UHF IGZO Schottky diode

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High-performance Schottky diodes based on amorphous IGZO (Indium-Gallium-Zinc Oxide) semiconductors were fabricated and fully characterized. S-parameter measurements and subsequent analysis prove that these diodes have a cutoff frequency over 900MHz, making these diodes an excellent choice for UHF applications, such as energy-harvesters for passive RFID tags on foil. Moreover, when used in a single stage rectifier, the diodes provide DC voltages higher than 1.2V at 900MHz, which is enough supply for circuitry on foil based on current metal-oxides technologies [1,2].

Thin-film circuits fabricated directly on plastic foil [2] are contenders for low-cost 'plastic' electronic tags. Preferably, such tags are passive, i.e. powered by the electromagnetic wave sent by the receiver. To that end, a rectifier is required on the tag. In the past it was shown that organic semiconductor rectifiers can operate at HF (13.56MHz) [3,4]; to reach UHF (~900MHz), we here propose rectifiers based on amorphous metal-oxide semiconductors such as IGZO, as they combine a higher intrinsic mobility and air stability while still allowing processing with low thermal budgets compatible with plastic substrates [5].

Pd electrodes were deposited and patterned by photolithography on a glass substrate. A 260nm thick amorphous IGZO layer was subsequently deposited by rf sputtering from a InGaZnO₄ ceramic target at room temperature. The oxygen content of the (Ar+O₂) gases was maintained at 20% and the working pressure in the deposition chamber was 2×10^{-2} mbar. The IGZO layer was wet etched in a solution of oxalic acid and water. As final step, Ohmic Mo top contacts with different sizes were also formed by a lift-off process, providing vertical diodes with areas from $20 \times 10 \mu\text{m}^2$ to $220 \times 200 \mu\text{m}^2$ (Figure 1a).

The high O₂ pressure is one of the requisites to obtain a Schottky barrier, because it reduces the IGZO subgap surface states and, consequently, the Fermi level pinning. The obtained Schottky behavior is visible in Figure 1b. We achieved a further improvement of the off-current by performing an in-situ O₂ plasma treatment on the Pd bottom electrode prior to IGZO deposition (Figure 1c). A final post-annealing in 1atm O₂ at 200°C reduces even further the off-current, while still enabling a high on-current level. The final devices have rectification ratios higher than 10^8 at $\pm 1\text{V}$, current densities of up to $100\text{A}/\text{cm}^2$ at forward bias of 2V and reverse breakdown voltages higher than 10V, as shown in Figure 2. State of art organic Schottky diodes, on the other hand, have much smaller rectification ratios at $\pm 1\text{V}$ of up to 50 [3] and 10^4 [4]. Figure 3 shows the on and off-current dependency on the diodes' area and the homogeneity of the devices over a $3 \times 3 \text{cm}^2$ sample. Although some spread of the current levels is seen, the rectification ratio is constant around 10^8 for all devices. Our diodes are the first IGZO Schottky diodes in which the charge transport mechanism can be explained via a pure thermionic emission process over the Schottky barrier. We prove this by modeling the measured forward current of the diodes by the thermionic emission model with the parameters shown in Table I over the whole forward bias regime (Figure 4). Temperature dependent IV measurements are shown in Figure 5a with its respective Richardson plot (Figure 5b), confirming the uniformity of the Schottky barrier.

The inset of Figure 6 shows that capacitance of the diode is almost constant at negative bias, because the IGZO film is fully depleted at negative voltages. The obtained 6 pF corresponds to the geometrical capacitance of the semiconductor layer. Therefore, we extracted the relative dielectric constant ϵ_s of IGZO to be 14.9. Based on this value and the CV measurements shown in Figure 6, it is possible to extract the built-in potential V_{bi} and the ionized atoms concentration within the depletion region N_{depl} . In covalent semiconductors, the depletion region of a Schottky diode reveals the ionized dopant concentration which is fully correlated to the free charge concentration. In amorphous semiconductors, however, due to subgap traps, the depletion region also reveals ionized atoms that do not contribute to the free charge concentration. Therefore, N_{depl} corresponds to subgap trap density. The free charge concentration N_e , on the other hand, is extracted from the resistivity of the diodes obtained from IV measurements by assuming a mobility equal to $10 \text{ cm}^2/(\text{V.s})$.

One-port scattering parameter measurements were taken of the diodes. S_{11} of a $120 \times 100 \mu\text{m}^2$ area diode is shown in Figure 7 at different bias voltages for frequencies ranging from 10MHz to 10GHz. The top-left inset shows the small-signal model used to extract the various device components: a parallel variable resistance (R_b) that depends on the applied bias and a capacitance (C_b), representative of the diode's barrier, in series with a second resistance (r_s), representing any series resistance due to contacts. A photograph of the device used for RF measurement is shown on the top-right inset.

At sufficiently high frequency the junction capacitance dominates the barrier conductance. Accordingly, a useful "figure-of-merit" has proved to be the frequency at which $1/\omega C_b$ equals r_s , which is called the cutoff frequency. Figure 8 shows the value of r_s and X_b extracted from S_{11} at 0V as a function of the frequency. It is clear that the diode has a RC-cutoff frequency over 900MHz. The inset shows C_b extracted from X_b as a function of the frequency: its value is the same as obtained previously from CV measurements with the diode in negative bias shown in Figure 6.

Finally, the diode was connected in a single stage rectifier using a 100nF capacitor and $1\text{M}\Omega$ load resistance. A 50Ω resistor was used for proper termination of the incoming RF signal (Figure 9a). Figure 9b presents the average DC component of the rectified output signal (V_{out}) obtained for an incoming sine wave with amplitudes of 3V (i.e. 6V peak-to-peak) or 5V (i.e. 10V peak-to-peak) for different frequencies. For a 1MHz signal, stable rectified DC outputs of 2.4V (Figure 10b) and 4.5V are obtained, for AC input of 3V and 5V, respectively. At 800MHz, the DC values dropped to 0.37V and 1.26V as shown in Figure 10d. Comparing to organic diodes, IGZO diodes supplies more voltage at the same frequency due its low turn-on voltage (low V_{bi}) and high rectification ratios.

In summary, we have demonstrated for the first time high performance, low turn-on and ultra-fast IGZO Schottky diodes, with f_{RC} over 900MHz that supplies more than 1V DC at UHF regime.

[1] M. Rockele *et al.*, Organic Electronics 12, 1909 (2011). [2] A. K. Tripathi *et al.*, Appl. Phys. Lett. 98, 162102 (2011). [3] S. Steudel *et al.*, IEDM Tech.Dig., (2008). [4] D. Im *et al.*, Adv. Mater., 23, 644 (2011). [5] K. Nomura *et al.*, Nature 432, 488 (2004).

Figure 1: (a) Top-view image and cross-section schematic of the IGZO diodes' topology. The influence of the Pd bottom contact pre-treatment and the annealing step on the diode characteristics are shown on (b) and (c). The diode area is $120 \times 100 \mu\text{m}^2$.

Figure 2: Wide bias curve showing the diode's typical forward and reverse current density at +2V and -10V, respectively. The diode area is $120 \times 100 \mu\text{m}^2$.

Figure 3: On and off-current for diodes with different sizes at $V = \pm 1\text{V}$ within a sample of $3 \times 3 \text{cm}^2$. There are 10 devices measured for each size and the black squares are the average value.

Figure 4: Forward current experimental data (symbols) and fit with a pure thermionic emission model with the parameters from Table I (full lines). The diode area is $120 \times 100 \mu\text{m}^2$.

Figure 5: (a) Temperature dependence of the IV characteristics of a Pd Schottky diode and (b) corresponding Richardson plot. The diode area is $120 \times 100 \mu\text{m}^2$.

Figure 6: The diodes' CV characteristics. The inset shows the capacitance measured at negative bias: the value is almost constant at 6pF. The diode's area is $120 \times 100 \mu\text{m}^2$.

barrier height	$\Phi_{B, IV}(eV)$	0.81
saturation current	$I_s (pA)$	12.2
ideality factor	n	1.36
series resistance	$R_s(\Omega)$	238
free charge density	$N_e (cm^{-3})$	5.8×10^{14}
built-in potential	$\Phi_{bi, CV}(eV)$	0.33
barrier height	$\Phi_{B, CV}(eV)$	0.62
charge density depletion region	$N_{depl} (cm^{-3})$	7.9×10^{15}
depletion region thickness	$W (nm)$	260

Table I. Characteristics of the Schottky diodes from IV and CV measurements at RT.

Figure 7: S_{11} parameters from 10MHz to 10GHz at different bias voltages. The red curve is the 0V measurement. Top-left inset shows the equivalent small signal model of the diode. The top-right image reveals the structure used for these RF measurements.

Figure 8: Imaginary and real part of the diode's impedance as a function of the frequency at bias of 0V. The cut-off frequency f_{RC} of the diode is shown. The inset shows the value of the capacitance C_b extracted from X_b as a function of the frequency.

Figure 9: (a) Photograph of the measurement setup and (b) average DC component of the rectified output signal (V_{out}) as a function of the applied AC frequency signal for two different AC amplitudes. The inset shows the rectifier schematic.

Figure 10: Rectified voltage (V_{out} of the inset of Fig.9) at (a) 1MHz and $C_L=0$ (b) 1MHz and $C_L=100nF$, (c) 200MHz and $C_L=100nF$, (d) 800MHz and $C_L=100nF$.