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Current-Voltage (I-V) and Capacitance-Voltage (C-V) Characteristics of $Au/Bi_4Ti_3O_{12}/SnO_2$ Structures

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ABSTRACT

The electrical properties of $Au/Bi_4Ti_3O_{12}/SnO_2$ structures were investigated by forward bias I-V, forward and reverse bias C-V and G/ω-V measurements. The results indicate structural disordering, presence of the interface states in the BTO capacitors and existence of polarization. Dielectric constant(ε'), dielectric loss(ε'') and dielectric tangent(tanδ) were found as 170, 309 and 1,8 respectively at 50 kHz. C-V and G/ω-V were measured in the frequency range of 1 kHz-5 MHz. It was found that dielectric constant(ε') and dielectric loss(ε'') systematically decrease with increasing frequency in 10 kHz-1 MHz frequency range and tanδ versus frequency plot exhibits a minimum at about 5 kHz. The ideality factor and series resistance were found to be 1,5 and 1030 Ω respectively from I-V measurements and series resistance was found as 350 Ω from the measured conductance in strong accumulation region. The observations are comparable with the other values for BTO structures reported in the literature.

Key Words: $Au/Bi_4Ti_3O_{12}/SnO_2$ structures, Dielectric constant, Dielectric loss, Frequency dependence, Series resistance

1. INTRODUCTION

When a metal is brought into intimate contact with a semiconductor, a potential barrier is formed at the metal- semiconductor (MS) interface [1]. In 1938, Schottky suggested that the rectifying behavior could arise from a potential barrier as a result of the stable space charges in the semiconductor. This model is known as the Schottky Barrier (SB). Metal-semiconductor devices can also show non-rectifying behavior; that is, the contact has a negligible resistance regardless of the polarity of the applied voltage. Such a contact is called an ohmic contact. The height of potential barrier can be determined by the difference between the work function of the metal (Φ_m) and semiconductor (Φ_s) [1]. The work function is the energy difference between the vacuum level and Fermi level (E_F). When a forward bias voltage V_a is applied to the junction, the effective barrier height in the semiconductor becomes q (Φ_B-V_a) and the electron flow from the semiconductor into the metal is enhanced by a factor, $\exp(qV_a/kT)$. Experimentally obtained barrier heights deviate from this rule and the basic mechanisms of the Schottky Barrier formation are still a field of intensive research. $Bi_4Ti_3O_{12}$ structures are the simplest and among the most well known compounds among the bismuth layer-structured ferroelectrics and are particularly interesting because of their peculiar switching behavior [2,3] resulting from a small c-axis component of the spontaneous polarization and a small coercive force. $Bi_4Ti_3O_{12}$ is a typical ferroelectric material with useful properties.

2. MATERIAL AND METHODS

The $Bi_4Ti_3O_{12}$ (BTO) thin film which is used in this study was obtained through hot compaction of $Bi_4Ti_3O_{12}$ powder. The mixture of Ar and O_2 was used as a working medium. The structure of the obtained BTO thin film was determined by rf magnetron sputtering. The BTO thin film was grown on SnO_2 substrate. The chemical composition of film was determined by the X-ray energy dispersive spectroscopy method using a scanning electron microscope REM-101M. The spectral line intensity relation for BTO films was compared with a standard sample. After composing the back ohmic contact, the gold top contacts (rectifying contacts), with a thickness of about 2000 Å and a diameter of 2.5 µm, were deposited on the films by using a shadow-mask at room temperature by rf sputtering. The electron diffraction patterns of $Bi_4Ti_3O_{12}$ film with a thickness of ~2 µm were obtained by magnetron sputtering on crystal substrate at

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temperatures around 700 °C. The measurements of capacitance vs. voltage (C-V) and conductance vs. voltage (G-V) characteristics for the Au/$Bi_4Ti_3O_{12}$/SnO_2 structure were performed by using a Hewlett-Packard HP 4192 A LF impedance analyser (5 Hz-13 MHz) at various frequencies between 1 kHz and 5 MHz. The current-voltage (I-V) characteristics for Au/$Bi_4Ti_3O_{12}$/SnO_2 structure were obtained by using a Keithley model 614 electrometer and 220 programmable constant current source at room temperature. The sample was mounted on a copper holder in a box and the electrical contacts were created with the upper gold electrodes by using tiny silver coated wires with silver paste.

2.1. Current-Voltage Characteristics

A typical forward bias semi-logarithmic ln(I)-V characteristics of Au/$Bi_4Ti_3O_{12}$/SnO_2 structures is shown in Figure 1. The ln(I)-V curve consists of two linear regions with different slopes, one at low bias ≤0,7 V and one at mid bias region (0,7V≤V≤ 0,9V) showing the exponential relationship between the current and voltage.

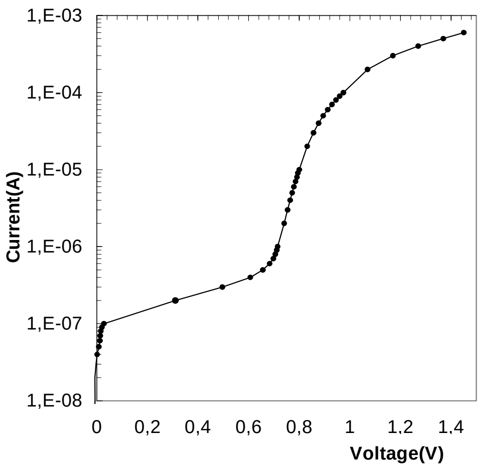

Figure 1. Forward bias I-V characteristics of Au/$Bi_4Ti_3O_{12}$/SnO_2 structures.

In high bias region (≥ 0,9 V) the series resistance R_s can be dominated from linear part. The most interesting region for a Schottky diode, i.e., the mid bias region which is dominated by the diffusion component of the current, shows a linear behaviour in the semi-logarithmic plot enabling one to extract the important diode parameters (ideality factor n, reserve saturation current I_s and barrier height). The most common theory of Schottky barrier diode is based on the thermionic emission (TE) and according to this model, the current-voltage (I-V) relationship is given by;

$$I = I_S\left[\exp\left(\frac{qV_B}{kT}\right) - 1\right] \quad (1)$$

where q is the electronic charge, k is the Boltzman constant, T is the absolute temperature, V_B is the voltage across the junction and I_S is the reserve saturation current and described by [1],

$$I_S = AA^*T^2 \exp(-q\phi_B / kT) \quad (2)$$

where A is the area of rectifying contact (diode), A^* is the modified Richardson constant and ϕ_B is the effective barrier height from metal to semiconductor. The I_S was found as $6,13.10^{-15}$ Amphere by extrapolating the linear mid bias region of the curve to zero applied voltage axis and the ideality factor n was found to be 1,5 from the slope of this linear region. When the structure has a series resistance and interface states, ideality factor n becomes higher than unity; most practical Schottky diodes show deviation from the ideal thermionic theory. For the case of the diode with a high series resistance and ideality factor, the relation between the applied forward bias V and the current I can be written as [10-13],

$$I = I_S \exp\left[\frac{q}{kT}(V - IR_S)\right] \quad (3)$$

when V_D > 3kT/q [1]. A method to extract the series resistance R_s of ideal Schottky diode (i.e., n=1) was first proposed by Norde [10]. For 1<n<2 case, Sato and Yasamura [11] and n>>1 case Bohlin [12] modified Norde's approach to extract the values of n, R_S and ϕ_B from the forward bias I-V data of any Schottky diode. The equation can be written as:

$$V = R_S AI + n\phi_B + n\frac{kT}{q}Ln\left(I/ AA^*T^2\right) \quad (4)$$

Differentiating Eq.(4) with respect to I and rearranging the terms,

$$\frac{d(V)}{dLn(I)} = n\left(\frac{kT}{q}\right) + R_S I \quad (5a)$$

$$H(I) = V - \left(n/\beta\right)\ln\left(I/AA^*T^2\right) = n\phi_B + R_s I \quad (5b)$$

can be obtained [13]. Thus, a plot of d(V)/dln(I) vs I will give R_s as the slope and n(kT/q) as the y-axis intercept. At room temperature the d(V)/dln(I) vs. I plot for Au/$Bi_4Ti_3O_{12}$/SnO_2 structure is shown in Figure 2 (a). The values of ideality factor n and series resistance R_s were found as 1,5 and 1030 Ω respectively. As can be seen, the values determined for the ideality factor n, obtained from the plots, are incompatible with each other.

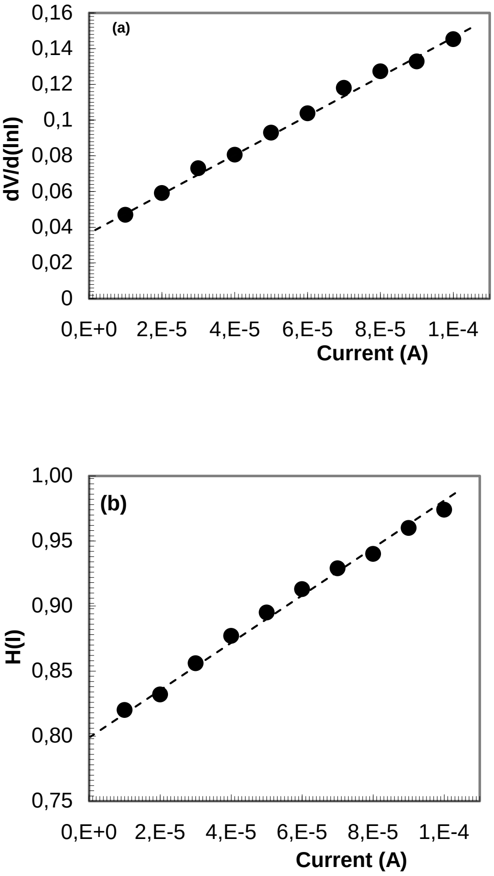

Figure 2. The experimental dV/d(lnI) vs. I and H(I)vs.plots for $Au/Bi_4Ti_3O_{12}/SnO_2$ structure.

Using the n value determined from Eq.(5a), H(I) vs. I plot will also give a straight line (Figure 2b) with y-axis intercept equal to $n\phi_B$. The slope of this plot also provides a second determination for R_s, which can be used to check the consistency of this approach. A departure from the linearity in ln(I)-V characteristics at high forward bias ($V \geq 0.9$ V) is usual and attributed to interface states and the series resistance of device[14,1].

2.2. Capacitance -Voltage Characteristics

With the top and bottom metal electrodes, the parameters of the Schottky diode, including the depletion layer capacitance (C_i), built-in voltage (V_{bi}) and space charge density (N_D or N_A) can be determined from a plot of $1/C_m$ (C_m is the measured capacitance) versus d_m (d_m is measured thickness), at various bias voltages. In this section we will show our calculations to determine the built in voltage V_{bi}, space charge density N_D, series resistance R_s and frequency dependence of dielectric constant (ε'), dielectric loss (ε'') and dielectric tangent (tanδ) quantitatively by using C-V and G/ω-V measurements and a detailed equivalent circuit analysis of BTO structures.

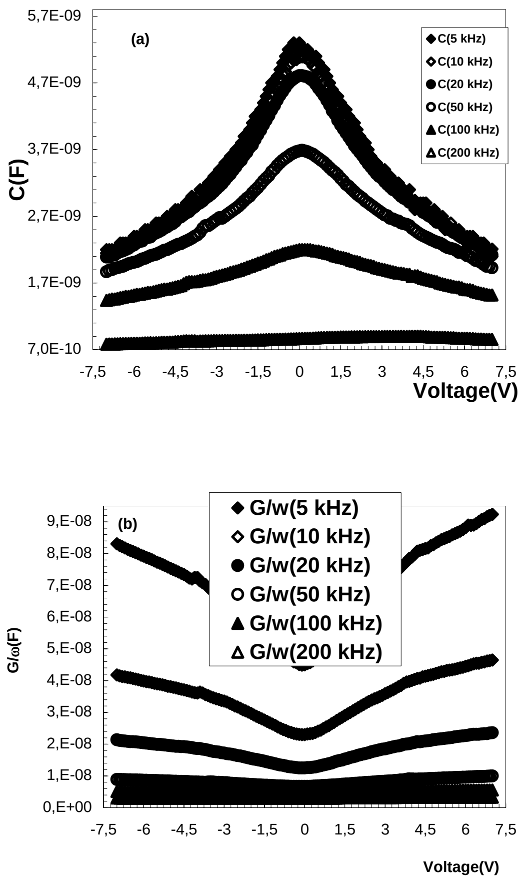

Figure 3. Measured capacitance(C) and conductance(G/ω) vs. gate bias for $Au/Bi_4Ti_3O_{12}/SnO_2$ at different frequency.

Figures 3(a) and 3(b) shows typical C-V, and G/ω-V curves of the structure whose BTO layer has a thickness d is 2 μm, at different frequencies (5 kHz -200 kHz). Additionally, the figures indicate the C-V-f and G/ω-V-f response for the Schottky diode, showing that the measured capacitance (C) and conductance (G/ω) are dependent on bias voltage and frequency. The voltage and frequency dependence is a function of a Schottky barrier; interface state density and high series resistance [16]. In Figure 4(b), the series resistance versus frequency curves show that at high frequency ($f \geq 100$ kHz) the series resistance of the diode decreases with increasing frequency. Figures 4(a) and (b) confirmed that the series resistance varies with applied bias and frequency. Here we assumed that Schottky barriers were formed at the top and bottom interfaces [11,13]. With built in voltage V_{bi}, a depletion width should follow a relationship such that

$$W_D = \left[\frac{2\varepsilon_i \varepsilon_o}{qN_D} \left(V_{bi} - V \right) \right]^{1/2} \tag{6}$$

where N_D, is the donor density, ε_i is the relative permitivity of interfacial layer and ε_o is the permitivity of vacuum [1].

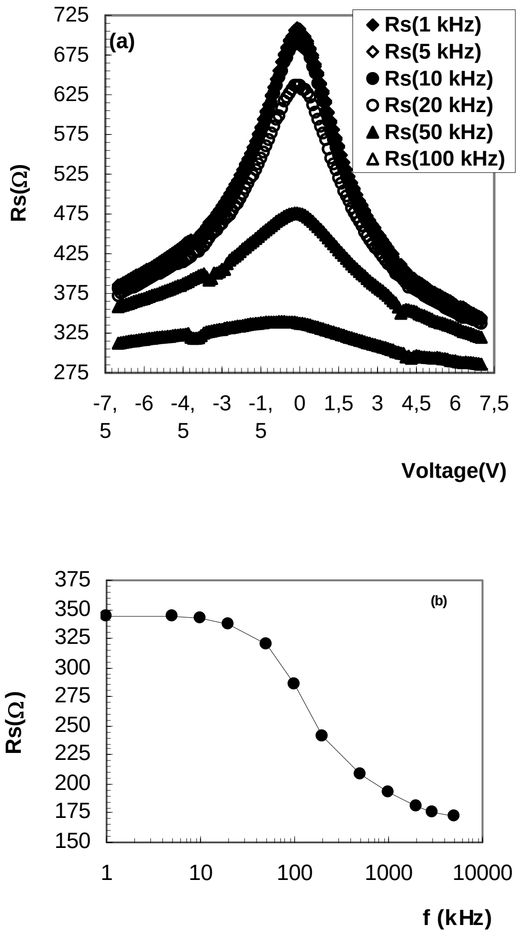

Figure 4. Frequency dependence of series resistance(Rs) for $Au/Bi_4Ti_3O_{12}/SnO_2$ structure.

It is known that a capacitance of a Schottky diode [1] can be represented by:

$$\frac{1}{C_m^2} = \frac{2\left(V_{bi} - V_i \right)}{q\varepsilon_s \varepsilon_o N_D A^2} \tag{7}$$

where V_i represents a drop of an external voltage at the interface of the capasitor when an external voltage is applied. The Eq.7 predicts a linear relationship between ($1/C^2$) and V under strong bias conditions. The carrier doping density (N_D) values used in the calculations were determined from the slope of the linear part plot of C^{-2} vs. V curves (Figure 5).

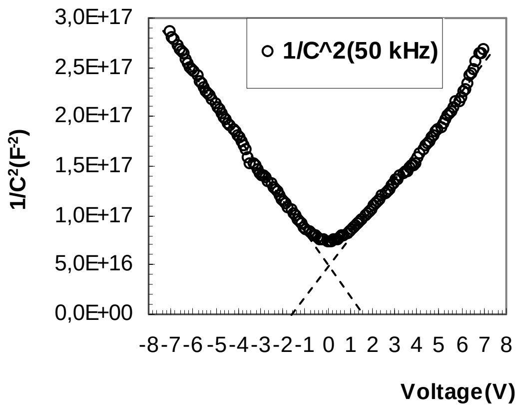

Figure 5. Plot of $1/C^2$ vs V for BTO structure at frequency of 50 kHz.

In 50 kHz frequency and at room temperature N_D value was found in the range of $1{,}36 \times 10^{15}$ cm^{-3}. The built in voltages of the BTO structure is cowed and obtained by fitting the high field with linear lines. From the x-axis (voltage) intercepts, it was found that V_{bi}=1,6 Volt. Additionally, series resistance can be calculated from the measured admittance (C-V and G-V) when the devices are based in a strong accumulation region according to [17]:

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

where G_m and C_m represent equivalent parallel conductance and capacitance in the strong accumulation (at 6 volt) for the measured device. The series resistance is calculated ~350 Ω from the C-V and G-V curves in the strong accumulation bias. This value is higher than that of obtained from d(V)/dln(I) vs. I plot because I-V measurement was carried out only under forward bias conditions.

Additionally ε', ε'' and tanδ were obtained at various frequencies, as shown in Figure 6. Dielectric constant ε' decreases with increasing frequency above 20 kHz. The measured small signal ε', ε'' and tanδ were found to be 170, 309 and 1,8 respectively at 50 kHz. These observations are comparable to the reported values for BTO structures [18-22].

3. RESULTS AND DISCUSSION

A small signal of 40 mV amplitude and 50 kHz frequency was applied to the bias across the sample while bias was swung between -7 V and +7V. There was a decrease in the capacitance at strong bias and this reduction in the capacitance may be attributed to increased conductivity at strong dc bias. The dielectric constant (ε'), dielectric loss (ε") and dielectric tangent (tanδ) at frequency 50 kHz were found to be 170, 309 and 1,8 respectively. Frequency response for dielectric

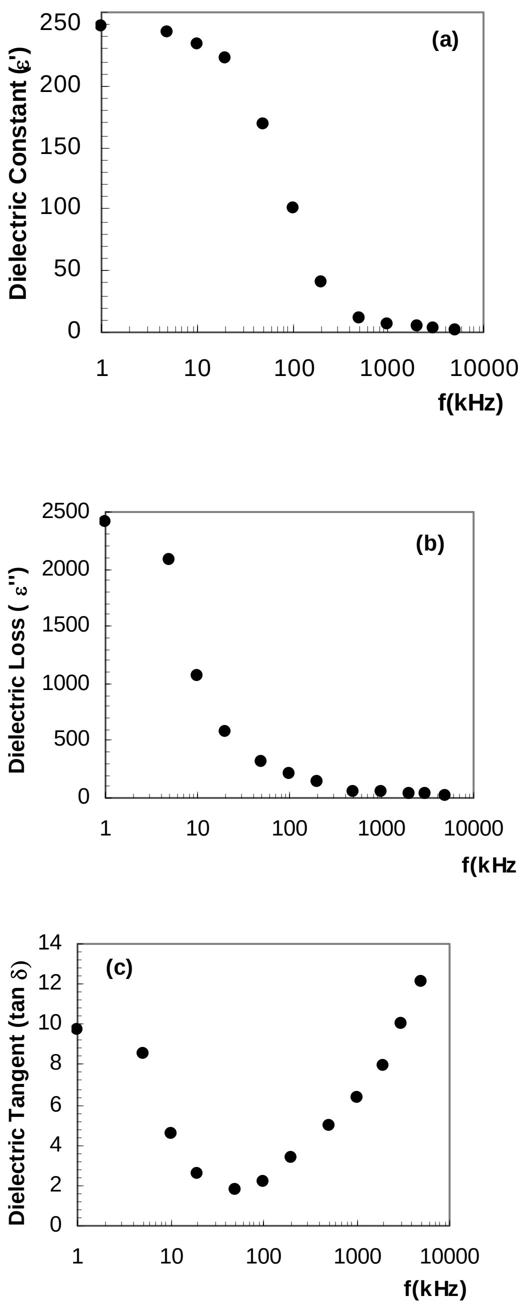

Figure 6. Dielectric constant, loss and tangent as a function of the frequency for $Au/Bi_4Ti_3O_{12}/SnO_2$.

properties, C-V and G/ω-V of $Au/Bi_4Ti_3O_{12}/SnO_2$ structures were measured in the frequency range of 1 kHz-5 MHz. While dielectric constant(ε') and dielectric loss (ε") decrease with increasing frequency, in the 10 kHz-5MHz frequency range, show a minimum at about 5 kHz. The ideality factor n and series resistance R_s were found at room temperature to be 1,5 and 1030 Ω respectively in forward bias I-V measurement. Additionally series resistance R_s was found to be 350Ω from the measured conductance in the strong accumulation region. The higher value of the ideality factor n and the dielectric constant (ε') may be attributed to a structural disorder of the structure, and also indicates the thickness of the structure layer and surface charge density. C-V-f and G/ω-V-f measurements confirmed that the measured capacitance C and conductance G strongly depend on applied bias voltage and frequency. This dependence is due to the presence of Schottky barrier, doping concentration (N_A or N_D), density of interface states (D_{it}) and series resistance (R_s). These observations are comparable to the reported values for BTO structures.

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REFERENCES

[1] Sze, S. M., “Physics of Semiconductor Devices 2nd ed.”, ***John Wiley & Sons***, New York, 362-390 (1981).

[2] Cummins, S.E., “A new bistable ferroelectric light gate or display element”, ***Proc. IEEE***, 55: 1537-1538 (1967).

[3] Cummins, S. E., Cross L. E., "Crystal symmetry, optical properties, and ferroelectric polarization of $Bi_4Ti_3O_{12}$ single crystals", ***Appl. Phys. Letters***, 10: 14-16 (1967).

[4] Wu, S.Y., Takei, W.J. , Francoma, M.H., “Transient switching response and partial switching phenomena in coarse-grained rhombohedral-phase PLZT ceramics”, ***Ferroelectrics***, 10: 43-46 (1976).

[5] Agasiyev, A. A., Mamedov, M.Z., Muradov, M. B., “Electrical Conductivity and Dielectric Properties of $Bi_4Ti_3O_{12}$”, ***J. Phys. III France***, 6 (7): 853-861 (1996).

[6] B.H., Park, S. J., Hyun, "Imprint failures and asymmetric electrical properties induced by thermal processes in epitaxial $Bi_4Ti_3O_{12}$ thin films", ***Journal of Applied Physics***, 84: 4428-4435 (1998).

[7] Joshi, P.C., Krupanidh, S.B., "Structural and electrical studies on rapid thermally processed ferroelectric $Bi_4Ti_3O_{12}$ thin films by metalloorganic solution deposition", ***Journal of Applied Physics***, 72 (12): 5817-5819 (1992).

[8] Pintilie, L., Pintilie, I., Petre, D., Botila, T., Alexe M., "Trap characterization of $Bi_4Ti_3O_{12}$ thin films by thermally stimulated currents", ***Appl. Physica A***, 69: 105-109 (1999).

[9] Fu, L., Liu, K., Zhang, B., Chu, J., "Capacitance-voltage characteristics of $Bi_4Ti_3O_{12}$/p-Si interface", ***Appl. Phys. Letters***, 72 (14): 1784-1786 (1998).

[10] Norde, H., "A modified forward I-V plot for Schottky diodes with high series resistance", ***Journal of Applied Physics***, 50 (7): 5052-5053 (1979).

[11] Sato, K., Yasamura, Y., "Study of forward I-V plot for Schottky diodes with high series resistance", ***J.Appl.Phys.***, 58 (9): 3655-3657 (1985).

[12] Bohlin, K.E., "Generalized Norde plot including determination of the ideality factor", ***J.Appl.Phys.***, 60 (3): 1223-1224 (1986).

[13] Cheung, S.K., Cheung, N.W., "Extraction of Schottky diode parameters from forward current-voltage characteristics", ***Appl.Phys. Lett.***, 49 (2): 85-87 (1986).

[14] Green, M.A., King, F.D., Shewchun, J., "Minority Carrier MIS Tunnel Diodes and their Application to Electron and Photovoltaic Energy Conversion Part I: Theory", ***Solid-State Electronics***, 17: 551-561 (1974).

[15] Özdemir, S., Altındal, Ş., "Temperature dependent electrical characteristics of Al-SiOx-pSi solar cells", ***Solar Energy Materials and Solar Cells***, 32 (2): 115-127 (1994).

[16] W. P., Kang, J. L., Davidson, Y., Gurbuz, D. V., Kerns, "Temperature Dependence and Effect of Series Resistance on Electrical Characteristics of a Polycrystalline Diamond MIS Diode", ***Journal of Applied Physics***, 78 (2): 1101-1107 (1995).

[17] Nicollian, E.H., Brews, J.R., "Metal Oxide Semiconductor (MOS) Physics and Technology", ***John Wiley & Sons***, New York, 423–491 (1982).

[18] Kong, L. B., Ma, J., "Randomly oriented Bi4Ti3O12 thin films derived from a hybrid sol-gel process", ***Thin Solid Films***, 379: 89-93 (2000).

[19] Wang, H., Fu, L. W., Hang, S. X., "Preparation and Properties of $Bi_4Ti_3O_{12}$ Single-Crystal Thin Films by Atmospheric Pressure Metalorganic Chemical Vapor Deposition", ***J. Appl. Phys.***, 73 (11): 7963 (1993).

[20] Joshi, P.C., Krupandihi, S.B., "Switching, fatigue, and retention in ferroelectric $Bi_4Ti_3O_{12}$ thin films", ***Appl.Phys. Lett.***, 62 (16): 1928-1930 (1993).

[21] A.Q., Jiang, G.H., Li,, L.D., Zhang, "Dielectric study in nanocrystalline $Bi_4Ti_3O_{12}$ prepared by chemical coprecipitation", ***J.Appl.Phys.***, 83 (9): 4878-4883 (1998).

[22] Lee, J.J., Alluri, P., Dey, S.K., "Effect of interfaces on the electrical behavior of (Pb0.72La 0.28) TiO3 thin films", ***Appl.Phys.Lett.***, 65 (16): 2027-2029 (1994).