Properties of AlN thin film as dielectric for Au/Ti/n-Si device

Esra Dilber YILDIZ (✉ desrayildiz@hitit.edu.tr)

<https://orcid.org/0000-0003-2212-199X>

A. Tataroglu

Research Article

Keywords: AlN thin film, Admittance measurements, Dielectric parameters, Conductivity, Modulus

Posted Date: February 9th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1332886/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Properties of AlN thin film as dielectric for Au/Ti/n-Si device

D.E. Yıldız ^{1*} and A. Tataroglu ²

¹ Physics Department, Faculty of Arts and Sciences, Hitit University, Çorum, Turkey

² Department of Physics, Faculty of Science, Gazi University, Ankara, Turkey

Corresponding author: desrayildiz@hitit.edu.tr (D.E. Yıldız)

Abstract

The purpose of this study is to investigate the electric and dielectric properties of Au/Ti/AlN/n-Si device with using admittance measurements. Aluminum nitride (AlN) epitaxial template on n-Si substrate was deposited by a hydride vapor phase epitaxy (HVPE) technique. Au/Ti contact was thermally evaporated on AlN thin film. Thus, admittance measurements ($Y=G+i\omega C$) of the fabricated device were performed and analyzed for frequencies ranging from 1 kHz to 1000 kHz and at room temperature. The capacitance-voltage (C-V) and conductance-voltage (G/ω -V) characteristics shown a strong frequency dependence. This behavior is associated with the reaction of the interface traps to the applied ac signal. Also, the dielectric parameters, conductivity, and electric modulus of the device were extracted from capacitance and conductance data. The obtained results suggest that the prepared device can be used as a capacitor in electronic circuits.

Keywords: AlN thin film; Admittance measurements; Dielectric parameters; Conductivity; Modulus

1. Introduction

The III-V nitride thin films such as gallium nitride (GaN), indium nitride (InN) and aluminum nitride (AlN) have a major potential in the technology of compound semiconductors and electronic/optoelectronic device applications [1-3]. Moreover, the III-V nitrides are used as insulator or dielectric materials for metal-insulator/oxide-semiconductor (MIS/MOS) capacitors and MIS/MOS-high electron mobility transistors (MIS/MOS-HEMTs [4-6]. Aluminum nitride (AlN) is one of the significant III-V nitrides due to the electrical properties such as a high dielectric constant, excellent thermal conductivity, high electrical resistivity and wide bandgap [6-8]. Therefore, AlN with good dielectric properties are particularly suitable for applications in metal-insulator-metal (MIM) and MIS/MOS devices. The point defects such as N vacancies and Si atoms diffusing from Si substrate due to the high grown temperatures are accounted for the dielectric response of AlN through the formation of dipoles [8]. AlN films can be successfully deposited on various substrates such as silicon (Si) and silicon carbide (SiC) by metal-organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), magnetron sputtering, and atomic layer deposition (ALD) [7-9].

The admittance spectroscopy (AS) is an experimental method used to investigate the electrical characteristics of the semiconductor devices [10-13]. On the other words, admittance spectroscopy examines the current response of a device to ac bias voltage. Admittance spectroscopy includes the measurement of the complex admittance. Admittance consists of a parallel connection of a capacitance and a conductance. Therefore, admittance measurements are based on the capacitance-voltage (C-V) and conductance-voltage (G-V) measurements of a device as a function of frequency and temperature. Admittance spectroscopy allows the determination of the interface trap density, time constant of the traps and series resistance. At the same time, the frequency-dependent dielectric properties are extracted from the admittance data.

In this study, we analyzed the dielectric and electric properties of the prepared Au/Ti/AlN/n-Si/Au device with the use of the admittance measurements. The fabricated device was modeled with a parallel equivalent circuit and the admittance data were evaluated assuming this circuit. The capacitance and conductance measurements were implemented in the frequency range of 1 kHz-1000 kHz with variation dc bias voltage. The dielectric behavior of the device was characterized using the admittance measurements.

2. Experimental details

The Au/Ti/AlN/n-Si device was fabricated using AlN epitaxial template on n-Si wafer. AlN epitaxial template on Si (AlN/n-Si) has been prepared by a hydride vapor phase epitaxy (HVPE)- a based method where the sample is purchased from MTI Corporation. For the fabrication process, first the Si/AlN sample were exposed to a sequential cleaning process including acetone, 2-propanol and de-ionized water (18 MW.cm) using ultrasonic bath for 5 mins, respectively. There after the cleaning step, Si/AlN samples were dried under N₂ gas flow and final treatment was done by placing Si/AlN sample into Harrick Plasma Cleaner for 5 mins. Then, high purity (99.999%) gold (Au) (100 nm) was thermally evaporated onto the whole backside of Si/AlN sample at a pressure of $\sim 10^{-6}$ Torr and ohmic contacts were formed by thermal annealing at 500 °C for 5 min. After ohmic contact, titanium (Ti) (5 nm) and Au (100 nm) were thermally evaporated onto the AlN surface through metal mask with circular dots of ~ 1 mm diameter, respectively and Au/Ti/AlN/n-Si device was formed. The schematic model and energy band diagram of the device is shown in Fig.1(a). In order to analyze surface morphology of the AlN layer, (SEM) images were obtained by Zeiss-Evo SEM. SEM image of the AlN is shown in Figure 1 (b).

The capacitance and conductance measurements of the Au/Ti/AlN/n-Si device were performed by a HP 4192A LF impedance analyzer in the wide range of dc voltage (± 5 V) by 50 mV steps and in the frequency range of 1 kHz-1000 kHz at room temperature.

Figure 1 **(a)** Energy-band diagram and **(b)** SEM image of device

3. Results and discussion

Figure 2 (a) $C - V$ and (b) $C - f$ plots of the device at room temperature

Electrical characteristics of the device are investigated by $G - V$ and $C - V$ measurements in the range of 1 kHz – 1000 kHz at room temperature under dark conditions by impedance analyzer. Figure 2 (a) and (b) indicate the variations of the C with V at various frequencies and the variations of C with f at different voltages of the device, respectively. Figure 2 (a) indicated that the voltage dependence of C especially had a peak in the frequency range 1 kHz to 30 kHz and the C was frequency-independent down below 0.2 V and above 1.6 V. In addition, the value of C increased with decreasing frequency. As seen Figure 2 (b), the value of C was changed to be a function of voltage in the frequency range 1kHz to 100 kHz. The frequency dependent of C indicated decrease with increasing frequency at each voltage.

At low frequencies, the increase in capacitance values was associated with the presence of interfacial states in the device, and observed capacitance was affected by the formation of interfacial space charge [14]. The C value at low frequencies was higher than at higher frequencies. This is due to the capacitance caused by the interface state density in equilibrium with the semiconductor, which could trace the ac signal at low frequencies. In fact, the interface

state density could easily trace the signal in these range and increase the capacitance of the device. This behavior is attributed the relaxation time of the charges and the intrinsic properties of the interface states according to the applied frequency. The interfacial layer could be polarized by displacement of charges in the interfacial states from their equilibrium and exhibit an electrochemical response to the electric field [15, 16]. Therefore, the polarization created by the interface state charges affects the high capacitance due to their time-dependent response. However, at high frequencies, charges cannot follow the ac signal, so their effect on the total capacitance is negligible. Therefore, the non-ideal behavior observed in the input spectra may be due to the barrier height in the device and the formation and inhomogeneities in the insulator layer.

In this case, R_s and D_{it} are especially important parameters affecting the frequency dependence of electrical parameters such as capacitance, conductance, dielectric constant, tangent loss and modulus [17].

Figure 3 (a) $G/w - V$ and (b) $G/w - f$ plots

Figure 4 (a) $R_s - V$ and (b) $R_s - f$ plots

Figure 3 (a) and (b) show the variations of the G/w with V at different frequencies and the variations of G/w with f at different voltages of the device, respectively. As can be seen Figure 3 (a), at low frequencies, the obtained G/ω value as a function of V is responsive in the forward bias region. As seen Figure 3 (b), G/w shows a gradual decrease with increasing frequency at each voltage.

The AlN dielectric material at the interface can be the cause in series resistance (R_s) change in the device along with the localization and presence of surface states [18, 19]. C-V plot indicates a peak in deep depletion region, and G/w -V plot has decrease with increasing frequency. As seen Figure 2 (a) and Figure 2 (b), the frequency and voltage dependence capacitance can be occurred due to localized interface charges and R_s [20]. The non-ideal behaviors show the impact of AlN interfacial that is account for the changes in D_{it} and R_s . The variation in bias voltage can be assessed under capacitance of the AlN layer, internal resistance, and the impacts of interfacial resistance. Discarding the AlN layer with boundaries at semiconductor layers and metal, series resistance can be based on inhomogeneity in the device,

charges flow from rectifying contact to the ohmic contact direct the device and ohmic contact behavior [18, 21]. The contribution of the AlN interfacial capacitance to the values of R_s is analyzed using frequency and voltage dependent C and G/w measurements. The results are calculated by Nicollian and Brews method in strong accumulation region [22]:

$$R_s = \frac{G_{ma}}{G_{max}^2 + (\omega C_{max})^2} \quad (1)$$

R_s -V and R_s -f plots are shown in Figure 4. As seen these plots, the values of R_s are remarkably dependent on both frequency and voltage. In reality, it is watched that the change in value of R_s is more violent at low frequency regions. As seen Figure 4. (a) R_s -V plots have a peak from 1 kHz to 10 kHz range. The peak values of R_s -V plots are 3.57×10^4 W in 0.25 V and 2.58×10^3 in 0.40 V for 1 kHz and 10 kHz, respectively. It's seen that R_s -V plot peaks shift to the positive voltage region and the R_s decreases with increasing frequency [17]. As seen Figure 4. (b), the values of R_s are 1567 W at 10 kHz and 741 W at 10 kHz for 0.65 V and 1.20 V, respectively. As seen these results and Figure 4 (b), the values of R_s decrease with increasing voltage at frequencies lower than 50 kHz. After 50 kHz, R_s values increase with increasing frequency. As seen Figure 4 (b), the value of R_s is 267 W at 100 kHz and 408 W at 100 kHz for 0.65 V and 1.20 V, respectively. In addition, the R_s decrease with increasing frequency each voltage (from 0.65 V to 1.20 V) (Figure 6 (b)).

Figure 5 (a) $\epsilon' - V$ and (b) $\epsilon' - f$ plots

The dielectric properties of the device are examined by dielectric spectroscopy. In dielectric spectroscopy, the complex permittivity ϵ^* is given by [23-26]

$$\epsilon^* = \epsilon' - i\epsilon'' \quad (2)$$

where ϵ' is the real part of dielectric permittivity that is a measure of the energy stored in dielectric material and ϵ'' is imaginary part of dielectric permittivity that is a measure of the energy dissipated in dielectric material. The complex permittivity is as following [23-26]

$$\epsilon^* = \frac{Y^*}{i\omega C_o} \quad (3)$$

where C_o is capacitance of free space, Y^* is the complex admittance and ω is the angular frequency. The ϵ' and ϵ'' are given by [23-26]

$$\epsilon' = \frac{C}{C_o} = \frac{Cd}{\epsilon_o A} \quad (4)$$

$$\epsilon'' = \frac{G}{\omega C_o} = \frac{G}{\omega \epsilon_o A} \quad (5)$$

where ϵ_0 is permittivity of free space, d is the thickness of insulator layer, C is value of capacitance, G is value of conductance and A is area of the rectifying contact.

Figure 5 (a) and (b) show the variations of the ϵ' with bias voltage (V) at different frequencies and the variations of ϵ' with frequency (f) at different voltages of the device, respectively. The dielectric constant of any material is due to the ionic, electronic, dipolar and interfacial polarizations [27]. As can be seen from Figure 5 (a), the behavior of $\epsilon' - V$ plot is like behavior of C-V plot and the voltage dependence of ϵ' has particularly a peak in the frequency range 1 kHz to 30 kHz. This peak behavior of $\tan\delta$ relies on some parameters such as the thickness of insulator layer, series resistance and interface states density [26]. In addition, ϵ' has very weak dependences on the voltage above 30 kHz and is rather small. The interfacial and dipolar polarizations are account for the dielectric behavior of the material at low frequencies [27]. At low frequencies, the polarization of the space charge at the grain boundaries creates a charge accumulation at the grain boundary and thus a potential barrier which causes the ϵ' values to increase, is formed [28,29]. The electronic polarization is responsible for the AlN material and contribution of dipolar polarization becomes negligible at higher frequencies [27].

It is seen in Fig. 5 (a) that ϵ' is constant at about 1.8 in the greater than 2 V region and the negative voltage region. As seen Figure 5 (b), ϵ' shows rapidly decrease because the response of space charge polarization effect with increasing frequency in the voltage range 0.65–1.20 V. If this situation is explained in a little more detail, the reason for the increase in ϵ' with decreasing frequency might be that the polarization increases with decreasing frequency since the electron hopping cannot trace the alternative field beyond certain frequency of external field. The dispersion in ϵ' can be cited to the Maxwell-Wagner type interfacial polarization

[30]. It is well known that the decreasing polarization is account for interface states cannot follow a.c. signal as its frequency is increase and cannot yield excess polarization [23, 31,32].

Figure 6 (a) and (b) show the variations of the ε'' with V at different frequencies and the variations of ε'' with frequency (f) at different voltages of the device, respectively. As can be seen from Figure 5 (a), the ε'' increases with decreasing frequency and ε'' is rather small and has very weak dependences on the voltage below about 0.5 V for each frequency. As seen Figure 6a and insert in Figure 6b, the value of ε'' is higher at low frequencies (1-70 kHz) than at high frequencies (100-1000 kHz). In addition, the value of ε'' is high on the voltage above about 0.5 V for each frequency. At a low frequency, the high resistivity of grain boundaries which are more influential than the grains of AlN material were accounted for the high value of ε'' [33]. An important contribution to the ε'' may occur in bulk interface layer by defects associated with the grain boundaries. Therefore, high values of ε'' may be because of the interfacial effects and electron effect in which the motion of free charge carrier within the AlN material [34–37]

As seen Figure 6 (b), ε'' shows rapidly decrease with increasing frequency in the voltage range 0.65–1.20 V similar to $\varepsilon' - f$ plot (Figure 5 (b)).

Figure 6 (a) $\varepsilon'' - V$ and (b) $\varepsilon'' - f$ plots

The loss tangent ($\tan \delta$) can be expressed as follows [24,38,39],

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{G}{\omega C} \quad (6)$$

The dielectric loss tangent versus voltage at various frequencies is indicated in Figure 7 (a). As seen Figure 7 (a), the $\tan \delta$ sharply decreases with decreasing in the voltage range from 2 V to about 1.2 V for each frequency, and after that it decreases smoothly. It is well known that the $\tan \delta$ of the AIN is based on three different agents: dipole loss (movement of the molecular dipoles), interfacial polarization contribution (space charge migration) and direct current (DC) conduction [40, 41]. Figure 7 (b) shows the frequency dependent of $\tan \delta$ at different voltage. As seen this figure, the $\tan \delta$ increases with decreasing frequency and its value, especially, were high at low frequencies. The high resistivity of grain boundaries causes the high value of $\tan \delta$ at a low frequency [33].

Figure 7 (a) $\tan \delta - V$ and (b) $\tan \delta - f$ plots

Figure 8 (a) $M' - V$ and (b) $M' - f$ plots

The complex electric modulus (M^*) is given as $M^* = i\omega C_i \varepsilon^*$ [42,43]. Then, its real (M') and imaginary (M'') parts of modulus can be given as,

$$M' = \varepsilon' / (\varepsilon'^2 + \varepsilon''^2) \quad (7)$$

and

$$M'' = \varepsilon'' / (\varepsilon'^2 + \varepsilon''^2) \quad (8)$$

respectively.

In Fig.8 (a), the M' vs. V is indicated as a function of frequency. The M' is found in a sharply increasing behavior decreasing voltage in the frequency range from 1 kHz to 100 kHz. In Fig.8 (b), the M' versus frequency is indicated as a function of voltage. As seen this figure, the M' increases with increasing frequency for each voltage and the value of M' at 100 kHz is 0.44 and 0.26 for 0.65 V and 1.20 V, respectively. The lifetime of localized charges and contribution of them at the interface trap states define the relaxation process if these charges can follow the frequency changes [44]. Although M' shows an increasing trend with decreasing in frequency, as seen Figure 9 (a) and Figure 9 (b) the value of M'' have a peak. The electrical non-uniformities and the above two factors in the device may lead to asymmetry of the M'' peak and an increased peak width (Figure 9 (a)). An increase in frequency may lead to a change of both dipole interactions and charge carrier densities [45]. As seen Figure 9 (a), the peak point of M'' shifted to the positive voltage region with increasing frequency. Similarly, the peak of the $M'' - f$ plot shifted to the high frequency region with increasing voltage (Figure 9 (b)). The M'' indicates a single relaxation, centered at the dispersion region of M' related to the grain effect.

In the $M' - f$ plot, the frequency region bellows the loss peak maximum determines the range in which charge carriers are mobile over long distances. At the frequency above peak maximum

(high frequency), the carriers are mobile over short distances, and they are confined to potential wells. The peak region of the transition from long-range to short-range mobility with increase in frequency. The behavior of $M'' - f$ plot is attributed a frequency-dependent hopping type mechanism for charge transport in the device [46]. The dielectric relaxation time (τ) of the device is obtained by the relation $\tau = 1/\omega = 1 / 2\pi f$. τ is obtained from the plot of $M'' - f$ (Figure 9 (b)) [33,47-49]. The value of τ is $3.18 \mu s$ for 0.65 V and $1.59 \mu s$ for 1.20 V. As seen experimental results, τ increases with increasing the voltage.

Figure 9 (a) $M'' - V$ and (b) $M'' - f$ plots

The M'' vs. M' (Cole-Cole) for the device at 300 K is indicated in Figure 10. The M'' vs. M' is more efficient than the Z'' vs. Z' in allocating the relaxation effects from grain boundaries (resistive plates) and grains (conducting regions) in dielectric materials [33,47]. As can be seen Fig. 10, M'' vs. M' plot has the existence of one semicircle for the device. This

result is indicated that the grain boundaries impact is more dominant than the grain impact in the charge transport [47,48].

Figure 10 $M'' - M'$ plot

4. Conclusions

This study was interested in the use of AlN as an alternate interface layer for MIS/MOS structure. Electric and dielectric properties of the Au/Ti/AlN/n-Si device were analyzed with the change in both voltage and frequency. The ϵ' , ϵ'' and $\tan\delta$ values were indicated in

decreasing behavior at high frequency whereas there is an increase in low frequencies. At higher frequencies, the characteristics of the Au/Ti/AlN/n-Si device was associated with the weak reaction of the interface states that cannot follow the applied AC signal at this region.

In contrast to the high frequency region, at lower frequencies, the Au/Ti/AlN/n-Si device performance was attributed to the mighty impact of the dielectric parameters of the AlN layer that is because of the localized states at the interface and along with the series resistance. Moreover, M' showed an increasing with decreasing in frequency and the value of M'' had a peak. The peak of the $M'' - f$ plot shifted to the high frequency region with increasing voltage. M'' indicated a single relaxation, centered at the dispersion region of M' related to the grain effect. The values of τ were $3.18 \mu s$ for 0.65 V and $1.59 \mu s$ for 1.20 V. Result shows that τ increases with increasing the voltage. M'' vs. M' plot has the existence of one semicircle for the device. The experimental results confirm that the prepared device can be used as a capacitor in electronic circuits.

CRediT authorship contribution statement

Dilber Esra Yildiz: Conceptualization, Writing - review & editing, Methodology, Visualization, Formal analysis, Data curation, Supervision. Adem Tataroğlu: Investigation, Formal analysis, Data curation, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] M. Razeghi, M. Henini, *Optoelectronic Devices: III Nitrides* (Elsevier, Amsterdam, 2005).
- [2] M.O. Manasreh, *III-Nitride Semiconductors: Electrical, Structural and Defects Properties* (Elsevier, Amsterdam, 2000).
- [3] D. Nirmal, J. Ajayan, *Handbook for III-V high electron mobility transistor technologies* (CRC Press, Boca Raton, 2019).
- [4] E. Simoen, D. Visalli, M. Van Hove, M. Leys, G. Borghs, A deep-level analysis of Ni–Au/AlN/(111)p+Si metal–insulator–semiconductor capacitors, *J. Phys. D: Appl. Phys.* **44**, 475104 (2011).
- [5] S. Liu, S. Yang, Z. Tang, Q. Jiang, C. Liu, M. Wang, K.J. Chen, Al₂O₃/AlN/GaN MOS-channel-HEMTs with an AlN interfacial layer, *IEEE Electron Device Lett.* **35** (2014) 723-725.
- [6] C.R. Ortiz, V.M. Pantojas, W. Otaño-Rivera, Effect of annealing on the electrical properties of insulating aluminum nitride in MIM and MIS structures, *Solid-State Electron.* **91**, 106 (2014).
- [7] X. Song, R. Fu, H. He, Frequency effects on the dielectric properties of AlN film deposited by radio frequency reactive magnetron sputtering, *Microelectron. Eng.* **86**, 2217 (2009).
- [8] Z.X. Bi, Y.D. Zhang, R. Zhang, B.L. Gu, X.Q. Xiu, L.L. Zhou, B. Shen, Dielectric properties of AlN film on Si substrate, *J. Mater. Sci.: Mater. Electron.* **15**, 317 (2004).
- [9] T. Adam, J. Kolodzey, C.P. Swann, M.W. Tsao, J.F. Rabolt, The electrical properties of MIS capacitors with ALN gate dielectrics, *Appl. Surface Sci.* **175-176**, 428 (2001).
- [10] C. P. Symth, *Dielectric Behaviour and Structure*, McGraw-Hill (New York, 1995).
- [11] E.H. Nicollian, J.R. Brews, *MOS Physics and Technology* (Wiley, New York, 1982).
- [12] S.M. Sze, K.K. Ng, *Physics of Semiconductor Devices* (3rd edn., Wiley, New Jersey, 2007).
- [13] H. Bentarzi, *Transport in Metal-Oxide-Semiconductor Structures* (Springer-Verlag, Berlin Heidelberg, 2011).

- [14] K. Prabakar, S. K. Narayandass, D. Mangalaraj, Dielectric properties of Cd_{0.6}Zn_{0.4}Te thin films, *Phys. Status Solidi A* **199**, 507 (2003).
- [15] D. E. Yıldız, M. Yıldırım, M. Gokcen, Investigation on dielectric properties of atomic layer deposited Al₂O₃ dielectric films, *J. Vac. Sci. Technol. A* **32**, 031509 (2014).
- [16] Z. Tekeli, M. Gokcen, S. Altındal, S. Ozcelik, E. Ozbay, On the profile of frequency dependent dielectric properties of (Ni/Au)/GaN/Al_{0.3}Ga_{0.7}N heterostructures, *Microelectron. Eng.* **51**, 581 (2011).
- [17] A. Turut, A. Karabulut, K. Ejderha, N. Biyikli, Capacitance–conductance–current–voltage characteristics of atomic layer deposited Au/Ti/Al₂O₃/n-GaAs MIS structures, *Mater. Sci. Semicond. Process.* **39**, 400 (2015).
- [18] A.A.M. Farag, B. Gunduz, F. Yakuphanoglu, W.A. Farooq, Controlling of electrical characteristics of Al/p-Si Schottky diode by tris(8-hydroxyquinolato) aluminum organic film, *Synth. Met.* **160**, 2559 (2010).
- [19] E. E. Tanrikulu, D. E. Yıldız, A. Günen, Ş. Altındal, Frequency and voltage dependence of electric and dielectric properties of Au/TiO₂/n-4H-SiC (metal-insulator-semiconductor) type Schottky barrier diodes, *Physica Scripta* **90(9)**, 095801 (2015).
- [20] N. Shiwakoti, A. Bobby, K. Asokan, B. Antony, Temperature dependent dielectric studies of Ni/n-GaP Schottky diodes by capacitance and conductance measurements, *Mater. Sci. Semicond. Process.* **42**, 378 (2016).
- [21] J.R. Brews, E.H. Nicollian, Improved MOS capacitor measurements using the Q-C method, *Solid State Electron.* **27**, 963 (1984).
- [22] H. H. Gullu, D. E. Yildiz, Capacitance, conductance, and dielectric characteristics of Al/TiO₂/Si diode, *J. Mater. Sci. Mater. Electron.* **32**, 13549 (2021).

- [23] D. E. Yıldız, D. H. Apaydın, L. Toppare, A. Cirpan, Dielectric and Electrical Properties of an Organic Devices Containing Benzotriazole and Fluorene Bearing Copolymer, *J. Polym. Sci.* **128**, 1659 (2013).
- [24] A. Tataroglu, Electrical and dielectric properties of MIS Schottky diodes at low temperatures, *Microelectron. Eng.* **83**, 2551 (2006).
- [25] F.I.H. Rhouma, A. Dhahri, J. Dhahri, M.A. Valente, Dielectric, modulus and impedance analysis of lead-free ceramics $\text{Ba}_{0.8}\text{La}_{0.133}\text{Ti}_{1-x}\text{Sn}_x\text{O}_3$ ($x=0.15$ and 0.2), *Appl. Phys. A-Mater.* **108**, 593 (2012).
- [26] S. Demirezen, A. Kaya, S.A. Yeriskin, M. Balbası, I. Uslu, Frequency and voltage dependent profile of dielectric properties, electric modulus, and ac electrical conductivity in the PrBaCoO nanofiber capacitors, *Results in Physics* **6**, 180 (2016).
- [27] D. Varshney, A. Kumar, K. Verma, Effect of A site and B site doping on structural, thermal, and dielectric properties of BiFeO₃ ceramics, *J. Alloys Compd.* **509**, 8421 (2011).
- [28] M. Abdullah Dar, K. Majid, K. Mujasam Batoo, R. K. Kotnala, Dielectric and impedance study of polycrystalline $\text{Li}_{0.35}\text{0.5XCd}_{0.3}\text{NiXFe}_{2.3}\text{50.5XO}_4$ ferrites synthesized via a citrate-gel auto combustion method, *J. Alloys Compd.* **632**, 307 (2015).
- [29] L. Chauhan, A. K. Shukla, K. Sreenivas, Dielectric and magnetic properties of Nickel ferrite ceramics using crystalline powders derived from DL alanine fuel in sol–gel auto-combustion, *Ceram. Int.* **41**, 8341 (2015).
- [30] A. Chelkowski, *Dielectric Physics* (Elsevier, Amsterdam, 1980=.
- [31] E. Arslan, Y. Badali, M. Aalizadeh, Ş. Altındal, E. Özbay, Current transport properties of (Au/Ni)/HfAlO₃/n-Si metal–insulator–semiconductor junction, *J. Phys. Chem. Solids* **148**, 109758 (2021).

- [32] H.H. Gullu, D.E. Yildiz, Temperature and frequency effects on electrical and dielectric properties of n-4H SiC based metal-insulator-semiconductor (MIS) diode interlayered with Si₃N₄ thin film, *J. Mater. Sci.Mater. Electron.* **31**, 8705 (2020).
- [33] Ch. Rayssi, S. El. Kossi, J. Dhahri, K. Khirouni, Frequency and temperature-dependence of dielectric permittivity and electric modulus studies of the solid solution Ca_{0.85}Er_{0.1}Ti_{1-x}Co_{4x/3}O₃ ($0 \leq x \leq 0.1$), *RSC Adv.* **8**, 17139 (2018).
- [34] P. Dutta, S. Biswas, S. K. De, Dielectric relaxation in polyaniline–polyvinyl alcohol composites, *Mater. Res. Bull.* **37**, 193 (2002).
- [35] C. V. Subba Reddy, X. Han, Q.Y. Zhu, L.Q. Mai, W. Chen, Dielectric spectroscopy studies on (PVP + PVA) polyblend film, *Microelectron. Eng.* **83**, 281 (2006).
- [36] Md. M. Hoque, A. Duta, S. Kumar, T.P. Sinha, Dielectric Relaxation and conductivity of Ba(Mg_{1/3}Ta_{2/3})O₃ and Ba(Zn_{1/3}Ta_{2/3})O₃, *J. Mater. Sci. Technol.* **30**, 311 (2014).
- [37] S. Ramesh, A.H. Yahaya, A. K. Arof, Dielectric behavior of PVC-based polymer electrolytes, *Solid State Ionics* **152–153**, 291 (2002).
- [38] A. Kocyigit, D. E. Yıldız, A. Sarılmaz, F. Ozel, M. Yıldırım, The dielectric performance of Au/CuCo 5 S 8/p-Si heterojunction for various frequencies, *J. Mater. Sci. Mater. Electron.* **31**, 22408 (2020).
- [39] I. Dokme, D. E. Yildiz, S. Altindal, Illumination intensity effects on the dielectric properties of Schottky devices with Co, Ni-doped PVA nanofibers as an interfacial layer, *Adv. Polym. Technol.* **31**, 63 (2012).
- [40] M. Popescu, I. Bunget, *Physics of Solid Dielectrics* (Elsevier, Amsterdam, 1984).
- [41] K. Yang, X. Huang, Y. Huang, L. Xie and P. Jiang, FluoroPolymer@BaTiO₃ hybrid nanoparticles prepared via RAFT polymerization: toward ferroelectric polymer

nanocomposites with high dielectric constant and low dielectric loss for energy storage application, *Chem. Mater.* **25**, 2327(2013).

[42] H.H. Gullu, O. Bayrakli Surucu, M. Terlemozoglu, D.E. Yildiz, M. Parlak, Frequency effect on electrical and dielectric characteristics of In/Cu₂ZnSnTe₄/Si/Ag diode structure, *J. Mater. Sci. Mater. Electron.* **30**, 9814 (2019).

[43] M. Coskun, O. Polat, F.M. Coskun, Z. Durmus, M. Caglar, A. Turut, Frequency and temperature dependent electrical and dielectric properties of LaCrO₃ and Ir doped LaCrO₃ perovskite compounds, *J. Alloy. Compd.* **740**, 1012 (2018).

[44] E. Arslan, Y. Safak, I. Tascioglu H. Uslu, E. Ozbay, Frequency and temperature dependence of the dielectric and AC electrical conductivity in (Ni/Au)/AlGa_N/Al_N/Ga_N heterostructures, *Microelectron. Eng.* **87**, 1997 (2010).

[45] J. de Los. S. Guerra, J. A. Eiras, Mechanical and electrical driving field induced high-frequency dielectric anomalies in ferroelectric systems. *J. Phys.: Condens. Matter.* **19**, 386217 (2007).

[46] R. Tang, C. Jiang, W. Qian, J. Jian, X. Zhang, H. Wang, H. Yang, Dielectric relaxation, resonance, and scaling behaviors in Sr₃Co₂Fe₂₄O₄₁ hexaferrite, *Scientific Reports*, **5**, 13645 (2015).

[47] S. T. Assar, H. F. Abosheisha, M. K. El Nimr, Study of the dielectric behavior of Co–Ni–Li nanoferrites, *J. Magn. Magn. Mater.* **350**, 12 (2014).

[48] M. Hashim, S. Kumar, S. Ali, B. H. Koo, H. Chung, Ravi Kumar, Structural, magnetic and electrical properties of Al³⁺ substituted Ni–Zn ferrite nanoparticles, *J. Alloys Compd.* **511**, 107 (2012).

[49] S. Narayanan, A. K. Baral and V. Thangadurai, Dielectric characteristics of fast Li ion conducting garnet-type $\text{Li}_{5+2x}\text{La}_3\text{Nb}_{2x}\text{Y}_x\text{O}_{12}$ ($x = 0.25, 0.5$ and 0.75), *Phys. Chem. Chem. Phys.*, **18**, 15418 (2016).

Figure Captions

Figure 1 **(a)** Energy-band diagram and **(b)** SEM image of device

Figure 2 **(a)** $C - V$ and **(b)** $C - f$ plots of the device at room temperature

Figure 3 **(a)** $G/w - V$ and **(b)** $G/w - f$ plots

Figure 4 **(a)** $R_s - V$ and **(b)** $R_s - f$ plots

Figure 5 **(a)** $\varepsilon' - V$ and **(b)** $\varepsilon' - f$ plots

Figure 6 **(a)** $\varepsilon'' - V$ and **(b)** $\varepsilon'' - f$ plots

Figure 7 **(a)** $\tan\delta - V$ and **(b)** $\tan\delta - f$ plots

Figure 8 **(a)** $M' - V$ and **(b)** $M' - f$ plots

Figure 9 **(a)** $M'' - V$ and **(b)** $M'' - f$ plots

Figure 10 $M'' - M'$ plot