High performance Schottky diodes based on indium-gallium-zinc-oxide

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High performance Schottky diodes based on indium-gallium-zinc-oxide

AQ1

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Indium-gallium-zinc-oxide (IGZO) Schottky diodes exhibit excellent performance in comparison with conventional devices used in future flexible high frequency electronics. In this work, a high performance Pt IGZO Schottky diode was presented by using a new fabrication process. An argon/oxygen mixture gas was introduced during the deposition of the Pt layer to reduce the oxygen deficiency at the Schottky interface. The diode showed a high barrier height of 0.92 eV and a low ideality factor of 1.36 from the current–voltage characteristics. Even the radius of the active area was 0.1 mm, and the diode showed a cut-off frequency of 6 MHz in the rectifier circuit. Using the diode as a demodulator, a potential application was also demonstrated in this work. © *2016 American Vacuum Society*. [http://dx.doi.org/10.1116/1.4945102]

I. INTRODUCTION

Indium-gallium-zinc-oxide (IGZO) is an emerging n type metal oxide semiconductor which has been widely used in display industries as the active material in back-panel driving units.[1,2] It has been regarded as an alternative of amorphous silicon due to its relatively high mobility ($\sim 10\,\text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$), good visible light transparency, high uniformity over large areas, and compatibility with low temperature deposition techniques.[3] However, most of the studies on IGZO to date have been based on thin film transistors (TFTs), which normally operated at low frequencies.[4] As the operation frequencies of TFTs are limited by the mobility, the channel length, and the overlay between source/drain and gate electrodes, in order to realize gigahertz electronics by using IGZO TFTs, the scale of the active area needs to be reduced to submicron, which is difficult for photolithography processes.[5] In recent years, IGZO Schottky diodes have drawn much attention due to their advantages in high speed operations.[6–10] In 2015, the cut-off frequencies of IGZO Schottky diodes were improved to 16 GHz,[9] which covers most of daily used frequency bands. Several potential applications have also been demonstrated in the last few years.[7,11] However, due to the nature of metal oxide semiconductors, the properties of the Schottky contacts highly depend on the oxygen contents at the metal–semiconductor interfaces.[12–14] Postannealing treatment is one of the methods to improve the rectification properties.[6] Another method is to create an oxygen rich layer at the Schottky interface by introducing a pretreatment such as oxygen plasma etching or UV ozone oxidation on the Schottky contacts.[12] For ZnO Schottky diodes, the interface properties can be improved by using oxidized noble contacts.[13,14] It is found that the inclusion of oxygen during the deposition of the noble metal is able to reduce the defects caused by oxygen vacancies at the interface between metal and single crystalline ZnO.[13,14] Despite the amorphous structure, it is plausible that such techniques may also be used to improve the interface properties of IGZO Schottky diodes.

In this work, we have successfully presented the high-performance Pt-IGZO Schottky diodes fabricated at room temperature (RT) by introducing oxygen during the deposition of Pt without any postannealing treatment. The properties of the diodes have been analyzed in terms of current–voltage characteristics, capacitance–voltage characteristics, and frequency response. We also demonstrated a simple crystal radio system by using the Pt-IGZO Schottky diode as the demodulator.

II. EXPERIMENT

Si-SiO$_2$ wafers were used as substrates in this work. The substrates were degreased by supersonic cleaning in deionized water, acetone, and methanol, then dried with nitrogen and placed in UV/ozone chamber for 30 min. Pt electrodes of 50 nm-thick were deposited by using RF sputtering at 80 W in pure Ar (devices A and B) and Ar/3% O$_2$ mixture gas (device C). IGZO (In$_2$O$_3$:Ga$_2$O$_3$:ZnO = 1:1:2) was sputtered at 80 W for 50 nm in Ar (devices A and C) and Ar/3% O$_2$ mixture gas (device B). The Al top electrodes were deposited by using thermal evaporation and defined by shadow masks. The current–voltage (J-V) characteristics were measured by using Agilent E5260B Semiconductor analyser at RT in dark. Agilent E4980A LCR meter was used to measure the capacitance–voltage (C-V) characteristics. The frequency response of the IGZO Schottky diodes was measured by Agilent 34401A digital multimeter, and the AC signal was generated by HP 8116A signal generator.

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III. RESULTS AND DISCUSSION

The structure of the diode is shown as the inset in Fig. 1(a). The active area of the device was determined by the top Al electrode. The radius of the contact equaled 0.1 mm. In Fig. 1(a), the J-V characteristics of devices A, B, and C are shown. According to the thermionic emission theory,[15] the J-V characteristics of the Schottky diode can be described as

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$$J = J_0\left\{\exp\left[\frac{q(V-JR_s)}{nk_BT}\right]-1\right\}$$
$$= A^*T^2\exp\left(-\frac{q\varphi_b}{k_BT}\right)\left\{\exp\left[\frac{q(V-JR_s)}{nk_BT}\right]-1\right\}, \qquad (1)$$

where J_0 is called the saturation current density, A^* is the Richardson constant which equals 41 A cm^{-2} K^{-2} for IGZO,[6] k_B is the Boltzmann constant, T is the temperature, φ_b represents the barrier height of the diode, R_s is the series resistance, and n is defined as the ideality factor. By fitting the J-V curves according to Eq. (1) at low biases where $V \gg JR_s$, the barrier height, on/off ratio, and ideality factor can be obtained, which are shown in Table I. For device A, it showed a relatively low barrier height of 0.52 eV and an ideality factor of 2.50. The rectification ratio at ±1 V was only 10^3. For device B, the on/off ratio became 2.0×10^4, and the ideality factor dropped to 1.56. Compared with device A, device B showed a higher barrier height of 0.72 eV. When depositing Pt with 3% O_2, device C exhibited a better performance compared with devices A and B. The barrier height was found to be 0.92 eV, which agreed well with the estimation if assuming the work function of Pt is 5.4 eV and the electron affinity of IGZO is 4.5 eV.[6] The ideality factor was also close to unity, which suggested that the barrier height was uniform at the interface. The on/off ratio was found to be higher than 10^6.

Figure 1(b) shows the C-V characteristics of devices B and C. The relation between the diode capacitance and the applied bias can be described by

$$C^{-2} = \frac{2(V_{bi}-V)}{q\varepsilon_0\varepsilon_r N_{bg}}, \qquad (2)$$

where V_{bi} is the built-in voltage, ε_0 is the vacuum permittivity, ε_r is the relative dielectric constant of IGZO, and N_{bg} is called the background doping density. By assuming the diodes were fully depleted at −1 V, the relative dielectric constant of IGZO was found to be 15 for device B and 14 for device C. The differences might be caused by the different oxygen content in the IGZO layer. By using Eq. (2), the extracted parameters are shown in Table I. It is found that for device B, the built-in voltage was 0.46 V and the background doping density was 3.50×10^{18} cm^{-3}. Device C showed a higher built-in voltage of 0.60 V and a background doping density of 4.05×10^{18} cm^{-3}.

TABLE I. Effects of oxygen during sputtering.

Pt	Ar	Ar	Ar + 3% O_2
IGZO	Ar	Ar + 3% O_2	Ar
n	2.50	1.56	1.36
φ_b	0.52 eV	0.72 eV	0.92 eV
On/off ratio at ±1 V	103	2.0×10^4	2.4×10^6
R_{tot} at 1.5 V	40.27 ~~eV~~	138.54 ~~eV~~	507.21 ~~eV~~
V_{bi}	N/A	0.46 V	0.60 V
N_{bg}	N/A	3.50×10^{18} cm^{-3}	4.05×10^{18} cm^{-3}

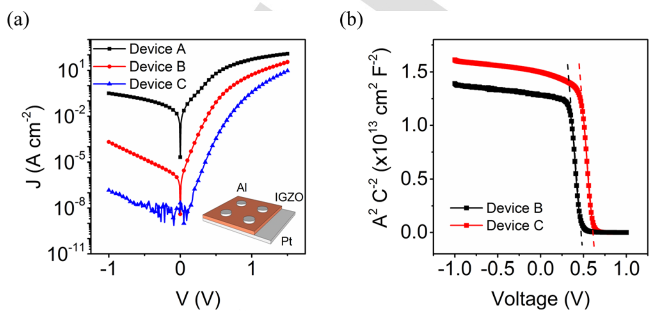

FIG. 1. (Color online) (a) J-V characteristics of Pt-IGZO Schottky diodes with different fabrication conditions. The inset shows the structure of the diodes. (b) C^{-2}-V characteristics of devices B and C. The fittings were shown by the dashed lines.

The oxygen content at the interface is vital for metal oxide semiconductors to form high-quality Schottky junctions.[10,12–14] Allen *et al.* have reported that for ZnO Schottky diodes, oxygen deficiency can induce defects at the interface and cause Fermi level pinning.[13,14] This explains why device A, where Pt and IGZO were deposited in pure Ar, exhibited the lowest barrier height and the highest ideality factor. Introducing 3% O_2 during the deposition of IGZO serves to reduce the number of dangling bonds at the Pt-IGZO interface and may unintentionally oxidize the Pt surface, thus improving the rectification properties of the diode.

An alternative solution is to intentionally create an oxygen-rich phase at the Pt–IGZO interface. It is found that device C showed the highest barrier height, the highest on/off ratio, and the lowest ideality factor among the three devices. In the C-V measurements, it also showed a higher built-in voltage than the value of device B, which suggests that depositing Pt in Ar/O_2 mixture gas helps to reduce oxygen deficiencies and thus contributes to a better Schottky junction.

The current-voltage-temperature characteristics of device C are shown in Figs. 2(a) and 2(b). The linear dependency of $\ln(J_0/T^2)$ on T^{-1} indicates that the thermionic emission dominates the current transport in the diode. The barrier height decreases with increasing temperature, which may be due to the inhomogeneities at the Schottky interface.[16] Assuming these inhomogeneities in barrier height are Gaussian distributed,[16] the mean barrier height is found to be 1.46 eV with a standard deviation of 0.16 eV. The potential fluctuation at the Schottky junction may be caused by the amorphous structure of IGZO, the grain boundaries, and the different crystalline orientations of the Pt layer. An additional thermal annealing step could serve to minimize these fluctuations.

The rectification properties of device C at different frequencies are shown in Fig. 3. The inset shows the setup of

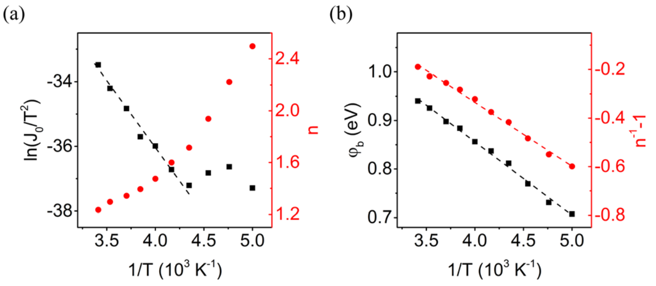

FIG. 2. (Color online) (a) Richardson plot (~~black~~ dots) and ideality factor (~~red~~ dots) as a function of 1/T. (b) Barrier height (~~black~~ dots) and ($n^{-1}-1$) shown as ~~red~~ dots at different temperatures. AQ4

the single-stage rectifier circuit. The signal was generated by HP8116A signal generator through a 50 Ω resistor. The output voltage was measured by Agilent 34401A digital multimeter. As shown in Fig. 3, when the peak amplitude of the input signal was 1.0 V, the output voltage was found to be around 0.56 V. Thus, the −3 dB point was found to be around 6 MHz when the output voltage dropped to 0.39 V. At 13.56 MHz, the diode was still able to generate an output voltage of around 0.14 V with the input voltage of 1 V. As the capacitance of the fully depleted diode is around 0.16 nF and the input resistance is 50 Ω, the cut-off frequency is estimated to be 20 MHz by using $f = 1/2\pi RC$. This value is higher than the experimental results, which might be due to the extra series resistance in the diode. By adopting a similar design as mentioned in Ref. 9, it is possible to further improve the operating frequency.

In the setup shown in Fig. 4(a), an amplitude modulation (AM) signal with a carrier frequency, $f_c = 1.5$ MHz, and an information frequency, $f_A = 1$ kHz, is used as the input signal. The diode in the setup was fabricated under the same conditions as device C. The radius of the active area was increased to 0.5 mm to reduce the total resistance of the diode. The low pass filter is composed of a 12 kΩ resistor and a 1 nF capacitor. The rectified voltage is amplified 20 times and measured by an oscilliscope. Figure 4(b) shows the waveforms of the input and the output signals. The amplitude of the AM signal was set to be 250, 300, and 350 mV, respectively. The peak voltage of the corresponding rectified signals are found to be 0.565, 0.653, and 0.931 V, respectively. Figure 4(c) shows a potential application, namely, an AM radio receiver, using the IGZO Schottky diode as the demodulator. A 5 m-long metal wire was used as the antenna to receive the radio signal (Gold at 1.458 MHz in Manchester). The input AM signal was rectified by the IGZO Schottky diode. The rectified AM signal was converted to the audio signal with a cut-off frequency of 13 kHz through the low-pass filter and amplified 20 times by an SR560 low noise voltage amplifier. Then, the amplified audio signal was connected to a speaker. The demonstration of the fully functional radio receiver is shown in supplementary video.[17] AQ5

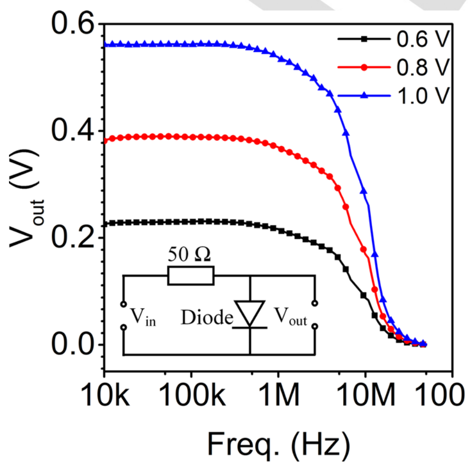

FIG. 3. (Color online) Output voltage as a function of frequency at input signal voltages. The peak amplitudes of the input signals were 0.6, 0.8, and 1.0 V, respectively. The inset shows the diagram of the rectifier circuit.

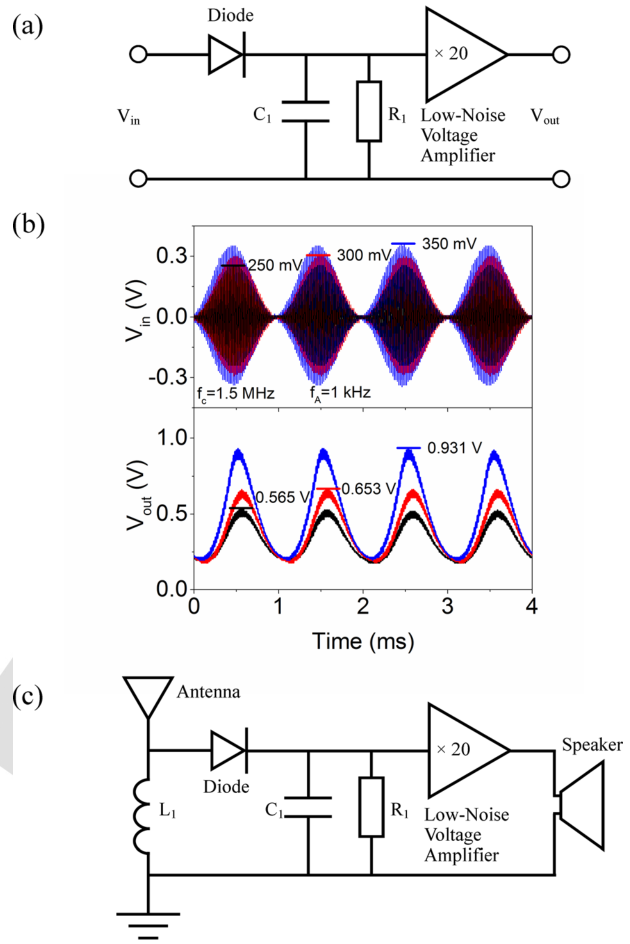

FIG. 4. (Color online) (a) Schematic of the demodulation test setup. C$_1$ equals 1 nF and R$_1$ is 12 kΩ. The demodulation signal is amplified 20 times by a low-noise voltage amplifier. (b) Input waveforms and output waveforms. The carrier frequency is 1.5 MHz, and the information frequency is 1 kHz. (c) Schematic of the crystal radio receiver by using the IGZO Schottky diode.

IV. SUMMARY AND CONCLUSIONS

In this work, we proposed an alternative fabrication process to improve the rectification properties of Pt-IGZO Schottky diodes. The J-V and C-V characteristics showed superior performance to the values obtained from the devices fabricated with the conventional processes. The role of oxygen in the formation of the Schottky barrier has been elucidated and could be further understood by the use of quantitative analytical methods such as secondary ion mass spectroscopy. The cut-off frequency of the diode was found to be around 6 MHz, which could be further improved by adopting the high-frequency coplanar waveguide design. We also demonstrated an AM radio receiver by using the Pt-IGZO Schottky diode as the demodulator. These results shed light on potential applications of IGZO Schottky diodes.

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[1] T. Kamiya and H. Hosono, NPG Asia Mater. **2**, 15 (2010).
[2] J.-S. Park, H. Kim, and I.-D. Kim, J. Electroceram. **32**, 117 (2014).
[3] E. Fortunato, P. Barquinha, and R. Martins, Adv. Mater. **24**, 2945 (2012).
[4] J. S. Park, W.-J. Maeng, H.-S. Kim, and J.-S. Park, Thin Solid Films **520**, 1679 (2012).
[5] N. Munzenrieder, L. Petti, C. Zysset, T. Kinkeldei, G. A. Salvatore, and G. Troster, IEEE Trans. Electron Devices **60**, 2815 (2013).
[6] D. H. Lee, K. Nomura, T. Kamiya, and H. Hosono, IEEE Electron Device Lett. **32**, 1695 (2011).
[7] A. Chasin, L. Zhang, A. Bhoolokam, M. Nag, S. Steudel, B. Govoreanu, G. Gielen, and P. Heremans, IEEE Electron Device Lett. **35**, 642 (2014).
[8] Q. Xin, L. Yan, Y. Luo, and A. Song, Appl. Phys. Lett. **106**, 113506 (2015).
[9] J. Zhang, Y. Li, B. Zhang, H. Wang, Q. Xin, and A. Song, Nat. Commun. **6**, 7561 (2015).
[10] J. Zhang, L. Zhang, X. Ma, J. Wilson, J. Jin, L. Du, Q. Xin, and A. Song, Appl. Phys. Lett. **107**, 093505 (2015).
[11] A. Chasin *et al.*, IEEE Trans. Electron Devices **61**, 3289 (2014).
[12] A. Chasin, S. Steudel, K. Myny, M. Nag, T.-H. Ke, S. Schols, J. Genoe, G. Gielen, and P. Heremans, Appl. Phys. Lett. **101**, 113505 (2012).
[13] M. W. Allen, S. M. Durbin, and J. B. Metson, Appl. Phys. Lett. **91**, 053512 (2007).
[14] M. W. Allen, R. J. Mendelsberg, R. J. Reeves, and S. M. Durbin, Appl. Phys. Lett. **94**, 103508 (2009).
[15] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. (Wiley-Interscience, Hoboken, NJ, 2007), p. 157.
[16] J. H. Werner and H. H. Guttler, J. Appl. Phys. **69**, 1522 (1991).
[17] See supplementary material at http://dx.doi.org/10.1116/1.4945102 for ■. AQ6