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Investigation of diode parameters of Al/Al_2O_3/n-Si Schottky diode produced by RF sputtering method according to current-voltage and capacitance-voltage characteristics

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The primary goal of this work is to ascertain the Al/Al_2O_3/n-Si MIS type structure's current-voltage (I-V) and capacitance-conductance-voltage (C-G-V) performance when fabricated on an n-Si wafer using the sputtering method. The I-V electrical measurements of the fabricated MIS-type Schottky diode structure were taken at room temperature and in the dark. Critical electrical parameters, such as saturation current (I_0), ideality factor (n), barrier height (Φ_b), series resistance (R_s), and rectification rate (RR), are extracted using thermionic emission (TE) theory. At ± 1 V, the structure's rectifying ratio (RR) was discovered to be roughly 7965. The values of ideality factor, barrier height and saturation current are found to be about 1.56, 0.816 eV and 6.37 nA, respectively. Using Norde's approach and the TE method, the series resistance values were found to be 3.32 kΩ and 1.06 kΩ, respectively. It was discovered that the interface density of states was roughly between 10^{11} and 10^{12} eV^{-1} cm^{-2}. 4.66×10^{11} eV^{-1} cm^{-2} in the energy range (E_c-0.72 eV) and 2.17×10^{12} eV^{-1} cm^{-2} in the energy range (E_c-0.53 eV) were determined to be the interface density of states. Additionally, frequency dependent capacitance (C) and conductance (G) data for the Al/Al_2O_3/n-Si structure produced at room temperature were investigated in the voltage range of -4 - +4 V and the frequency range of 20 kHz - 1 MHz. The doping donor atoms (N_D), barrier height (Φ_b), and Fermi level (E_F) for each frequency were determined by computing the interception and slope of the C^{-2}-V plot. As the frequency increases, both the Φ_b and N_D values increase. Additionally, voltage dependence profiles of frequency and R_s were extracted from C and G data using the Nicollian-Brews method.

Keywords: *MIS diode, Al_2O_3, n-Si, current-voltage, capacitance-voltage, diode parameters*

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1. Introduction

Understanding the electrical behavior of metal/insulator/semiconductor (MIS) structures, which are the most basic devices, is crucial for the electronic industries [1,2]. In high-frequency and power electronic devices, the metal-insulator-semiconductor (MIS) Schottky diode is used extensively [3,4]. In order to produce a reaction between the metal and semiconductor, an insulator layer, such as Si_3N_4, SiO_2, HfO_2, or Al_2O_3, is typically placed at the metal/semiconductor contact [5].

In fact, high-k materials decrease leakage current and provide more capacitance [6,7]. Among them, Al_2O_3 is the most resilient and stable oxide. It has been extensively researched for a variety of uses, particularly in optoelectronics and microelectronics. The dielectric permittivity (~9), large band gap (9 eV) [8], large band offset with Si, which is crucial for preserving low leakage currents through devices, kinetic stability, thermodynamic stability on Si up to high temperatures, good interface with silicon, low bulk defect density, and amorphous nature under the conditions of interest [9] are some of the intriguing characteristics that Al_2O_3 has demonstrated.

We created the $Al/Al_2O_3/n$-Si Schottky diode in order to evaluate basic diode properties such as ideality factor and barrier height and compare them with metal/insulator/semiconductor (MIS) Schottky diode contact results reported in the literature. Based on the results of the I-V test, we discussed the diode's current-voltage (I-V) properties. In this work, the thermionic emission (TE) and Norde method were used to determine the ideality factor (n), barrier height (Φ_b), saturation current (I_0), series resistance (R_s), and interface state density (N_{ss}) of the Al/ Al_2O_3/n-Si MIS type Schottky diode. Furthermore, based on the results of the C-G-V measurement, we discussed the diode's capacitance-conductance-voltage (C-G-V) properties. These data allowed us to calculate the diode parameters, frequency-dependent diffusion potential (V_D), doping donor atoms (N_D), Fermi level (E_F) and barrier height (Φ_b), as well as the frequency-dependent series resistance (R_s) values.

2. Experimental

In this study, a n-type Si semiconductor with a polished surface, surface orientation of (100), thickness of 525 µm, and resistivity of 1–20 Ω-cm was employed.A chemical cleaning process was applied to remove the oxide layer and unwanted impurities on the n-type Si crystal. The silicon cleaning method was as follows: a) Ultrasonic washing with trichloroethylene, methanol, and acetone for 5 minutes. b) Cleaning with deionized water for 5 minutes between each cleaning process. c) The crystal was cleaned in a 1:10 HF:H_2O solution for 5 minutes. d) Then, it was washed with 5 liters of deionized water and dried with dry nitrogen. First, 200 nm of aluminum metal (Al, 99.999% purity) was evaporated onto the matte side of the silicon using a thermal evaporation device and a thickness gauge. The Si crystal was then held in a nitrogen oven at 450°C for 5 minutes. This created an ohmic contact on the matte side of the silicon crystal. After establishing the ohmic contact, an Al_2O_3 interface layer was grown on the polished surface of the n-Si surface using RF sputtering, as described below. The deposition of the Al_2O_3 layer on n-Si was carried out at radio frequency (13.6 MHz). A 2-inch diameter Al_2O_3 target (3 mm thickness, 99.99% purity) was used. The distance between the silicon and the Al_2O_3 was 15 cm. The argon gas (99.999% purity) flow rate was 20 sccm. The sputtering power and operating pressure were 200 W and 0.4 Pa, respectively. The Al_2O_3 deposition rate was 0.9 nm/min. 50 nm of Al_2O_3 material was deposited on the silicon crystal using a thickness gauge connected to the sputtering device. After the Al_2O_3 was coated using the RF sputtering method, rectifier contacts were formed by depositing 200 nm of aluminum (Al) metal with a 2 mm radius on the Al_2O_3 deposited surface using a thermal evaporation device and a thickness gauge using a 2 mm radius metal mask. Metal evaporation was carried out at a pressure of $5x10^{-5}$ Torr. The structure of the $Al/Al_2O_3/n$-Si/Al Schottky diode in Fig.1 was formed by the ohmic contact, the deposition of the Al_2O_3 interfacial layer, and its deposition on the rectifier contact. Current-voltage (I-V) measurements of the $Al/Al_2O_3/n$-Si/Al Schottky diode produced in this thesis were taken in the range of -1 V to 1 V with the help of a Keithley 2400 current-voltage source. Furthermore, capacitance-voltage (C-V) characteristics were taken in the dark with the help of a Keysight E4990A Impedance Analyzer between -4 V and 4 V and 20 kHz - 1 MHz.

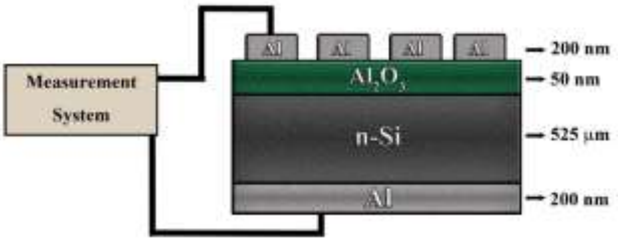


Figure 1: Sturucture of $Al/Al_2O_3/n$-Si/Al MIS-type Schottky diode

3. Results

The $Al/Al_2O_3/n$-Si Schottky barrier diode's experimental semi-logarithmic current-voltage (I-V) characteristic is shown in Figure 2. Figure 2 illustrates the rectification behavior of the produced diode, and further investigation of its characteristics is possible. The following equation (1) represents the relationship between the applied forward bias and current for a MIS Schottky diode in accordance with the thermionic emission method [10,11]:

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

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

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

where A^* is Richardson constant for n-Si (112 Acm^{-2} K^{-2} [10]) and A is the area of diode. The intercept and slope of the ln I-V graph are used to compute the ideality factor (n) and barrier height (Φ_b). Φ_b and n are obtained using [10,11]:

$$\Phi_b = \frac{kT}{q} ln\left(\frac{AA^*T^2}{I_0} \right) \tag{3}$$

$$n = \frac{q}{kT} \frac{dV}{d(lnI)} \tag{4}$$

Fig. 2 displays reverse features and good rectifying behavior. The series resistance effect causes the characteristics to depart from linearity at increased bias. Table 1 displays the diode parameters as Φ_b, n and I_0. For the diode shown in Fig. 2, the rectification ratio (RR) is 7965. The fact that n in Table 1 is greater than 1 indicates that the generated diode is not ideal. Some possible causes of this include interfacial states, series resistance, and leakage current [12].

Table 1. The I_0, Φ_b and n values of Al/Al$_2$O$_3$/n-Si Schottky diode

Sample	n	Φ_b (eV)	I_0 (nA)
Al/Al$_2$O$_3$/n-Si	1.56	0.816	6.37

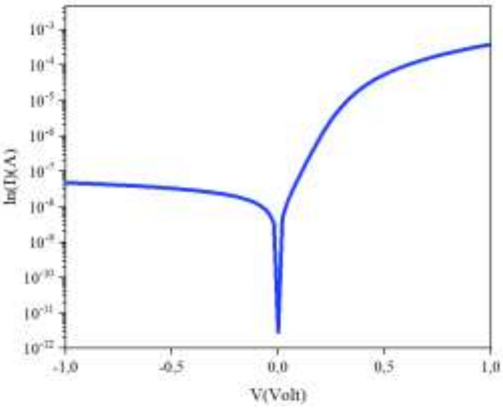


Figure 2: $lnI - V$ curve of the Al/A$_2$O$_3$/n-Si Schottky diode at room temperature and in dark.

The barrier height and ideality factor values are obtained as 0.816 eV and 1.56, respectively.

The series resistance (R_s), and shunt resistance (R_{sh}) magnitudes were determined using Ohm's equation ($R_i = dV/dI$) [13]. Fig. 3 displays the Rj-V plot of the sample. According to Fig.3, The values of R_{sh} and R_s are obtained as 43.3 MΩ and 1.06 kΩ, respectively.

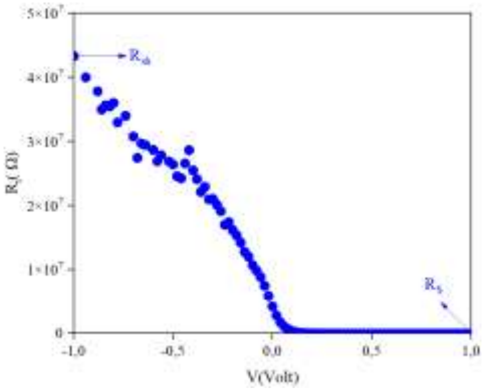


Figure 3: $R_i - V$ plot of the Al/Al$_2$O$_3$/n-Si Schottky diode.

In this study, the series resistance was also determined from the diode properties using the Norde method [14]. The following formulas can be used to determine barrier height and series resistance values using this method:

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

$$R_s = \frac{kT(\gamma - n)}{qImin} \tag{6}$$

$$\Phi_b = F(V_{min}) + \frac{V_{min}}{\gamma} - \frac{kT}{q} \tag{7}$$

where V_{min} and I_{min} are the minimum voltage and current, respectively, and the corresponding minimal value of $F(V)$ is displayed by $F(V_{min})$. For the Al/Al$_2$O$_3$/n-Si Schottky diode, γ is the first integer value greater than n. The $F(V) - V$ curves of the Al/Al$_2$O$_3$/n-Si Schottky diode are shown in Figure 4. The diode parameters derived from Fig. 4 are shown in Table 2.

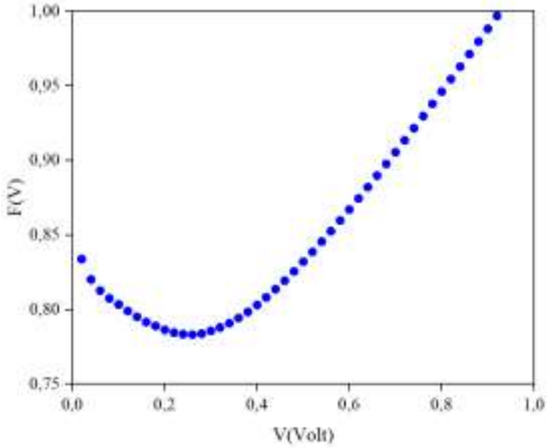


Figure 4: $F(V) - V$ curve of the Al/Al$_2$O$_3$/n-Si Schottky diode.

Table 2. The values of $F(V_{\mathrm{min}})$, Φ_b and R_s determined from Norde plot of Al/Al$_2$O$_3$/n-Si Schottky diode.

Sample	$F(V_{\mathrm{min}})$ (V)	Φ_b (eV)	R_s (kΩ)
Al/Al$_2$O$_3$/n-Si	0.78	0.812	3.32

The interface state density (N$_{ss}$) versus $E_c - E_{ss}$ plot is shown in Fig. 5 for the MIS type diode. Figure 5 shows that the N_{ss} increases exponentially from the mid-gap to the conduction band's bottom. It was discovered that the interface density of states was roughly between 10^{11} and 10^{12} eV^{-1} cm^{-2}. 4.66x10^{11} eV^{-1} cm^{-2} in the energy range (E_c-0.72 eV) and 2.17x10^{12} eV^{-1} cm^{-2} in the energy range (E_c-0.53 eV) were determined to be the interface density of states. These values are also given in Table 3.

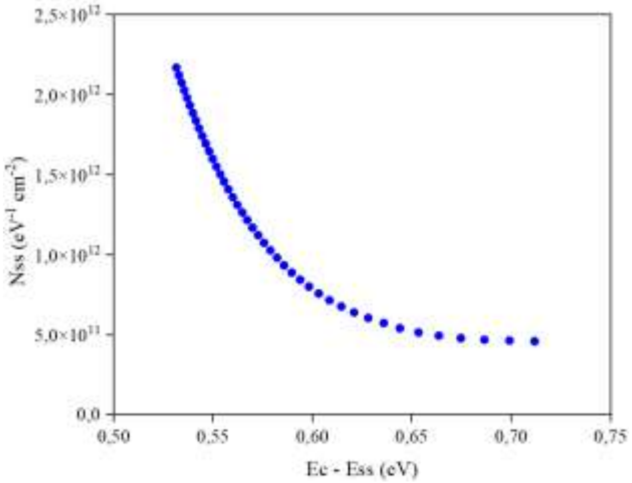
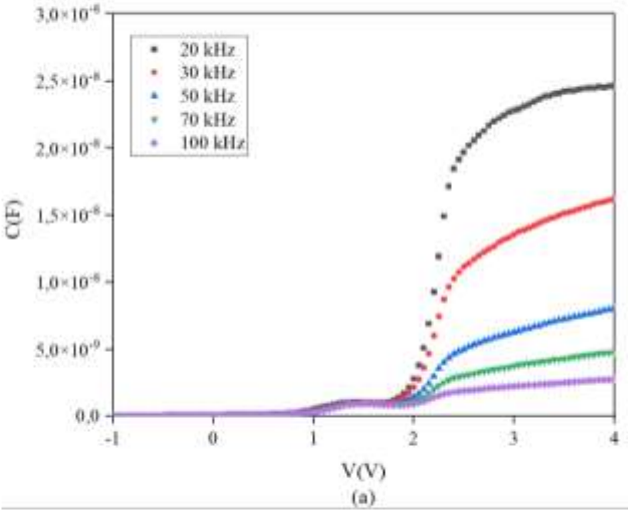


Figure 5: The N_{ss}– $(E_c - E_{ss})$ plot of the Al/Al$_2$O$_3$/n-Si diode.

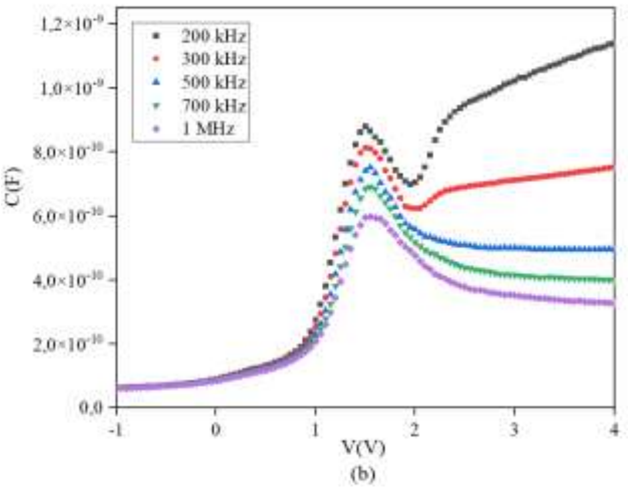
Table 3. The values of N_{ss} and $(E_c - E_{ss})$ for Al/Al$_2$O$_3$/n-Si diode.

Sample	$E_c - E_{ss}$ (eV)	N_{ss} (eV^{-1}cm^{-2}) x10^{12}
Al/Al$_2$O$_3$/n-Si	$E_c - 0.53$	2.17
	$E_c - 0.72$	0.46

The measured capacitance-voltage (C-V) measurements of the produced diode are plotted in Figure 6 (a) and (b) over a wide measurement range such as -1V-+4V and 20 kHz-1 MHz.



(a)

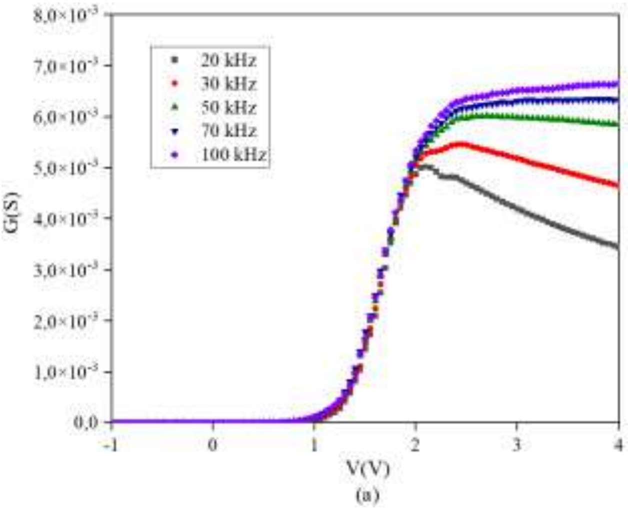


(b)

Figure 6: Plots of C_m-V of the Al/Al$_2$O$_3$/n-Si diode in various frequencies (a) 20 kHz-100 kHz and (b) 200 kHz-1 MHz.

The interfacial oxide layer, interface states, series resistance, and oxide charges [15] may all be responsible for the apparent shift of the C-V curves along the total voltage axis seen in Figure 6. This indicates that MOS structures' electrical properties have changed significantly and that they no longer follow the ideal C-V curves [16].

The measured conductance-voltage (G-V) measurements of the produced diode are plotted in Figure 7 (a) and (b) over a wide measurement range such as -1V-+4V and 20 kHz-1 MHz.



(a)

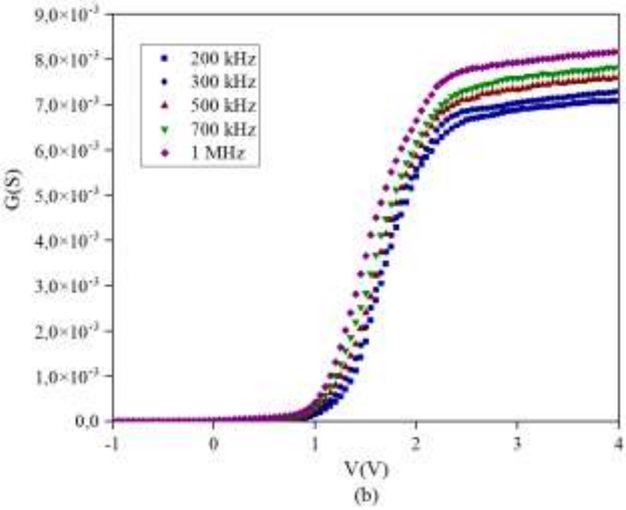


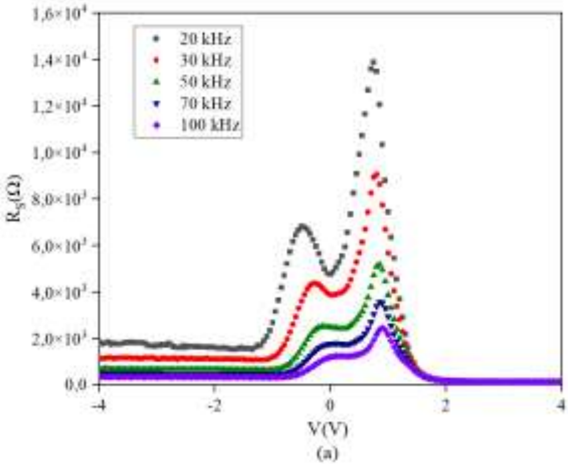
Figure 7: Plots of G_m-V of the Al/Al$_2$O$_3$/n-Si diode in various frequencies (a) 20 kHz-100 kHz and (b) 200 kHz-1 MHz.

The Niccolian and Goetzberger method can be used to determine the produced diode's series resistance (R_s) values [17]:

$$R_s = \frac{G_m}{G_m^2 + (\omega C_m)^2} \tag{8}$$

where C_m and G_m are the measured capacitance and conductance values, respectively.

The calculated R_s-V characteristics of the produced diode are plotted in Figure 8 (a) and (b) over a wide measurement range such as -4V-+4V and 20 kHz-1 MHz.



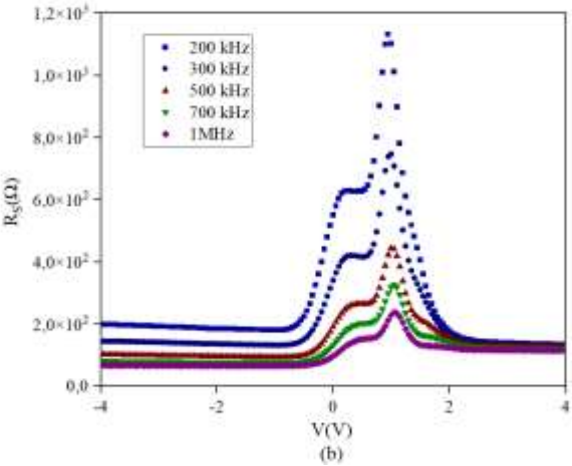


Figure 8: Plots of R_s-V of the Al/Al$_2$O$_3$/n-Si diode in various frequencies (a) 20 kHz-100 kHz and (b) 200 kHz-1 MHz.

After removing the series resistance effect from the measured capacitance values, C_c^{-2}-V curves were plotted in Figure 9 to calculate the diode parameters. The calculated C_c^{-2}-V characteristics of the produced diode are plotted in Figure 9 over a wide measurement range such as 20 kHz-1 MHz.

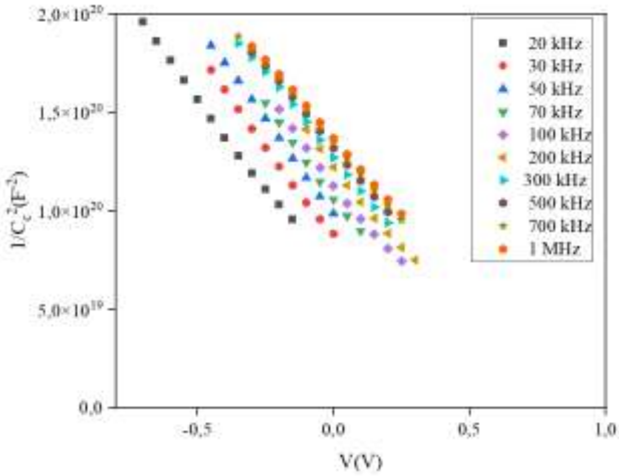


Figure 9: Plots of C_c^{-2}-V of the Al/Al$_2$O$_3$/n-Si diode in various frequencies 20 kHz-1 MHz.

The calculated diffusion potential (V_D), doping donor atoms (N_D), Fermi level (E_F) and barrier height (Φ_b) parameters of the produced diode are showed in Table 4 over a wide measurement range such as 20 kHz-1 MHz.

Table 4. The values of V_D, N_D, E_F and Φ_b of Al/Al$_2$O$_3$/n-Si Schottky diode determined from C_c^{-2}-V plots.

Frequency	**V$_D$** (V)	**N$_D$** (cm^3)x10^{13}	**E$_F$** (eV)	**Φ$_b$** (eV)
20 kHz	0.37	6.53	0.335	0.71

30 kHz	0.48	6.49	0.335	0.82
50 kHz	0.53	6.46	0.335	0.87
70 kHz	0.59	6.45	0.335	0.92
100 kHz	0.68	7.00	0.333	1.02
200 kHz	0.76	7.29	0.332	1.09
300 kHz	0.77	7.15	0.332	1.11
500 kHz	0.82	7.32	0.332	1.15
700 kHz	0.87	7.63	0.331	1.20
1 MHz	0.89	7.70	0.331	1.22

The barrier height value calculated from capacitance-voltage measurements at 1 MHz frequency was found to be 1.22 eV, while the barrier height value calculated from current-voltage measurements was found to be 0.816 eV. The reasons why the barrier height calculated from capacitance-voltage measurements is greater than the barrier height calculated from current-voltage measurements include the inhomogeneity of the barrier height, the method of the measurement systems, the layer formed between the semiconductor and the metal, and impurities [18].

4. Conclusion

Characteristic properties of the Al/Al$_2$O$_3$/n-Si Schottky diode have been studied using current-voltage (I–V) and capacitance-conductance-voltage (C-G-V) measurements. The Al/Al$_2$O$_3$/n-Si structure exhibits diode behavior and has a high rectification ratio of 7965. The values of ideality factor, barrier height and saturation current are found to be about 1.56, 0.816 eV and 6.37 nA, respectively. Using capacitance-voltage measurements at a frequency of 1 MHz, the barrier height value was determined to be 1.22 eV. The Al/Al$_2$O$_3$/n-Si Schottky diode's interface state density was computed, and it was found that the interface states varied between 10^{11} and 10^{13} eV^{-1} cm^{-2}.

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