Available online at www.sciencedirect.com

ScienceDirect

Nuclear Instruments and Methods in Physics Research B 254 (2007) 113–117

NIM B Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

The effects of frequency and γ-irradiation on the dielectric properties of MIS type Schottky diodes

A. Tataroğlu *, Ş. Altındal

Department of Physics, Faculty of Arts and Sciences, Teknikokullar, Gazi University, 06500 Ankara, Turkey

Received 19 September 2006
Available online 22 November 2006

Abstract

The effects of γ-irradiation on the dielectric properties of Al/SiO_2/p–Si (MIS) Schottky diodes were investigated using capacitance–voltage (*C–V*) and conductance–voltage (*G/ω–V*) characteristics. Before irradiation, the *C–V* and *G/ω–V* characteristics were measured by applying a small ac signal of 50 mV amplitude and 100 Hz–1 MHz frequencies, while the dc voltage was swept from positive bias to negative bias for MIS Schottky diodes. Afterwards, the *C–V* and *G/ω–V* measurements carried out at various radiation doses and 1 MHz. The MIS Schottky diodes were exposed to a ^{60}Co γ-radiation source at a dose of 2.12 kGy/h and the total dose range was from zero to 450 kGy. The dielectric constant (ε'), dielectric loss (ε''), loss tangent ($\tan\delta$) and ac electrical conductivity (σ_{ac}) were calculated from the *C–V* and *G/ω–V* measurements and plotted as a function of frequency and radiation dose. Experimental results show that the ε' and ε'' were found to decrease with increasing frequency while increase with increasing radiation dose. In addition, $\tan\delta$ versus log f show a peak, which was not present in the $\tan\delta$ versus radiation dose. Also, the σ_{ac} is found to increase with increasing radiation dose. These changes were attributed to mobile charge carriers or dipolar molecules generated by structural changes in the irradiated samples.

PACS: 61.80.−x; 73.40.Qv; 84.37.+q; 73.20.−r; 77.22.−d; 72.20.−i

Keywords: γ-ray effects; MIS Schottky diodes; *C–V* and *G/ω–V* characteristics; Dielectric properties; Conductivity

1. Introduction

Semiconductor devices such as metal-semiconductor (MS), metal-insulator-semiconductor (MIS) or metal-oxide-semiconductor (MOS) structures and solar cells used to in outer space are required to operate in strongly ionization radiation field and high-temperature atmospheres. At radiation doses greater than a few kilorad, exposure may cause strong electrical and dielectric changes in the MIS type Schottky diode or structure. Also, the main materials forming MIS or MOS structures semiconductor (Si) and insulator layer (SiO_2), are known to have different sensitivity to ionization radiation. Most of the radiation-induced damage in such devices is located at or near the SiO_2/Si interface. Extensive studies have been completed and have shown that most kinds of radiation have two primary effects on MIS Schottky diodes: positive charge accumulation in the oxide and creation of new electron states at the SiO_2/Si interface.

Furthermore, the exposure of these devices to high-level particles results in a considerable amount of lattice defects. These defects that act as recombination centers or minority/majority carrier trapping centers cause degradation of the diode performance and applications. Recently, several groups have investigated the effect of radiation on such devices [1–12].

These devices are required to have radiation-resistant characteristics. Therefore, it is of interest to investigate the damage defect centers on the performance of these types of semiconductor devices. Further, improvements in radiation resistance of MIS and MOS structures are

* Corresponding author. Tel.: +90 312212 6030; fax: +90 312212 279.
E-mail address: ademt@gazi.edu.tr (A. Tataroğlu).

0168-583X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2006.10.066

necessary for widespread γ-ray irradiation dose on their electrical and dielectric characteristics [1–12]. Ma [2,8] and Winokur et al. [9,10] were among the first to make a systematic observation of the after-irradiation behavior of radiation-induced interface traps in MIS and MOS devices. Interface traps, also referred to as interface states or surface states (N_{ss}), are electronic energy levels located at the MIS interface and they are important parameters like series resistance.

In our previous work [13] we studied the electrical characteristics of ^{60}Co γ-ray irradiated MIS Schottky diodes exposed to maximum cumulative dose of 450 kGy at room temperature. The experimental results show that an increase in the change in capacitance and conductance due to the irradiation-induced defects at the interface.

In this work, we present results of a study effect of the ^{60}Co γ-ray irradiation on the dielectric properties of MIS Schottky diode at room temperature. The dielectric properties determined from capacitance–voltage (C–V) and conductance–voltage (G/ω–V) measurements for MIS Schottky diodes were investigated before, and after, γ-irradiation of doses up to 450 kGy. The observed change in dielectric properties can be understood by considering the displacement damage introduced by irradiation.

2. Experimental detail

The Al/SiO_2/p–Si (MIS) Schottky diodes used in this study were fabricated using boron-doped single crystals silicon wafer with ⟨100⟩ surface orientation having thickness of 280 μm, 2″ diameter and 8 Ω cm resistivity. For the fabrication a process, Si wafer was decreased in organic solvent of $CHClCCl_2$, CH_3COCH_3 and CH_3OH consecutively and then etched in a sequence of H_2SO_4 an H_2O_2, 20% HF, a solution of 6HNO_3:1HF:35 H_2O, 20% HF and finally quenched in de-ionised water for a prolonged time. Preceding each cleaning step, the wafer was rinsed thoroughly in de-ionized water of resistivity of 18 MΩ-cm. Immediately after surface cleaning, to form ohmic contacts on the back surface of the Si wafer, high purity Al metal (99.999%) with a thickness of ~2000 Å was thermally evaporated from the tungsten filament onto the whole back surface of the Si wafer in the pressure of $\sim 2\times10^{-6}$ Torr in oil vacuum pump system and the evaporated aluminum (Al) was sintered. The oxidations are carried out in a resistance-heated furnace in dry oxygen with a flow rate of a 2 l/min and the oxide layer thickness is grown at the temperatures of 700 °C within 60 min. To form the Schottky contacts, the circular dots of ~1 mm diameter and ~2000 Å thick Al are deposited onto the oxidized surface of the wafer for through a metal shadow mask in a liquid nitrogen trapped vacuum system in a vacuum of $\sim 2\times10^{-6}$ Torr. The interfacial insulator layer thickness was estimated to be about 34 Å from high frequency (1 MHz) measurement of the interface insulator capacitance in the strong accumulation region for MIS Schottky diode.

The capacitance–voltage (C–V) and conductance–voltage (G/ω–V) measurements were carried out using an HP 4192A LF impedance analyzer (5 Hz–13 MHz). A low-distortion oscillator generated the ac signal with the amplitude attenuated to 50 mV_{rms} to meet the small signal requirement for oxide capacitors while dc voltage was swept from positive bias to negative bias. The C–V and G/ω–V measurements were performed at 1 MHz before and after γ-ray source irradiation with the dose of 2.12 kGy/h and total dose range was 0–450 kGy at room temperature. All measurements were carried out with the help of a microcomputer through an IEEE-488 ac/dc converter card.

3. Results and discussion

3.1. Frequency dependence of dielectric properties

The frequency dependencies of dielectric constant (ε'), dielectric loss (ε''), loss tangent ($\tan\delta$) and ac electrical conductivity (σ_{ac}) are studied for MIS Schottky diode. The values of the dielectric properties were calculated from the C–V and G/ω–V measurements in the frequency range of 100 Hz–1 MHz and at room temperature.

The complex permittivity can be defined in the following complex form [14,15],

$$\varepsilon^* = \varepsilon' - i\varepsilon'', \tag{1}$$

where ε' and ε'' are the real and the imaginary of complex permittivity, and i is the imaginary root of −1. The complex permittivity formalism has been employed to describe the electrical and dielectric properties. In the ε^* formalism, in the case of admittance measurements, the following relation holds:

$$\varepsilon^* = \frac{Y^*}{i\omega C_o} = \frac{C}{C_o} - i\frac{G}{\omega C_o}, \tag{2}$$

where Y^*, C and G are the measured admittance, capacitance and conductance of the dielectric and ω the angular frequency ($\omega = 2\pi f$) of the applied electric field [16].

The real part of the complex permittivity, the dielectric constant (ε'), at the various frequencies is calculated using the measured capacitance values at the strong accumulation region from the relation [17,18],

$$\varepsilon' = \frac{C}{C_o}, \tag{3}$$

where C_o is capacitance of an empty capacitor. $C_o = \varepsilon_o(A/d)$; where A is the rectifier contact area in cm^{-2}, d is the interfacial insulator layer thickness and ε_o is the permittivity of free space charge ($\varepsilon_o = 8.85\times10^{-14}$ F/cm). In the strong accumulation region, the maximal capacitance of MIS Schottky diode corresponds to the insulator capacitance (C_{ox}) ($C_{ac} = C_{ox} = \varepsilon'\varepsilon_o A/d$). The imaginary part of the complex permittivity, the dielectric loss (ε''), at the various frequencies is calculated using the measured conductance values from the relation,

$$\varepsilon'' = \frac{G}{\omega C_o}. \tag{4}$$

The loss tangent ($\tan\delta$) is the ratio of the imaginary ε'' and the real ε' parts of the dielectric constant and is giving by [14–19],

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}. \tag{5}$$

The ac electrical conductivity (σ_{ac}) of the dielectric material can be given by the following equation [14,20,21],

$$\sigma_{ac} = \omega C \tan\delta(d/A) = \varepsilon''\omega\varepsilon_o. \tag{6}$$

Fig. 1 shows the dielectric constant (ε'), dielectric loss (ε'') and loss tangent ($\tan\delta$) of Al/SiO_2/p–Si (MIS) Schottky diode as a function of the frequency, respectively. From the measured values of capacitance and conductance, the values of the ε', ε'' and $\tan\delta$ were found a strong function of frequency especially at low frequencies. On the other hand, it should be noted that at high frequencies, up to about 100 kHz, no appreciable changes in the ε' and ε'' were observed. This indicates that the motion of the free change carriers is constant at high frequencies and so the ε' and ε'' does not change. As can be seen from these figures, ε' and ε'' decrease as the frequency are increased. This observed decrease in ε' and ε'' with increasing frequency reflects dielectric relaxation caused by the inability of the dipolar molecules in the sample to change orientation direction with increasing rates of alteration of the applied field [22]. In principle, at low frequencies, all the four types of polarization processes, i.e. the electronic, ionic, dipolar, and interfacial or surface polarization contribute to the values of ε' and ε''. On raising frequency, the contributions of the interfacial, dipolar or the ionic polarization become ineffective leaving behind only the electronic part. Furthermore, the decrease in ε' and ε'' with increase in frequency is explained by the fact that as the frequency is raised, the interfacial dipoles have less time to orient themselves in the direction of the alternating field [23–27]. According to our opinion, the surface states in equilibrium with the semiconductor can easily follow the ac signal at low frequencies and an excess ε' and ε' occurs in addition to real dielectric ε' and ε''.

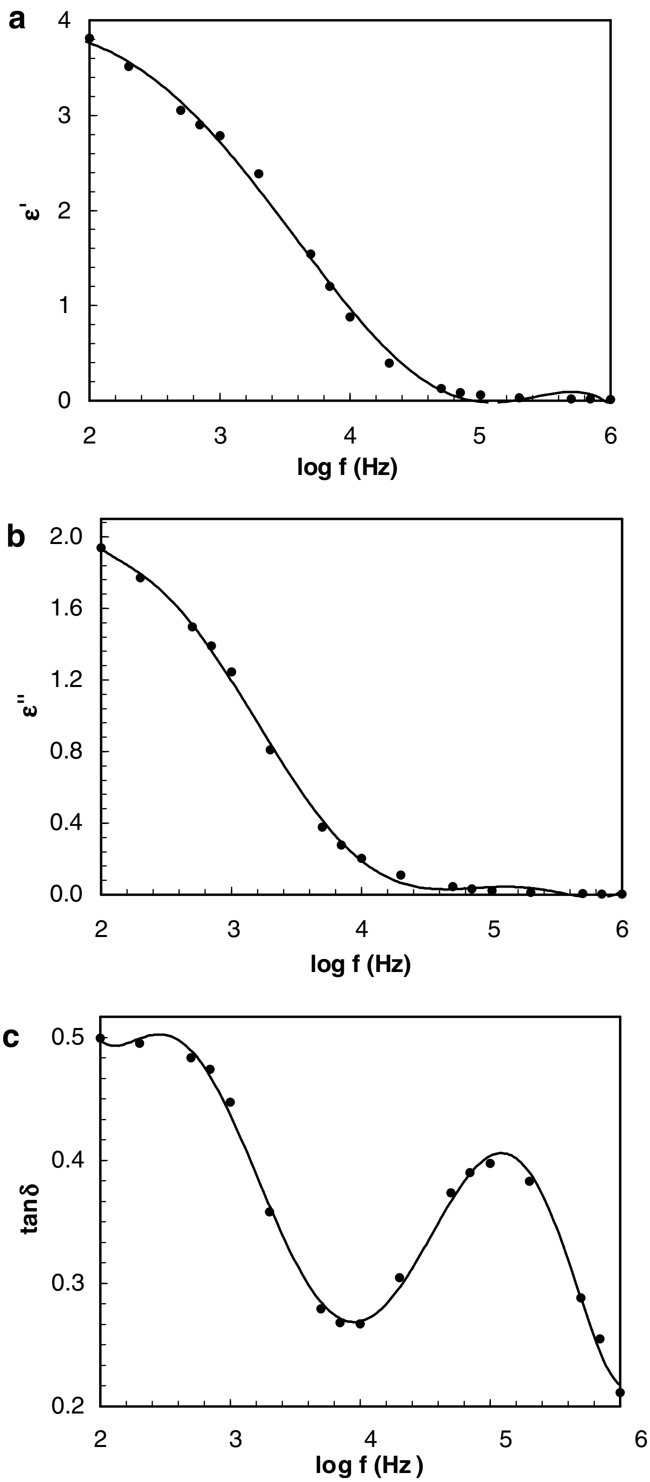

Fig. 1. Frequency dependence of the (a) ε', (b) ε'' and (c) $\tan\delta$ at room temperature for MIS Schottky diode.

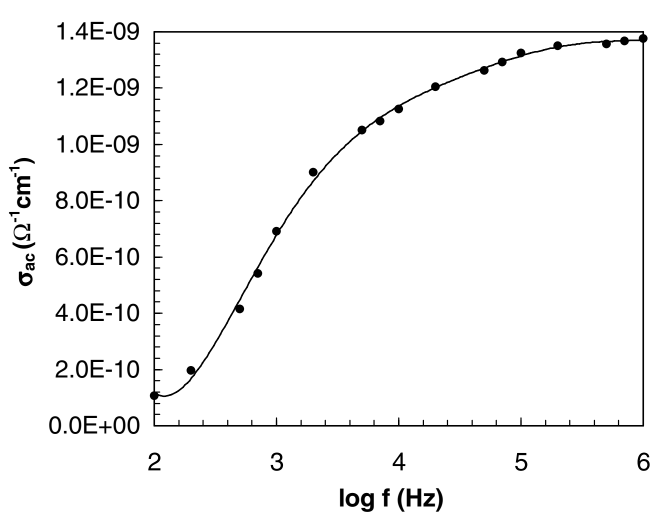

Fig. 2. Frequency dependence of ac electrical conductivity (σ_{ac}) for MIS Schottky diode.

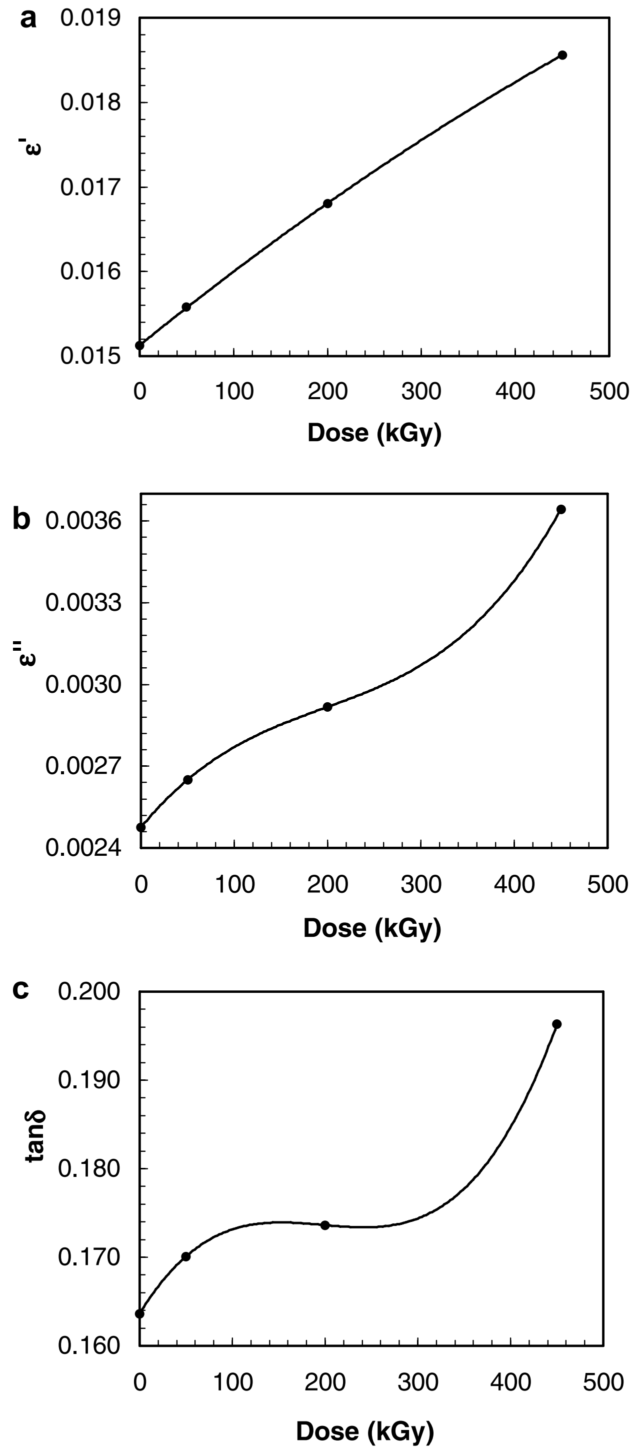

Fig. 3. Radiation dependence of the (a) ε', (b) ε'' and (c) $\tan\delta$ at high frequency (1 MHz) for MIS Schottky diode.

The variation of the loss tangent ($\tan\delta$) with respect to frequency of MIS Schottky diode is shown in Fig. 1(c). The $\tan\delta$–log f curve gives a peak about 100 kHz. The presence of peaks in loss tangent can be explained on the basis of relative variation of ε' and ε'' with frequency [28]. Therefore peak in the loss tangent can be attributed to the Maxwell–Wagner interfacial polarization (matching of hopping frequency with frequency of external electric field) [28–30].

Fig. 2 illustrates the dependence of the ac electrical conductivity (σ_{ac}) on the frequency. Fig. 2 depicts the variation of the ac conductivity σ_{ac} with frequency at room temperature for MIS Schottky diode. It is clear that the ac conductivity increases with increasing frequency. Similar results have been reported in the literature [20,21,24,31–33]. The increase of the conductivity σ is accompanied by an increase of the eddy current, which in turn increases the energy loss $\tan\delta$.

3.2. The effects of γ-irradiation dependence on the dielectric properties

The γ-ray dose dependencies of dielectric constant (ε'), dielectric loss (ε'') and loss tangent ($\tan\delta$) for MIS Schottky diode at 1 MHz and room temperature are given in Fig. 3(a–c), respectively. As show in Fig. 3(a) and (b), the ε' and ε'' increase with increasing radiation dose. The observed increase in ε' and ε'' values with increasing radiation dose may be attributed to a gradual formation of mobile charge carriers or easily orientable dipolar molecules that are capable of conducting the electric current. It is presumed that these charge carriers or dipolar molecules were formed from structural modifications (cross-linking, oxidation, etc.) caused by irradiation [22,26]. As shown in Fig. 3(c), the $\tan\delta$ increases with increasing radiation dose. The observed increase in $\tan\delta$ and thus increase in conductivity is brought about by an increase in the conduction of residual current and the conduction of absorption current [29,34,35].

The radiation dependence of ac electrical conductivity (σ_{ac}) for MIS Schottky diode at 1 MHz is given in Fig. 4. As show in Fig. 4, the σ_{ac} increases with increasing radiation dose. The increase in ac electrical conductivity due to irradiation may be attributed to charge centers created. When an ac field of sufficiently high frequency applied to

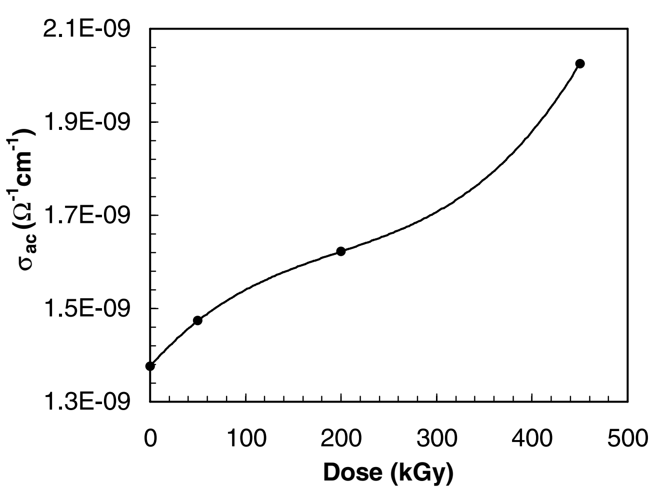

Fig. 4. Radiation dependence of ac electrical conductivity (σ_{ac}) at 1 MHz.

MIS Schottky diode may cause a net polarization, which is out of phase with the field. This results in ac conductivity that appears at frequency greater than that at which traps are filled or emptied [29,34,36,37].

4. Conclusions

The study of the effect of ^{60}Co γ-irradiation on dielectric properties of MIS Schottky diode indicates that irradiation induces structural changes that lead to the creation of mobile charge carriers. As a result, the values of the dielectric constant (ε') and dielectric loss (ε'') were found to decrease with increasing frequency. The increase in both ε' and ε'' towards the lower frequency region may be attributed to the presence of interfacial polarization mechanism and the surface states in equilibrium with the semiconductor can follow the ac signal and low frequencies. Furthermore, the values of the ε', ε'' and loss tangent ($\tan\delta$) are increased upon irradiation. The increase in the ε', ε'' and $\tan\delta$ due to γ-irradiation appears to be independent of the applied dc bias voltage. The increase in ac electrical conductivity with frequency due to irradiation may be attributed to charge centers created. The observed change in dielectric properties can be understood by considering the displacement damage introduced by irradiation.

References

[1] T.R. Oldham, Ionizing Radiation Effects in MOS Oxides, World Scientific Publishing, Singapore, 1999.
[2] T.P. Ma, P.V. Dressendorfer, Ionizing Radiation Effect in MOS Devices and Circuits, Wiley, New York, 1989.
[3] S. Kaschieva, Zh. Todorova, S.N. Dmitriev, Vacuum 76 (2004) 307.
[4] E.A. De Vascancelas, E.F. Da Silva Jr., H. Khoury, V.N. Freire, Semicond. Sci. Technol. 15 (2000) 794.
[5] G.A. Umana-Membreno, J.M. Dell, G. Parish, B.D. Nener, L. Faraone, U.K. Mishra, IEEE Trans. Electron Dev. 50 (12) (2003) 2326.
[6] R.K. Chauhan, P. Chakrabarti, Microelectron. J. 33 (2002) 197.
[7] K. Naruke, M. Yoshida, K. Maegushi, H. Tango, IEEE Trans. Nucl. Sci. NS-30 (6) (1983) 4054.
[8] T.P. Ma, Semicond. Sci. Technol. 4 (1989) 1061.
[9] P.S. Winokur, J.M. McGarrity, H.E. Boesch, IEEE Trans. Nucl. Sci. 23 (1976) 1580.
[10] P.S. Winokur, J.R. Schwank, P.J. McWhorter, P.V. Dressendorfer, D.C. Turpin, IEEE Trans. Nucl. Sci. 31 (6) (1984) 1453.
[11] A. Tataroğlu, Ş. Altındal, S. Karadeniz, N. Tuğluoğlu, Microelectron. J. 34 (2003) 1043.
[12] M.Y. Feteha, M. Soliman, N.G. Gomaa, M. Ashry, Renew. Energy 26 (2002) 113.
[13] A. Tataroğlu, Ş. Altındal, Nucl. Instr. and Meth. B 252 (2006) 257.
[14] C.P. Symth, Dielectric Behaviour and Structure, McGraw-Hill, New York, 1955.
[15] Vera V. Daniel, Dielectric Relaxation, Academic Press, London, 1967.
[16] P. Pissis, A. Kyritsis, Solid State Ionics 97 (1997) 105.
[17] M. Popescu, I. Bunget, Physics of Solid Dielectrics, Elsevier, Amsterdam, 1984.
[18] A. Chelkowski, Dielectric Physics, Elsevier, Amsterdam, 1980.
[19] A. Tataroğlu, Ş. Altındal, M.M. Bülbül, Microelectron. Eng. 81 (2005) 140.
[20] M.S. Mattsson, G.A. Niklasson, K. Forsgren, A. Harsta, J. Appl. Phys. 85 (4) (1999) 2185.
[21] K. Prabakar, S.K. Narayandass, D. Mangalaraj, Phys. Status Solidi (a) 199 (3) (2003) 507.
[22] A.M. Al-Karmi, Radiat. Measur. 41 (2006) 209.
[23] D. Maurya, J. Kumar, S.R.P. Tandon, J. Phys. and Chem. Solids 66 (2005) 1614.
[24] A.A. Sattar, S.A. Rahman, Phys. Status Solidi (a) 200 (2) (2003) 415.
[25] S.A. Nouh, S.A. Gaafar, H.M. Eissa, Phys. Status Solidi (a) 175 (1999) 699.
[26] C. Fanggao, G.A. Saunders, E.F. Lambson, R.N. Hampton, G. Carini, G.D. Marco, M. Lanza, J. Appl. Poly. Sci. 34 (1996) 425.
[27] M.R. Ranga Raju, R.N.P. Choudhary, S. Ram, Phys. Status Solidi (b) 239 (2) (2003) 480.
[28] M. Singh, A. Dogra, R. Kumar, Nucl. Instr. and Meth. B 196 (2002) 315.
[29] N. Shah, N.L. Singh, C.F. Desai, K.P. Singh, Radiat. Measur. 36 (2003) 699.
[30] N. Konofaos, E.K. Evangelou, X. Aslanoglou, M. Kokkoris, R. Vlastou, Semicond. Sci. Technol. 19 (2004) 50.
[31] M.D. Migahed, M. Ishra, T. Fahmy, A. Barakat, J. Phys. and Chem. Solids 65 (2004) 1121.
[32] A.S. Riad, M.T. Korayem, T.G. Abdel-Malik, Physica B 270 (1999) 140.
[33] S.A. Mazen, H.M. Zaki, Phys. Status Solidi (a) 199 (2) (2003) 305.
[34] N.L. Singh, A. Sharma, V. Shrinet, A.K. Rakshit, D.K. Avasthi, Bull. Mater. Sci. 27 (3) (2004) 263.
[35] B. Tareev, Physics of Dielectric Materials, Mir Publication, Moscow, 1975.
[36] A.K. Jonscher, Nature 267 (1977) 673.
[37] N. Singh, A. Sharma, D.K. Avasthi, Nucl. Instr. and Meth. B 206 (2003) 1120.