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AC Impedance Analysis of the Al/ZnO/*p*-Si/Al Schottky Diode: C-V Plots and Extraction of Parameters

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In this research, we report on the measurement of the capacitance-voltage (C-V) characteristics Al / ZnO / p-Si / Al Schottky diode at room temperature and in dark condition fabricated by spray pyrolysis process. C-V characteristics, within the range of frequencies 5 kHz-5 MHz, are investigated and microelectronic parameters are extracted. Donor density and diffusion potential vary with frequency from 15 to 28 1014 cm – 3, 0.21 to 0.45 V. Besides, the interface state density of Al /ZnO /pSi/Al Schottky is determined and found to be 1012 (eV·cm²) – 1. Calculated at 1 MHz, the interfacial layer thickness and depletion layer width are of 760 Å and 0.28 μm.

Keywords: Spray pyrolysis, ZnO / *p*-Si Schottky diode, C-V characteristics, Capacitance-Voltage, Interface density.

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1. INTRODUCTION

Zinc oxide (ZnO) films and diodes have been among the most investigated oxides in recent years, principally due to its applications in opto-electronic devices [1-3]. Many processes have been used to fabricate device based on ZnO like sputtering, sol gel method [4-5]. A Schottky diode based on a wide band gap semiconductor ZnO, $E_g > 3$ eV with a good rectifying behavior has been fabricated and its capacitance-voltage is investigated. In order to fabricate the solar cell based on wide band gap semiconductor, we achieve this device and we determine its microelectronic parameters such as height barrier, diffusion voltage, and donor density, at room temperature in dark and at various work frequencies 5k-5 MHz.

2. EXPERIMENTAL PROCEDURE

ZnO films are grown by USPD route from zinc acetate (Zn $(CH_3COO)_2$, $2H_2O$) used as precursor. 0.1 mole of zinc acetate was dissolved in 100 ml of methanol. Both Al and Sn doping were added from the aluminum chloride ($AlCl_3$) and tin chloride ($SnCl_2$) to the precursor with a density of 2 %. The used substrates were successively cleaned by methanol for 15 min and distilled water for 20 min. We deposit our films at fixed substrate temperature of 350 °C and the time deposition was 5 min and the distance nozzle substrate was around 5 cm. The metallic contacts were made by thermal evaporation in vacuum at 10^{-6} Torr, using a mask. The cross section of Al / ZnO / *p*-Si / Al structure is sketched in figure 1A. The obtained Al contacts are circular with a diameter of 1.5 mm and thickness of 250 nm. Capacitance-voltage measurements are performed by the use of a Agilent HP 4294A impedance analyzer as shown in figure 1B.

3. MEASUREMENT AND RESULTS

The measurement of capacitance-voltage of Al / ZnO / *p*-Si diode was carried out at frequencies range within 50 kHz-5 MHz, is plotted in figure 2.
It is seen in figure 2 that the capacitance of the as-fabricated diode increases with a decrease in frequency as indicated by arrow, and the reached high point is of 16 nF at 50 kHz, and these characteristics demonstrate a step down, around 0.3 nF, in the reverse-bias region as depicted in figure 2. This attenuation of capacitance is ascribed to series resistance and interface presence as mentioned above or even to deep levels existence in the semiconductor bandgap. At zero bias voltage, C-V values descend from 3.78 to 0.45 nF when frequency ranges within the 50 kHz-5 MHz band. As seen in the C-V variation, two regions of capacitance frequency-dependent for the forward bias can be estimated, the lower frequency ($f < 500$ kHz) and the higher ones ($f \geq 500$ kHz). In the first regions, the capacitance goes from 8 to 16 nF while

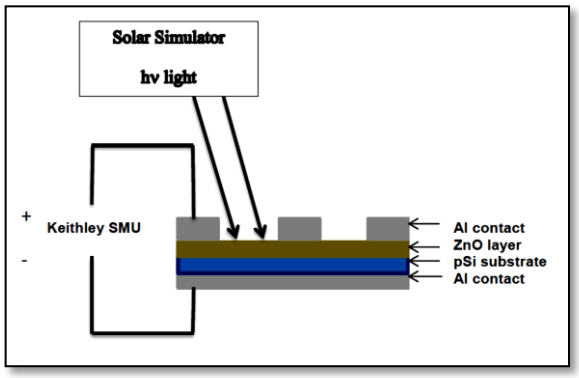

Fig. 1A – A schematic cross-section of the Al / ZnO / *p*-Si / Al structure

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the second one from 0.35 to 3 nF. In general, at sufficiently high frequencies the interface states do not contribute to the capacitance as mentioned in literature [6-8]. It is suitable to study C-V data for Schottky diodes by plotting $1 / C^2$-V, for reverse bias, expressed by eqn. 1.

Fig. 1B – Experimental system for diode fabrication and electrical characterization system. 1. Diode with Al contacts are fabricated, 2. Thermal evaporator with vacuum set up, 3. Agilent HP 4294A Impedance analyzer for C-V measurement

Using this plot showed in figure 2, we determine the carrier density N_D according to the following relation [9-10];

$$\frac{1}{C^2} = \frac{2(V_D + V)}{q\varepsilon A^2 N_D}. \quad (1)$$

It is seen in figure 3 that the capacitance of the Al / ZnO / p-Si diode and the derivate of $1/C^2$ and the coordinate at bias $V = 0$ are then determined from;

$$\frac{d\ 1/C^2}{dV} = \frac{2}{q\varepsilon A^2 N_D}, \quad (2)$$

where ε is a dielectric constant of ZnO and p-silicon ($\varepsilon_i = 8.47 \cdot \varepsilon_0$, $\varepsilon_s = 11.9 \cdot \varepsilon_0$, where $\varepsilon_0 = 8.84 \cdot 10^{-12}$ F/m), the value contact area of A is found to be 0.018 cm^2, V_d is the diffusion potential at zero bias and N_d is a donor carrier density.

$$\left(\frac{1}{C^2}\right)_{V=0} = \frac{2V_D}{q\varepsilon A^2 N_D}. \quad (3)$$

The slope gives the carrier density N_D, and the extrapolation to $1/C^2 = 0$ gives the potential V_d. From the C-V characteristics, the potential Φ_B is obtained as follows [11-12],

$$\Phi_B = V_D + V_n. \quad (4)$$

This expression is available for an ideal diode but for a rectifying one it is a bit corrected as $\Phi_B = cV_D + V_n$

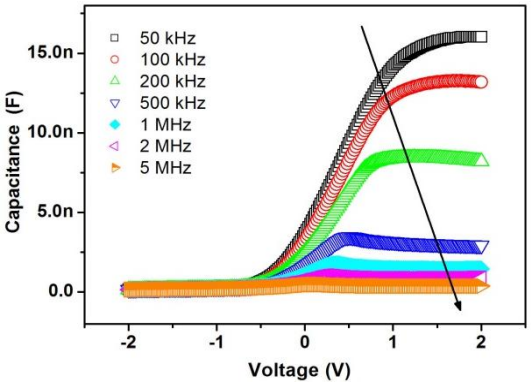

Fig. 2 – C-V characteristics at room temperature in dark condition of Al / ZnO / p-Si diode at various frequencies

where c correspond to $1/n$. The obtained value of the carrier density N_d, calculated at 1 MHz, is about $23 \cdot 10^{14}$ cm^{-3} as depicted in figure 4 and V_d is found to be 0.135 V. As found above, $\Phi_B = 0.74$ V and thus we deduce the potential V_n which is equal to 0.605 V. Furthermore, from the C-V investigation it is well-known that depletion layer width and built-potential can be determined. V_d is the diffusion potential at zero bias and V_n is the difference between the Fermi level energy and the bottom of conduction band.

The bias dependence of BH, electron tunneling through the barrier and the carrier recombination within the depletion region are the main elements which make n values greater than unity. Where $R_s = 5.4$ kΩ and $I_0 = 32$ nA are calculated from I-V measurement in dark behavior (not mentioned here). Where ideality factor versus bias voltage is given by [11-12],

$$n(V) = 1 + \frac{\delta}{\varepsilon_i}\left(\frac{\varepsilon_s}{d} + qN_{ss}\right), \quad (6)$$

where n is dependent on applied voltage,

$$E_{ss} - E_V = q(\varphi_e - V), \quad (7)$$

where E_{ss} is the energy corresponding to the bottom of the conduction band BC at the surface of the semiconductor, V is the voltage and Φ_e is the effective barrier height depending applied voltage due to an interfacial layer given by equation;

$$\varphi_e = \varphi_b + (1 - 1/n)V. \quad (8)$$

If ε_i and ε_s are respectively the permittivity of the interfacial layer and the semiconductor, d is the space charge width and δ is the ZnO layer thickness, the interface density N_{ss} is determined by the equation 9. In this study, ideality factor dependence of interface states densities were obtained using eqn. 6 [9].

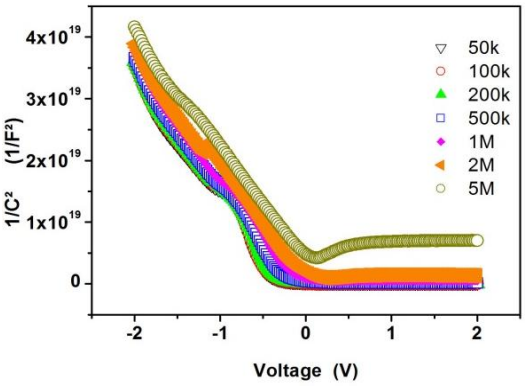

Fig. 3 – Plot of $1/C^2$ versus voltage of Al / ZnO / p-Si diode at various frequencies 50 kHz-5 MHz

$$N_{ss} = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n(V) - 1) - \frac{\varepsilon_s}{d}\right]. \quad (9)$$

From I-V characteristics (not shown here) n is found to be 3.5. The interfacial layer thickness was found from C-V plots in the strong accumulation region using the interfacial layer capacitance relation $C_i = \varepsilon_i\ \varepsilon_0\ A / \delta$ [10]. Determined from C-V curve at 1 MHz, $C_i = 1.783$ nF.

Knowing that the dielectric constant of silicon and ZnO are respectively $\varepsilon_s = 11.9\ \varepsilon_0$ and $\varepsilon_i = 8.47\ \varepsilon_0$, the value of contact area is $A = 0.018\ \text{cm}^2$ and δ is of 760 Å as listed in table 1 and d is deduced from eqn. 10 [9].

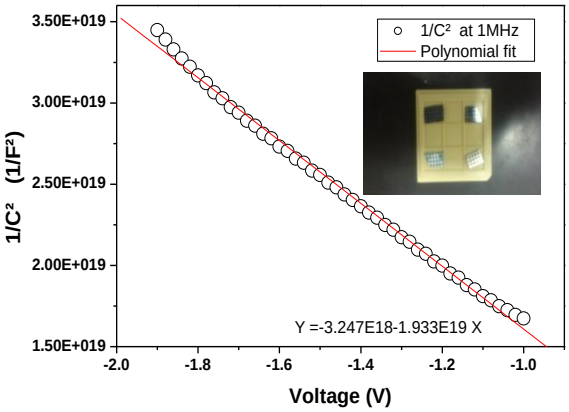

Fig. 4 – Plot of $1/C^2$ vs. V of the Al / ZnO / p-Si / Al Schottky diode at 1 MHz, red solid line is a linear fit. The inset shows the as-fabricated Al / ZnO / p-Si / Al Schottky barrier diode

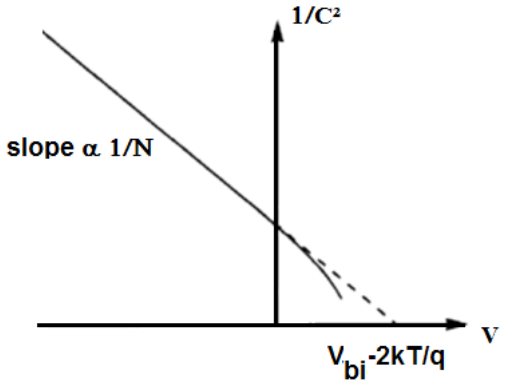

Fig. 5 – Plot of $1/C^2$ versus bias voltage, the extrapolation intercept the voltage axis gives the potential in built V_{bi} and the slope is proportional to donor concentration

$$d = \left(\frac{2\varepsilon_s \varepsilon_0}{qN_D} V_D \right)^{1/2}, \qquad (10)$$

$$V_D = V_{bi} - 2kT/q, \qquad (11)$$

where V_{bi} is the built-in potential and V_D is the diffusion potential. The figure 5 shows how we determine the value of V_{bi}-$2kT/q$ and the slope of linear part of the $1/C^2$ curve.

The figure 6 depicts the density of states of interfaces (N_{ss}) versus energy ($E_{ss} - E_v$). As shown in fig. 6, the N_{ss} variation is plotted within the 0.58-0.68 eV energy range, two curves corresponding respectively to with and without series resistance R_s are plotted. The decay of N_{ss} from 10^{12} to 10^{11} $(\text{eV}\cdot\text{cm}^2)^{-1}$ is observed.

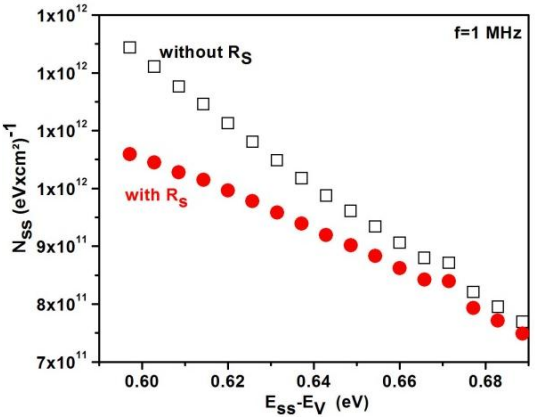

Fig. 6 – Interface state density distribution profile of Al / ZnO / p-Si / Al Schottky diode at room temperature

4. CONCLUSION

Al / ZnO / p-Si Schottky diode has been successfully fabricated by spray pyrolysis and thermal evaporation processes in vacuum. The capacitance verus voltage has been measured at room tempearture and various frequencies and electronic parameters have been determined. At 1 MHz, we find then $N_D = 23.21\ 10^{14}\ \text{cm}^{-3}$, $V_D = 0.135$ V, $d = 0.28$ µm and $\delta = 760$ Å, the potential V_D and the depletion width decreased when the frequency increased while the donor density and interfacial layer thickness increased with frequency. The diode presents a non-ideal behavior due to interface density which is evaluated at 1 MHz of 10^{12} $(\text{eV} \times \text{cm}^2)^{-1}$.

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Table 1 – Frequency, donor carrier concentration, the voltage V_{bi}-$2kT/q$, the slope, the depletion layer width and interfacial layer thickness

Frequency (kHz)	N_D ($\times 10^{14}\ \text{cm}^{-3}$)	V_D (V)	The ratio V_D / N_D ($\text{V}\cdot\text{cm}^3\ 10^{-14}$)	Slope of linear part of $1/C^2$ vs. V ($\times 10^{19}$)	depletion layer width d (µm)	Interfacial layer thickness δ (Å)
50	15.7	0.45	0.028	3.3	0.61	84
100	14.6	0.43	0.029	3.5	0.62	101
200	15.1	0.39	0.025	3.4	0.57	150
500	18.4	0.29	0.016	1.99	0.46	370
1000	23.2	0.135	0.006	2.2	0.28	760
2000	26.3	0.008	0.0003	1.86	0.06	1357
5000	28.1	0.21	0.007	1.78	0.30	2772

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