Air stable Indium-Gallium-Zinc-Oxide diodes with a 6.4 GHz extrinsic cut-off frequency fabricated using adhesion lithography

Gwenhivir Wyatt-Moon, Kham M. Niang, Chris B. Rider and Andrew J. Flewitt

***Abstract*— High speed rectifiers that can be fabricated at low cost whilst still maintaining a high performance are of interest for wireless communication applications. In this letter amorphous indium gallium zinc oxide (a-IGZO) has been used with adhesion lithography (a technique to create asymmetric planar electrodes separated by a nanogap) to fabricate high performance Schottky diode rectifiers. The diode area and junction capacitance can be significantly reduced using this technique, improving device cut-off frequencies. Devices of different widths have been fabricated showing rectification ratios between 10^3-10^4. Capacitances measured for devices of various sizes were all on the order of 0.1 pF. By applying ac signals to the diode and measuring the output voltage across a load resistor a cut-off frequency was found. a-IGZO diodes with an extrinsic cut-off frequency of 6.4 GHz at a 15 dBM input power have been realized. The devices also show good air stability with little change in current-voltage characteristics after 12 months.**

***Index Terms*— UHF technology, Schottky diode, Rectifiers, Large scale fabrication, Nanogap electrodes, Nanolithography**

I. Introduction

The move towards high degrees of automation and the internet of things (IoT) is dependent on successful communication between devices. A crucial component in this area is the radio frequency identification (RFID) tag, with passive tags of interest due to their low cost and power consumption. These tags have three distinct parts: the rectifier, the antenna and the logic circuit. The rectifier converts the AC signal captured by the antenna into a DC signal which is used to power the logic circuit. The current leading technology is high frequency tags operating at 13.56 MHz. These tags have a short read-range limiting their applications. Many technologies within the flexible sensor and IoT fields require RFID tags operating at much higher frequencies of 900 MHz and above [1].

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Thin film indium gallium zinc oxide (IGZO) gained widespread attention when in 2004 it was shown to be able to have a large electron mobility even in the amorphous state [2]. The material has been researched extensively and is now used commercially in thin film transistors (TFTs) for active matrix displays [3]. Amorphous IGZO (a-IGZO) is optically transparent, compatible with large area patterning and due to its low temperature processing, can be deposited on flexible substrates [2]. For rectifying applications transistor devices have been explored and typically show transition frequencies f_T (frequency at which current gain is unity) in the 100s of MHz [4], [5]. TFTs have significant overlap capacitance and so for higher frequencies Schottky diodes are normally preferred. A recent study has, however, optimized the contact overlaps and produced f_T values over 1 GHz [6]. Previous Schottky diodes that have used a-IGZO as the active material have shown good air stability and high rectification ratios (10^6-10^8) [7]–[9]. Devices that have specifically designed architecture and optimized layers of a-IGZO have shown extrinsic cut-off frequencies from 1-4.2 GHz [10]–[12].

Adhesion lithography (a-Lith) is a technique for large area patterning of nanogap electrodes at low cost. The size of the gap between the electrodes has repeatedly been shown to be around 10 nm [13][14]. These electrodes can be made from dissimilar metals allowing for the creation of planar Schottky diodes simply via the deposition of a semiconductor material on top of the two asymmetric electrodes. A-Lith has already been used to create high performance devices including photodiodes [15], light emitting diodes [16], memristors [17], TFTs [18] and RF diodes [19]. For RF applications, the fact that the asymmetric electrodes are planar and have a nanoscale channel allows for higher cut-off frequencies due to a reduced device area and hence a smaller junction capacitance. Previous reports creating RF diodes using solution-processed ZnO and a-Lith have shown cut-off frequencies higher than the measurement setup could measure (over 20MHz) [19]. These devices were measured in a nitrogen atmosphere and are expected to degrade rapidly in air.

The Schottky diodes created for this study combine sputtered a-IGZO and a-Lith to create air-stable devices. The I-V and C-V characteristics of the devices are analyzed; an extrinsic cut-off frequency 6.4 GHz at 15 dBM input power is measured without any encapsulation. Further, due to their novel structure, diodes created using a-Lith are easy to integrate into circuits with other devices typically used in RFID tags.

II. EXPERIMENTAL

A-Lith was used to create coplanar Al and Au electrodes separated by a nanogap as previously reported [13]. In this study a 40 × 40 mm Corning glass substrate was used onto which 40 nm of Al was sputtered and patterned with a photolithographic lift-off process using AZ5214E photoresist. Octadecylphosphonic acid (ODPA) was then used to form a self-assembled monolayer (SAM) on the Al via dip coating to reduce adhesion to the Al. A second thin film metal of 40 nm Cr/Au was then thermally evaporated and also patterned using lift-off. The photoresist was then removed using acetone and the Cr/Au was peeled using glue (First Contact adhesive from Photonic Cleaning Technologies). The Cr/Au electrode remained in areas where there was glass but removed from areas where there was ODPA SAM. This forms a ~10 nm gap between the two metals. An a-IGZO film was then deposited by rf-magnetron sputtering (CCR GmbH) on top of the electrodes using an IGZO target with an atomic ratio of In_2O_3:Ga_2O_3:ZnO (1:1:1) target (Pi-Kem; 99.99% purity) in an argon (BOC Gases; 99.999%) atmosphere at room temperature without intentional substrate heating. The material was sputtered for 33 minutes at a pressure of 7×10^{-3} mbar with an RF power of 75 W and a 12.5 cm separation between the substrate and the target. The devices were then annealed at 200°C in air for 60 minutes. The 3D device structure is shown in Fig. 1; the electrodes have been designed to allow for contact with a GSG probe for frequency measurements.

An Agilent semiconductor device analyser (B1500A) was used for I-V and C-V measurements. Cut-off frequency measurements were made using an Agilent function generator and a Keithley 236 source measure unit connected via a bias tee. All measurements were carried out under ambient conditions.

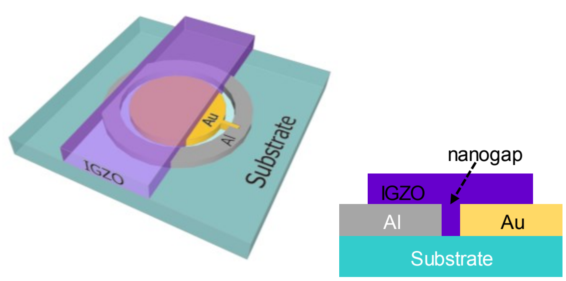

Fig. 1 3D and 2D schematics of a-IGZO, a-Lith Schottky diode.

III. RESULTS AND DISCUSSION

The 2D schematic (Fig. 1) shows a cross sectional view of the diode where the a-IGZO is expected to sit in between and on top of the planar Al and Au electrodes. The Au electrode is expected to form a Schottky barrier with the a-IGZO due to the work function of each material while the Al should form an ohmic contact with IGZO.

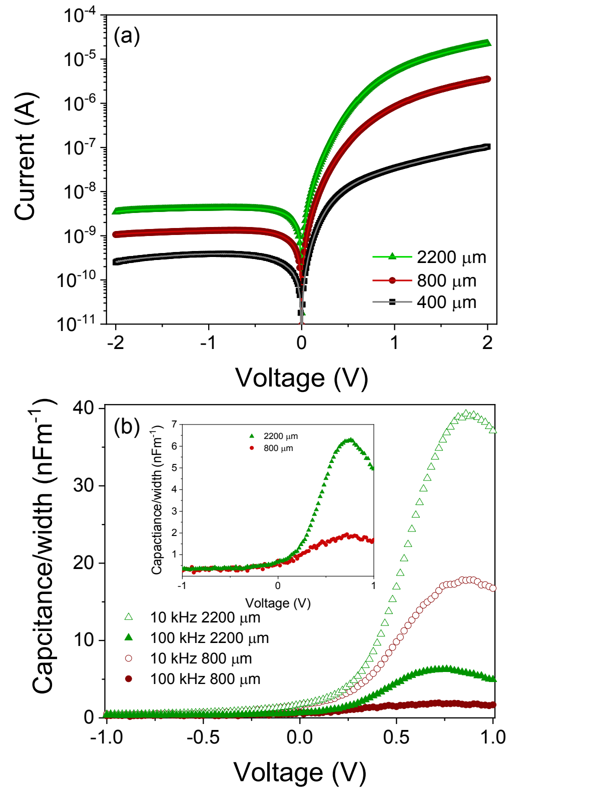

Fig. 2 (a) I-V characteristics a-IGZO diodes with different widths showing increasing forward current with increasing width, and (b) Capacitance per width vs voltage measurement of 800 µm and 2200 µm width diodes at 10kHz and 100 kHz. Inset: 100 kHz measurements. Removing device dimension from the measured capacitance, the two different sized devices show the same capacitance per width at reverse bias and follow a similar trend at forward biases.

In this device structure, the diode area is determined by a combination of the film thickness and the width of the device (where width is the length of the a-IGZO covering the electrodes in the direction perpendicular to the current flow). The I-V characteristics of three diodes of different widths are shown in Fig. 2(a). As expected, the forward current scales with the width of the device. The rectification ratios for each device, however, are all very similar: between 10^3-10^4. This is due to the proportionally similar increase in reverse current with increasing width. The reverse breakdown voltage for all the devices is typically 4.5 V. Due to the nanoscale nature of these diodes, the I-V characteristics are not expected to follow the typical thermionic theory for standard Schottky devices and this is observed experimentally. Further device modelling is needed to take account of transport mechanisms such as tunnelling that are likely to affect the current at this scale.

In Fig. 2(b) the capacitance per unit width vs voltage of the two larger devices (measured with a 10 kHz and a 100 kHz AC signal) are shown. By removing the effect of area from the C-V measurement, it is clear that the capacitance per unit width in reverse bias is the same value for both devices at both frequencies. The difference in the characteristics due to varying the measurement frequency indicates that any traps are screened out as the frequency is increased. We see that the devices are depleted in the reverse bias and as the voltage becomes more positive, charge accumulates as is expected in a Schottky diode. As seen in the inset of Figure 2(b) at 100 kHz the devices turn-on voltage is below 0 V with the capacitance increasing from -0.32 V. This is also the point where the reverse current starts to decrease on the I-V characteristics. The capacitance begins to decrease above 0.5 V. This is probably because of the high fields being applied to the nanoscale channel of the device affecting charge injection and the shape of any depletion region.

The fact that the maximum capacitance per unit width occurs at the same voltage for both devices suggests that the effect is due to the nanoscale length of the devices. The slight difference in capacitance per width value at forward bias for each width is seen at both frequency values and is believed to be caused by the parasitic capacitance of the substrate scaling due to the different area of the electrodes for each device size. The actual capacitance measured for the devices when depleted (between -1 and -0.32 V) are 0.25 pF for the 800 µm width device and 0.77 pF for the 2200 µm device. These incredibly small capacitances allow for the high frequency operation of the device.

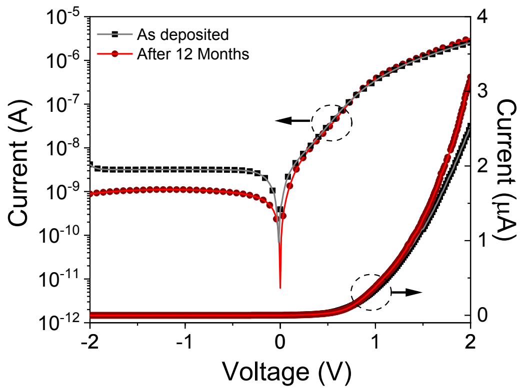

Fig. 3 Semi-log and linear plots of I-V characteristics for a 800µm a-IGZO, a-Lith diode as deposited and after 12 months in air. The diode shows good stability.

Fig. 3 shows an 800 µm device measured just after semiconductor deposition and after 12 months' storage in ambient conditions. The devices remain very stable with a small reduction in the reverse current and a minor increase in the forward current, slightly improving the device's rectification ratio. The stability of the devices is likely due to the small size of the devices as this means the probability of oxygen absorption is very small.

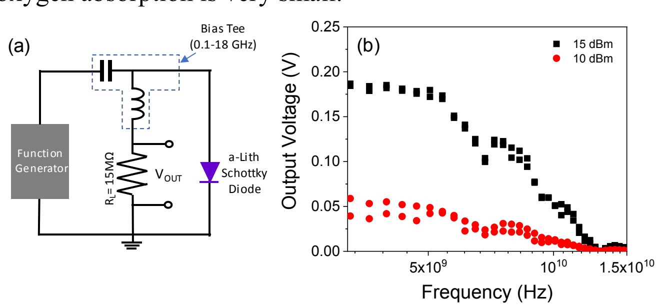

Fig. 4 (a) RF measurement setup for diodes. A function generator is connected to a bias-tee to apply an AC to the diode with the output voltage measure across a load resistor (R_L). (b) The output voltage at different frequencies of a 800 µm width diode at input powers of 10 and 15 dBm to measure the diode cut-off frequency (-3dBm point).

Fig. 4(a) shows the measurement setup used to calculate the extrinsic cut-off frequency of the diodes. A function generator is connected to the diode via a bias tee. The output voltage of the diode is measured across a load resistor of 15 MΩ. The frequency vs output voltage has then been plotted to calculate the cut-off frequency of the diode from -3 dBM point (Fig. 4(b)). This is where the output voltage drops to $1/\sqrt{2}$ of its initial value. For both sets of data there is a slight dip in the decay slope this is a measurement artefact due to the system not being perfectly matched. For a 10 dBm input power, the cut-off frequency is near 5.9 GHz with an output voltage of 0.05 V whilst at 15 dBM the cut-off frequency is around 6.4 GHz and the output voltage is 0.2 V. These extrinsic cut-off frequencies are the highest shown for an a-IGZO diode. The authors believe this value could be increased by improving the measurement setup of the diodes which experiences losses due to input resistance from the function generator and unmatched impedances. The output voltages for these devices could also be improved by circuit design such as adding more diode stages to a rectifying circuit. The devices also have a lower rectification ratio as compared to previously reported IGZO Schottky diodes. To improve this further studies could be carried out on the electrode materials, perhaps exchanging Au for Pt or Pd. Further optimisation of the deposition conditions for the IGZO layer, including adding O_2 to the deposition chamber, could also improve this but may reduce the forward current of the device.

IV. Conclusions

Schottky diodes that are air stable with high rectification ratios and 6.4 GHz extrinsic cut-off frequencies in a practical rectifier setup have been shown. This cut-off frequency is compatible with UHF communication applications and the planar nature of the devices makes them easy to integrate with typical circuit components for RFID tags. Adhesion lithography can also be up-scaled and is compatible with flexible substrates. If utilised with other fabrication technologies, low-cost RFID tags that operate in the UHF regime can be fabricated.

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