x insulated layer start to degrade at a temperature of approximately 250 °C (Fig. 3). This is significant in thermal energy harvesting applications, where the diode may be exposed to high temperatures [5].

The diodes were subjected to the various temperatures for approximately 5 minutes each time before measurements were taken. Further investigation revealed that the insulating layers (both for OTS and TiO_x diodes) starts to degrade significantly at lower temperatures (than in Fig. 3) when the devices were exposed to the same temperatures as in Fig. 3, but for a longer period of time.

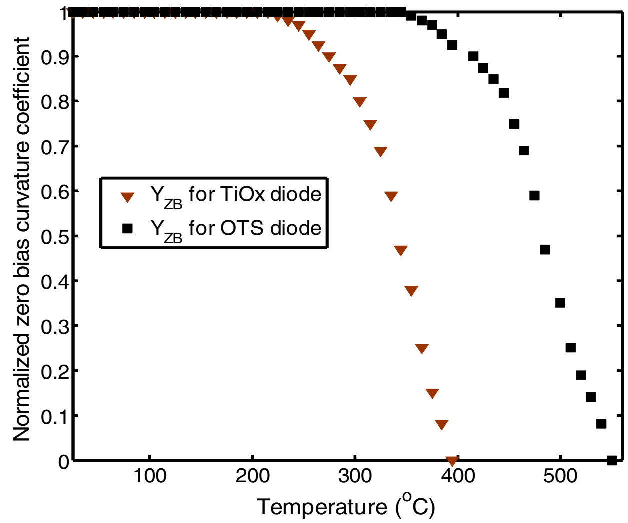

Fig. 3. Plot of normalized zero bias curvature coefficient (γ_{ZB}) of Ti/OTS/Pt and Ti/ TiO_x/Pt diodes as a function of temperature.

IV. CONCLUSION

Low-cost MIM diodes with an OTS insulating layer have been fabricated and tested. Electrical analysis shows that the diodes have a strong non-linear *J-V* characteristics and excellent voltage responsivity, when compared to other MIM diodes with conventional insulators. The process is very cost effective, is performed at low temperature and can be potentially ported to a roll-to-roll commercial production of MIM diodes on flexible substrates. Also, reliability tests performed on the fabricated OTS diodes show that the OTS layer of the diodes remains unaffected by high temperature up to approximately 450 °C which is significant in thermal energy harvesting applications, where the diode may be exposed to high temperatures.

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