



Comprehensive charge transport and interface-state analysis of Au/Al₂O₃/n-Si Schottky diodes via multi-technique electrical characterization

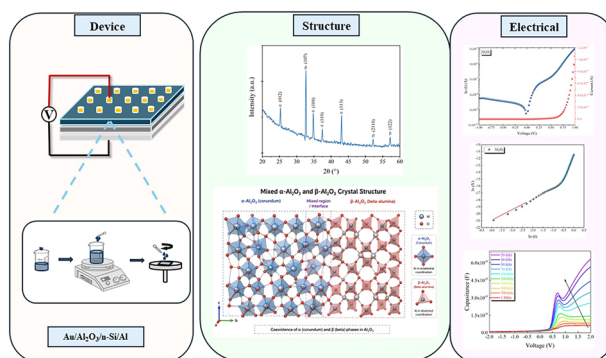
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Abstract

In this study, an Al₂O₃ interfacial layer was fabricated on n-type Si substrates via a sol-gel route and integrated into Au/Al₂O₃/n-Si/Al Schottky diodes. The structural, morphological, and electrical properties of the Al₂O₃ thin film and their influence on charge transport and interface-state dynamics were investigated. X-ray diffraction (XRD) revealed the coexistence of dominant α -Al₂O₃ and transition alumina phases, indicating partial phase transformation and structural disorder. FE-SEM and EDS confirmed a uniform, dense morphology with homogeneous elemental distribution; however, combined with XRD results, these findings suggest nanoscale inhomogeneities, including phase boundaries and crystallographic defects. Electrical characterization was performed using *I*-*V*, *C*-*V*, and *G*-*V* measurements. The diode exhibited strong rectification with a barrier height of ≈ 0.85 eV and an ideality factor of ≈ 2.30 , indicating non-ideal transport dominated by interface states and the Al₂O₃ interfacial layer. Charge transport behavior evolves from ohmic-like conduction to SCLC-like and trap-influenced transport regimes. Under reverse bias, the low-field transport behavior is found to be more consistent with Schottky-emission-like conduction, while trap-assisted processes become increasingly significant at higher electric fields. The interface state density (N_{ss}), evaluated using Hill-Coleman and high-low frequency methods, was on the order of 10^{12} eV⁻¹cm⁻² with strong energy and frequency dependence. Frequency-dependent *C*⁻²-*V* analysis showed that donor concentration, barrier height, and depletion width are influenced by interface states and interfacial polarization. Overall, the structural and electrical results reveal a physically consistent qualitative relationship between sol-gel-derived microstructural features and the observed non-ideal device characteristics.

Graphical Abstract



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Keywords MIS-type Schottky diode · Sol–gel-type formation mechanism · I – V · C – V · Charge transport mechanisms · Interface states

Highlights

- Sol–gel-derived Al_2O_3 interfacial layers were successfully integrated into $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}$ Schottky diodes.
- XRD analysis revealed coexistence of α - Al_2O_3 and transition alumina phases, indicating structural disorder.
- The diode exhibited a barrier height of ~ 0.85 eV and an ideality factor of ~ 2.30 .
- Charge transport evolved from ohmic-like conduction to SCLC-like and trap-assisted mechanisms.
- Interface-state density ($\sim 10^{12}$ eV $^{-1}$ cm $^{-2}$) strongly affected the electrical characteristics and frequency response.

1 Introduction

Metal–semiconductor (MS) and metal–insulator–semiconductor (MIS) Schottky diodes have attracted significant attention due to their wide range of applications in optoelectronics, sensors, high-frequency electronics, and photovoltaic devices [1–4]. The electrical performance of these devices is strongly governed by the metal–semiconductor interface, where parameters such as barrier height, interface states, and interfacial layers play a critical role in determining carrier transport mechanisms [5, 6]. In particular, the introduction of an insulating interfacial layer in MIS structures has been shown to significantly modify the electrical characteristics by reducing leakage currents, tuning barrier height, and influencing charge transport dynamics [7, 8].

Among various dielectric materials, Al_2O_3 has emerged as a promising interfacial layer due to its wide band gap, high dielectric constant, and good chemical stability [9–11]. The incorporation of Al_2O_3 into Schottky structures improves device performance by passivating surface states and suppressing interface recombination. However, despite these advantages, the presence of interface states and trap levels at the metal/insulator/semiconductor interface continues to introduce non-ideal effects, such as deviation from ideal thermionic emission behavior, frequency dispersion in capacitance, and trap-controlled conduction mechanisms [12–14].

Understanding the charge transport mechanisms in MIS-type Schottky diodes requires a comprehensive analysis using multiple electrical characterization techniques. While current–voltage (I – V) measurements provide insight into barrier height and conduction mechanisms, capacitance–voltage (C – V) and conductance–voltage (G – V) measurements are essential for evaluating interface states, dielectric properties, and frequency-dependent behavior. Previous studies have often focused on individual characterization techniques; however, a unified approach that correlates transport mechanisms with interface state dynamics is still limited.

In particular, the identification of dominant reverse current transport mechanisms—such as Fowler–Nordheim

tunneling, Poole–Frenkel emission, and Schottky emission—remains a key challenge in MIS structures [15–17]. Similarly, accurate determination of interface state density using different methods (e.g., energy distribution, Hill–Coleman, and high–low frequency techniques) is crucial for understanding trap dynamics and their impact on device performance. Furthermore, the extraction of frequency-dependent diode parameters from corrected capacitance data provides deeper insight into the role of interfacial layers and series resistance effects [18–20].

In this study, a comprehensive electrical characterization of $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}$ MIS Schottky diodes is presented by combining I – V , C – V , G – V , and admittance-based analyses within a unified framework. The charge transport mechanisms are systematically investigated across different bias regimes, including ohmic, space charge limited current (SCLC), and trap-controlled conduction regions. Reverse current mechanisms are examined using Fowler–Nordheim, Poole–Frenkel, and Schottky emission models, and the dominant conduction processes are identified.

Additionally, interface state density is evaluated using multiple complementary methods, and key diode parameters such as donor concentration, barrier height, depletion width, and electric field are extracted from corrected capacitance analysis. By correlating transport behavior with interface state dynamics, this work provides a detailed understanding of non-ideal effects in MIS-type Schottky diodes and offers valuable insights for the optimization of semiconductor devices.

2 Experimental

$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (%95), (Sigma Aldrich), ethanol (%99.9) and acetic acid were used as the initial precursors for producing Al_2O_3 thin films. The substrate material used for the thin-film deposition process was n-type Si with a (100) crystal orientation and a resistivity of 1–10 Ω ·cm. Aluminum oxide (Al_2O_3) precursor solution (0.25 M) was prepared via a sol–gel route using aluminum nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) as the metal source. The salt

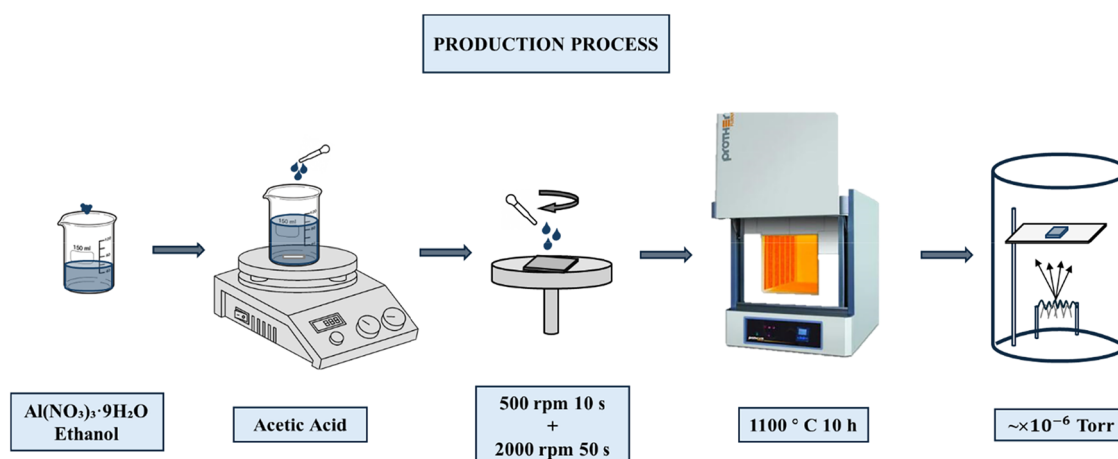


Fig. 1 The schematic representation of the production process

was dissolved in ethanol under continuous stirring at room temperature. Acetic acid was added dropwise as a stabilizing and complexing agent to control the hydrolysis and condensation reactions. The solution was stirred for 2 h until a clear and homogeneous sol was obtained. The prepared solution was applied to n-type Si substrates using the spin-coating method at 500 rpm for 10 s, followed by 2000 rpm for 50 s, resulting in a total of four coating layers. Subsequent to each coating step, the samples were subjected to a 5-min pre-annealing process at 140 °C with the objective of solvent removal. The prepared thin films were then subjected to annealing at a temperature of 1100 °C for a duration of 10 h, with the objective of facilitating the formation of the Al_2O_3 crystal structure. The schematic representation of the production process is illustrated in Fig. 1. For electrical measurements, Al ohmic contacts were deposited on the back surface of the Si substrate using the thermal evaporation method. Subsequently, to ensure ohmic contact behavior, the samples were annealed in a N_2 atmosphere at 570 °C for 5 min. Following this process, Al contacts were deposited onto the Al_2O_3 thin film surface using the thermal evaporation method with a shadow mask to form Schottky contacts.

The crystal structures of all samples were determined by X-ray diffraction (XRD) (Bruker D8 Advance). The measurement process was performed under the influence of $\text{Cu}_{\text{K}\alpha}$ (1.54) radiation. Furthermore, XRD measurement was conducted at step 0.02° in range from 20° to 90° . The surface morphology and of the samples was examined by means of a field emission scanning electron microscope (FE-SEM) (Hitachi High-Tech SU8700). Elemental analyses and mapping studies were carried out using an integrated energy-dispersive X-ray spectroscopy (EDS) system equipped with an Oxford Ultim Max 100 EDS detector at an accelerating voltage of 10 kV. The current–voltage (I–V) measurements were conducted using a Keithley 2400

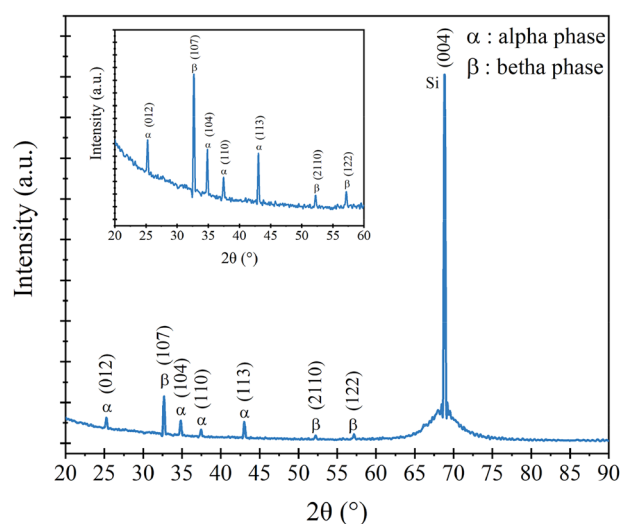


Fig. 2 XRD graph of the Al_2O_3 thin film on Si substrate

SourceMeter within the range of -1 V to $+1$ V, with a step size of 0.01 V, in ambient conditions. Capacitance and conductivity measurements were performed using an HP 4192 A LF impedance analyzer device within the same voltage range (-2 V to $+2$ V), with a step size of 0.01 V, and under different frequency range.

3 Results and discussion

The diffraction pattern obtained from the measurements is shown in Fig. 2. The dominant peak observed in Fig. 2 corresponds to the Si (004) plane, located at $2\theta \cong 69^\circ$. Due to the low thin film thickness, the peak corresponding to the Si substrate is observed as dominant, while the diffraction peaks corresponding to Al_2O_3 appear with lower intensity. As a result of the indexing of the diffraction peaks associated with Al_2O_3 , it was observed that the sample contains

Table 1 Calculated crystallographic parameters

(hkl)	(2θ) (degree)	<i>d</i> (Å)	β (degree)	<i>D</i> (nm)	δ (nm ⁻²)	ε
α-(012)	25.79	3.45	0.157	51.91	3.71 × 10 ⁻⁴	2.99 × 10 ⁻³
α-(104)	35.36	2.54	0.168	49.63	4.06 × 10 ⁻⁴	2.30 × 10 ⁻³
α-(110)	37.98	2.37	0.159	52.84	3.58 × 10 ⁻⁴	2.02 × 10 ⁻³
α-(113)	43.55	2.08	0.150	57.03	3.07 × 10 ⁻⁴	1.64 × 10 ⁻³
β-(107)	33.00	2.69	0.170	48.74	4.21 × 10 ⁻⁴	2.50 × 10 ⁻³
β-(211)	52.73	1.73	0.208	42.63	5.50 × 10 ⁻⁴	1.83 × 10 ⁻³
β-(122)	57.68	1.59	0.224	40.49	6.10 × 10 ⁻⁴	1.77 × 10 ⁻³

both the α-Al₂O₃ phase and transition alumina phases denoted as the β-Al₂O₃ phase. The (012), (104), (110), and (113) planes corresponding to the α phase were observed, while the (107), (210), and (122) planes corresponding to the β phase were identified. The 2θ values and corresponding interplanar spacing (*d*) values were found to be consistent with the ICDD reference data 00-001-1296 for the α-Al₂O₃ phase and 00-051-0769 for the β phase. The sharp and narrow nature of the diffraction peaks indicates improved crystallinity of the structure [21]. Consequently, the sharper and narrower peaks corresponding to the α phase indicate that this phase possesses higher crystallinity. Conversely, the broader peaks associated with the β phase suggest that this phase exhibits lower crystallinity.

Using the obtained XRD pattern, the interplanar spacing (*d*), FWHM (β), crystallite size (*D*), dislocation density (δ), and microstrain (ε), as well as the lattice parameters, were calculated for the sample. The crystallite sizes of the samples were calculated using the Scherrer equation [22] given in Eq. (1).

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

In this equation, *K* is the Scherrer constant (≈ 0.9), λ is the wavelength (0.154 nm, CuK_α), and β is the full width at half maximum (FWHM) [23]. The value of β was obtained from the XRD pattern. The interplanar spacings of the samples were calculated using Bragg's law (Eq. (2)) [24], while the lattice parameters were calculated using Eqs. (3) and (4). Since Al₂O₃ has a hexagonal structure, Eq. (3) was used, whereas Eq. (4) was used for the Si crystal due to its cubic structure.

$$n\lambda = 2d \sin \theta \quad (2)$$

$$\frac{1}{d^2} = \frac{4}{3} \left[\frac{h^2 + hk + k^2}{a^2} \right] + \frac{l^2}{c^2} \quad (3)$$

$$a = d\sqrt{h^2 + k^2 + l^2} \quad (4)$$

In these equations, *d* represents the interplanar spacing, *h*, *k*, and *l* are the Miller indices, *a* and *c* are the lattice

parameters, λ is the wavelength, and θ is the diffraction angle corresponding to the most intense peak in the XRD pattern. Furthermore, in order to evaluate structural changes in the samples, such as variations in interatomic distances, the ε values for each sample were calculated using Eq. (5) [25]. Finally, the dislocation density (δ) was calculated using Eq. (6) [25]. The obtained results are presented in Table 1.

$$\beta \cos \theta = \frac{K\lambda}{D} + 4\varepsilon \sin \theta \quad (5)$$

$$\delta = \frac{1}{D^2} \quad (6)$$

The lattice parameter was calculated using the Si (004) diffraction peak and was found to be *a* ≈ 5.42 Å. The lattice parameters of the α-Al₂O₃ phase were calculated using equations applicable to hexagonal structures, based on the *d*-spacings of the (012), (104), (110), and (113) diffraction peaks. The results showed that *a* ≈ 4.75 Å and *c* ≈ 12.98 Å. The consistency of these values with the literature indicates that the crystal structure of the formed α phase remains relatively stable.

Upon examining Table 1, significant differences are observed in the crystallographic parameters of the α and β phases. It was determined that the crystallite sizes of the α-Al₂O₃ phase are larger than those of the β phase. The smaller crystallite sizes of the β phase indicate that this phase has a lower degree of crystallinity. Examination of the β values reveals that the diffraction peaks corresponding to the β phase are broader. This indicates structural disorder and smaller crystallite sizes. Additionally, the δ values were found to be higher for the β phase, suggesting a higher density of crystal defects. When the ε values are considered, it is observed that the α phase exhibits relatively lower values, whereas higher ε values are obtained for the β phase, indicating greater internal strain and structural disorder. When all these results are evaluated together, it is concluded that the α phase is more ordered, more stable, and possesses better crystallinity, whereas the β phase is more disordered

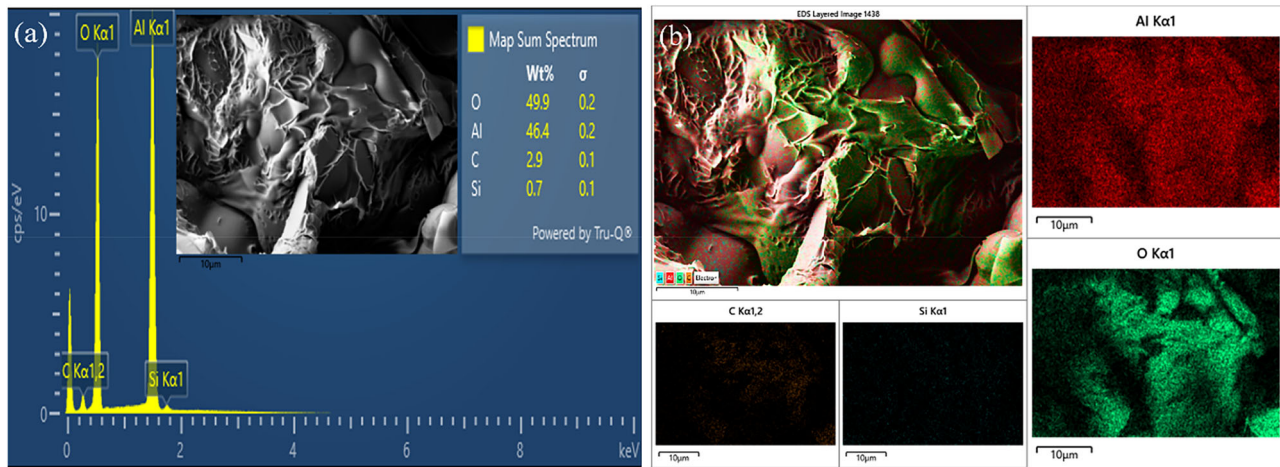


Fig. 3 **a** FE-SEM image and EDS spektrum of the Al_2O_3 thin film on n-Si, **b** Elemental mapping images

and exhibits lower crystallinity. When the XRD results are evaluated together with the electrical measurement results, it is suggested that the coexistence of the β - Al_2O_3 phase and the reduced crystallinity observed in the sample may contribute to increased structural disorder and the formation of defect-related states that are consistent with the interface-state and trap-assisted transport behavior observed in the electrical measurements. In particular, the higher β values and smaller D values associated with the β phase indicate a higher density of crystal defects and structural disorder. These structural disorders are correlated with a high ideality factor ($n \gg 2$), a high interface state density ($N_{ss} \approx 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$), and SCLC-TCLC conduction mechanisms. Furthermore, the higher crystallinity of the α phase, along with its larger D values and lower δ values, indicates that this phase is more stable and possesses a lower defect density. In contrast, the presence of the β phase may be associated with increased structural disorder and local defect formation, which could contribute to carrier trapping and the trap-influenced transport behavior observed at higher bias regions. When the XRD results are considered together with the electrical measurements, they reveal a physically consistent relationship between structural disorder and non-ideal electrical behavior.

It should be emphasized that the present study does not directly identify the microscopic origin of the interface traps. The proposed relationship between the β - Al_2O_3 phase and the observed defect-assisted transport behavior is therefore based on the combined interpretation of structural and electrical characterization results. The broader diffraction peaks, smaller crystallite sizes, and higher strain values associated with the β phase suggest increased structural disorder, while the elevated interface-state density, frequency dispersion, and trap-influenced transport characteristics indicate the presence of electrically active defect

states. Although these observations are physically consistent, direct identification of the specific defect species would require complementary defect-sensitive techniques such as XPS, DLTS, or high-resolution interfacial characterization.

In order to further elucidate the structural features of the Al_2O_3 thin film, surface morphology and compositional analyses were performed using FE-SEM and EDS techniques, and the results are presented in Fig. 3.

The FE-SEM image (inset of Fig. 3a) reveals that the Al_2O_3 thin film exhibits a uniform and dense surface morphology, without any observable cracks, or agglomerated regions. The absence of such morphological defects indicates that the sol-gel deposition followed by high-temperature annealing resulted in a well-covered and compact film structure. This type of morphology may help in MIS-type devices, as it minimizes leakage pathways and suppresses local electric field enhancements at the interface.

The EDS spectrum (Fig. 3a) obtained from the same region confirms that the film is primarily composed of Al and O elements, corresponding to the Al_2O_3 . The presence of a Si signal is attributed to the interaction volume of the electron beam extending into the underlying substrate due to the limited film thickness. In addition, a weak C signal is detected, which is likely associated with surface contamination or residual organic species originating from the sol-gel precursor or ambient exposure. The elemental mapping images (Fig. 3b) further demonstrate that both Al and O elements are uniformly distributed across the surface, without any noticeable clustering or segregation. This homogeneous elemental distribution indicates that the film formation process resulted in a chemically uniform coating, consistent with an effective sol-gel reaction and subsequent thermal treatment. When the structural (XRD) and morphological (SEM-EDS) results are considered together, it

can be inferred that although the Al_2O_3 thin film exhibits a morphologically smooth and homogeneous surface, the coexistence of α - Al_2O_3 and β - Al_2O_3 phases revealed by XRD suggests the presence of nanoscale structural heterogeneities, including crystallographic defects, phase boundaries, and local lattice distortions. These structural inhomogeneities may contribute to the formation of electrically active defect states and trap centers, which are consistent with the non-ideal electrical behavior observed in the device. It should be noted that the present study focuses on the detailed structural and electrical characterization of a single Au/ Al_2O_3 /n-Si device fabricated under fixed processing conditions. Therefore, the observed relationship between microstructural features and electrical properties is interpreted qualitatively based on the consistency between the structural disorder indicators (crystallite size, strain, phase composition, and morphology) and the measured electrical characteristics. A rigorous quantitative structure–property correlation would require a systematic investigation involving multiple samples with controlled variations in microstructural parameters.

3.1 Current–voltage (I–V) characteristics and resistance analysis

The current–voltage (I–V) characteristics of the Au/ Al_2O_3 /n-Si/Al Schottky diode were measured at room temperature under dark conditions, and the obtained results are shown in the inset of Fig. 4. The device exhibits a clear rectifying behavior, with the forward current increasing exponentially while the reverse current remains relatively low, indicating the successful formation of a Schottky barrier at the metal/semiconductor interface.

To further investigate the conduction mechanism, the semi-logarithmic $\ln(I)$ –V plot was examined (Fig. 4). A well-defined linear region is observed in the low-to-

moderate forward bias region, suggesting that the current transport is governed by the thermionic emission (TE) mechanism. According to TE theory, the current is given by [1, 20]:

$$I = I_0 \left[\exp\left(\frac{q(V - IR_s)}{nkT}\right) - 1 \right] + \frac{(V - IR_s)}{R_{sh}}; I_0 = AA^*T^2 \exp\left(-\frac{q\Phi_b}{kT}\right) \quad (7)$$

where the I_0 is the reverse saturation current, n is the ideality factor, Φ_b is the barrier height, A is the Schottky area, A^* is the Richardson constant, k is the Boltzmann constant, T is the room temperature, R_s is the series resistance and R_{sh} is the shunt resistance [1, 26].

From the slope of the linear region of the $\ln(I)$ –V plot, the ideality factor (n) was calculated as 2.30, while the saturation current (I_0) was determined as 1.623×10^{-9} A. Using these parameters, the zero-bias barrier height (Φ_b) was obtained as 0.851 eV. The extracted barrier height is relatively high compared to conventional metal–semiconductor (MS) structures, indicating that the insertion of the Al_2O_3 interfacial layer effectively modifies the barrier profile and enhances the diode performance. High- k dielectric materials such as Al_2O_3 are known to improve barrier homogeneity, reduce leakage current, and suppress interface defects. The ideality factor ($n=2.30$) is significantly larger than the ideal value ($n \approx 1$), indicating non-ideal diode behavior. This deviation is likely associated with the combined influence of interface states (N_{ss}), interfacial-layer effects, local barrier-height inhomogeneities, and recombination-related processes within the space-charge region. Since these mechanisms may coexist simultaneously in MIS-type Schottky structures, the present room-temperature electrical measurements do not allow a rigorous quantitative separation of their individual contributions. Similar deviations have been widely reported in MIS-type Schottky structures, where interfacial oxide layers, interface states, and barrier inhomogeneities collectively influence carrier transport and lead to departures from ideal thermionic-emission behavior. The relatively high ideality factor observed in the present Au/ Al_2O_3 /n-Si structure suggests the presence of multiple non-ideal transport processes. In MIS-type Schottky diodes, interface-state-assisted recombination, interfacial-layer effects, local barrier-height inhomogeneities, carrier trapping, and series-resistance-related voltage drops may collectively contribute to deviations from ideal thermionic-emission behavior. The elevated interface-state density ($\sim 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$), pronounced frequency dispersion observed in the C–V and G–V characteristics, and the trap-influenced transport behavior identified from the current-transport analyses are all consistent with the coexistence of such non-ideal mechanisms. Therefore, the ideality factor

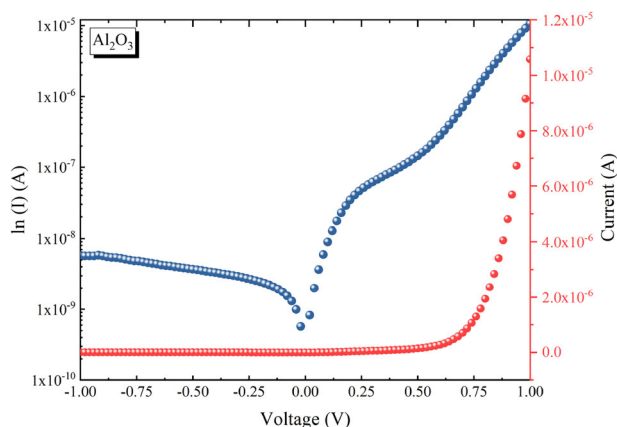


Fig. 4 $\ln(I)$ –V and I–V characteristic of the Au/ Al_2O_3 /n-Si/Al Schottky diode measured at room temperature under dark conditions

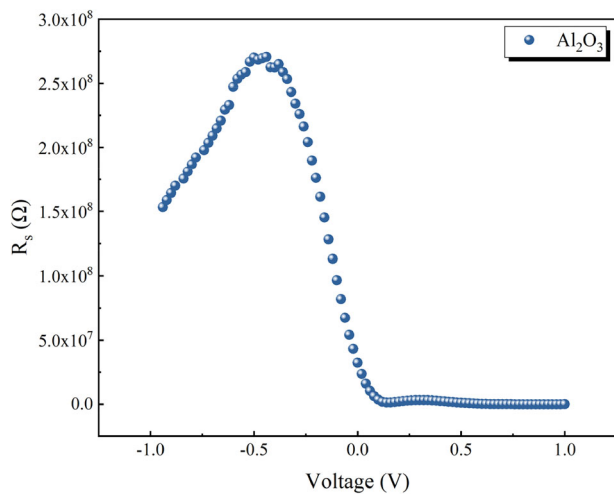


Fig. 5 $R_s - V$ characteristic of the Au/ Al_2O_3 /n-Si/Al Schottky diode measured at room temperature under dark conditions

obtained from the $I-V$ characteristics should be interpreted as reflecting the combined influence of these interface-related effects rather than a single dominant transport process.

At higher forward bias voltages, the $\ln(I) - V$ curve deviates from linearity, which is attributed to the increasing effect of the series resistance (R_s). In this region, a considerable portion of the applied voltage drops across R_s , limiting the current flow and causing deviation from ideal TE behavior [27]. Under reverse bias conditions, the current remains relatively small but exhibits a slight increase with increasing voltage. This behavior can be associated with thermally generated carriers, interface trap-assisted tunneling, and leakage currents through the Al_2O_3 interfacial layer [28]. In order to evaluate the rectification performance of the device, the rectification ratio (RR) was calculated using the ratio of forward to reverse current at ± 1 V. The rectification ratio was found to be 1.817×10^3 , indicating strong rectifying behavior and low reverse leakage current. The relatively high RR value suggests that the Al_2O_3 interfacial layer contributes to suppressing reverse leakage current and modifying the effective barrier properties of the junction. However, the rectification ratio alone should not be regarded as definitive evidence of ideal device performance, since significant interface-related transport processes may still be present in MIS-type structures. Similar improvements have been reported in MIS-type Schottky structures with dielectric interlayers [29, 30]. Although the Au/ Al_2O_3 /n-Si/Al structure exhibits a relatively high rectification ratio, this parameter should be interpreted together with other electrical characteristics of the device. The interface-state densities obtained in this study remain on the order of $10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$, while the reverse-bias transport analyses indicate contributions from Schottky-emission-like and

trap-assisted conduction processes. Furthermore, the transition from ohmic to SCLC-like and trap-influenced transport regions suggests that defect-mediated carrier transport remains active. Therefore, the improved rectification behavior is more appropriately attributed to the combined effects of leakage-current suppression and barrier modification induced by the Al_2O_3 interfacial layer rather than to the complete elimination of interfacial defects.

In addition to the $I - V$ analysis, the voltage-dependent resistance ($R - V$) characteristics were obtained using Ohm's law ($R = V/I$), and the results are presented in Fig. 5. The $R - V$ curve exhibits a strong dependence on the applied voltage. At reverse bias and low forward bias regions, the resistance reaches very high values (on the order of $10^8 \Omega$), which corresponds to the shunt resistance (R_{sh}). The shunt resistance was calculated as 275 M Ω , indicating low leakage current and good junction quality. As the forward bias voltage increases, the resistance decreases sharply and approaches a minimum value. This region corresponds to the series resistance (R_s), which originates from the bulk resistance of the semiconductor, contact resistance, and the interfacial Al_2O_3 layer. The series resistance was determined as 94 k Ω . The decrease in resistance with increasing forward bias voltage confirms that the effect of R_s becomes dominant at higher voltages. This behavior is consistent with the deviation observed in the $\ln(I) - V$ characteristics at high forward bias. The relatively high R_{sh} and moderate R_s values indicate that the Al_2O_3 interfacial layer effectively suppresses leakage currents while maintaining acceptable conduction properties. Similar behavior has been reported in MIS-type structures where the interfacial layer improves device performance by reducing defect-assisted conduction mechanisms [31, 32].

Overall, the $I - V$ and $R - V$ analyses demonstrate that the Au/ Al_2O_3 /n-Si/Al diode exhibits strong rectifying behavior, enhanced barrier height, reduced leakage current, and improved junction quality. However, the deviation from ideality suggests that interface states and series resistance effects play a significant role in determining the electrical characteristics of the device.

In order to determine the diode parameters more accurately and to validate the results obtained from the thermionic emission (TE) method, the Norde method was applied. The Norde function $F(V)$ is defined as [33, 34]:

$$F(V) = \frac{V}{\gamma} - \frac{kT}{q} \left[\ln \left(\frac{I(V)}{AA^*T^2} \right) \right] \quad (8)$$

where γ is an integer greater than the ideality factor. The plot of the Norde function $F(V)$ versus V is shown in Fig. 6. The function exhibits a minimum point at a certain voltage $V_{\min}$, which is used to calculate the barrier height and series resistance. The series resistance and barrier height are

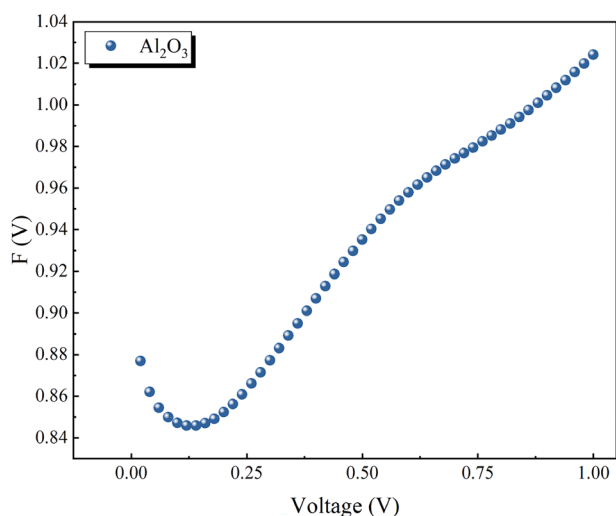


Fig. 6 Norde function $F(V)$ versus V for the Au/Al₂O₃/n-Si/Al Schottky diode

determined from:

$$R_s = \frac{kT(\gamma - n)}{qI_{\min}} \quad (9)$$

$$\Phi_b = F(V_{\min}) + \frac{V_{\min}}{\gamma} - \frac{kT}{q} \quad (10)$$

As seen in Fig. 6, the $F(V)$ curve initially decreases, reaches a minimum, and then increases with increasing voltage. This behavior is characteristic of Schottky diodes and reflects the transition from ideal TE-dominated conduction to series resistance-limited conduction. The minimum point of the curve corresponds to the optimum condition where the effects of series resistance and barrier height can be simultaneously evaluated. From the $F(V) - V$ plot, The R_s and Φ_b were determined as $4.03 \times 10^5 \Omega$ and 0.848 eV, respectively. The barrier height obtained from the Norde method (0.848 eV) is in very good agreement with the value obtained from the thermionic emission method (0.851 eV). The close agreement between the barrier-height values obtained from the TE and Norde methods suggests a reasonable degree of consistency between the extracted parameters. However, since the two methods probe different voltage regions and are influenced differently by series resistance and interfacial effects, this agreement should be interpreted cautiously and does not by itself constitute definitive evidence of a perfectly homogeneous barrier structure. The slight difference between the two methods can be attributed to the fact that the TE method is based on the low-bias region, while the Norde method takes into account the effect of series resistance and uses a wider voltage range. The series resistance obtained from the Norde method ($\approx 4.03 \times 10^5 \Omega$) is substantially higher than

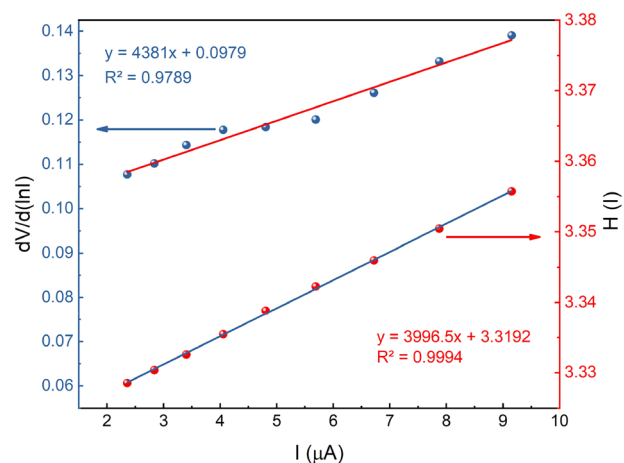


Fig. 7 Plots of $dV/d(\ln I) - I$ and $H(I) - I$ for the Au/Al₂O₃/n-Si/Al Schottky diode

the values extracted from other approaches. This difference suggests that the parameter obtained from the Norde analysis should be interpreted as an effective resistance that includes not only the intrinsic series resistance of the device but also additional contributions associated with voltage drops across the interfacial Al₂O₃ layer, interface-state charging effects, carrier trapping processes, and non-uniform current distribution.

To evaluate the series resistance and diode parameters in more detail in the high forward voltage region, we applied the Cheung and Cheung method to the $I - V$ data. This method is based on thermionic emission (TE) theory and is particularly effective in the region where the effect of series resistance (R_s) becomes dominant. The expressions for Cheung's functions are [35, 36]:

$$\frac{dV}{d\ln(I)} = \frac{nkT}{q} + IR_s \quad (11)$$

$$H(I) = V - n \frac{kT}{q} \ln\left(\frac{I}{AA^*T^2}\right) = n\Phi_b + IR_s \quad (12)$$

The graphs of $dV/d(\ln I) - I$ and $H(I) - I$ for the Au/Al₂O₃/n-Si/Al Schottky diode are displayed in Fig. 7. As shown in Fig. 7, both $dV/d(\ln I)$ and $H(I) - I$ plots exhibit excellent linearity with high correlation coefficients ($R^2 \approx 0.98$ – 0.999), indicating that the Cheung method is applicable and that the extracted parameters are reliable. The slopes and intercepts of these linear regions are used to extract the series resistance, ideality factor, and barrier height. The $dV/d(\ln I) - I$ curve yields $n=3.916$ and $R_s = 4381 \Omega$, while the $H(I) - I$ curve yields $\Phi_b = 0.848$ eV and $R_s = 3997 \Omega$. The series resistance values obtained from both Cheung functions (4381Ω and 3997Ω) are in very good agreement with each other, confirming the consistency and reliability of the method. Moreover, the barrier height

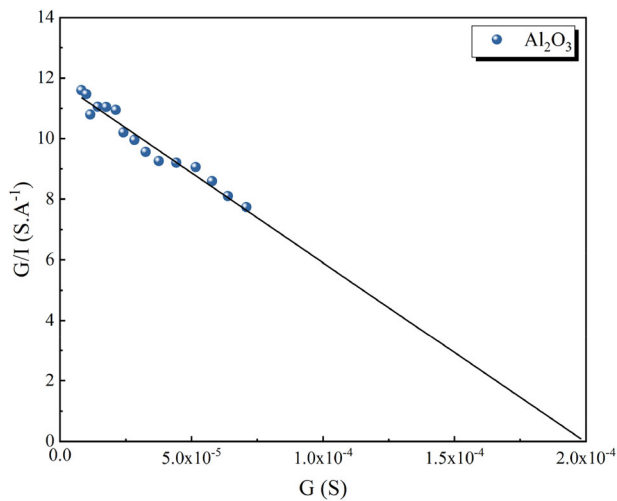


Fig. 8 Plot of $G/I - G$ for the Au/Al₂O₃/n-Si/Al Schottky diode

obtained from the $H(I)$ function (0.848 eV) is in excellent agreement with the values obtained from both thermionic emission (TE) method (0.851 eV) and Norde method (0.848 eV). The relatively close barrier-height values obtained from the TE, Norde, and Cheung analyses indicate that the extracted parameters remain broadly consistent across different characterization approaches. Nevertheless, because these methods operate in different bias regimes and are affected differently by interface states, interfacial-layer effects, and series resistance, the observed agreement should not be interpreted as definitive proof of a perfectly uniform barrier structure. It should also be noted that the TE, Norde, and Cheung methods probe different regions of the forward-bias characteristics. While the TE method mainly reflects the low-bias transport regime, the Cheung approach is more sensitive to high-forward-bias conditions where series-resistance and interface-related effects become increasingly significant. Similarly, the Norde method incorporates a broader voltage range and partially accounts for voltage-drop effects within the device. Therefore, the observed consistency among the extracted barrier-height values is considered supportive evidence of internally consistent electrical characterization rather than direct proof of barrier homogeneity.

The ideality factor obtained from the Cheung method ($n \approx 3.916$) is higher than the value obtained from the $\ln(I)-V$ analysis ($n = 2.30$). This difference is expected because Cheung method uses high forward bias region and TE method uses low bias region. At higher voltages, additional effects such as series resistance (R_s), interface states (N_{ss}), carrier scattering and recombination, and voltage drop across the Al₂O₃ interfacial layer become more dominant, leading to an apparent increase in the ideality factor.

In order to further investigate the series resistance and ideality factor of the Au/Al₂O₃/n-Si/Al Schottky diode, the

Werner method was applied using the conductance-based approach. This method provides an alternative way to extract diode parameters from the forward bias $I-V$ characteristics by utilizing the ratio of conductance to current. The conductance (G) is defined as $G = dI/dV$. From the thermionic emission (TE) model including series resistance, the following relation can be derived [37]:

$$\frac{G}{I} = \frac{\beta}{n} (1 - GR_s) \quad (13)$$

The graph of $G/I - G$ for the Au/Al₂O₃/n-Si/Al Schottky diode are displayed in Fig. 6. Plotting G/I vs G for the Au/Al₂O₃/n-Si/Al Schottky diode using Eq. (13) produces a straight line that can be used to get $1/R_s$ and β/n from the x- and y-axis intercepts, respectively. The device's high quality and clearly defined interfaces are indicated by the straight line seen in Fig. 8. From the linear fitting of the $G/I - G$ plot, the R_s and n values were calculated as 4957 Ω and 3.26, respectively. The series resistance obtained from the Werner method ($\approx 4957 \Omega$) is in good agreement with the values obtained from the Cheung method ($\approx 4 \text{ k}\Omega$), confirming the consistency of the extracted R_s values. Similarly, the ideality factor obtained from the Werner method ($n \approx 3.26$) is higher than the value obtained from the thermionic emission method ($n \approx 2.30$). This increase is expected since the Werner method, like the Cheung method, is based on the high forward bias region where non-ideal effects become more significant. The elevated ideality factor can be attributed to voltage drop across the series resistance, interface states (N_{ss}) recombination processes in the space charge region, barrier inhomogeneities influence of the Al₂O₃ interfacial layer. Such behavior is commonly observed in MIS-type Schottky diodes and indicates that the current transport deviates from pure thermionic emission at higher bias voltages [38]. The relatively close series-resistance values obtained from the Cheung and Werner analyses ($\sim 4\text{--}5 \text{ k}\Omega$) indicate that these methods provide mutually consistent estimates of the effective resistance under strong forward-bias conditions. Since both approaches primarily probe the high-current region where the voltage drop across the series resistance becomes significant, these values are considered more representative of the practical forward-conduction regime of the device. It should be noted that the series resistance extracted from different methods does not necessarily represent a unique intrinsic device parameter. In MIS-type Schottky structures, the apparent resistance may vary depending on the voltage region being analyzed and the relative contributions of interface states, interfacial-layer polarization, carrier trapping, and current-crowding effects. Consequently, different extraction techniques may yield different effective resistance values. In the present study, the $\text{k}\Omega$ -range values obtained from the Cheung and Werner methods are

considered more representative of the forward-conduction regime, whereas the larger apparent resistance obtained from the Norde analysis likely includes additional interfacial and bias-dependent contributions. Therefore, the observed variation in the extracted series-resistance values does not indicate a contradiction between the applied methods but rather reflects the bias-dependent and interface-sensitive nature of the effective resistance in the Au/Al₂O₃/n-Si structure.

The interface state density (N_{ss}) is one of the most critical parameters determining the electrical performance of Schottky and MIS-type diodes. These states originate from dangling bonds, defects, and imperfections at the metal/insulator/semiconductor interface and significantly influence carrier transport mechanisms. In this study, the energy distribution of interface states was analyzed as a function of the energy difference between the conduction band edge (E_c) and the interface state energy level (E_{ss}). Card and Rhoderick quickly determined the connection between n and N_{ss} for a n-type Schottky diode as [39]

$$N_{ss} = \frac{1}{q} \left[\frac{\epsilon_i}{\delta} (n(V) - 1) - \frac{\epsilon_s}{W_d} \right] \quad (14)$$

$$E_c - E_{ss} = q\Phi_e - qV; \Phi_e = \Phi_b + (1 - 1/n)V \quad (15)$$

where Φ_e is the effective barrier height, the permittivity of n-Si crystal is represented by $\epsilon_s (=11.8\epsilon_0)$, the interface layer thickness of Al₂O₃ is represented by δ ($=28.1$ nm), the permittivity of Al₂O₃ is represented by ϵ_i ($=9$), and the depletion region width, W_d , is computed as 2.38×10^{-4} cm from the 1 MHz frequency $C-V$ plot (Fig. 15) for the Al₂O₃/n-Si Schottky diode.

The variation of N_{ss} as a function of ($E_c - E_{ss}$) is shown in Fig. 9. The calculated interface state density values

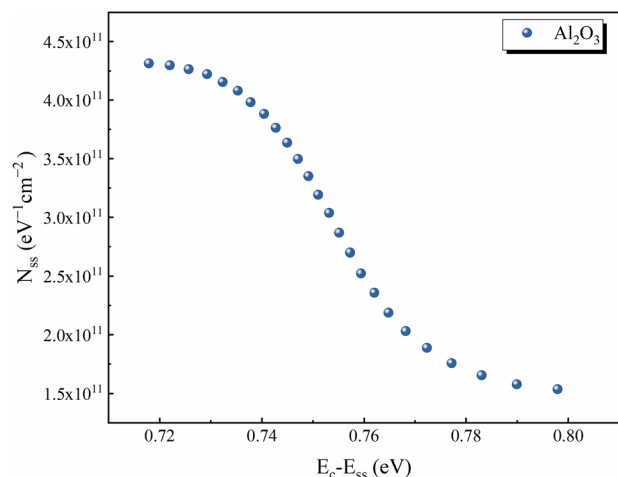


Fig. 9 Energy distribution of interface state density (N_{ss}) as a function of ($E_c - E_{ss}$) for the Au/Al₂O₃/n-Si/Al Schottky diode

exhibit a clear energy dependence within the bandgap. Specifically, the interface state density was determined as $6.16 \times 10^{12} \text{eV}^{-1}\text{cm}^{-2}$ at an energy level of ($E_c - 0.718$) eV, and it decreases to $2.17 \times 10^{12} \text{eV}^{-1}\text{cm}^{-2}$ at ($E_c - 0.798$) eV. This decreasing trend indicates that the density of interface states is higher near the conduction band edge and gradually diminishes toward deeper energy levels within the bandgap. Such behavior is consistent with the continuous distribution of interface states commonly reported for MIS-type Schottky diodes. These states are generally attributed to dangling bonds, structural defects, and interface imperfections at the metal/insulator/semiconductor interface. The higher density of interface states near the conduction band implies a greater probability of carrier trapping and recombination processes, which contributes to the non-ideal behavior observed in the $I-V$ characteristics.

In the literature, typical interface state density values for MIS and MPS-type Schottky structures are reported in the range of 10^{11} – $10^{13} \text{eV}^{-1}\text{cm}^{-2}$, depending on the interfacial layer quality, fabrication method, and measurement conditions. The N_{ss} values obtained in this study fall within this range, indicating that the fabricated Au/Al₂O₃/n-Si/Al diode possesses a moderate interface quality. Moreover, the observed decrease in N_{ss} with increasing energy suggests that the Al₂O₃ interfacial layer partially passivates interface defects, thereby improving the electronic properties of the device. In summary, the residual interface states still affect the charge transport mechanisms and lead to departures from ideal diode performance even if the Al₂O₃ layer improves the barrier properties and lowers leakage currents.

The interface-state densities obtained in this study are on the order of $10^{12} \text{eV}^{-1}\text{cm}^{-2}$, which falls within the range commonly reported for MIS-type Schottky structures incorporating oxide interlayers. These interface states may originate from several sources, including dangling bonds at the Al₂O₃/Si interface, oxygen-vacancy-related defects within the oxide layer, grain-boundary-related disorder, and residual structural imperfections associated with the sol-gel deposition process. In addition, the coexistence of α - and β -Al₂O₃ phases may contribute to local structural disorder, thereby increasing the probability of electrically active defect formation. Although the obtained N_{ss} values indicate that the Al₂O₃ layer provides partial interface passivation, the remaining defect density is still sufficiently high to influence carrier transport and contribute to the observed non-ideal electrical behavior.

The current transport mechanism of the Au/Al₂O₃/n-Si/Al diode was further analyzed using the $\ln(I) - \ln(V)$ plot, as shown in Fig. 10. The relationship between current and voltage in such structures can be expressed as [40]:

$$I \propto V^m \quad (16)$$

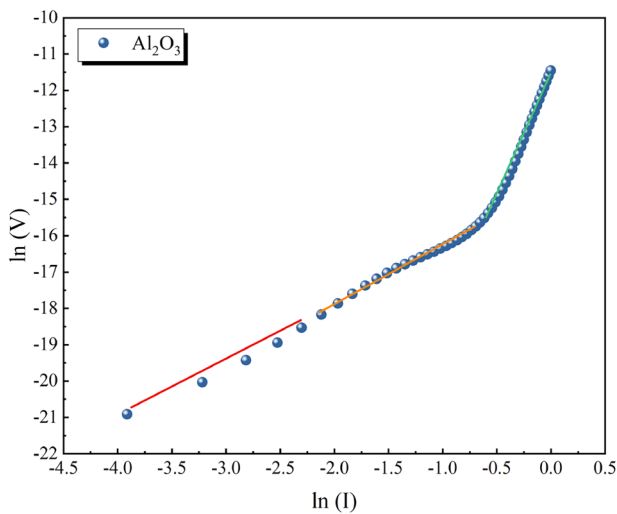


Fig. 10 $\ln I - \ln V$ plot for the Au/Al₂O₃/n-Si/Al Schottky diode

where m is the slope of the $\ln(I) - \ln(V)$ plot and indicates the dominant conduction mechanism. The plot exhibits three distinct linear regions with different slope values, corresponding to different conduction mechanisms.

In the low voltage region (~ 0.05 – 0.2 V), the slope is found to be close to unity ($m \approx 1$), indicating ohmic conduction, where the current is linearly proportional to voltage ($I \propto V$). In this region, the current is controlled by thermally generated free carriers and the effect of traps is negligible. In the intermediate voltage region (~ 0.2 – 0.7 V), the slope increases to approximately $m \approx 2$, which is consistent with SCLC-like transport behavior commonly reported in MIS-type structures. In this region, the injected carrier density exceeds the thermally generated carrier density, leading to the formation of space charge within the device. At higher voltages (~ 0.7 – 1.0 V), the slope further increases ($m > 2$), suggesting transport behavior consistent with trap-influenced SCLC (TCLC)-like conduction. In this region, the traps become filled, and the current is dominated by trap-controlled conduction mechanisms, resulting in a rapid increase in current. The observed slope transitions from ohmic-like to SCLC-like and subsequently trap-influenced transport regions suggest that interface states and electrically active trap levels play an important role in the charge-transport behavior of the diode. Such conduction mechanisms are commonly observed in MIS-type Schottky structures with interfacial layers, where traps and defects strongly influence carrier transport [41].

The assignment of the observed transport regions is based on the characteristic slope transitions obtained from the $\ln(I) - \ln(V)$ analysis and their consistency with transport behaviors frequently reported for MIS-type structures. Additional support is provided by the Mott–Gurney analysis and the extraction of physically meaningful transport parameters, including carrier mobility and diffusion

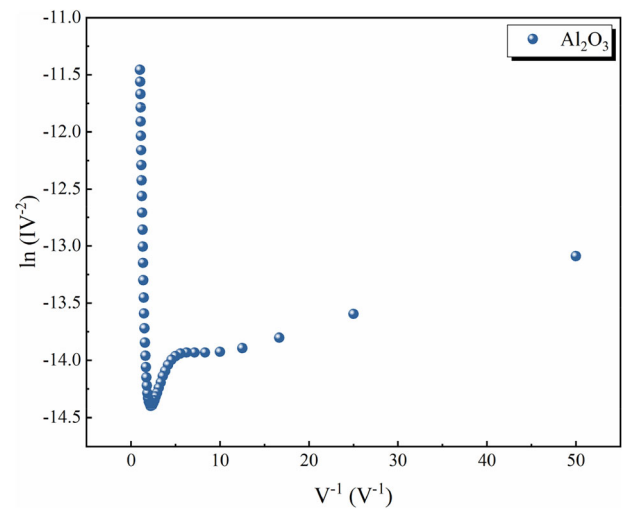


Fig. 11 Fowler–Nordheim (FN) plot of $\ln(I/V^2)$ versus $1/V$ for the Au/Al₂O₃/n-Si/Al Schottky diode under reverse bias conditions

coefficient. Therefore, the identified regions should be interpreted as being indicative of ohmic-like, SCLC-like, and trap-influenced transport behavior within the investigated voltage range rather than as exclusive proof of a single transport mechanism.

Fowler–Nordheim (FN), Poole–Frenkel emission (PFE), and Schottky emission (SE) are taken into consideration via the interface to examine the reverse current transport processes in the SD and MPS diodes. However, at particular applied voltages, a variety of conduction processes may also occur. Because of this, it is difficult to fully understand and evaluate the dependable current transport procedure for the FN, PFE, and SE.

To investigate the dominant reverse current transport mechanism in the Au/Al₂O₃/n-Si/Al diode, Fowler–Nordheim (FN) tunneling analysis was carried out. FN tunneling describes the quantum mechanical tunneling of carriers through a triangular potential barrier under high electric fields. The FN across the junction controls the current, which is described as [42, 43]:

$$I \propto E^2 \exp\left(-\frac{\beta}{E}\right) \quad (17)$$

which can be rearranged in terms of applied voltage as:

$$\ln\left(\frac{I}{V^2}\right) \propto -\frac{1}{V} \ln\left(\frac{I}{V^2}\right) \propto -\frac{1}{V} \quad (18)$$

Therefore, a linear relationship in the plot of $\ln(I/V^2)$ versus $1/V$ indicates that FN tunneling is the dominant current transport mechanism. The corresponding FN plot is shown in Fig. 11. As observed, the curve does not exhibit a clear linear behavior over the entire voltage range. Although limited quasi-linear regions are observed in the FN representation, sustained linearity is not maintained over the

entire investigated reverse-bias range. This suggests that Fowler–Nordheim tunneling is unlikely to be the dominant overall transport mechanism under the present measurement conditions. The overall non-linear behavior of the FN plot suggests that field-emission-related transport, if present, is likely restricted to limited electric-field regions rather than governing the entire reverse-bias characteristic. Therefore, the reverse current is more reasonably interpreted as arising from a combination of field-assisted transport processes, including Schottky-emission-like and trap-assisted mechanisms. This result implies that the electric field across the Al_2O_3 interfacial layer is not sufficiently high to induce significant Fowler–Nordheim tunneling, and that trap-assisted or barrier-lowering mechanisms play a more dominant role in the reverse bias region. It should be noted that the presence of limited quasi-linear regions in the Fowler–Nordheim representation does not allow the complete exclusion of FN-related transport contributions. However, because linearity is not preserved throughout the investigated electric-field range, the observed behavior does not support pure Fowler–Nordheim tunneling as the dominant reverse-current mechanism. Therefore, the FN analysis is interpreted as indicating a possible secondary contribution of tunneling processes under specific field conditions rather than a transport mechanism governing the entire reverse-bias regime.

To identify the dominant reverse current transport mechanism in the $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}/\text{Al}$ diode, Poole–Frenkel emission (PFE) and Schottky emission (SE) mechanisms were analyzed using the $\ln(I_R)$ versus $V_R^{1/2}$ plot, as shown in Fig. 12.

The PFE mechanism describes the field-enhanced thermal emission of carriers from trap states within an insulator, while Schottky emission describes thermionic emission

across a barrier lowered by an electric field. The currents are given by [44, 45]:

$$I_R = I_0 \exp\left(\frac{\beta_{PFE} V^{1/2}}{kTd^{1/2}}\right) \quad (19)$$

$$I_R = AA^* T^2 \exp\left(\frac{-\phi_b}{kT}\right) \exp\left(\frac{\beta_{SE} V^{1/2}}{kTd^{1/2}}\right) \quad (20)$$

$$\beta_{PFE} = 2\beta_{SE} = \left(\frac{q^3}{\pi\epsilon_0\epsilon_r}\right)^{1/2} \quad (21)$$

Theoretical values for β_{PFE} and β_{SC} are determined using Eq. (20); the values for $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}/\text{Al}$ diode are $2.524 \times 10^{-5} \text{ eVm}^{1/2}\text{V}^{-1/2}$ and $1.262 \times 10^{-5} \text{ eVm}^{1/2}\text{V}^{-1/2}$, respectively.

The $\ln(I_R)$ versus $V_R^{1/2}$ plot exhibits two distinct linear regions, indicating different conduction mechanisms. In the low-field region, the experimental value of β was found to be $1.550 \times 10^{-5} \text{ eVm}^{1/2}\text{V}^{-1/2}$ which is in good agreement with the theoretical Schottky emission value. This result shows closer agreement with the theoretical Schottky-emission coefficient than with the Poole–Frenkel coefficient, suggesting that the low-field reverse current behavior is more consistent with Schottky-emission-like transport. In the high-field region, the β value decreases to $7.034 \times 10^{-6} \text{ eVm}^{1/2}\text{V}^{-1/2}$, which deviates from both theoretical PFE and SE values. This deviation suggests the presence of additional effects such as trap-assisted conduction, barrier inhomogeneity, and strong electric field effects. Therefore, the low-field reverse current behavior is more reasonably interpreted as being predominantly consistent with Schottky-emission-like transport, whereas at higher electric fields additional trap-assisted and barrier-lowering processes become increasingly significant.

The distinction between Poole–Frenkel emission and Schottky emission was made based on the relative agreement between the experimentally obtained field-dependent behavior and the theoretical expectations of the respective transport models. The experimental low-field coefficient exhibited closer agreement with the theoretical Schottky-emission value than with the Poole–Frenkel coefficient. Nevertheless, because MIS-type structures frequently exhibit multiple field-assisted transport processes simultaneously, the present analysis should be interpreted as identifying the most probable transport behavior rather than establishing an exclusive conduction mechanism. Consequently, minor contributions from Poole–Frenkel-type transport cannot be completely excluded under certain electric-field conditions.

To further investigate the charge transport properties of the $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}/\text{Al}$ diode under forward bias, the space charge limited current (SCLC) region was analyzed using

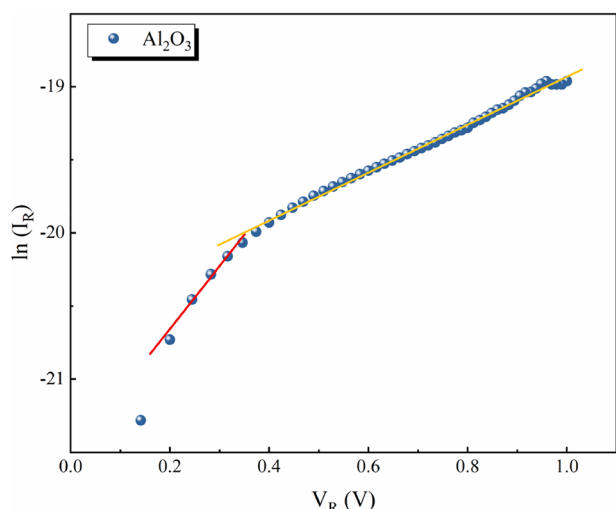


Fig. 12 Plot of $\ln(I_R)$ versus $V_R^{1/2}$ for the $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}/\text{Al}$ Schottky diode

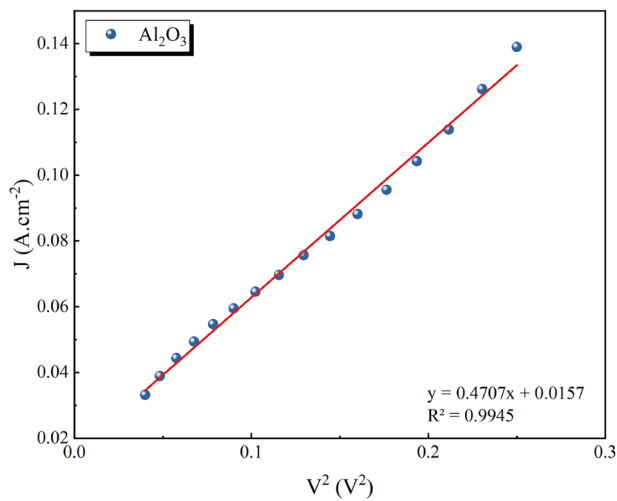


Fig. 13 Current density (J) versus V^2 plot of the Au/Al₂O₃/n-Si/Al diode

the $J - V^2$ characteristics, as shown in Fig. 13. As previously discussed from the $\ln(I) - \ln(V)$ analysis, the device exhibits three conduction regions: ohmic, SCLC, and trap-controlled SCLC (TCLC). Among these, the SCLC region is particularly important for extracting charge transport parameters such as effective carrier mobility (μ_{eff}), transit time (τ), diffusion coefficient (D), and diffusion length (L_D). In the SCLC regime, the current density is governed by the Mott–Gurney equation [46]:

$$J = \frac{9\mu_{eff}\epsilon_0\epsilon_{ox}}{8} \frac{V^2}{d^3} \quad (22)$$

where ϵ_{ox} is the permittivity of Al₂O₃ and J is the current density.

From the relation of Eq. (21), plotting $J - V^2$ yields a linear behavior in the SCLC region. Effective carrier mobility (μ_{eff}) was calculated as $1.17 \times 10^{-7} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ from the slope of the plot. The diffusion coefficient (D) is related to mobility through the Einstein relation [47]:

$$D = \mu_{eff} \frac{kT}{q} \quad (23)$$

Using the calculated mobility value, the diffusion coefficient (D) was calculated as $3.03 \times 10^{-9} \text{ m}^2\text{s}^{-1}$. The linear behavior observed in the plot is consistent with charge transport characteristics commonly associated with the SCLC regime. In this regime, the injected carrier density exceeds the thermally generated carrier density, and the current becomes limited by the space charge formed within the device. The calculated effective mobility (μ_{eff}) is relatively low, which indicates that carrier transport is influenced by scattering processes, interface states, and the presence of the Al₂O₃ interfacial layer. Such reduced mobility values are commonly reported in MIS-type structures, where the insulating layer

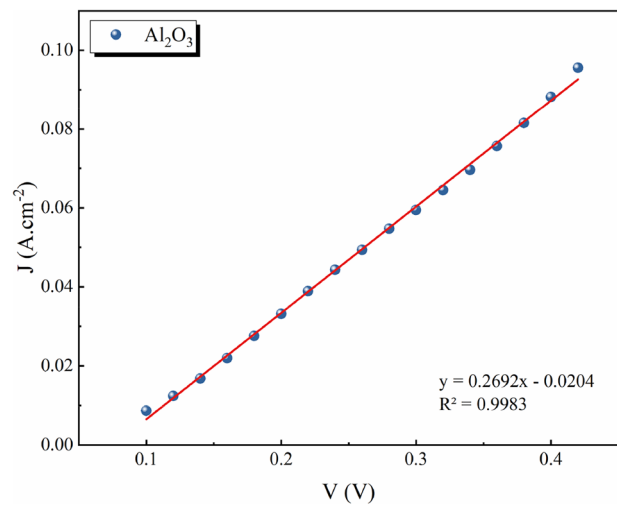


Fig. 14 Current density (J) versus voltage (V) characteristics of the Au/Al₂O₃/n-Si/Al diode

introduces additional barriers and trap states. Similarly, the diffusion coefficient (D) reflects the carrier transport capability within the device. The obtained value suggests limited carrier diffusion, which is consistent with the presence of traps and defects previously identified through N_{ss} analysis. These results support the earlier findings from the $\ln(I) - \ln(V)$ analysis, where the transition from ohmic to SCLC and eventually to trap-controlled conduction was observed. The consistency between these analyses supports the interpretation that space-charge effects and trap-related processes contribute significantly to the charge-transport behavior of the Au/Al₂O₃/n-Si/Al diode.

To further investigate the carrier transport properties of the Au/Al₂O₃/n-Si/Al diode, the transit time (τ) and diffusion length (L_D) were extracted from the forward bias $J - V$ characteristics shown in Fig. 14. As observed in the figure, the $J - V$ curve exhibits a highly linear behavior in the selected voltage range with a strong correlation coefficient ($R^2 = 0.9983$), indicating that this region is suitable for extracting transport parameters. The transit time represents the average time required for charge carriers to traverse the active region of the device. It is related to the carrier mobility and electric field, and can be determined from the slope of the $J - V$ characteristics in the appropriate region. The transit time (τ) and the diffusion length (L_D) are defined as [48]:

$$\tau = \frac{9\epsilon_0\epsilon_r V}{8d J} \quad (24)$$

$$L_D = \sqrt{2D\tau} \quad (25)$$

From the linear region of the $J - V$ curve, the transit time (τ) and the diffusion length (L_D) were calculated as

1.18×10^{-4} s and 8.47×10^{-7} m, respectively. The linear behavior of the J–V curve indicates that the charge transport in this region is governed by drift-dominated carrier motion. The high linearity ($R^2 \approx 0.9983$) confirms the reliability of the extracted parameters. The calculated transit time ($\tau \approx 10^{-4}$ s) suggests relatively slow carrier transport across the device. This behavior can be attributed to the presence of the Al_2O_3 interfacial layer, carrier trapping due to interface states (N_{ss}), and scattering mechanisms within the structure. The diffusion length ($L_D \approx 0.85$ μm) indicates that carriers can travel a moderate distance before recombination. This value is consistent with the previously obtained diffusion coefficient (D) and mobility (μ_{eff}), confirming the internal consistency of the transport analysis. The obtained results support earlier findings from SCLC and trap-controlled conduction analyses, indicating that carrier transport in the Au/ Al_2O_3 /n-Si/Al diode is significantly influenced by trap states and interface effects.

3.2 Capacitance–voltage (C–V) characteristics

The capacitance–voltage ($C - V$) characteristics of the Au/ Al_2O_3 /n-Si/Al diode were measured in the frequency range from 10 kHz to 1 MHz under dark conditions, and the results are presented in Fig. 15. The obtained $C - V$ curves exhibit three distinct regions that are characteristic of MIS-type structures: inversion, depletion and accumulation regions. However, due to the Schottky nature of the contact, these regions show slight deviations from ideal MOS behavior.

In the voltage range from -1 V to ~ 0.3 – 0.4 V, the capacitance remains almost constant and relatively low. This region corresponds to the inversion region, where the depletion layer width increases with increasing reverse bias voltage. However, due to the relatively slow variation of the

depletion width, the capacitance appears nearly constant over this voltage range. As the applied voltage increases beyond 0.3 – 0.4 V toward positive bias, the capacitance begins to increase rapidly. This region corresponds to the depletion region, where the depletion width decreases and more charge carriers are involved in the conduction process. The increase in capacitance in this region is associated with the narrowing of the depletion layer and enhanced carrier response. At higher forward voltages, the capacitance reaches a maximum and then tends to remain almost constant, especially at high frequencies. This region corresponds to the deposition region where a high density of carriers accumulates at the semiconductor interface. In this region, the capacitance is determined by the dielectric layer and exhibits a relatively weak voltage dependence.

As can also be seen in Fig. 15, a strong frequency dependence is observed in all regions. At low frequencies (10–100 kHz), the capacitance values are higher, while at higher frequencies (≥ 500 kHz–1 MHz), the capacitance decreases. This behavior is attributed to interface states. At low frequencies, interface states can follow the AC signal and contribute to the capacitance. At high frequencies, interface states cannot respond, and their contribution becomes negligible. Therefore, the capacitance decreases with increasing frequency. The arrows shown in Figs. 15, 16, 17, 18 and 19 represent the direction of increasing frequency. The presence of well-defined inversion, depletion, and accumulation regions indicates that the Au/ Al_2O_3 /n-Si/Al structure behaves similarly to a MIS-type device, although it is not an ideal MOS capacitor. The nearly constant capacitance in the reverse bias region confirms that the depletion layer is fully developed and stable. The sharp increase in capacitance in the intermediate region reflects the voltage-dependent modulation of the depletion width. Finally, the saturation of capacitance at higher forward bias voltages confirms the formation of an accumulation layer. The strong frequency

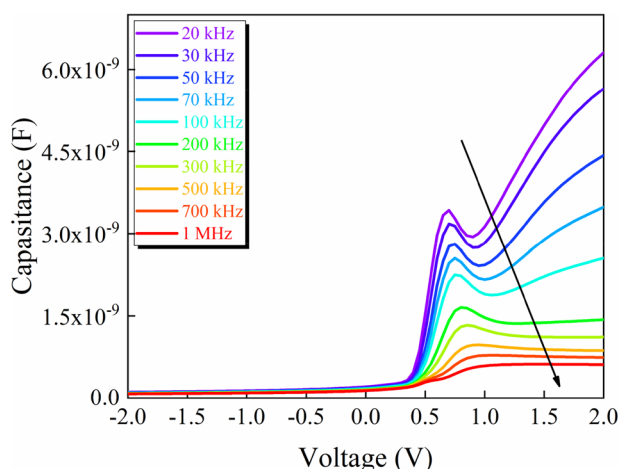


Fig. 15 Capacitance–voltage ($C - V$) characteristics of the Au/ Al_2O_3 /n-Si/Al diode measured at different frequencies (10 kHz–1 MHz)

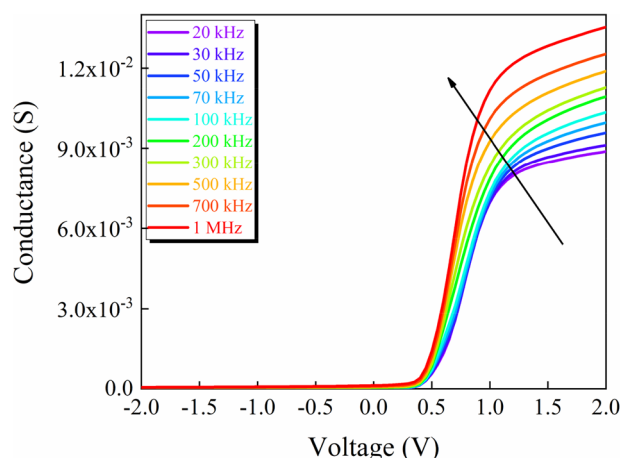


Fig. 16 Conductance–voltage ($G - V$) characteristics of the Au/ Al_2O_3 /n-Si/Al diode measured at different frequencies (10 kHz–1 MHz)

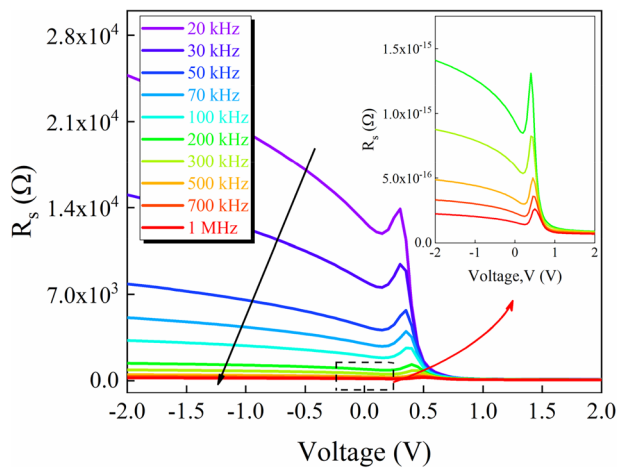


Fig. 17 Series resistance (R_s) versus V for the Au/Al₂O₃/n-Si/Al diode at different frequencies

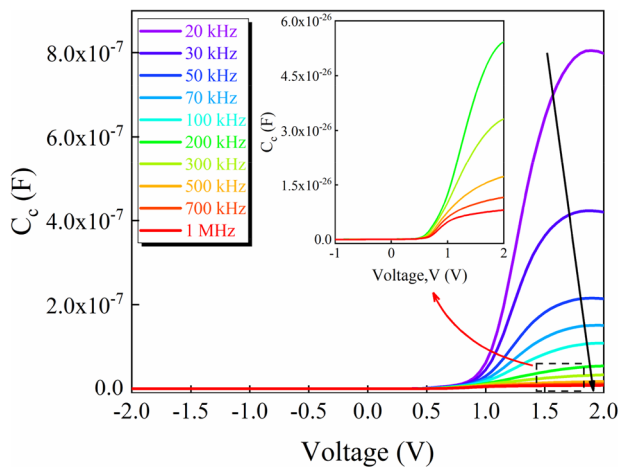


Fig. 18 Corrected capacitance (C_c) versus V characteristics at different frequencies

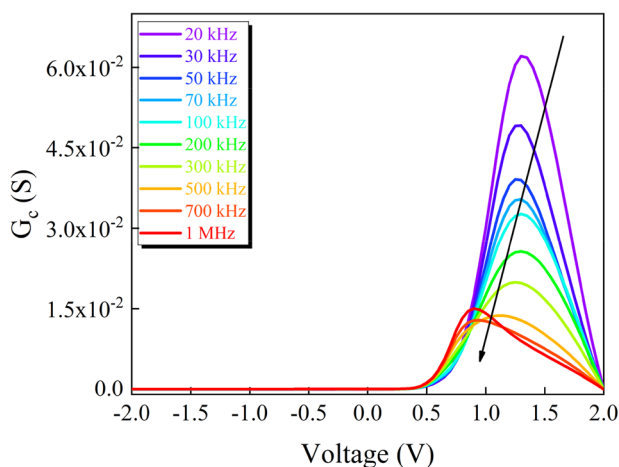


Fig. 19 Corrected conductance (G_c) versus V characteristics showing a pronounced peak due to interface states

dispersion observed across all regions suggests that interface states (N_{ss}) and interfacial polarization effects play a significant role in the electrical response of the device.

The conductance–voltage ($G - V$) characteristics of the Au/Al₂O₃/n-Si/Al diode were measured in the frequency range from 10 kHz to 1 MHz under dark conditions, and the results are presented in Fig. 16. As observed in the Fig. 16, the conductance strongly depends on both the applied voltage and frequency. In the reverse bias region (-1 V to -0.3 – 0.4 V), the conductance remains very low and nearly constant for all frequencies. This behavior indicates that the carrier transport is limited due to the wide depletion region and the absence of significant charge exchange processes.

As the applied voltage increases toward the forward bias region, the conductance increases sharply. This increase begins around 0.4 – 0.5 V, which corresponds to the transition from the depletion region to the accumulation region. In this region, the depletion width decreases, carrier injection increases, and charge exchange between interface states and the semiconductor becomes more significant. As a result, the conductance rises rapidly with increasing voltage. At higher forward bias voltages, the conductance continues to increase and tends to saturate. This behavior is associated with carrier accumulation at the interface, enhanced conduction through the device, and influence of series resistance. Moreover, The observed $G - V$ characteristics confirm that the electrical behavior of the Au/Al₂O₃/n-Si/Al diode is strongly influenced by interface states and interfacial polarization effects. The frequency-dependent behavior further supports the presence of interface states, which contribute to energy loss mechanisms and affect the AC response of the device. These findings are consistent with the previously obtained N_{ss} results and the non-ideal diode behavior observed in $I - V$ analysis.

3.3 Series resistance (R_s) and corrected capacitance/ conductance analysis

To further investigate the non-ideal electrical behavior of the Au/Al₂O₃/n-Si/Al diode, the series resistance (R_s) and corrected capacitance (C_c) and conductance (G_c) characteristics were analyzed using the admittance data obtained from $C - V$ and $G - V$ measurements. In MIS-type structures, the presence of an interfacial layer and interface states leads to significant deviations from ideal behavior. One of the main contributors to this non-ideality is the series resistance (R_s), which arises from the bulk semiconductor, interfacial layer, and contact resistance.

The series resistance was calculated using the Nicollian–Goetzberger method based on the measured capacitance (C_m) and conductance (G_m) values [49, 50]:

$$R_s = \frac{G_m}{G_m^2 + (\omega C_m)^2} \quad (26)$$

where $\omega = 2\pi f$ is the angular frequency. The variation of R_s as a function of applied voltage for different frequencies is shown in Fig. 17. As observed in the $R_s - V$ plots, R_s values are relatively high in the reverse bias region, R_s decreases significantly with increasing forward bias voltage, and a pronounced peak is observed around the transition region (~ 0.4 – 0.5 V). This peak behavior is associated with the transition from depletion to accumulation, maximum interaction between interface states and carriers, and enhanced charge trapping and detrapping processes. Furthermore, R_s decreases with increasing frequency, which is consistent with literature reports. This behavior is attributed to the reduced contribution of interface states at higher frequencies.

To eliminate the effect of series resistance, the measured capacitance and conductance values were corrected using the following relations [51]:

$$C_c = \frac{(G_m^2 + \omega^2 C_m^2)C_m}{a^2 + \omega^2 C_m^2}, G_c = \frac{(G_m^2 + \omega^2 C_m^2)a}{a^2 + \omega^2 C_m^2} \quad (27)$$

Where

$$a = G_m^2 - (G_m^2 + \omega^2 C_m^2)R_s \quad (28)$$

These correction equations are widely used in MIS structures to obtain intrinsic dielectric parameters free from series resistance effects. The variation of C_c as a function of applied voltage for different frequencies is shown in Fig. 18. As seen in Fig. 18, the corrected capacitance values increase significantly in the forward bias (accumulation) region and remain nearly unchanged in the reverse bias (inversion) region. The increase in C_c at higher voltages is associated with carrier accumulation at the interface and increased polarization of the Al_2O_3 layer. The negligible difference between corrected and uncorrected capacitance in the depletion region indicates that the effect of R_s is minimal in this region.

The variation of G_c as a function of applied voltage for different frequencies is shown in Fig. 19. The $G_c - V$ plots exhibit a pronounced peak in the forward bias region (around 0.9–1.3 V), which becomes more evident after correction. This peak is attributed to the distribution of interface states, maximum energy exchange between traps and carriers, and resonance-like response of interface states. Such peak behavior is a well-known characteristic of MIS structures and is directly related to the interface state density distribution.

The combined analysis of R_s , C_c , and G_c confirms that series resistance significantly affects the forward bias region, interface states dominate the dielectric response, and the Al_2O_3 interfacial layer introduces polarization and trapping effects. The decrease of R_s with increasing

frequency and voltage indicates improved carrier transport at higher energies, while the corrected conductance peak strongly supports the presence of interface traps.

In order to further investigate the interface properties of the $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}/\text{Al}$ diode, the interface state density (N_{ss}) was determined using the Hill–Coleman method based on the corrected conductance (G_c) data. This method is widely used for extracting interface state density in MIS structures by utilizing the peak values of conductance in the $G - V$ characteristics. According to the Hill–Coleman approach, the interface state density is given by [52]:

$$N_{ss} = \frac{2(G_{c,\max}/\omega)}{q} A \left[(G_{c,\max}/\omega C_{ox})^2 + (1 - C_c/C_{ox})^2 \right]^{-1} \quad (29)$$

where $G_{c,\max}$ is the maximum conductance value at a given frequency, C_c is the corrected capacitance, C_{ox} is the oxide capacitance, and A is the diode area. The interface state density values were calculated at different frequencies using the peak points of the $G_c - V$ curves and are plotted as a function of frequency in Fig. 19. As observed in Fig. 20, N_{ss} increases with frequency up to ~ 500 kHz and reaches a maximum value of about $7.15 \times 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$, and then decreases at higher frequencies.

The variation of N_{ss} with frequency exhibits a non-monotonic behavior. At low frequencies (20–100 kHz), N_{ss} values are relatively low because interface states can fully follow the AC signal, leading to efficient charge exchange. At intermediate frequencies (200–500 kHz), N_{ss} increases significantly and reaches a maximum. This region corresponds to the frequency range where the interface states respond partially to the AC signal, resulting in maximum energy loss and conductance peak. At high frequencies

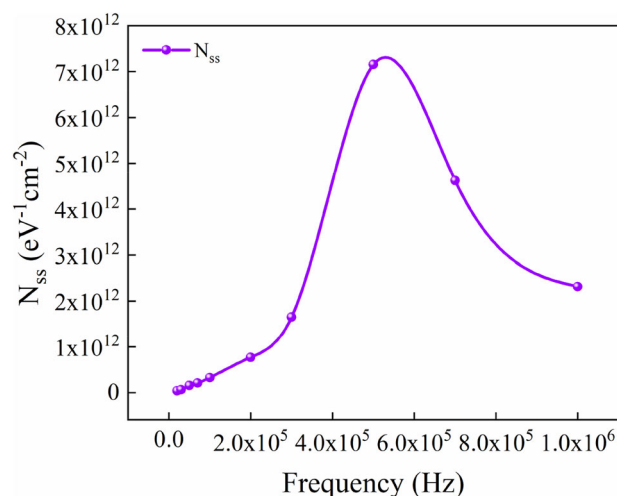


Fig. 20 Variation of interface state density (N_{ss}) as a function of frequency for the $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}/\text{Al}$ diode obtained using the Hill–Coleman method

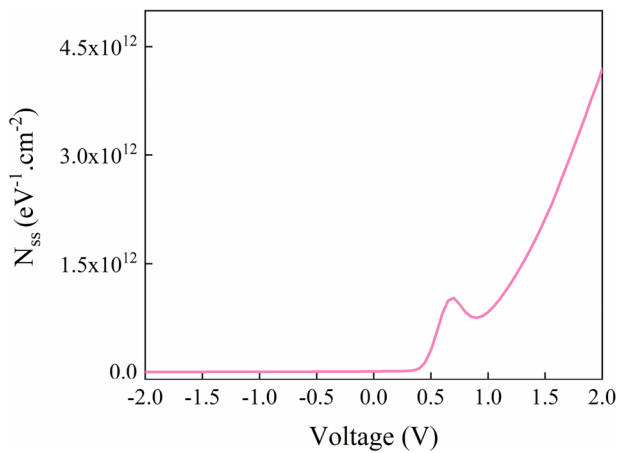


Fig. 21 Interface state density (N_{ss}) as a function of applied voltage obtained using the high–low frequency method (20 kHz–1 MHz) for the Au/Al₂O₃/n-Si/Al diode

(≥ 700 kHz–1 MHz), N_{ss} decreases because interface states can no longer follow the AC signal, and their contribution becomes negligible.

In order to further evaluate the interface state density (N_{ss}) of the Au/Al₂O₃/n-Si/Al diode, the high–low frequency capacitance method was applied using the $C-V$ data measured at 20 kHz (low frequency) and 1 MHz (high frequency). The resulting $N_{ss}-V$ variation is shown in Fig. 21.

The high–low frequency method is based on the fact that interface states can follow low-frequency AC signals but cannot respond to high-frequency signals. At low frequency (20 kHz), the interface states contribute to the measured capacitance. At high frequency (1 MHz), the interface states cannot respond, and only the depletion capacitance is measured

The interface state density is calculated using [53]:

$$N_{ss} = \frac{1}{qA} \left[\left(\frac{1}{C_{LF}} - \frac{1}{C_{HF}} \right)^{-1} - \left(\frac{1}{C_{HF}} - \frac{1}{C_{ox}} \right)^{-1} \right] \quad (30)$$

where C_{LF} is the low-frequency capacitance, C_{HF} is the high-frequency capacitance, C_{ox} is the oxide capacitance, and A is the diode area.

As shown in Fig. 21, the interface state density exhibits a strong dependence on the applied voltage. In the reverse bias region, N_{ss} remains very low and nearly constant. The low N_{ss} values in the reverse bias region indicate that the interface states are not actively participating in carrier exchange due to the wide depletion region. In the transition region (~ 0.4 – 0.6 V), N_{ss} increases sharply. As the voltage increases, the depletion width decreases and the Fermi level moves closer to the interface states, enabling stronger interaction between carriers and traps. This leads to a significant increase in N_{ss} . In the forward bias region, N_{ss}

continues to increase and reaches values on the order of $10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$. The rapid increase in N_{ss} corresponds to the region where interface states actively exchange charge with the semiconductor. The continuous increase in the forward bias region reflects the enhanced carrier trapping and detrapping, increased interface state activity, and strong influence of the Al₂O₃ interfacial layer

3.4 Determination of electrical parameters from the $1/C_c^2 - V$ characteristics

To obtain the main electrical parameters of the Au/Al₂O₃/n-Si/Al diode, the corrected capacitance data were used and the $1/C_c^2 - V$ plots were analyzed at different frequencies. In MIS-type structures, the corrected capacitance is more suitable than the measured capacitance for extracting junction parameters because it minimizes the influence of series resistance and yields more reliable depletion-region information. Similar approaches have been widely used in the literature for MIS structures. For an n-type MIS diode, the depletion capacitance is related to the donor concentration by [3, 54]:

$$\frac{1}{C^2} = \frac{2(V_0 + V)}{\epsilon_s \epsilon_0 q A^2 N_D} \quad (31)$$

where V is the applied voltage, q is the electronic charge, A is the diode area, ϵ_s is the dielectric constant of Si, ϵ_0 is the permittivity of free space, and N_D is the donor concentration. Therefore, the slope of the linear part of the $1/C_c^2 - V$ plot gives the donor concentration, while the intercept yields the intercept voltage V_0 . This treatment is standard for MIS junction analysis. The donor concentration was calculated from the slope using:

$$N_D = \frac{2}{A^2 \epsilon_s \epsilon_0 q} \frac{dV}{d(C^{-2})} \quad (32)$$

From the extracted V_0 and N_D values, the diffusion potential V_D , Fermi level E_F , maximum electric field E_m , image-force barrier lowering $\Delta\Phi_b$, barrier height Φ_b , and depletion width W_D were determined using the following relations:

$$V_D = V_0 + \frac{kT}{q}; E_F = \frac{kT}{q} \ln \left(\frac{N_c}{N_D} \right) \quad (33)$$

$$W_D = \left(\frac{2\epsilon_s \epsilon_0 V_D}{q N_D} \right)^{-1/2}; E_m = \left(\frac{2q N_D V_0}{\epsilon_s \epsilon_0} \right)^{1/2}; \Delta\Phi_b = \left(\frac{q E_m}{4\pi \epsilon_s \epsilon_0} \right)^{1/2} \quad (34)$$

$$\Phi_b(C - V) = V_D + E_F - \Delta\Phi_b \quad (35)$$

$$c_2 \cong \frac{N_D(\text{experimental})}{N_D(\text{theoretical})} = \frac{1}{1 + \beta}; \beta = q\delta N_{ss}/\epsilon_{ox} \quad (36)$$

The variation of $1/C_c^2$ as a function of applied voltage for different frequencies is shown in Fig. 22. The $1/C_c^2 - V$ plots obtained at different frequencies show good linearity in the reverse-bias region, indicating that the corrected capacitance data are suitable for extracting the electrical parameters of the device. The calculated values are summarized in Table 2. According to the results, the donor concentration N_D decreases from $3.828 \times 10^{14} \text{ cm}^{-3}$ at 20 kHz to $1.939 \times 10^{14} \text{ cm}^{-3}$ at 1 MHz, whereas V_0 , V_D , E_F , Φ_b , and W_D increase with frequency. In contrast, the image-force barrier lowering $\Delta\Phi_b$ and the maximum electric field E_m decrease slightly with increasing frequency. This frequency dependence indicates that interface states, interfacial polarization, and the frequency-dependent response of the depletion region influence the extracted electrical parameters. This apparent reduction in donor concentration is not due to a physical change in doping, but rather reflects the reduced contribution of interface states and slow traps at higher frequencies, leading to a more intrinsic capacitance response. Similar frequency-dependent behavior has been reported for MIS-type structures in the literature.

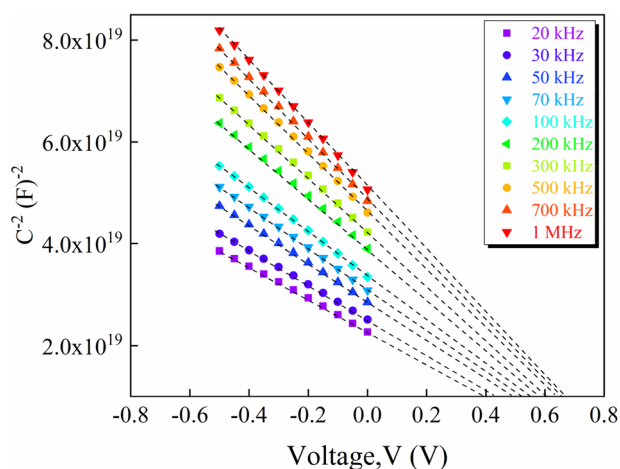


Fig. 22 $1/C_c^2 - V$ plots of the Au/Al₂O₃/n-Si/Al diode measured at different frequencies

The Fermi level E_F shifts slightly upward with increasing frequency (from 0.234 eV to 0.252 eV), which is consistent with the decrease in N_D and indicates a shift in the equilibrium carrier distribution. Similarly, both the intercept voltage V_0 and built-in potential V_D increase with frequency, suggesting that the junction potential becomes more pronounced when the influence of interface states diminishes. The depletion width W_D increases with frequency, ranging from $1.597 \times 10^{-4} \text{ cm}$ at 20 kHz to $2.380 \times 10^{-4} \text{ cm}$ at 1 MHz. This behavior is directly related to the decrease in N_D and reflects a widening of the depletion region when fewer charges contribute to the capacitance at higher frequencies. The maximum electric field E_m decreases slightly with increasing frequency, which is consistent with the reduction in effective charge concentration contributing to the space charge region. Consequently, the image-force barrier lowering $\Delta\Phi_b$ also shows a slight decrease, indicating a reduced electric field-induced barrier deformation at higher frequencies.

The barrier height Φ_b extracted from the $C - V$ analysis shows a noticeable increase from 0.972 eV at 20 kHz to 1.084 eV at 1 MHz. This trend is a well-known phenomenon in MIS-type structures and arises because, at low frequencies, interface states can follow the AC signal and artificially increase the measured capacitance, leading to an underestimation of the barrier height. At higher frequencies, their contribution is suppressed, and the extracted barrier height approaches the true Schottky barrier.

The interfacial capacitance parameter c_2 decreases significantly with increasing frequency, reflecting the reduced polarization and interface state contribution at higher frequencies. In parallel, the interface state density N_{ss} exhibits a non-monotonic variation: it increases from $8.94 \times 10^{11} \text{ eV}^{-1} \text{ cm}^{-2}$ at 20 kHz to a maximum of $\sim 5.48 \times 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$ around 700 kHz, followed by a decrease to $2.45 \times 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$ at 1 MHz. This behavior indicates a distribution of interface states with different time constants, where mid-frequency ranges correspond to maximum trap activity.

Table 2 Electrical parameters extracted from the $1/C_c^2 - V$ analysis of the Au/Al₂O₃/n-Si/Al diode at different frequencies

Frequency	$N_D \text{ (cm}^{-3}\text{)}$	$E_f \text{ (eV)}$	$V_0 \text{ (V)}$	$V_{bi} \text{ (V)}$	c_2	$\Phi_b \text{ (eV)}$	$E_m \text{ (V.cm}^{-1}\text{)}$	$\Delta\Phi_b \text{ (eV)}$	$W_d \text{ (cm)}$	$N_{ss} \text{ (eV}^{-1}\text{.cm}^{-2}\text{)}$
20 kHz	3.82×10^{14}	0.23	0.72	0.75	0.83	0.97	9.36×10^3	1.07×10^{-2}	1.59×10^{-4}	0.89×10^{12}
30 kHz	3.61×10^{14}	0.24	0.75	0.75	0.78	1.00	9.27×10^3	1.06×10^{-2}	1.68×10^{-4}	1.20×10^{12}
50 kHz	3.22×10^{14}	0.24	0.76	0.76	0.70	1.02	8.82×10^3	1.04×10^{-2}	1.79×10^{-4}	1.86×10^{12}
70 kHz	3.00×10^{14}	0.24	0.77	0.77	0.65	1.03	8.55×10^3	1.02×10^{-2}	1.86×10^{-4}	2.31×10^{12}
100 kHz	2.79×10^{14}	0.24	0.78	0.78	0.60	1.04	8.29×10^3	1.01×10^{-2}	1.94×10^{-4}	2.80×10^{12}
200 kHz	2.46×10^{14}	0.25	0.80	0.80	0.53	1.06	7.87×10^3	0.98×10^{-2}	2.09×10^{-4}	3.76×10^{12}
300 kHz	2.29×10^{14}	0.24	0.81	0.80	0.50	1.07	7.65×10^3	0.97×10^{-2}	2.17×10^{-4}	4.33×10^{12}
500 kHz	2.12×10^{14}	0.25	0.81	0.81	0.46	1.08	7.39×10^3	0.95×10^{-2}	2.27×10^{-4}	5.04×10^{12}
700 kHz	2.03×10^{14}	0.25	0.81	0.81	0.44	1.08	7.22×10^3	0.94×10^{-2}	2.33×10^{-4}	5.48×10^{12}
1 MHz	1.94×10^{14}	0.25	0.82	0.82	0.42	1.08	7.07×10^3	0.93×10^{-2}	2.38×10^{-4}	2.45×10^{12}

Overall, these results demonstrate that the electrical parameters extracted from the $1/C_c^2 - V$ analysis are strongly frequency-dependent and are significantly influenced by interface states, interfacial polarization, and the dielectric properties of the Al_2O_3 layer. The consistent trends observed across all parameters further confirm that the device exhibits non-ideal MIS-type behavior dominated by interface-related effects.

4 Conclusion

In conclusion, a comprehensive and self-consistent analysis of the $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}$ MIS Schottky diode was achieved by combining structural, morphological, and advanced electrical characterization techniques. XRD analysis revealed the coexistence of dominant α - Al_2O_3 and transition alumina phases, indicating partial phase transformation and structural disorder. SEM and EDS analyses indicated a relatively uniform and dense surface morphology without observable large-scale cracks or voids, along with homogeneous elemental distribution across the film surface. These results confirm that the sol-gel process produces a well-covered and compositionally uniform Al_2O_3 layer at the microscale. However, when evaluated together with XRD findings, it is evident that the film contains nanoscale structural inhomogeneities, including phase coexistence, lattice distortions, and crystallographic defects. This apparent contrast between morphological uniformity and electrical non-ideality indicates that defect generation is governed primarily by crystallographic disorder rather than surface-level imperfections.

The electrical characterization results exhibit a physically consistent qualitative relationship with these structural findings. The diode exhibits non-ideal behavior with an ideality factor $n \approx 2.30$ and a barrier height of ~ 0.85 eV, consistently obtained from different methods. The charge transport behavior evolves from ohmic-like conduction to SCLC-like and trap-influenced transport regimes, suggesting that electrically active trap states contribute significantly to the carrier-transport behavior, particularly at higher bias levels. Reverse-bias analysis suggests that the low-field transport behavior is more consistent with Schottky-emission-like conduction, while trap-assisted processes become increasingly important at higher electric fields. The interface state density (N_{ss}) was systematically evaluated using multiple complementary techniques, including the Hill-Coleman method and high-low frequency capacitance approach, yielding consistent values on the order of $10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$. The agreement between these independent methods supports the reliability of the extracted interface parameters and reveals a strong energy and frequency dependence, indicating a continuous distribution of interface traps across

the bandgap. Furthermore, frequency-dependent $C-V$ analysis demonstrates that key parameters such as donor concentration, barrier height, and depletion width are significantly influenced by interface states and interfacial polarization effects. Consequently, the combined structural and electrical characterization results suggest that structural disorder and interface-state dynamics contribute significantly to the observed non-ideal electrical behavior of the device.

While the Al_2O_3 interfacial layer improves rectification behavior and reduces leakage currents, the presence of defects arising from phase coexistence and morphological inhomogeneity remains the dominant factor limiting ideal device performance. This study highlights the critical importance of controlling the microstructure and interface quality of dielectric layers, as well as employing complementary characterization techniques, for achieving improved performance in MIS-type Schottky devices.

Future studies involving multiple samples with systematically controlled microstructural variations and complementary defect-sensitive characterization techniques will be necessary to establish a rigorous quantitative correlation between crystallographic disorder, interface-state density, and charge-transport behavior. Such investigations would provide deeper insight into the structure-property relationships governing the electrical performance of $\text{Au}/\text{Al}_2\text{O}_3/\text{n-Si}$ MIS Schottky devices.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions N Kaya: Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Writing - Review & Editing, A Seçkin: Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Writing - Original Draft, P Oruç: Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Writing - Original Draft. The final manuscript was read and approved by all authors.

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Compliance with ethical standards

Competing interests The authors declare no competing interests.

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