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Fabrication, Characterization and Simulation of Sputtered Pt/In-Ga-Zn-O Schottky Diodes for Low-Frequency Half-Wave Rectifier Circuits

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ABSTRACT Amorphous In-Ga-Zn-O (IGZO) is a high-mobility semiconductor employed in modern thin-film transistors for displays and it is considered as a promising material for Schottky diode-based rectifiers. Properties of the electronic components based on IGZO strongly depend on the manufacturing parameters such as the oxygen partial pressure during IGZO sputtering and post-deposition thermal annealing. In this study, we investigate the combined effect of sputtering conditions of amorphous IGZO (In:Ga:Zn=1:1:1) and post-deposition thermal annealing on the properties of vertical thin-film Pt-IGZO-Cu Schottky diodes, and evaluated the applicability of the fabricated Schottky diodes for low-frequency half-wave rectifier circuits. The change of the oxygen content in the gas mixture from 1.64% to 6.25%, and post-deposition annealing is shown to increase the current rectification ratio from 10^5 to 10^7 at ± 1 V, Schottky barrier height from 0.64 eV to 0.75 eV, and the ideality factor from 1.11 to 1.39. Half-wave rectifier circuits based on the fabricated Schottky diodes were simulated using parameters extracted from measured current-voltage and capacitance-voltage characteristics. The half-wave rectifier circuits were realized at 100 kHz and 300 kHz on as-fabricated Schottky diodes with active area of 200 μm $\times$ 200 μm, which is relevant for the near-field communication (125 kHz – 134 kHz), and provided the output voltage amplitude of 0.87 V for 2 V supply voltage. The simulation results matched with the measurement data, verifying the model accuracy for circuit level simulation.

INDEX TERMS Amorphous In-Ga-Zn-O, capacitance-voltage characteristics, current-voltage characteristics, half-wave rectifiers, Schottky diodes, sputtering.

I. INTRODUCTION

Amorphous indium-gallium-zinc oxide (In-Ga-Zn-O or IGZO) is an established material of electronic devices due to its optical transparency, high electron mobility, low temperature processability, mechanical flexibility and ease of structuring because of the amorphous nature [1]. IGZO with Hall effect mobility of 10 $cm^2V^{-1}s^{-1}$, which is an order of magnitude higher than for hydrogenated amorphous silicon, is employed as the active channel in transparent thin-film transistors (TFTs) [2]. Nowadays, IGZO TFTs have been widely utilized in various applications such as active-matrix back planes of flexible organic light emitting diode displays in smart phones and tablet computers [3], [4].

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Schottky diodes based on amorphous IGZO have been demonstrated for ultra-high frequency energy harvesters [5], memory devices [6], metal-semiconductor field-effect transistors [7], glucose sensors [8], and temperature sensors [9].

Schottky diodes based on amorphous oxide semiconductors often suffer from surfaces sensitivity to ambient exposure, which changes the concentration of intrinsic oxygen vacancies and induced trap states at the interfaces. For amorphous oxide semiconductors all manufacturing parameters such as pressure, temperature, atmosphere, elemental ratio, pre- and post-deposition treatments as well as a contact metal lead to the modification of oxygen concentration in the film itself and at the device interfaces, thus determining electrical properties of the final device. Most process parameters depend on the sputtering system configuration and need to be optimized for each individual case. Additionally, pre- or post-deposition treatments are selected according to the properties of the materials and interfaces.

UV-ozone treatment [10] or oxygen plasma treatment [11] of Pd bottom electrode have been demonstrated for reducing the IGZO subgap states and Fermi level pinning. Introducing of 20% O_2 during the sputtering of IGZO after bottom electrode treatment and post-annealing at 200°C were applied to fabricate Schottky diodes with a rectification ratio up to 10^8 and ideality factor of 1.22 [11]. Thermal annealing at 200°C and an oxygen-containing atmosphere were utilized for the fabrication of the AgO_x/IGZO Schottky diodes with rectification ratio of 10^9 at ±2V and an ideality factor of 1.7 [12]. The Pt/IGZO Schottky diodes on flexible plastic substrates operating beyond 2.45 GHz were fabricated by applying UV-ozone treatment and 3% O_2 atmosphere during the IGZO sputtering without any thermal annealing process [13]. Gradual doping of oxygen from 0% to 37.5% along the vertical profile of the a-IGZO layer allowed achieving the transparent conducting oxide/a-IGZO Schottky junction with rectification ratio of 10^3 [14].

It has been reported that the inclusion of oxygen during the noble metal deposition can reduce the oxygen deficiency at the Pt-IGZO Schottky interface, resulting in a barrier height of 0.92eV and an ideality factor of 1.36 [15].

Previous studies report different O_2 levels, annealing temperatures, annealing time and additional treatment of metal contact for obtaining best performance of Schottky diodes in terms of ideality factor, rectification ratio, Schottky barrier height, and cut-off frequency (Table 1), and focus on high-frequency and ultra-high frequency applications. The flow chart for the proposed systematic study on a-IGZO Schottky diodes development and testing is presented in Fig. 1. We performed the fabrication and current-voltage (*I-V*) and capacitance-voltage (*C-V*) characterization of the vertical thin-film Pt-IGZO-Cu Schottky diodes. The process optimization was proposed based on the analysis of the combined effect of the oxygen-containing atmosphere for sputtering of a-IGZO (ln:Ga:Zn=1:1:1) and post-deposition thermal annealing on the characteristics of the fabricated diodes. Transient simulation of a low-frequency half-wave rectifier circuit, where the Schottky diodes were described by extracted from *I-V* and *C-V* parameters, and characterization of the fabricated diodes in the circuit were realized to evaluate the potential application of the Pt-IGZO Schottky diodes for the near-field communication (NFC) 125 kHz – 134 kHz.

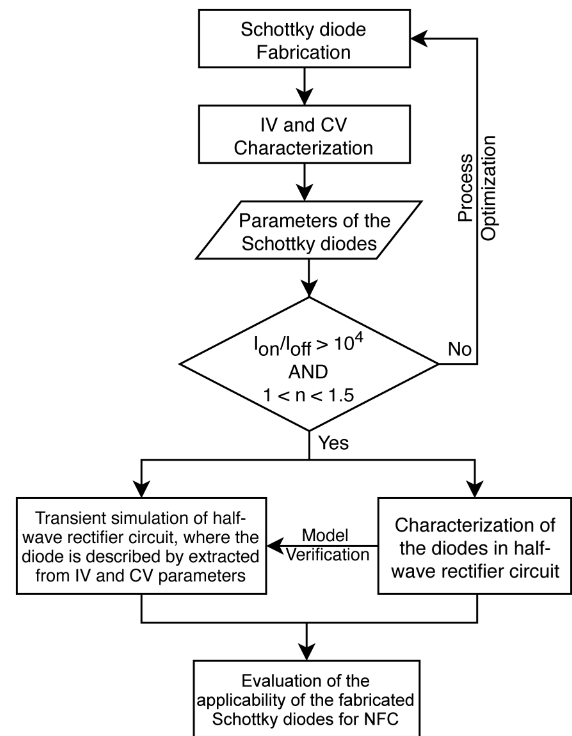

FIGURE 1. Flow chart for the a-IGZO Schottky diode development and testing in the half-wave rectifier circuit.

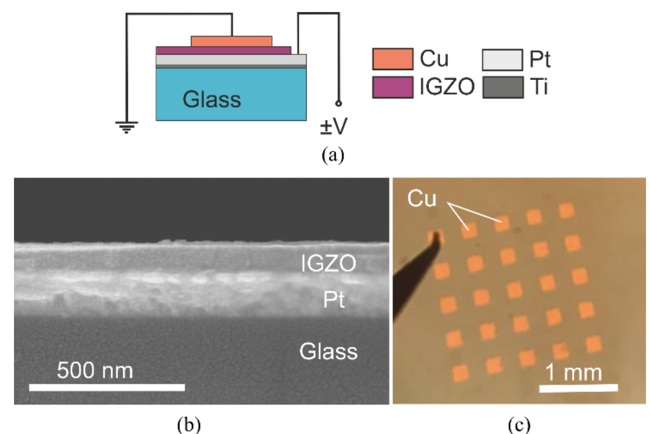

FIGURE 2. (a) Structure of the vertical Schottky diode Ti-Pt/IGZO/Cu, (b) SEM image of the a-IGZO Schottky diode, and (c) top-view microscope photograph of the array of the fabricated diodes on the substrate.

II. FABRICATION

Vertical IGZO Schottky diodes (Fig. 2) were fabricated on alkali-free borosilicate glass (Corning 7059) to prevent a contamination of IGZO semiconductor film with alkali metals

TABLE 1. Characteristics of the Schottky diodes fabricated in different process parameters.

Parameter / Contact metal	Contact area, μm^2	O_2 during IGZO sputtering	Treatment before IGZO sputtering	T_{ann}, °C	t, h	n	I_{on}/I_{off}	φ_b, eV	R_s, Ohm	V_{bi}, V	N_{depl}, cm^{-3}	Cut-off frequency	Ref.
Pd	10^4	20%	UV-ozone	150	1	1.51	10^7	0.79	64.9	0.65	1.4×10^{17}	–	10
Pd	10^4	20%	UV-ozone	150	2	1.71	10^6	0.72	23.6	0.75	6×10^{17}	–	10
Pd	1.2×10^4	20%	O_2 plasma	200	*	1.22	10^8	0.85	160	0.33	7.9×10^{15}	1.8 GHz	11
Pd	200	20%	O_2 plasma	200	*	1.24	10^8	0.83	226	0.38	1.4×10^{17}	1.1 GHz	11
AgO_x	1.28×10^4	–	–	150	1	1.71	10^9	1.14	694	0.94	9.8×10^{17}	–	12
Pt	200	3%	–	–	–	2.1	10^3	0.51	10^4	0.45	–	6.3 GHz	13
Pt	3×10^4	–	–	–	–	1.36	10^6	0.92	507	0.6	4.1×10^{18}	6 MHz	15
Pt	3×10^4	3%	–	–	–	1.56	10^4	0.72	138	0.46	3.5×10^{18}	–	15
Pt	9×10^4	6.9 Pa	–	200	1	1.04	10^8	1.2	300	0.38	3.6×10^{16}	–	16
Pt	4×10^4	6.25%	–	200	1	1.39	10^7	0.75	4.24	0.55	7.7×10^{17}	–	this work

Where T_{ann} is annealing temperature, t is annealing time, n is ideality factor, φ_b is Schottky barrier height, R_s is series resistance, V_{bi} is built-in potential, N_{depl} is charge density at depletion region, *no value is specified

and minimize defects formation on the metal-semiconductor interface. First, the substrate was cleaned in a diluted acetic acid solution and then deionized water in an ultrasonic bath at 80°C for 40 min. Since electron affinity of IGZO with an atomic ratio of In:Ga:Zn=1:1:1 equals to 4.16 eV [17], metals with work function exceeding 5 eV are required to achieve a high potential barrier. The Pt thin film was deposited by radio frequency (RF) sputtering on a Ti adhesive layer on the glass substrate at a pressure of 0.28 Pa and a power density of 2.96 W·cm^{-2} to form the Schottky contact. Total thickness of the bottom electrode was about 100 nm.

Continuous amorphous IGZO thin films (60-70 nm) were deposited by RF magnetron sputtering at room temperature from an IGZO ceramic target (composition In:Ga:Zn = 1:1:1) in an Ar/O_2 atmosphere with oxygen concentrations of 1.64%, 2.44% or 6.25% at a working pressure of 0.6 Pa and a power density of 1 W·cm^{-2}. Before the deposition of the top contact, the samples were annealed at 200°C for 1 hour on a hot plate in air. Similar post-deposition annealing process was applied to enhance the electrical performance of IGZO diodes [10], [16], [18].

As the final step, ohmic Cu top contact was evaporated through a metal mask under high vacuum ($< 4\cdot10^{-4}$ Pa). The area of the contact was 200 μm × 200 μm and the thickness of the layer was about 70 nm (Fig. 2 (c)).

Current-voltage and capacitance-voltage characteristics of the diodes were measured in air at room temperature in dark using Keithley 4200 characterization system; electrodes were contacted using a probe station Karl Suss PM8. The function generator (3022B Tektronix with 50 Ohm output) and oscilloscope (Wavesurfer 3034) were used for the diodes characterization in the half-wave rectifier circuit.

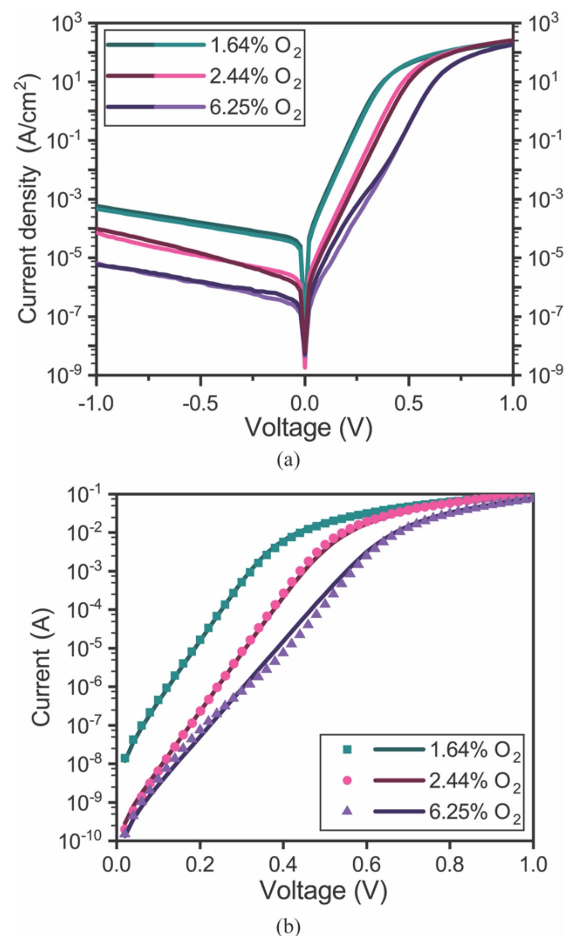

FIGURE 3. Current-voltage characteristics of the devices fabricated at variable oxygen content of the Ar/O_2 gases during a-IGZO RF sputtering: (a) experimental characteristics for two different devices on the substrate at the same oxygen content are presented by color gradient and (b) current-voltage forward characteristics of Pt-IGZO-Cu Schottky diodes (symbols represent experimental values, and full lines represent fitted).

III. CHARACTERIZATION AND SIMULATION

A. CURRENT-VOLTAGE CHARACTERIZATION

The typical current density – voltage characteristics of the Schottky diodes fabricated at 1.64%, 2.44%, and 6.25% of oxygen during IGZO RF sputtering and after thermal annealing are presented in Fig. 3, where color gradients correspond to the experimental characteristics for two different devices on the substrate at the same oxygen content.

The standard deviation of current density for two different devices fabricated at the same oxygen content is less than 0.5% for all analyzed groups of samples. The effect of annealing on the rectification ratio (I_{on}/I_{off}) depends on the initial oxygen content during the IGZO sputtering [18]. The maximum current density of 250 A/cm^2 at 1 V is observed for the samples deposited at lower oxygen content after thermal annealing. This effect can be explained by the increase of the free charge density when lowering oxygen concentration during thermal annealing.

The improvement of the off-current, and thus rectification ratio up to 10^7 at ± 1 V is observed for the samples fabricated at 6.25% of oxygen after annealing at 200°C due to the reduction of interfacial defects.

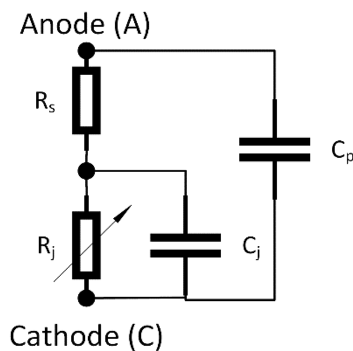

FIGURE 4. The equivalent circuit for the Schottky diode.

The equivalent circuit for the Schottky diode is shown in Fig. 4, where R_s represents the series resistance including the bulk resistance of the IGZO and the ohmic contact resistance. The junction resistance of the diode is denoted as R_j. The R_j is a voltage-dependent resistor that represents the diode itself. The capacitances C_j and C_p represent the junction capacitance (caused by the depletion layer) and the parasitic capacitance, respectively.

The current through a Schottky diode is described by the thermionic emission of majority carriers over the junction barrier [19]:

$$I = I_s\{\exp[q(U - IR_s)/nkT] - 1\}, \tag{1}$$

where I_s is the saturation current; q is the electron charge; n is the ideality factor; k is the Boltzmann constant; and T is the absolute temperature.

To extract the parameters of the Schottky diode, first a tangent line is built on the linear range of the forward current-voltage (I-V) characteristic using numerical methods to extract R_s, $R_s = dU/dI$. The logarithm of the measurement data of the diode current is taken to approximate the experimental curve to a straight line. Then the linearized data set obtained by the least squares method is approximated using the first-degree polynomial. The initial equation (1) becomes:

$$\ln I = \ln I_s + \ln\{\exp[q(UIR_s)/nkT] - 1\}, \tag{2}$$

and it can be viewed as a straight-line equation $y = ax + b$, where $y = \ln I$, $ax = \ln\{\exp[q(U - IR_s)/nkT]-1\}$, $b = \ln I_s$. The saturation current is calculated after determination of the polynomial coefficients as $I_s = \exp(b)$.

On the other hand, I_s can be expressed [19]:

$$I_s = AA^*T^2 \cdot \exp(-q\varphi_b/kT), \tag{3}$$

where A is the area of the diode; A^* is the effective Richardson constant which for IGZO has a theoretical value of 41 A·cm^{-2}K^{-2} [20]; φ_b is the Schottky barrier height and it can be calculated as:

$$\varphi_b = \ln\left(I_s/AA^*T^2\right) kT/q. \tag{4}$$

Another approach to extract the barrier height is to employ density-functional theory (DFT) calculations, as [1]. However, because the oxygen concentration in our a-IGZO films is not precisely determined, we rely on the extraction of the barrier height using equation (4).

The barrier height for an n-type semiconductor is defined by:

$$\varphi_b = W_{\mathrm{Pt}} - \chi_{\mathrm{IGZO}}, \tag{5}$$

where W_{Pt} is the work functions of the metal (W_{Pt} = 5.4 eV [19]), χ_{IGZO} is the electron affinity of the semiconductor and is calculated using equation (5).

After re-arranging terms in equation (1) the ideality factor n is calculated:

$$n = \frac{q(U - IR_s)}{kT\ln(I/I_s + 1)}. \tag{6}$$

The values of U and I are taken from the linear range of the forward current-voltage characteristic for calculation of the ideality factor n. Then the value of R_s is revised by solving of the equation (1) in relation to R_s, using calculated I_s and n, and experimental data of U and I. The method of successive approximations with a maximum relative error of 5% was used. The experimental and fitted current-voltage characteristics of fabricated diodes are presented in Fig. 3 (b).

B. CAPACITANCE-VOLTAGE CHARACTERIZATION

Because the area of the fabricated Schottky diodes is large we focused on the low-frequency range, suitable for the NFC applications Capacitance-voltage characteristics were measured in the range of test signal of 30 kHz – 1 MHz, where the lowest noise level of the capacitance was observed. Frequency shift in this range did not lead to a significant change of the measured capacitance and C-V characteristics obtained at 100 kHz are shown in Fig. 5 (a). The capacitance increases slowly with decreasing reverse bias voltage, indicating that the width of the depletion region varied with the applied bias voltage. The area of the diodes limits the capacitance to the values of 100 pF, 110 pF and 170 pF at reverse bias (Fig. 5 (a)) for the samples fabricated at 1.64%, 2.44% and 6.25% of oxygen during IGZO RF sputtering, respectively. The increase of capacitance is caused by the combination of two effects: different free carrier density in IGZO layer after

the sputtering and post-deposition annealing in air. Elevated oxygen partial pressure reduces the concentration of oxygen vacancies, thus lowering the free electron concentration in the IGZO layer [21], but during thermal annealing in air the free charge density and the surface defect density increase as oxygen is leaving the film [10].

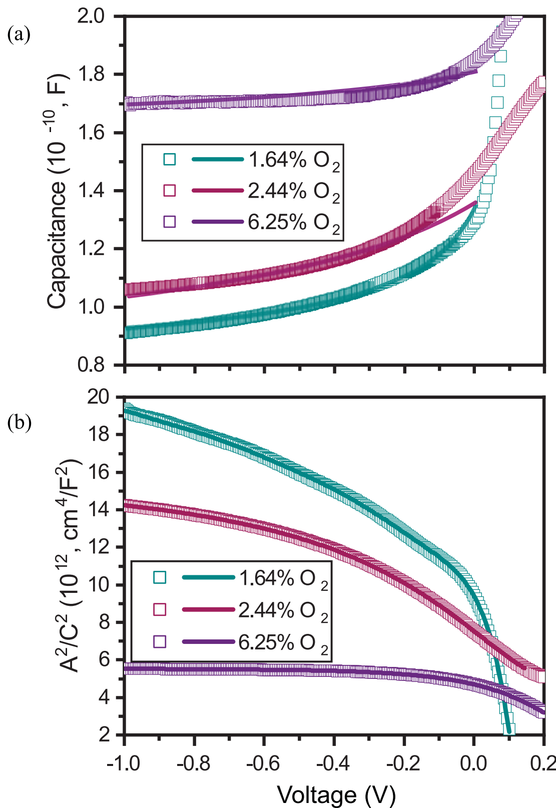

FIGURE 5. (a) Capacitance-voltage characteristics and (b) A^2/C^2 plots of Pt-IGZO-Cu Schottky diodes fabricated at variable oxygen content of the Ar/O_2 gases during a-IGZO RF sputtering (symbols represent experimental values, and full lines represent simulation results).

To analyze experimental capacitance-voltage characteristics of the diodes, the $(A/C)^2$ data set is approximated by the least squares method (Fig. 5 (b)). The capacitance of a Schottky junction is given by [5]:

$$\frac{A^2}{C^2} = \frac{2}{\varepsilon_s \varepsilon_0 N_{depl}} \left(V_{bi} - kT/q - U\right), \tag{7}$$

where ε_s is the static dielectric constant of the semiconductor, ε_0 is the dielectric constant of vacuum, V_{bi} is the built-in potential, and N_{depl} is the charge density at depletion region.

The x-intercept of a tangent line to the linear range of $(A/C)^2(U)$ corresponds to the value of the built-in potential V_{bi}. After re-writing equation (7) one obtains:

$$\frac{A^2}{C^2} = \frac{2}{\varepsilon_s \varepsilon_0 N_{depl}} \left(\frac{kT}{q} + U\right) + \frac{2V_{bi}}{\varepsilon_s \varepsilon_0 N_{depl}}. \tag{8}$$

A tangent line is described by $y = Kx + M$, whereby $y = A^2/C^2$, $K = -2/\varepsilon_s \varepsilon_0 N_{depl}$, $x = kT/q + U$, and $M = 2V_{bi}/(\varepsilon_s \varepsilon_0 N_{depl})$.

After solving the following system of equations:

$$\begin{cases} y_1 = Kx_1 + M, \\ y_2 = Kx_2 + M, \end{cases} \tag{9}$$

where x_1 and y_1 correspond to U_1, and x_2 and y_2 correspond to U_2, and if $y = 0$, one obtains $U = (kT/q + M/K) = V_{bi}$.

The dielectric constant of the semiconductor is calculated from $C = \varepsilon_s \varepsilon_0 A/d$ assuming that diodes are depleted at –1 V and d is the thickness of IGZO layer. The charge density at the depletion region is calculated as $N_{depl1} = -2/K\varepsilon_s \varepsilon_0 q$ and $N_{depl2} = 2V_{bi}/M\varepsilon_s \varepsilon_0 q$. The mean value is taken to minimize the calculation error.

In order to extract junction capacitance C_j and parasitic capacitance C_p, the transient simulation for the Schottky diode is enabled by modeling the capacitance-voltage behavior of the Schottky diode. The total capacitance C_{tot} is given by equation (10) [22]:

$$C_{tot} = C_j(1 - \frac{V}{V_{bi}})^{-1/2} + C_p. \tag{10}$$

The junction capacitance C_j and parasitic capacitance C_p are extracted from the C-V measurements of the devices in the reverse biased region. The Levenberg–Marquardt algorithm is used to estimate the C_p and C_j by reducing the fitting error between the measured and modeled C-V curves. The model matches very well with the measurement data with a maximum relative error of 1.22% (Fig. 5 (a)).

TABLE 2. Characteristics of the Schottky diodes extracted from *I-V* and *C-V* measurements.

Parameters \ O_2, %	1.64	2.44	6.25
I_{on}/I_{off}	10^5	10^6	10^7
I_s, A	1.5×10^{-8}	9.2×10^{-10}	3.9×10^{-10}
φ_b, eV	0.64±0.01	0.72±0.03	0.75±0.03
χ_{IGZO}, eV	4.76±0.01	4.68±0.03	4.65±0.03
n	1.11±0.02	1.18±0.07	1.39±0.09
R_s, Ohm	5.94±0.32	4.14±0.03	4.24±0.16
V_{bi}, V	0.15±0.03	0.37±0.01	0.55±0.03
ε_{IGZO}	17.5±0.5	17.7±0.1	19.4±0.7
N_{depl}, cm^{-3}	1.06×10^{17}	3.48×10^{17}	7.69×10^{17}
C_j, F	6.4×10^{-11}	7.8×10^{-11}	5.7×10^{-11}
C_p, F	7.1×10^{-11}	5.7×10^{-11}	1.5×10^{-10}

Extracted electrical characteristics of the fabricated diodes are summarized in Table 2. It can be seen, that the increase of the oxygen content during IGZO RF sputtering from 1.64% to 6.25% and post-deposition thermal annealing enhances the rectification ratio, Schottky barrier height, ideality factor, build-in voltage, dielectric constant and charge density at the depletion region, but decreases electron affinity of IGZO and parasitic capacitance. Fig. 6 shows the schematic energy band diagram of Pt/IGZO Schottky contact with the obtained parameters. The maximum value of the junction capacitance C_j and minimum value of the series resistance R_s are obtained for the devices sputtered at 2.44% of oxygen.

It is difficult to directly compare the device parameters from the present study with the previously reported results

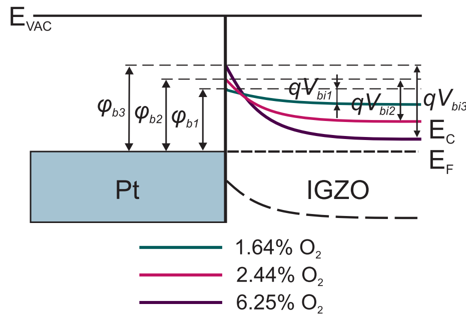

FIGURE 6. Schematic energy band diagram of Pt-IGZO Schottky contact fabricated at variable oxygen content of the Ar/O_2 gases during a-IGZO RF sputtering (V_{bi1} and φ_{b1}, V_{bi2} and φ_{b2}, V_{bi3} and φ_{b3} correspond to 1.64%, 2.44% and 6.25% of oxygen, respectively).

because of the difference in the process parameters, size of the structures and contact metals. However, following observations can be made. Compared to the reported Pt-IGZO-ITO diodes based on IGZO films with a higher Ga composition and sputtered at 1%, 5% or 10% of oxygen [23], a significant improvement in rectification ratio to 10^7 of the Schottky diodes fabricated in this study (In:Ga:Zn=1:1:1) was achieved. It was demonstrated that thermal annealing at 200°C helped to improve the rectification ratio of Pt-IGZO Schottky diodes based on IGZO sputtered in 2.44% of O_2 by two orders of magnitude in comparison with the previously reported diodes based on IGZO sputtered in 3% of O_2 [13]. The higher values of the rectification ratio were obtained for the fabricated diodes without any oxygen or ozone plasma treatment of the bottom electrode compared to the reported Pd-IGZO-Mo structures [11], where bottom contact treatment prior to IGZO deposition was used. The improvement of the fabricated diode parameters can be explained by the optimization of the process parameters and combined effect of the controlled oxygen atmosphere during deposition and post-deposition thermal annealing, which modified the free charge and surface defect densities in the Pt-IGZO structure.

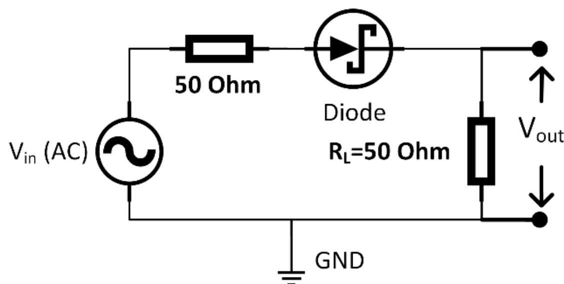

FIGURE 7. The half-wave rectifier circuit.

C. HALF-WAVE RECTIFIER

To demonstrate the functionality of the fabricated diodes in circuit, we realized a half-wave rectifier and characterized its performance. Using the aforementioned models, we performed the transient simulation of the circuit and compared the results with the experiments. The half-wave rectifier circuit is shown in Fig. 7. A signal generator is used to generate the sinusoidal input voltage V_{in} for the rectifier. The signal generator has an internal 50 Ohm resistance which is represented by resistor connected to the anode of the diode in the circuit. The diode is connected to the oscilloscope and the signal generator with probes. Probes have a resistance of 50 Ohm which represent the load resistor (R_L) of the half-wave rectifier. Measurements were performed with an input voltage of ±2 V and frequency of 100 kHz and 300 kHz and presented in Fig. 8. The frequency range was chosen based on the target application frequency i.e. near-field communication 125 kHz – 134 kHz [24]. The maximum output voltage is 0.77 V for 2 V supply voltage for the Schottky diodes fabricated at 1.64% O_2 because of the voltage drop across the input resistor and the diode, which is 0.77 V and 0.46 V, respectively (Fig. 8 (a, left)). The simulations were performed using open-source Ngspice simulator [25].

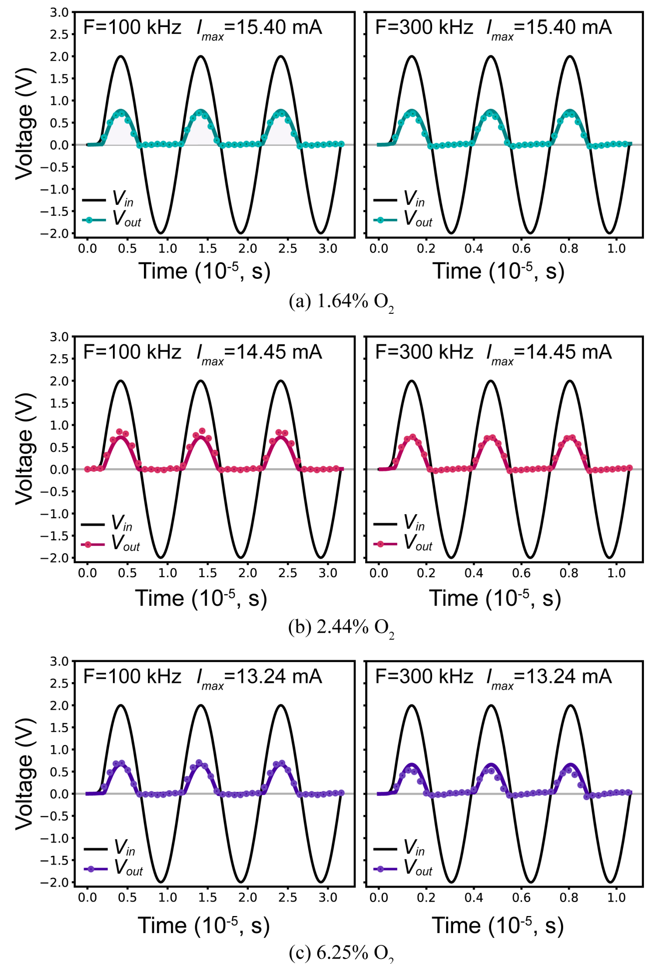

FIGURE 8. Half-wave rectifier input and output waveforms measured at 100 kHz and 300 kHz for Pt-IGZO-Cu Schottky diodes fabricated at variable oxygen content (dots represent experimental values, and full lines represent simulation results): (a) 1.64% O_2, (b) 2.44% O_2, and (c) 6.25% O_2; V_{in} is the input voltage, V_{out} is the output voltage, and I_{max} is the peak current.

It can be seen in Fig. 8 that simulation results match with measurements. It is observed that the output voltage amplitude V_{out} decreases with the increase of the oxygen

pressure in the simulation because the barrier height (φ_b) is increased and more potential is required to turn-on the diode compared to the diode with lower φ_b. In the measurement, it is also decreased except for the device fabricated at 2.44% O_2 where the output voltage of 0.87 V at 100 kHz is highest. This behavior cannot be explained and requires further investigation. It is observed that at 300 kHz the rectified output amplitude V_{out} decreases compared to the 100 kHz measurements. This effect is observed only for the devices that were fabricated at 2.44%, and 6.25% of oxygen content during IGZO RF sputtering. The reduction in the rectified output voltage amplitude can be attributed to the decreased barrier height at high frequencies, which is not captured by the presented model as the capacitance model does not include the frequency dependence. However, this effect has been reported before [26] and can be our future research task for the presented diodes.

IV. CONCLUSION

For the deposition of amorphous oxide semiconductors absolute values of the process parameters need to be optimized for each individual case depending on the target composition and sputtering system configuration. It was demonstrated that the concentration of oxygen in the Ar/O_2 mixture during IGZO RF sputtering and post-deposition thermal annealing affected the properties of the vertical thin-film Pt-IGZO-Cu Schottky diodes. The increase of the oxygen content during sputtering from 1.64% to 6.25% and post-deposition annealing at 200°C led to increasing the rectification ratio from 10^5 to 10^7 at ± 1 V, Schottky barrier height from 0.64 eV to 0.75 eV, and ideality factor from 1.11 to 1.39.

The half-wave rectifier circuits based on the Schottky diodes were simulated using parameters extracted from the measured *I-V* and *C-V* characteristics and characterized at 100 kHz and 300 kHz, which is relevant for the near-field communication (125 kHz – 134 kHz). The Schottky diodes with active area of 200 μm $\times$ 200 μm fabricated at 1.64% O_2 provided the output voltage amplitude of 0.77 V for 2 V supply voltage at 100 kHz. However, the highest output voltage amplitude of 0.87 V was observed for the samples fabricated at 2.44% O_2 and slightly decreased for the Schottky diodes fabricated at higher oxygen pressure. The simulation results matched with the measurements, verifying the model accuracy for circuit level simulation.

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