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Electrical characterization of Al/p-Si Schottky diodes with interfacial SiO_2 oxide layer fabricated at 500 °C

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To grow silicon dioxide (SiO_2) on the surface of p-Si, the Si crystal was placed in a resistance-heated oven and exposed to 500°C for 3 hours with a flow rate of 2 l/min in dry oxygen. Thus, the SiO_2/p-Si structure was formed. From the current-voltage (I–V) characteristics of the Al/SiO_2/p-Si/Al Schottky diode, barrier height, ideality factor, interface density of states and series resistance parameters are reported. To investigate the I-V properties, the thermionic emission (TE) theory is employed. The I-V characteristics of the Al/SiO_2/p-Si/Al Schottky diode were investigated in the voltage range of -2V – +2 V. A good rectification factor was obtained for this range. The ideality factor, barrier height, saturation current, and series resistance are determined to be 2.41, 0.795 eV, 7.85×10^{-9} A, and 6.38 kΩ, respectively. It was discovered that the interfacial state density values were roughly 10^{13} eV^{-1} cm^{-2}. The interfacial state density was 5.78×10^{13} eV^{-1} cm^{-2} in the E_{ss}-0.777 energy range and 8.76×10^{13} eV^{-1} cm^{-2} in the E_{ss}-0.520 energy range were calculated.

Keywords: *p-Si, SiO_2, Schottky diode, diode parameters, series resistance, interface state density*

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1. Introduction

Power and high-frequency electronic devices make considerable use of the metal-insulator-semiconductor (MIS) Schottky diode [1,2]. Aluminum serves as the metal contact, silicon dioxide (SiO_2) acts as an insulator, and p-type silicon functions as a semiconductor in the MIS Schottky diode [3]. Because of the inhomogeneity in the insulator layer composition, the insulator layer, such as In_2O_3, SnO_2, Al_2O_3 or SiO_2 between the metal and semiconductor, creates a potential barrier that suppresses the majority carriers and enhances the photogeneration current of the device. Unless the devices are specifically produced using sophisticated techniques, the native oxide layer at the metal/semiconductor Schottky diodes will always be consistent in thickness, a few nanometers [1-3].

SiO_2 is a common insulator material in many device applications because of its intriguing chemical and physical characteristics, which include low thermal conductivity, low refractive index, and low cost [3]. The type of metal contact and the thickness of the oxide or insulator layer determine how much the device performs better. Better electrical qualities than those of the metal/semiconductor Schottky diodes were demonstrated by the MOS and MIS contacts, which were created by depositing the metal/semiconductor contacts on an insulator or oxide layer [4-7]. Depas et al.'s research [8] demonstrated that the native insulator layer thickness, non-symmetry of the interfacial charges, and insulator layer composition all contribute to the barrier inhomogeneity of MIS Schottky diodes. Tseng and Wu [9] investigated how a MIS Schottky diode was affected by the SiO_2 insulator layer. They used the study of the I-Vcurves measured to their system to determine the barrier height and density of interfacial states.

To assess fundamental diode characteristics like ideality factor and barrier height and contrast them with literaturereported metal/insulator/semiconductor Schottky diode contact results, we produced the Al/SiO$_2$/p-Si/Al Schottky diodes. We talked about the current-voltage (I-V) characteristics of the diode based on the findings of the I-V measurement. The barrier height (Φ_b), ideality factor (n), saturation current (I_0), series resistance (R_s), and interface state density (N_{ss}) of the Al/SiO$_2$/p-Si/Al type Schottky diode were determined in this work using the thermionic emission (TE) and Norde function. The goal is to deliver dependable and accurate measures and to contrast the outcomes in various ways.

2. Experimental

A p-type Si semiconductor with a polished surface, 1-20 Ω-cm resistivity, 525 μm thickness, and (100) surface orientation was used in this investigation. First, the p-Si semiconductor crystal was cleaned chemically to form the Al/SiO$_2$/p-Si/Al Schottky diode. The semiconductor crystal was degreased by progressively washing it with trichlorethylene, acetone, and methanol for five minutes using an ultrasonic titration device. Ultimately, the oxide layer was removed from it by rinsing it with lots of ultrapure water after HF was applied for a minute. In the physical evaporation method, ~2000 Å thick high purity (99.99%) Al was thermally evaporated onto the rear matte surface of the p-Si substrate at a pressure of 10^{-6} Torr. The p-Si/Al structure was annealed at 575 ºC for 5 minutes in a dry nitrogen environment to provide a low resistance ohmic contact. To grow silicon dioxide (SiO$_2$) on the surface of p-Si, the Si crystal was placed in a resistance-heated furnace and exposed to 500°C for 3 h in dry oxygen with a flow rate of 2 l/min. Thus, the SiO$_2$/p-Si structure was formed. Aluminium (Al) metal was evaporated to form Schottky connections on the SiO$_2$ as points with a diameter of about 2 mm. Every evaporation phase was done at a pressure of around 5×10^{-5} Torr in a vacuum coating apparatus. Al/SiO$_2$/p-Si/Al Schottky diode (Figure 1) was thus developed. Using a Keithley 2400 Sourcemeter, the current and voltage of the generated diode were measured between -2V and +2V.

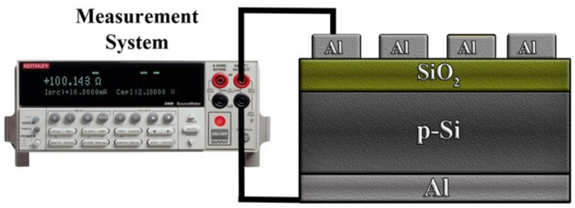

Figure 1: 3D view of Al/SiO$_2$/p-Si/Al Schottky diode

3. Results

The Al/SiO$_2$/p-Si/Al Schottky barrier diode's experimental current-voltage (I–V) characteristic is displayed in Fig. 2. Figure 3 displays the experimental semi-logarithmic current-voltage (I-V) characteristic of the Al/SiO$_2$/p-Si/Al Schottky barrier diode. The generated diode exhibits rectification behavior, as seen in Figures 2 and 3, and its properties can be explored more closely.

According to the thermionic emission hypothesis, the relationship between the applied forward bias and current for a MIS Schottky diode is as follows [10] and [11]:

$$I = I_0\left[exp\left(\frac{q(V-IR_s)}{nkT}\right)-1\right] \quad (1)$$

where T is the temperature in K, q is the electron charge, k is Boltzmann's constant, I_0 is the saturation, and R_s is the series resistance.

$$I_0 = AA^*T^2exp\left[\frac{-q\Phi_b}{kT}\right] \quad (2)$$

Where A is the area of diode and A^* is Richardson constant for p-Si (32 Acm^{-2} K^{-2} [10]). The values of barrier height (Φ_b) and ideality factor (n) are calculated from the intercept and slope of the ln I-V graph. n and Φ_b are calculated using [10,11]:

$$n = \frac{q}{kT}\frac{dV}{d(lnI)} \quad (3)$$

$$\Phi_b = \frac{kT}{q}ln\left(\frac{AA^*T^2}{I_0}\right) \quad (4)$$

Reverse features and good rectifying behavior are shown in Fig. 3. At higher bias, the features deviate from linearity due to the series resistance effect. The diode parameters as I_0, n and Φ_b are showed in Table 1. The rectification ratio (RR) for the sample from Fig. 2 is determined as 2015. The produced diode is not ideal, as shown by the fact that Table 1's n is more than 1. Leakage current, series resistance, and interfacial states are a few potential sources of this [12].

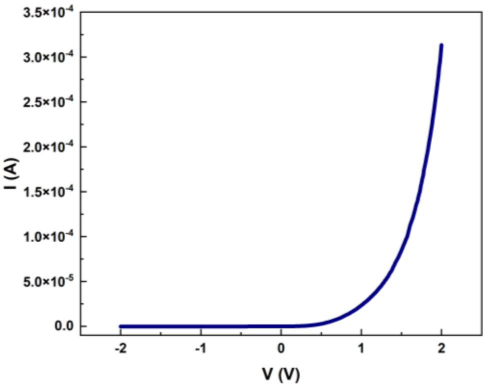

Figure 2: Current-voltage curve of the Al/SiO$_2$/p-Si/Al Schottky diode at dark and room temperature.

Table 1. The values of I_0, Φ_b and n of Al/SiO$_2$/p-Si/Al Schottky diode found from $lnI-V$ curves.

Sample	n	Φ_b (eV)	I$_0$ (nA)
Al/SiO$_2$/p-Si	2.410	0.795	7.85

The values of ideality factor and barrier height are determined as 2.410 and 0.795 eV, respectively.

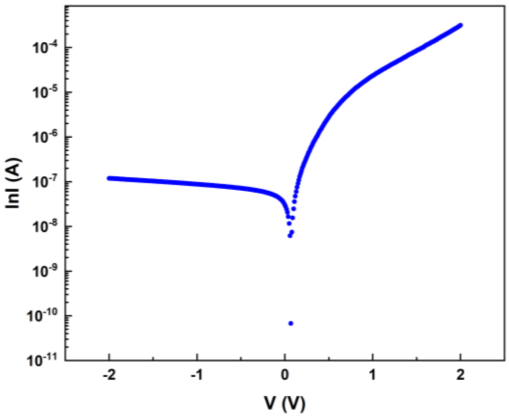

Figure 3: $lnI-V$ curve of the Al/SiO$_2$/p-Si/Al Schottky diode at dark and room temperature.

Ohm's equation ($R_i = dV/dI$I) was used to calculate the magnitudes of the diode, series resistance (R_s), and shunt resistance (R_{sh}) [13]. Fig. 4 displays the Rj-V plot of the sample. From Fig.4, The values of R_s and R_{sh} are determined as 6.38 kΩ and 44 MΩ, respectively.

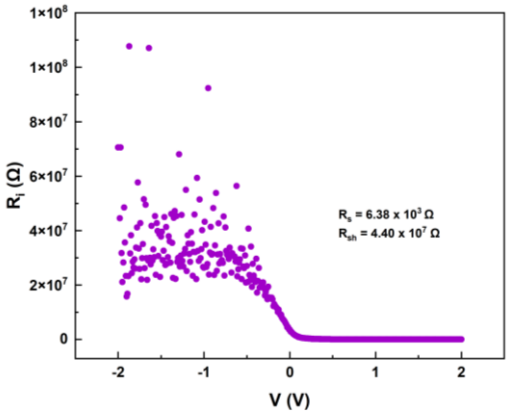

Figure 4: R_i-V curve of the Al/SiO$_2$/p-Si/Al Schottky diode.

The Norde technique [14] was used in this investigation to calculate the series resistance from the diode characteristics. Using this method, barrier height and series resistance values can be calculated using the following formulas [14]:

$$F(V) = \frac{V}{\gamma} - \frac{kT}{q} ln(\frac{I(V)}{AA^*T^2}) \tag{5}$$

$$\Phi_b = F(V_{min}) + \frac{V_{min}}{\gamma} - \frac{kT}{q} \tag{6}$$

$$R_s = \frac{kT(\gamma-n)}{qImin} \tag{7}$$

where I_{min} and V_{min} are the lowest current and voltage, respectively, and $F(V_{min})$ shows the equivalent smallest value of $F(V)$. The first integer number bigger than n for the Al/SiO$_2$/p-Si/Al Schottky diode is represented by γ.

Figure 5 depicts the $F(V) - V$ curves of the Al/SiO$_2$/p-Si/Al Schottky diode. Table 3 depicts the diode parameters calculated from Fig. 5.

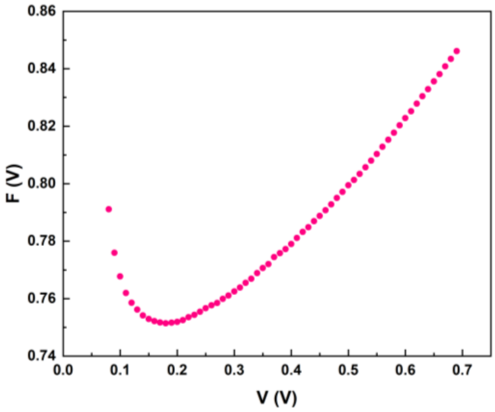

Figure 5: $F(V)-V$ curve of the Al/SiO$_2$/p-Si/Al Schottky diode.

Table 3. $F(V_{\mathrm{min}})$, Φ_b and R_s values calculated from Norde curve of Al/SiO$_2$/p-Si/Al Schottky diode.

Sample	$F(V_{\mathrm{min}})$ (V)	Φ_b (eV)	R_s (kΩ)
Al/SiO$_2$/p-Si	0.751	0.795	32.8

The semiconductor surface defects, such as doping bonds, oxygen vacancies, and structural rearrangements, that are sustained by metallization, doping concentration atoms, and native or deposited interfacial layer, are often responsible for the interface state density (N_{ss}) at the metal/insulator/semiconductor (MIS) interface. For an p-Si semiconductor (E_{ss}), the difference between the energy of the interface state density and the bottom border of the conduction band can be calculated using the formula $E_c - E_{ss} = q(\Phi_b - V)$[15,16].

Figure 6 depicts the energy dispersion of N_{ss}, calculated from the I-V characteristic of the sample, as a function of $E_{ss} - E_c$. Also, Table 4 and Figure 6 display that the interface states density increases exponentially from the mid-gap to the conduction band's bottom. It was discovered that the interfacial state density values were roughly 10^{13} eV^{-1} cm^{-2}. The interfacial state density was $5.78x10^{13}$ eV^{-1} cm^{-2} in the E_{ss}-0.777 energy range and $8.76x10^{13}$ eV^{-1} cm^{-2} in the E_{ss}-0.520 energy range were calculated.

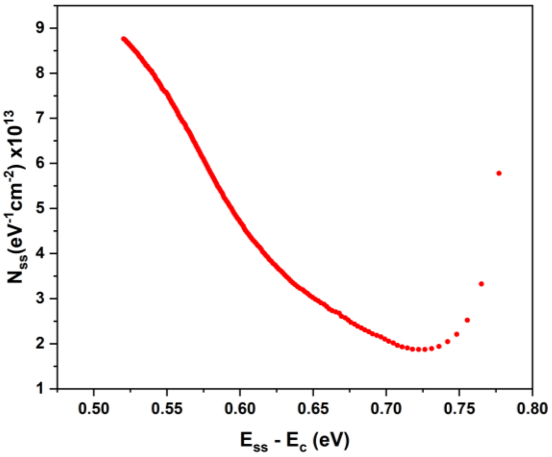

Figure 6: The plot of N_{ss}– $(E_{ss} - E_c)$ of the Al/SiO$_2$/p-Si/Al Schottky diode.

Table 4. N_{ss}– $(E_{ss} - E_c)$ values of Al/SiO$_2$/p-Si/Al Schottky diode.

Sample	$E_{ss} - E_c$ (eV)	N_{ss} ($eV^{-1}cm^{-2}$) x10^{13}
Al/SiO$_2$/p-Si	$E_{ss} - 0.520$	8.76
	$E_{ss} - 0.777$	5.78

4. Conclusion

In conclusion, Current-voltage (I–V) measurements have been utilized to investigate the Al/SiO$_2$/p-Si/Al Schottky diode's characteristic properties. Using thermionic emission (TE) and the Norde function, several of the fundamental diode features of the sample, such as n, Φ_b, and R_s were independently determined. Schottky barrier height and ideality factor values for Al/SiO$_2$/p-Si/Al Schottky contacts have been calculated as 0.795 eV and 2.41, respectively. The Al/SiO$_2$/p-Si/Al Schottky diode's interface state density (N_{ss}) was calculated, and 10^{13} eV^{-1} cm^{-2} were found to be the interface states.

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