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A NOVEL WAY TO CHARACTERIZE METAL-INSULATOR-METAL DEVICES VIA NANOINDENTATION

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ABSTRACT

Metal-Insulator-Metal (MIM) devices are crucial components for applications ranging from optical rectennas for harvesting sunlight to infrared detectors. To date, the relationship between materials properties and device performance in MIM devices is not fully understood, partly due to the difficulty in making and reproducing reliable devices. One configuration that is popular due to its simplicity and ease of fabrication is the point-contact diode where a metal tip serves as one of the metals in the MIM device. The intrinsic advantage of the point-contact configuration is that it is possible to achieve very small contact areas for the device thereby allowing very high-frequency operation. In this study, precise control over the contact area and penetration depth of an electrically conductive tip into a metal/insulator combination is achieved using a nanoindenter with in-situ electrical contact resistance measurement capabilities. A diamond probe tip, doped (degeneratively) with boron for conductivity, serves as the point contact and second 'metal' (b-Diamond) of the MIM diode. The base layer consists of Nb/Nb₂O₅ thin films on Si substrates and serves as the first metal/insulator combination of the MIM structure. The current-voltage response of the diodes is measured under a range of conditions to assess the validity and repeatability of the technique. Additionally, we compare the results of this technique to those acquired using a bent-wire approach and find that Nb/Nb₂O₅/b-Diamond MIM devices show an excellent asymmetry (60-300) and nonlinearity values (~6-9). This technique shows great promise for screening metal-insulator combinations for performance without the uncertainty that stems from a typical bent-wire point-contact.

INTRODUCTION

Although many exciting developments had been achieved in the PV arena, significant advances are still required from this and other clean energy technologies in order to compete with fossil fuels. In particular, transformative concepts that can provide dramatically higher efficiencies are increasingly desired. One such PV concept is the 'optical rectenna' (antenna + rectifier), in which sunlight is captured as a wave via an antenna and subsequently converted directly to DC power using a suitable rectifier. The calculated conversion efficiency of such a rectenna device operating in the visible region is as high as 90% [1]. Despite remarkable potential gains in efficiency, rectenna technology is still in the nascent stage because of

significant challenges, including the fabrication of a suitable ultra-high frequency rectifier [2, 3]. To ensure high rectification efficiency in the visible light (300-750 THz) regime, the rectifier should have (a) a fast electron transport mechanism, (b) device area of nanometer scale (to eliminate high-frequency capacitive leakage), and (c) efficient coupling with the antenna and other circuitry in the rectenna.

The Metal-Insulator-Metal (MIM) diode is a candidate rectifier device for rectenna applications due to the possibility of ultra fast rectifying electron transport via asymmetric tunneling. Various groups [4-8] have studied MIM devices over the last 5 decades. To date, the relationship between materials properties and device performance in MIM devices is not fully understood, partly due to the difficulty in making and reproducing reliable devices. One configuration that is popular due to its simplicity and ease of fabrication is the point-contact diode where a metal tip serves as one of the metals in the MIM device. The intrinsic advantage of the point-contact configuration is that it is possible to achieve very small contact areas for the device thereby allowing very high-frequency operation. The present authors have used a bent-wire point-contact MIM diode configuration to identify promising MIM combinations [9]. Major limitations with the bent-wire approach include the uncertainty in the resulting diode area and the lack of control on the penetration depth of the bent-wire into the insulator. This makes it difficult for quantitative analysis to compare MIM devices with different material combinations. In the present study, these challenges are overcome through the use of a nanoindenter with in situ electrical contact resistance measurement capabilities, which enables precise control over the contact area and depth of penetration of an electrically conductive tip into a metal-insulator combination. I-V measurements are repeatedly and reproducibly acquired at a range of fixed penetration depths.

EXPERIMENTAL DETAILS

A nanoindenter with nanoscale electrical contact resistance (nanoECR) capability is used in this study. The probe is a 3-sided pyramid-shaped boron-doped (degenerately) diamond tip. In this study, Nb/Nb₂O₅ bilayer thin films (on a Si substrate) are the metal/insulator combination of the MIM structure [9]. The Nb film (90 nm thick) was sputter deposited and anodically oxidized in 1M H₂SO₄ solution to grow Nb₂O₅ (15 nm thick). Contacting the boron-doped diamond tip (b-Diamond) on to the

bilayer completes the MIM ($\text{Nb}/\text{Nb}_2\text{O}_5/\text{b-Diamond}$) diode as schematically shown in Fig. 1.

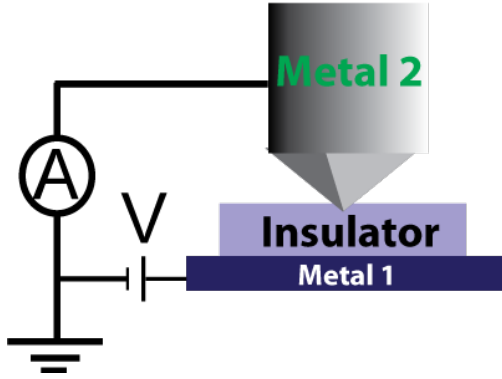


Figure 1 Schematic representation of MIM diode with the B-Diamond Indenter.

Figs. 2 and 3 show schematics of typical load function and load-displacement curves, respectively. A typical measurement involves contacting the b-Diamond tip to the insulator and then increasing the contact force to the desired value (loading). While holding at this point, the I-V is measured. Then unloading proceeds and the tip is retracted away.

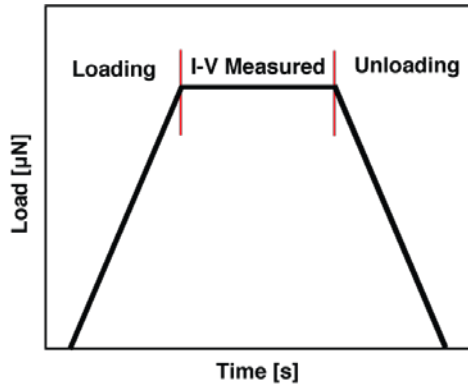


Figure 2 Typical loading function used while measuring I-V curves with the nanoindenter.

The performance metrics of the devices are characterized via asymmetry and nonlinearity. Asymmetry is defined by the ratio of forward to reverse current. Nonlinearity is given by $(dI/dV) \cdot (V/I)$, where V and I are the voltage and current, respectively [7].

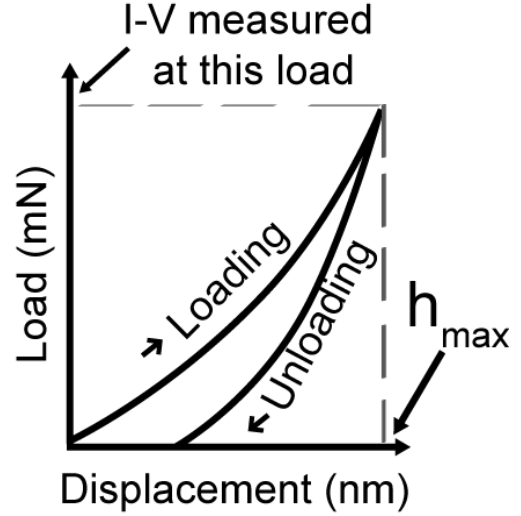


Figure 3 Typical Load-Displacement curve showing the maximum load and displacement.

RESULTS AND DISCUSSION

Fig. 4 shows the current-voltage (I-V) plot of $\text{Nb}/\text{Nb}_2\text{O}_5/\text{b-Diamond}$ MIM diodes for several tests that varied the displacement of the indenter into the oxide. The current magnitude increases with the increase in displacement (inset in Fig. 4) as expected because of reduced tunneling distance and increased device (contact) area. Figs. 5(a) and (b) show the asymmetry and nonlinearity curves as a function of displacement, respectively. The device shows excellent asymmetry and nonlinearity metrics. While asymmetry increases with displacement, nonlinearity is almost independent of displacement.

A very similar trend is noted in bent-wire point-contact experiments as a function of displacement (although in the bent-wire case, quantitative determination of contact area and pressure is not possible [9,10]). In a previous work by several of this study's authors, different metal bent-wires were used as metal 2 and several I-Vs were taken for each of the wires [9]. In such studies, it was observed that the nonlinearity is the most reliable performance metric of the two considered here to characterize different MIM devices; nonlinearity was found to be sensitive to different metal combinations, but independent of the bent-wire penetration depth. In this present study, Fig. 6 further corroborates that nonlinearity is independent of displacement and thus an excellent, geometry-insensitive direct measure of MIM performance. Further results will be reported on the reproducibility of I-V curves using b-Diamond tip in both constant-force and constant-displacement modes. This technique provides a platform upon which different metal-insulator combinations will be characterized and analyzed quantitatively.

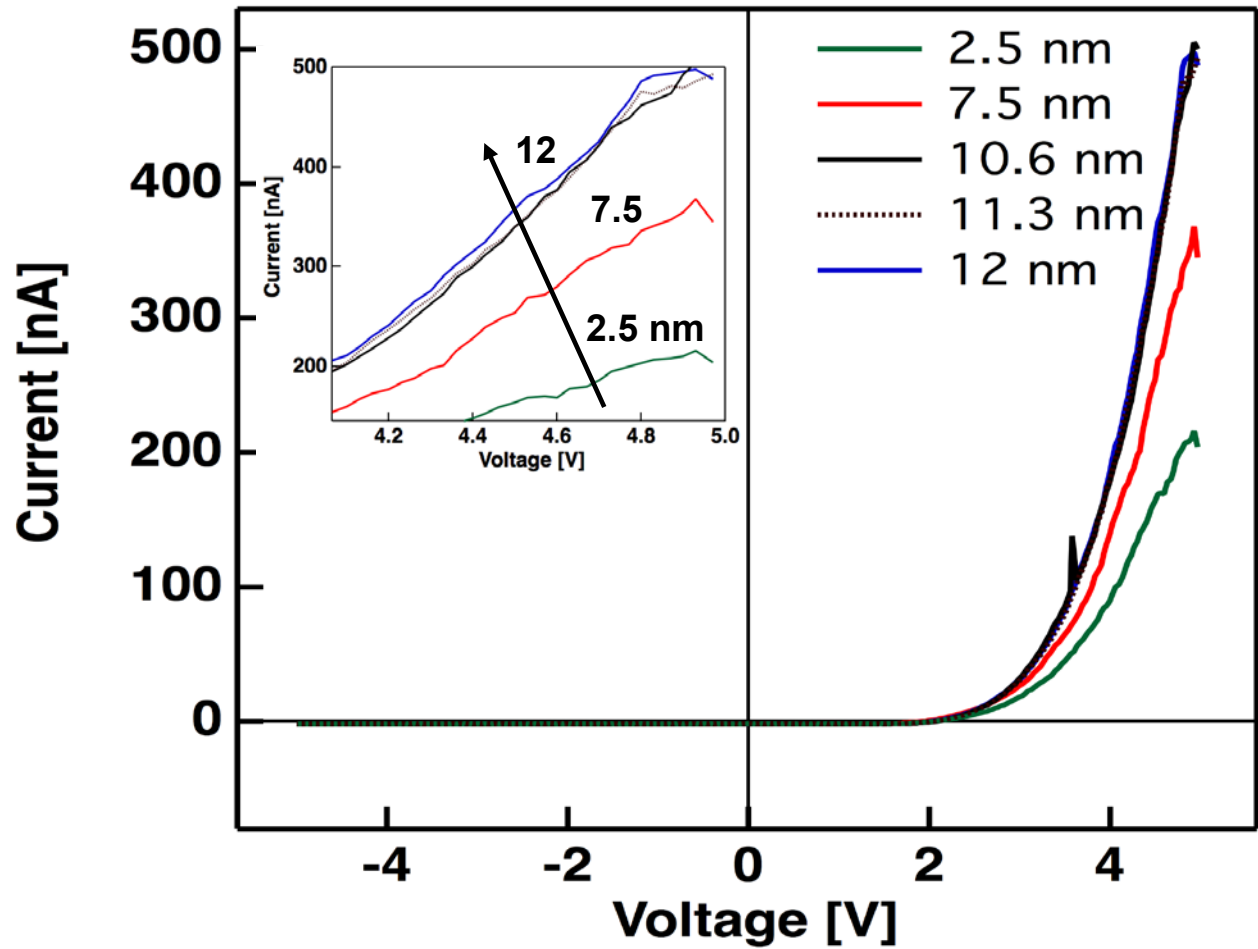


Figure 4. I-V curves of Nb/Nb₂O₅/B-Diamond as a function of penetration depth. Upper inset shows a zoomed view of the I-V to show the trend in current with increasing penetration depth (indicated by the arrow). Reported penetration depth (h_{max}) values are obtained from the load-displacement curves as shown in Fig. 3. The error on the reported h_{max} values is ± 2 nm.

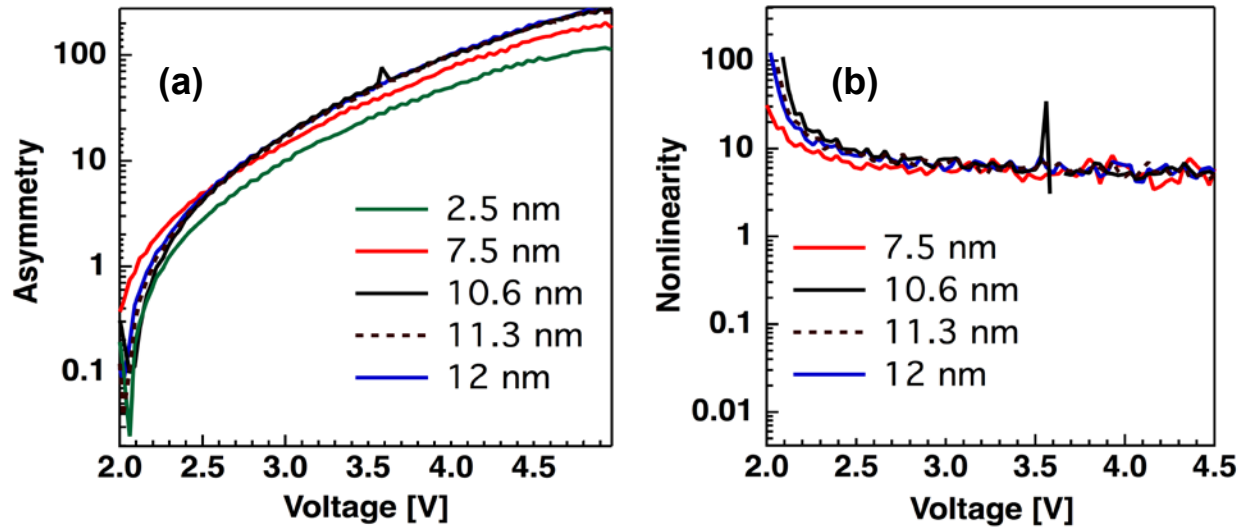


Figure 5: (a) Asymmetry and (b) Nonlinearity as a function of penetration depth. The device shows excellent asymmetry (60-300) and nonlinearity (6-9) values above 3V. Asymmetry increases with penetration depth whereas nonlinearity is independent of penetration depth in this range.

CONCLUSIONS

To summarize, characterizing MIM diodes via nanoindentation shows significant promise as a facile and systematic approach. For the first time we have reported MIM diodes fabricated using a nanoindenter with excellent asymmetry (60-300) and nonlinearity values (~6-9). Nonlinearity is found to be independent of penetration depth.

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