

Semiconducting Double-Layer Lead Monoxide Tin Oxide Nanostructures for Photodetectors

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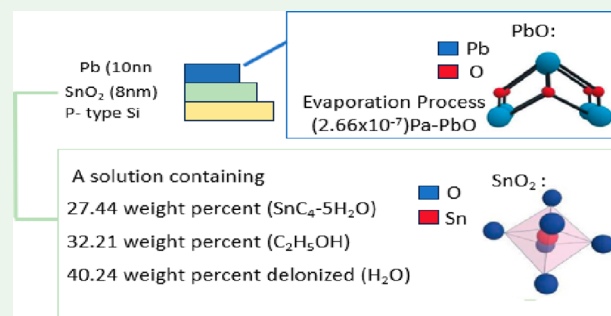
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ABSTRACT: This study examines the high-frequency-dependent characteristics of the PbO/SnO₂ double-layer semiconductor (DLS) structures. Recently, researchers have been particularly interested in such structures in terms of their use in electrical and photovoltaic applications. A PbO/SnO₂ double layer was successfully coated on a p-type Si substrate (100) wafer with a resistance of 10 Ω cm and a thickness of 280 μ m. The Al Schottky (round dot) connections, which have a thickness of 124 nm and a diameter of 1.3 mm, were produced by thermal evaporation. The present study proposes to measure the conductance–voltage (G – V) and capacitance–voltage (C – V) values of the studied Al/PbO/SnO₂/p-Si Schottky diode for the frequencies of 500 kHz, 800 kHz, and 1 MHz at a temperature of 300 K, which has been suggested for the first time in literature. Due to the presence of surface states (N_{ss}), PbO/SnO₂ double-layer, and series resistance R_s , the C – V and G – V plots show inversion, depletion, and accumulation zones depending on the strong frequency for each frequency tested. Based on the tested frequencies, the reverse-biased C_2 – V curves are used to compute the fundamental electrical characteristics of the Al/PbO/SnO₂/p-Si structures, including the depletion layer (W_D), Fermi energy level (E_F), diffusion potential (V_D), and thickness barrier height (ϕ_B). We also investigated the capacitance features and the energy density distribution of surface states (N_{ss}) in the PbO/SnO₂ double-layer structure by utilizing the measured values of G – V and C – V . The values of ϕ_B , V_D , and N_{ss} were observed to be 0.54 0.34, and 3.19 10 12 eV^{−1} cm^{−2} at 500 kHz, while they were 0.88 0.68, and 1.96 eV^{−1} cm^{−2} at 800 kHz and 0.95, 0.75, and 1.47 eV^{−1} cm^{−2} at 1 MHz, respectively. It was discovered that the capacitance characteristics of the PbO/SnO₂ double-layer structure were substantially dependent on the applied high frequencies. Furthermore, the C – V and G – V measurements revealed that the series resistance and the interface state density of the studied Al/PbO/SnO₂/p-Si Schottky diode were critical parameters that significantly affect the electrical parameters offered by the PbO/SnO₂ double-layer nanostructure. The results of the study reveal that the manufactured device exhibits outstanding electric characteristics and support the possibility of using DL thin films in electronic devices.

KEYWORDS: Double-layer film, Tin oxide, Lead oxide, Schottky diode, Interface states



1. INTRODUCTION

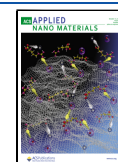
The heterostructures are crucial to the current semiconductor industry and are frequently employed as fundamental components in electronic devices. Two distinct semiconductors can be brought together to create a heterojunction. In this heterojunction, the electronic band structure that is close to the interface is altered by electrostatic forces. Semiconductor heterojunctions are widely used in numerous solid-state applications in electronics, including solar cells, light-emitting diodes (LEDs), photodetectors, and semiconductor lasers, and they use semiconductor heterojunctions. While Alferov, Kroemer, and Kilby were awarded the Nobel Prize in physics for their study on the development of semiconductor heterostructures,^{1,2} Akasaki, Amano, and Ellmer were recognized for their contributions to the invention and improvement of blue light emitting diodes.^{3,4}

With a variety of uses in flat panel displays, solar cells, electronics, and several other devices, transparent conducting oxides are crucial materials for technology, and these materials have an unusual combination of features of conducting electricity and being optically transparent.⁵ Tin oxide (SnO₂), which has special optical and electrical properties, as well as chemical stability and thermal stability, is among the most significant transparent conducting oxides (TCOs).

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Also known as stannic oxide, SnO_2 is a metal oxide, and it is a nondoped n-type semiconductor in a natural state. It has a wide band gap ranging between 3.6 eV (electronvolt) and 4.2 eV depending on various parameters and the preparation method, and it has a favorable workability, doping, and transmittance. Moreover, it offers high reflectivity in the infrared region, while it offers high conductivity in the visible region. With optical transmittance values reaching 95%, SnO_2 is very permeable when it is deposited as a thin film.^{5,6} Due to all these advantageous features, SnO_2 has a wide application area in technology, while it comes to the fore in the literature since this material is utilized in producing electronic devices including solar cells and gas sensors.^{7–10}

SnO_2 , which contains 2 tin atoms and 4 oxygen atoms, has a tetragonal rutile structure. A total of 6 oxygen atoms surround the Sn atom at the corners of regular octahedrons. The O–Sn distance is 3.7662 Å (Ångström), while the O–O distance is 4.6646 Å at the structure. SnO_2 has been reported to have the following lattice parameters: $a = b = 4.738$ Å and $c = 3.187$ Å.¹¹ Tin oxide is also significant with its high mechanical characteristics owing to its high optical transmittance stability and specific electrical resistance, which are low when heated and high when it is in the optical field. In the visible spectrum, tin oxide has high electrical conductivity; however, it is reflective in the infrared spectrum. The electrical conductivity of the tin oxide at room temperature has a range between 10^3 – 10^8 ($\Omega \text{ cm}$)^{–1}. It is an essential material particularly in electronic applications because many conditions, including light, heat, and magnetic field, may change its conductivity in the presence of minute numbers of impurity atoms. Electrical conductivity is one of the most significant features that is used to categorize solids. This material is transparent at visible and near-infrared light due to the broad forbidden field, which causes an absorption edge to emerge in the ultraviolet region at 0.36 μm .¹² It is frequently used in battery applications as an anode material,¹³ in the detection of nonflammable gases as a solid-state gas sensor,¹⁴ and in solar cells as a transparent electrode and buffer layer,¹⁵ as well as in the control of harmful emissions as a catalyst.¹⁶

Lead oxide (PbO) is among these oxides, and it is significant in terms of its technology because it has a variety of degrees of reflectivity that make it suitable for optical storage systems.¹⁷

The compound of lead oxide, which has a chemical formula of PbO , is called lead monoxide. It might have two polymorphs, usually red in tetragonal structure and yellow in orthorhombic structure.¹⁸ Due to its high volatility at low temperatures, the fabrication of PbO thin films is frequently challenging. PbO is known to have both a high-temperature orthorhombic phase (β - PbO) and a low-temperature tetragonal phase (α - PbO).^{19,20} It is possible to fabricate PbO thin films by using several methods, including spray pyrolysis, DC magnetron sputtering, SILAR, metal–organic chemical vapor deposition, and electrodeposition. PbO is an impressive material due to its low electrical conductivity, superior semiconductor, and photoconductive capabilities, suitability for applications involving laser technology, imaging devices, etc.^{21,22} Moreover, lead and lead oxide structures attract attention with their potential uses in nanodevices and functional materials owing to their regular electronic structure and high optical, sensor, and magnetic characteristics.

Lead exists in a variety of oxide forms, including PbO , PbO_2 , and Pb_2O_3 . For instance, the PbO photoactive semiconductor has widely drawn the attention of researchers in the past

decade due to its successful application in gas sensors, ceramics, and the glass industry besides being utilized as a catalyst in the organic chemical industry. Glass ceramics are vitreous materials that undergo a controlled crystallization process, typically by heating together with nucleating chemicals. Almeida et al.²³ investigated the effects of lead oxide on glass materials and revealed that it was a significant glass modifier that affected the chemical characteristics and mechanical stability of the materials, besides their radioactive and optical characteristics. Lead oxide nanoparticles, on the other hand, have been classified as dangerous and hazardous to human and environmental health. Moreover, lead and its byproducts are quite hazardous. As a heavy metal, lead is hazardous due to being selective and being retained in the nerve cells mostly permanently. Because of the improved thermal stability, high-temperature processing, and UV resistance characteristics of poly(vinyl chloride) (PVC), lead oxide is utilized as a lead stabilizer in processing. Droessler et al. reported the use of PbO as a surface modification layer in inverted polymer solar cells in addition to being used as a photoactive layer in the Schottky photovoltaic systems.²⁴ PbO 's dielectric constant (25.9) is about two folds of that of the other oxides.²⁵ As a result, incorporating a PbO layer in the passive films is expected to decrease the Mott–Schottky slope while improving the dielectric constant. Despite the fact that the exact figures of lead-doped compounds are not known, PbO polymorphs' optical and structural properties could be determined.^{26–28} In photovoltaic applications, α - PbO offers potential uses thanks to its band gap ranging between 1.9 and 2.2 eV,^{29,30} whereas β - PbO , which is the other form of it, can be utilized as surface modifiers.^{30–33} The β - PbO phase offers a band gap of 2.7 eV. It is observed that β - PbO is stable at temperatures above 488 °C. Moreover, the phase of conversion from α - PbO to β - PbO occurs at a temperature of about 490 °C. PbO yellow nanostructures are observed to show photoconductive properties. Because of its fascinating photoconductive and semiconductive features, lead oxide offers an appealing material for imaging and photonic applications.

Bhachu et al.³⁴ previously implanted PbO on TiO_2 for a process called photodegradation of $\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$, confirming the theoretical predictions that PbO on TiO_2 generated new electronic states above the TiO_2 valence band maximum and acted as a visible-light-active photocatalyst. As a result, with holes localized in PbO and electrons in TiO_2 , the electron–hole pairs were efficiently separated. Shi et al.³⁵ investigated the PbO on ZnO nanowires in terms of their wavelengths of visible light absorbance and photocurrent characteristics and discovered that ZnO and PbO had a band alignment of type II. Lim et al.³⁶ studied the characteristics of the layered PbO and SnO separately. The indirect energy band gap of SnO , which is a p-type semiconductor, is 0.7 eV. The researchers discovered that SnO outperformed PbO in the semiconductor in terms of hydrogen evolution and electron transfer. Kelaidis et al.³⁷ studied the SnO/PbO heterojunction and conducted a thorough theoretical examination of its characteristics; the researchers discovered that the studied heterojunction exhibited a broken-gap type II band lineup, offering a very promising feature in terms of photocatalytic water dissociation. SnO_2 has attracted much interest as an electron transport layer because it offers faster electron mobility, higher UV strength, and superior band orientation compared to other oxides such as TiO_2 .³⁸ Butler et al.³⁹ hypothetically researched the features of an ultrathin PbO_2

layer on SnO_2 , the researchers revealed that this ultrathin layer could be utilized to modify the work function of SnO_2 and obtain energy levels equivalent to significant technical materials for energy conversion. Tin oxide is especially appealing as a thin conductive substance for applications thanks to its electrical conductivity combined with strong thermal stability as well as transparency over the visible spectrum.

The materials used to create the heterojunction and their individual electrical structures determine how the band gap changes after the heterojunction is built. When two distinct semiconductor materials are brought together, an interface is created between them, forming a heterojunction. This interface can significantly impact the electrical features of the combined structure, in particular the band gap in particular. There are two major types of heterojunctions based on the band gap characteristics of the materials involved: Type I Heterojunction and Type II Heterojunction. In the Type I heterojunction, a material's conduction band minimum (CBM) aligns with the other material's valence band maximum (VBM). This results in a steplike formation at the interface. In this case, the band gap of the heterojunction may be smaller or larger than that of the individual materials, depending on the specific energy alignment: (i) If the CBM of the material with a smaller band gap is higher than the VBM of the other material, the heterojunction's band gap will be smaller than that of the individual materials. This is known as a staggered band alignment. (ii) If the CBM of the material with a smaller band gap is lower than the other material's VBM, the band gap of the heterojunction will be larger than that of the individual materials. This is known as a broken band alignment. In a Type II heterojunction, on the other hand, both the materials' CBM and VBM are misaligned, creating a staggered band alignment. In this case, there is a discontinuity at the interface, resulting in a larger effective band gap for the heterojunction compared to that of each material. Overall, the band gap change after the construction of a heterojunction can vary widely, and this is influenced by the specific characteristics of the materials constituting the heterojunction and their energy alignment at the interface. These band gap engineering techniques are extensively used in semiconductor device fabrication to tailor the electronic and optoelectronic properties of materials for specific applications.

Tin oxide must respond at its best in the visible range in order to maximize its potential for use as an active photocatalyst. As a result, tuning SnO_2 's band gap energy according to the situation could be an alternative. The alteration of the valence band and conduction band may be an option in one of three different methods to lower the band gap energy. The literature indicates that either doping SnO_2 nanostructures or connecting them with other possible nanostructures has consistently improved the photocatalytic response in the visible range. The direction of electron transmission may be changed by performing either doping or compositing, which allows for a significant degree of separation of electrons and holes compared to what would be achievable with a heterojunction. In the literature, there are many methods to improve photodetector performance.^{40,41} A suitable heterojunction driven by external or internal fields might be useful to increase the performance of the dissociation of electron–hole pairs. Therefore, heterostructure nanomaterials display better electrochemical characteristics including high conductivity, large specific capacitance, extended cycle

stability, high energy and power densities, etc. thanks to the synergistic interaction between the components.^{42,43}

To the best of the researchers' knowledge, the dielectric characteristics of the SnO_2/PbO heterojunction, which seems impressive both from a basic standpoint and from a technological standpoint, have not been examined before. Recently, lead monoxide (PbO) nanoparticles have been synthesized via calcination, anodic oxidation, sol–gel pyrolysis, chemical synthesis, the solvothermal method, chemical deposition, thermal breakdown, laser ablation, and green techniques. Furthermore, a one-pot nonhydrolytic sol–gel synthesis approach,⁴⁴ a low-cost synthetic method, and a microwave-assisted hydrothermal method⁴⁵ have been primarily used in experimental studies.

In this study, $\text{Al}/\text{PbO}/\text{SnO}_2/\text{p-Si}$ was fabricated to investigate the electrical features of these structures. The main electrical properties such as surface states (N_{ss}), barrier height (Φ_B), diffusion potential (V_D), Fermi energy (E_F) level, the width of the consumption layer (W_D), and the effective state's density in the valence band (N_D) have been researched. For these purposes, both forward and reverse biases of G and C measurements have been conducted at the frequencies of 500 kHz, 800 kHz, and 1 MHz at 300 K.

2. EXPERIMENTAL METHODS

2.1. Production of $\text{Al}/\text{PbO}/\text{SnO}_2/\text{p-Si}$ Schottky Structures.

The studied $\text{Al}/\text{PbO}/\text{SnO}_2/\text{p-Si}$ Schottky structures were created on a p-type Si (100) wafer with a thickness of 280 μm and 1–10 ohm. Ohmic contact and the cleaning procedures were described in refs 46 and 47. To build the SnO_2 layer on the Si substrate after ohmic contact, a solution containing 27.44 wt % stannic chloride ($\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$), 32.21 wt % ethyl alcohol ($\text{C}_2\text{H}_5\text{OH}$), and 40.35 wt % deionized water (H_2O) was sprayed to the substrate at 400 $^\circ\text{C}$. A chrome-aluminum thermocouple was used to measure the substrate's temperature. By using a temperature controller, the change in the substrate temperature during spray was kept within ± 5 $^\circ\text{C}$. A flow meter was used to regulate the spraying rate of the N_2 carrier gas, and it was kept at about 25 cm^3/min . By conducting an evaporation process at a pressure of 2.66×10^{-7} Pa, we deposited PbO as the second layer with a thickness of 10 nm on the $\text{SnO}_2/\text{p-Si}$ structure. The crystal structures of SnO_2 and PbO are depicted in Figure 1.

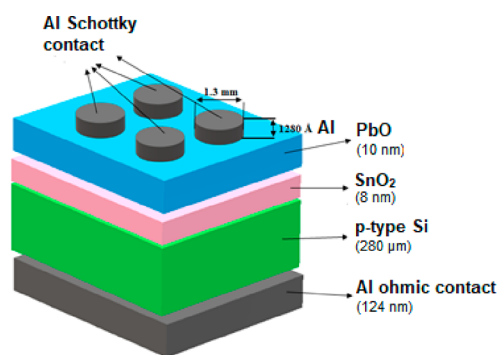


Figure 1. Schematic view of the $\text{Al}/\text{PbO}/\text{SnO}_2/\text{p-Si}$ Schottky diode.

Finally, an aluminum circular rectifying contact with a diameter of 1.3 mm and a thickness of 128 nm was deposited at a pressure of 2.66×10^{-7} Pa. The layer thickness was measured by utilizing a computerized quartz crystal thickness monitor. Thus, the $\text{Al}/\text{PbO}/\text{SnO}_2/\text{p-Si}$ structure was produced.

2.2. Characterization of $\text{Al}/\text{PbO}/\text{SnO}_2/\text{p-Si}$ Schottky Structures. Figure 1 depicts the $\text{Al}/\text{PbO}/\text{SnO}_2/\text{p-Si}$ structure schematically. High frequency (500 kHz–800 kHz–1 MHz) $C/G-V$

measurements were conducted by using an HP 4192A LF impedance analyzer at 300 K in the dark, and a 40 V_{rms} test was used.

3. RESULTS AND DISCUSSION

The characteristics of the produced PbO/SnO₂ DLS structure have been thoroughly investigated by measuring the capacitance/conductance vs voltage values. While evaluating the C - V values in frequencies higher than 500 kHz, the interface state density's effect can be ignored. That is because the alternating current (AC) signals cannot be followed by the electron charges in the interface states. With the semiconductor structure, the interface states are in equilibrium.⁴⁸ Capacitance-/conductance-voltage values are measured to investigate the electrical properties of MS or MIS structures. The basic electrical parameters of these structures, the interfacial states, were calculated at high frequencies to minimize excess capacitance in the dark at 300 K. The measured G - V and C - V values were examined in detail to investigate the prepared Al/PbO/SnO₂/p-Si structure's characteristics and double layer's effects. The value of the gate voltage was adjusted in a range between -2 and $+2$ V for the frequencies of 500 kHz–800 kHz–1 MHz.

Figure 2 shows the changes in the capacitance (C/V) variations under the effect of the bias voltage (V) of two diodes

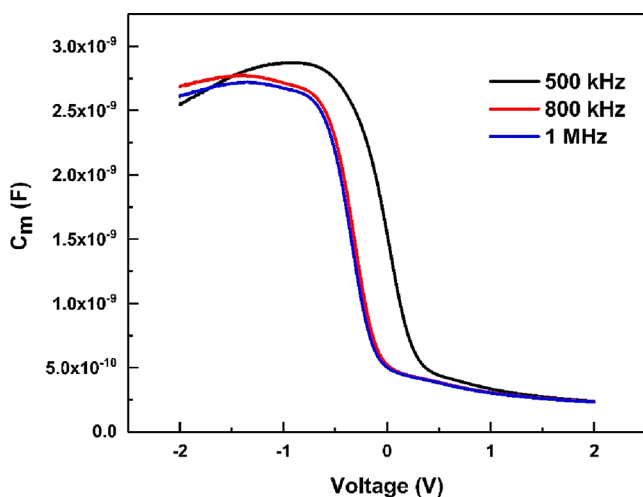


Figure 2. Capacitance vs voltage characteristics of the structure for the frequency range between 500 kHz–1 MHz.

at different high-frequency values. The plots show the measured values of the studied Al/PbO/SnO₂/p-Si structure's C - V properties for the studied frequencies. Also, the plots indicate the accumulation, depletion, and inversion regions of this structure.

Figure 2 reveals a significant correlation between the capacitance and the frequency. The increase in frequency causes a decline in the capacitance values. In this case, the applied AC signal's frequency determines the capacitance value. The interface states of the studied structure (PbO/SnO₂/p-Si) considered to be the reason for this. It is observed that the capacitance value changes at negative voltages, in the inversion zone, that is, the voltage affects the capacitance values in this zone.

Figure 3 shows the changes in the conductance (G/V) variations under the effect of bias voltage (V) of two diodes at the studied high frequencies (500, 800 kHz, and 1 MHz). G_m values decline with an increase in the value of the frequency. In

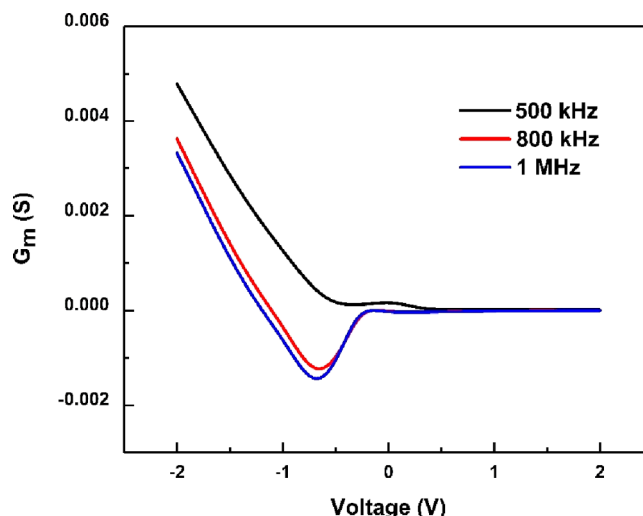


Figure 3. Conductance vs voltage values of the structure for the frequency range between 500 kHz–1 MHz.

the negative voltage zone, the G_m - V curves are observed to have a peak value. The charge carriers' distribution at the PbO/SnO₂/p-Si interface of the structure, i.e., the interface traps, causes this peak. As can be seen in Figure 3, similar to the C values, the G values decline with an increase in the frequency value. The downward bend observed in the strong accumulation zone in C is caused by the presence of R_s and interfacial PbO/SnO₂ layer. On the other hand, higher values of C and G at 500 kHz are caused by dipole and interfacial polarization, the unique density-distribution of N_{ss} at rePbO/SnO₂/p-Si interface, and the relaxation time/lifetime (τ). When the interface states and semiconductor are in equilibrium, a typical distribution may be observed in the fluctuations in the C/G with frequency for each bias voltage. The diode's capacitance value decreases as the speed rises. Also, the value of bulk resistance, which is both a function of frequency and related to the electron emission due to stalled responses of deep impurity levels, changes. Therefore, the space-charge capacitance of PbO/SnO₂/p-Si is essentially all that exists. Figures 2 and 3 show that the capacitance and conductivity values do not change at positive voltages, i.e., in the accumulation region. In other words, the voltage does not affect the capacitance and conductivity values in this region.

Eqs 1 and 2 give the corrected values of capacitance and conductivity.⁴⁹

$$C_c = \left(\frac{(G_m^2 + \omega^2 C_m^2) C_m}{(a^2 + \omega^2 C_m^2)} \right) G_c = \left(\frac{(G_m^2 + \omega^2 C_m^2) a}{(a^2 + \omega^2 C_m^2)} \right) \quad (1)$$

$$a = G_m - (G_m^2 + \omega^2 C_m^2) R_s C_i = C_m \left[1 + \frac{G_m^2}{(\omega C_m)^2} \right] = \frac{\epsilon_i \epsilon_0 A}{d} \quad (2)$$

where corrected conductivity (G_c) and capacitance (C_c) values are obtained from the measured values of G_m and C_m , respectively. While ϵ_0 stands for the permittivity of free space ($\epsilon_0 = 8.85 \times 10^{-14}$ F/cm), ϵ_i stands for the permittivity of the oxide layer interface ($\epsilon_i = 3.8 \epsilon_0$ for the SnO₂ layer,⁵⁰ and $\epsilon_i =$

25.9 ϵ_0 for the PbO layer).²⁵ d stands for the width of the layer's interface, while A stands for the determined diode area.

The organic layer capacitance, C_i is measured in the strong accumulation zone using the G and C characteristics.⁴⁹ We obtained the interfacial capacitance at 1.69 nF from the accumulation zone of the C_m – V curve.

In this way, the values of the corrected conductivity (G_c) and corrected capacitance (C_c) were obtained from the measured G_m and C_m values.

R_s is more successful just in the forward bias or accumulation zone; however, interface statistics seem to have a higher effectivity on the C/G – V data in the depletion region and inversion region. Therefore, if the capacitor is based on an accumulation area at a sufficiently high frequency, then the true values of R_s must be determined from the impedance values measured. However, using the relationship proposed by Nicollan and Brews,² it is possible to determine the structure's resistance (R_s) as a function of voltage considering each frequency. Figure 4 shows the $R_s(V)$ values that were obtained

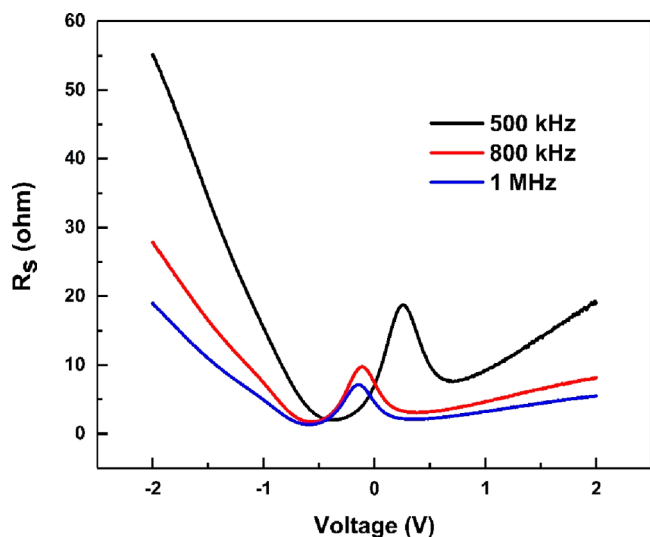


Figure 4. R_s – V curves of the structure for the frequency range between 500 kHz–1 MHz.

from the impedance data that were measured for each frequency. The value of R_s is calculated as follows:^{50–53}

$$R_s = \frac{G_m}{G_m^2 + \omega^2 C_m^2} \quad (3)$$

where the C/G values measured in the strong accumulation region are represented by C_m and G_m , respectively. In this equation, the applied frequency ($\omega = 2\pi f$) is associated with the applied AC voltage's angular frequency (ω).

Figure 4 shows the R_s – V curves for the different frequencies. Figure 4 also indicates that the rise in the conductivity leads to a decline in the R_s at high frequencies in the accumulation

zone. On the other hand, R_s gets higher values with the decrease in the frequency because of frequency-dependent interface loads. R_s must be taken into consideration when determining the voltage/frequency-dependent characteristics of the structure. The R_s – V curves have a peak, and this peak's height declines with the rise in the frequency, and the position of this peak moves in the range between +1 and –1 V. This is the outcome of an electric field-induced restructuring and reordering of surface states with a unique density distribution. Additionally, the increase in conductance leads to a decrease in R_s in the accumulation zone. At a strong accumulation zone, the value of R_s becomes almost constant, and it corresponds to the actual value of R_s at high frequency. The interface traps in the interlayer (PbO/SnO₂)/semiconductor (p-Si) that is under an external electric field together with the reconfiguration and reorganization of charges in surface states at the interface lead to a peak in the R_s value. It is possible to calculate the D_{it} voltage or energy-dependent profile by using a variety of methods including low-high-frequency capacitance, Hill–Coleman, parallel conductance, or admittance techniques.

In the present study, we employed the Hill–Coleman method⁵⁴ to calculate the interface state density (D_{it}) by using the following equation:

$$D_{it} = \frac{2}{qA} \frac{G_{c,max}/\omega}{\left(\frac{G_{c,max}}{\omega C_i}\right)^2 + \left(1 - \frac{C_c}{C_i}\right)^2} \quad (4)$$

where q stands for the elementary electrical charge, $G_{c,max}$ stands for the maximum G – V curve measured, A stands for the diode's area, C_c stands for the diode capacitance corresponding to $G_{c,max}$, and ω stands for the angular frequency. This technique was used on G_c – V curves at the frequencies of 500 kHz, 800 kHz, and 1 MHz. As shown in Table 1, D_{it} values increase with a decrease in frequency. This is because D_{it} can monitor a high-frequency AC signal but not a low-frequency AC signal.

Figure 5 shows that the C^2 – V properties are linear for each frequency. The C^2 – V properties of the Al/PbO/SnO₂/p-Si structure can be obtained from the C – V values measured at 500, 800, and 1 MHz. The following equation indicates the effect of the reverse bias voltage (V) on the depletion-layer capacitance in architectures of the MS, MIS, and MOS types.

$$C^{-2} = \frac{2}{q\epsilon_0 N_D A^2} (V_0 + V) \quad (5)$$

In this equation, A stands for the rectifier contact area, V_0 stands for the intercept of C^{-2} vs V curve at zero voltage (built-in potential), ϵ_0 stands for the semiconductor permittivity. The C^{-2} – V plot's slope and intercept voltage values are dependent on N_{ss} , frequency, and interlayer. It is possible to determine the intercept voltage (V_0) and the doping density of the donor atoms by extrapolating the C^{-2} – V curve to the voltage axis and slope for each frequency. The following relationships can also

Table 1. Electrical Parameters Calculated Using the C – V and G – V Values Measured at Room Temperature in the Dark for PbO/SnO₂ DLS Structures

Frequency (kHz)	V_D (V)	$N_D \times 10^{16}$ (cm ^{–3})	E_F (eV)	ϕ_B (eV)	W_D (Å)	D_{it} (eV ^{–1} cm ^{–2}) $\times 10^{12}$	R_s (Ω)
500	0.34	8.50	0.20	0.54	2276.48	3.19	17.1
800	0.68	9.72	0.20	0.88	3019.45	1.96	9.28
1000	0.75	8.50	0.20	0.95	3393.57	1.47	7.14

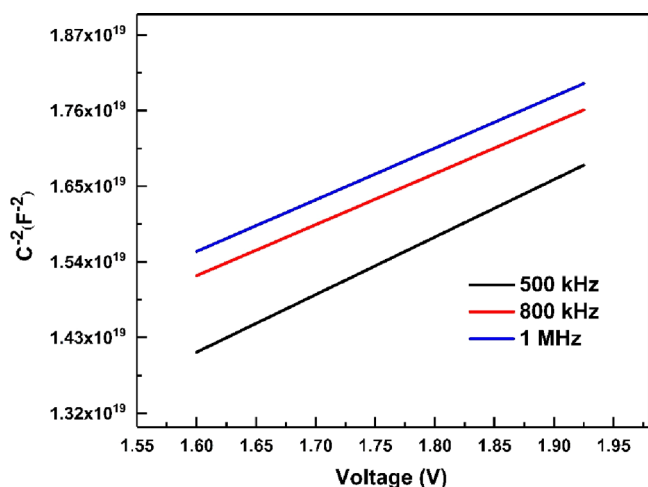


Figure 5. C^2 – V plot of structure for the frequency range between 500 kHz–1 MHz.

be used to calculate the values of Fermi energy (E_F), diffusion potential (V_D), the space charge layer width (W_D), donor carrier density (N_D), the maximum electric field (E_m), the effective state's density in the valence band for p-Si (N_v) at room temperature.^{55,56}

$$V_D = V_0 + \frac{kT}{q} \quad (6)$$

$$E_F = \frac{kT}{q} \ln\left(\frac{N_v}{N_D}\right) \quad (7)$$

$$W_D = \sqrt{\frac{2V_D \epsilon_0 \epsilon_s}{qN_D}} \quad (8)$$

$$N_D = \frac{2}{q\epsilon_0 \epsilon_s A^2 \tan \theta} \quad (9)$$

$$E_m = \sqrt{\frac{2qN_A V_D}{\epsilon_0 \epsilon_s}} \quad (10)$$

$$N_v = 4.82 \times 10^{15} T^{3/2} \left(\frac{m_h^*}{m_0}\right)^{3/2} \quad (11)$$

where m_h^* stands for the holes' effective mass and m_0 stands for the electron's rest mass ($m_h^* = 0.16m_0$).

The potential barrier height is also calculated using the diffusion potential (V_D), Fermi energy (E_F), and the image-force barrier height lowering ($\Delta\phi_B$). The barrier height can be calculated as follows:

$$\phi_B = V_D + E_F - \Delta\phi_B \quad (12)$$

The $\Delta\phi_B$ term in this equation is described as follows:

$$\Delta\phi_B = \sqrt{\frac{qE_m}{4\pi\epsilon_0\epsilon_s}} \quad (13)$$

All these characteristics of the studied Al/PbO/SnO₂/p-Si Schottky barrier diode are calculated for three different frequency values, namely, 500 kHz, 800 kHz, and 1 MHz. Table 1 gives several parameters depending on the high frequencies. The diffusion potential (V_D), the space charge

layer width (W_D), and potential barrier height (ϕ_B) values of Al/PbO/SnO₂/p-Si Schottky barrier diode get higher values as a result of an increase in the frequency values. However, Table 1 also indicates that the Interface state density (D_{it}) value decreases as a result of the increase in the frequency values. All variations in the values of the electrical parameters depending on the frequency listed in the table and discussed here are consistent with the literature, and similar variations have also been observed in previous studies.^{57,58} Moreover, these electrical parameters obtained from C – V analysis of the Al/PbO/SnO₂/p-Si Schottky barrier diode at room temperature were compared with the given C – V analysis results of the Al/p-Si Schottky barrier diode produced without using the SnO₂ interfacial layer. These comparisons have revealed that PbO-SnO₂ DLS has significantly improved the diode's electrical parameters.

C and G values drop as a result of an increase in the frequency since traps or charges in interface states may readily follow the AC signal. Also, this creates an excess capacitance, which relies on the relaxation/lifetime (τ) of the N_{ss} and the AC signal's frequency, which is indicated in Figures 2–4. The charges at these traps cannot contribute to the diode capacitance at frequencies that are sufficiently high ($f \geq 1$ MHz). Large point intercept voltage is another result of an interfacial layer that is sufficiently thick. The electrical parameters of N_D , ϕ_B , and W_D obtained from the slope and intercept of the C^2 – V plots significantly change with the frequency as a result of the dependence of the value of C on frequency, the interfacial layer, surface states, and their relaxation durations.

Since the diodes' electrical and dielectric properties are affected by the interface states (N_{ss}), the diode deviates from the desired features. That is, the existence of N_{ss} in the region between the interface layer and the semiconductor has an effect on the device's capacitance–voltage and current–voltage measurements. The change in N_{ss} energy can be plotted by using the following equations and the correct supply I – V data.^{56–59}

$$n(V) = qV / \left[kT \ln\left(\frac{I}{I_0}\right) \right] \quad (14)$$

$$\phi_e = \phi_{BO} + \left(1 - \frac{1}{n(V)}\right)V \quad (15)$$

Additionally, the energy location of N_{ss} is provided for p-type semiconductors as follows:⁶⁰

$$E_{ss} - E_v = q(\phi_e - V) \quad (16)$$

As a result, the plot of N_{ss} vs ($E_{ss} - E_v$) was obtained using eqs 14–16:⁶¹

$$N_{ss}(V) = \frac{1}{q} \left[\frac{\epsilon_i}{d} (n(V) - 1) - \frac{\epsilon_s}{W_D} \right] \quad (17)$$

The N_{ss} vs ($E_{ss} - E_v$) plot obtained for the device using the specified equations is given in Figure 6. The depletion layer width, which is denoted as W_D in eq 17, was calculated using the C – V measurements, and its value was found as 2.28×10^{-3} cm for 500 kHz. A special density distribution between the semiconductor and the metal was considered to be the cause of the variation in N_{ss} with energy. Depending on the interlayer thickness, N_{ss} controls the charge exchange between Al and the

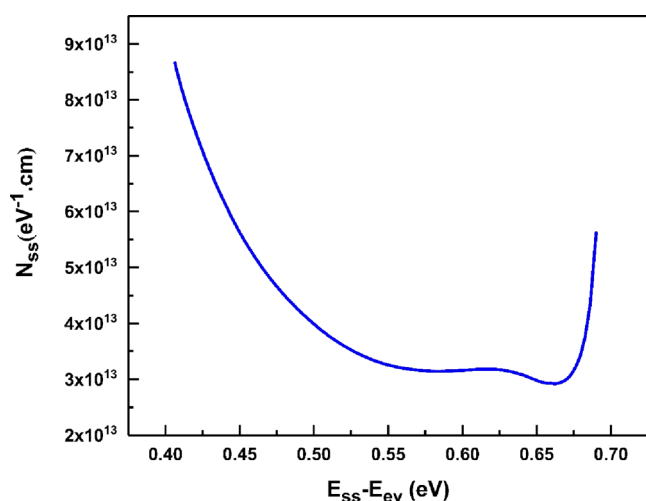


Figure 6. Energy distribution characteristic of N_{ss} for the studied structure.

semiconductor (p-type). The transport and chemical interactions between Al and p-type may be hampered by the PbO/SnO₂ interlayer. Additionally, it decreases the intensity of interfacial states and high gate leakage currents.

The interfacial layer neutralizes active dangling bonds on the semiconductor surface; moreover, it inhibits carriers from the metal–semiconductor junction from penetrating the semiconductor surface.^{62–64}

Several factors, such as a very thin native oxide layer that is naturally formed between the semiconductor and metal, impurities, the thickness of the consumption zone, and the interfacial layer's high dielectric value, lead to higher interfacial states.

4. CONCLUSION

Some electrical features of the Al/PbO/SnO₂/p-Si (DLS) structure were investigated by utilizing the conductance–voltage and the capacitance–voltage measurements for the frequencies 500 kHz, 800 kHz, and 1 MHz (with a voltage range between –2 and +2 V) at room temperature. The forward and reverse bias C – V and G – V properties of the DLS Schottky barrier diode structure indicate that particularly the conductivity and capacitance are both much sensitive to frequency and voltage. It was observed that the fabricated Al/PbO/SnO₂/p-Si (DLS) Schottky barrier diode had low capacitance and conductance values, particularly at higher frequencies. The unique distribution of surface states as well as their reordering and restructuring due to an electric field effect caused the formation of the peak at the G – V and C – V plots. The peak behavior is also observed in the C – V and G – V curves because of the series resistance and interface states. Experimental data reveal that both C and G strongly depend on voltage and frequency because of R_s , N_{ss} , and the interfacial PbO/SnO₂ layer. The observed levels of C and G at low and intermediate frequencies rise as a result of the extra C and G produced by the presence of N_{ss} . The diffusion potential (V_D), the space charge layer width (W_D), and potential barrier height (ϕ_B) values were observed to increase with the increase in the frequency because of the interface layer and the density distribution of the interface states. On the other hand, D_{it} and R_s values were observed to decline with the rise in the frequency value. Due to D_{it} 's inability to monitor an AC signal

at frequencies above the low frequencies, D_{it} values decline with the rise in frequency, which can be seen in Table 1. However, it was observed that the Fermi energy (E_F) values did not change with an increase in frequency. Eliminating the R_s effect also corrects the C and G values. N_{ss} values rise with a U-shaped distribution from the midgap toward the top of the valence band. All findings indicate that the series resistance together with the interface states affect the structure's electrical characteristics. Al/PbO/SnO₂/p-Si is suitable for use as an MOS or MIS device in electronic applications because of its constructed structure. The findings serve as a foundation for understanding semiconductor device technology. The PbO/SnO₂ interlayer ought to be taken into account as a photodetector for new insulator–semiconductor systems.

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Notes

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