Available online at www.sciencedirect.com
ScienceDirect
Microelectronic Engineering 85 (2008) 1518–1523
MICROELECTRONIC ENGINEERING
www.elsevier.com/locate/mee

Dielectric properties and ac electrical conductivity studies of MIS type Schottky diodes at high temperatures

A. Tataroğlu *, İ. Yücedağ, Ş. Altindal

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

Received 14 November 2007; received in revised form 4 February 2008; accepted 19 February 2008
Available online 4 March 2008

Abstract

Dielectric properties and ac electrical conductivity of the Al/SiO_2/p-Si (MIS) Schottky diodes were studied in the frequency and temperature range of 10 kHz–1 MHz and 300–400 K, respectively. Experimental results show that the dielectric constant (ε'), dielectric loss (ε''), loss tangent ($\tan\delta$), ac electrical conductivity (σ_{ac}) and the electric modulus were found a strong function of frequency and temperature. The values of the ε', ε'' and $\tan\delta$ decrease with increasing frequencies due to the interface states capacitance and a decrease in conductance with increasing frequency. Also, these values increase with increasing temperature. The σ_{ac} is found to increase with increasing frequency and increasing temperature. The variation of conductivity as a function of temperature and frequency reveals non-adiabatic hopping of charge carriers between impurities localized states. In addition, the experimental dielectric data have been analyzed by considering electric modulus formalism.

Keywords: MIS type Schottky diode; Dielectric properties; Ac electrical conductivity; Electric modulus

1. Introduction

The semiconductor devices such as metal–semiconductor (MS), metal–insulator–semiconductor (MIS)-type Schottky diodes and metal–oxide–semiconductor (MOS) capacitors have been still investigated and have attracted much attention during recent years [1–3]. In MIS and MOS structures, metal and semiconductor remain separated by an interfacial insulator layer such as SiO_2, SnO_2 and at metal/insulator interfaces there is a continuous distribution of surface states with energies located in the band gap of semiconductor. This interfacial insulator layer cannot only prevent inter-diffusion between metal and semiconductor, but also alleviate the electric field reduction in MIS Schottky diodes.

Also, semiconductor device parameters such as performance, stability and reliability are highly dependent on the interfacial properties of the interface insulator layer between metal and semiconductor. Because composition and stability of the interface insulator layers is not completely understood, the quality of devices with an interfacial insulator layer is not satisfactory [4–7].

The existence of such an insulator layer converts MS devices into MIS Schottky diodes and can have a strong influence on the diode characteristics as well as the interface states (N_{ss}), and series resistance (R_s) and can modify the electrical properties of MIS structure [8–10]. The interfacial insulator layer, interface state and series resistance values cause the electrical characteristics of MIS Schottky diodes to be non-ideal [11–13]. Therefore, the frequency and temperature dependent electrical characteristics are very important to get accurate and reliable results for semiconductor devices [10,11].

In this article, dielectric properties and the ac electrical conductivity of Al/SiO_2/p-Si (MIS) Schottky diode have been studied by C–V and G/ω–V measurements technique in the frequency and temperature range of 10 kHz–1 MHz and 300–400 K, respectively. To determine the dielectric constant (ε'), dielectric loss (ε''), loss tangent ($\tan\delta$), the

* Corresponding author. Tel.: +90 312 212 6030; fax: +90 312 212 2279.
E-mail address: ademt@gazi.edu.tr (A. Tataroğlu).

0167-9317/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.mee.2008.02.005

ac electrical conductivity (σ_{ac}) and the electric modulus of MIS Schottky diode, the admittance technique was used [2,14].

2. Experimental detail

The metal–insulator–semiconductor (Al/SiO_2/p-Si) Schottky diodes used in this study were fabricated using p-type (boron-doped) single crystal silicon wafer with ⟨1 0 0⟩ surface orientation, having thickness of 280 μm, 2″ diameter and 8 Ω cm resistivity. For the fabrication process, Si wafer was degreased in organic solution 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: $35H_2O$, 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, high purity (99.999%) aluminum with a thickness of ~2000 Å was thermally evaporated from the tungsten filament onto the whole backside of in half wafer at a pressure of $\sim 2 \times 10^{-6}$ Torr in oil vacuum pump system. The ohmic contacts were prepared by sintering the evaporated Al back contact at 750 °C for 60 minutes in flowing dry nitrogen ambient at rate of 2 l/min. This process served to sinter the aluminum on the upper surface of the Si wafer. After made ohmic contact, the front surface of the Si wafer was exposed to air in sterile glass box for a prolonged time at room temperature. Schottky contacts (front rectifier contacts) formed by evaporation of 2000 Å thick aluminum dots of ~1 mm diameter onto the Si wafer. The metal thickness layer and the deposition rates were monitored with the help of quartz crystal thickness monitor. In this way, metal–semiconductor (MS) diode with thin interfacial insulator layer (SiO2) was fabricated on p-type Si. The interfacial insulator layer thickness was estimated to be about 53 Å from high frequency (1 MHz) measurement of the oxide capacitance in the strong accumulation region.

The capacitance–voltage (*C*–*V*) and conductance–voltage (G/ω–*V*) measurements were carried out as a function of frequency (10 kHz–1 MHz), in the temperature range of 300–400 K, by using a HP 4192A LF impedance analyser (5 Hz–13 MHz) and a small ac test signal 40 mV_{rms} from the external pulse generator was applied to the sample in order to meet the requirement [3]. All measurements were controlled Janes vpf-475 cryostat, which enables us to make measurements in the temperature range of 77–450 K. The sample temperature was always monitored by using a copper–constantan thermocouple close to the sample and by measuring with a dmm/scanner Keithley model 199 and a Lake Shore model 321 auto-tuning temperature controllers with sensitivity better than ±0.1 K. In addition, 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. Temperature and frequency dependence capacitance and conductance measurements

The conductance technique [2,3] is based on the conductance losses resulting from the exchange of majority carriers at the metal/semiconductor interface and the majority carrier band of the semiconductor when a small ac test signal is applied to the MIS type Schottky diode. The applied ac signal causes the Fermi level to oscillate about the mean positions that is governed by the dc bias, when the MIS Schottky diode is in the depletion region.

The variation of the capacitance and conductance with temperature at different frequencies of the MIS Schottky diode are shown in Fig. 1a and b, respectively. As can be seen in Fig. 1a and b, the capacitance and conductance is sensitive to frequency at relatively high temperatures and

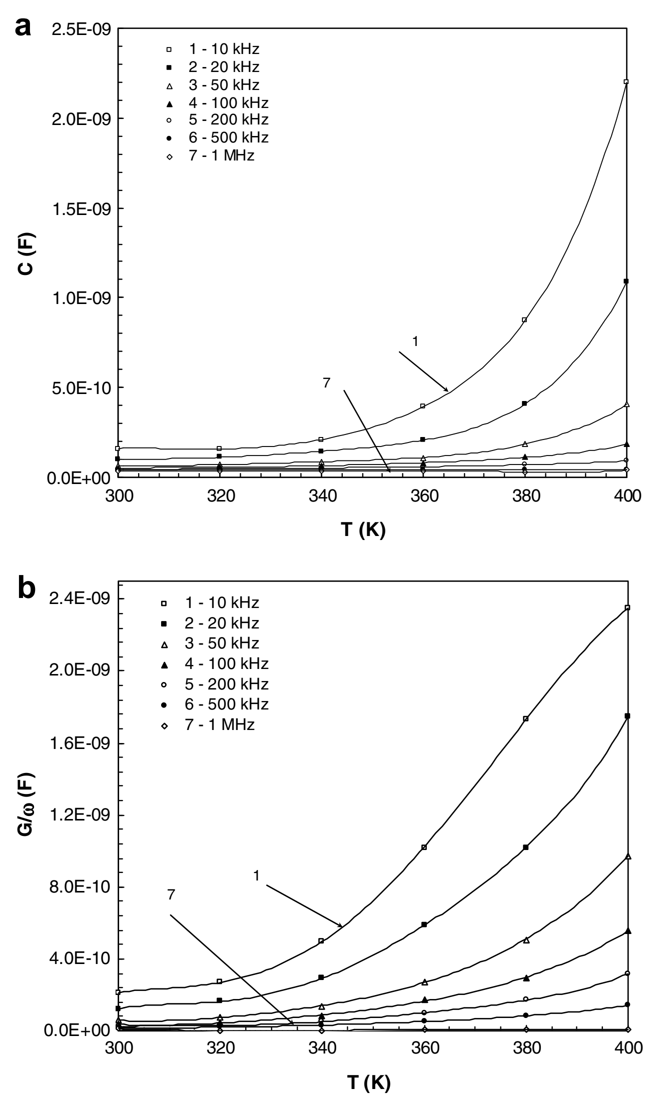

Fig. 1. Variation of the (a) capacitance (*C*) and (b) conductance (G/ω) with temperature at different frequencies for MIS Schottky diode.

at low frequencies. The capacitance and conductance decrease as the frequency is increased. The increase in capacitance towards the low-frequency region may be due to interfacial space charge formation, which would be effective at lower frequencies and hence the capacitance begins to decrease [15]. In addition, the values of both capacitance and conductance increase with increasing temperature.

The capacitance of such an inhomogeneous layer at the semiconductor/insulator interface acts in a series with the insulator capacitance causing frequency dispersion. Because at lower frequencies, the interface states can follow the ac signal and yield an excess capacitance, which depends on the frequency. In the high frequency limit ($f \geqslant 500$ kHz) the interface states cannot follow the ac signal. This makes the contribution of interface state capacitance to the total capacitance negligibly small [16].

3.2. Temperature and frequency dependence dielectric properties and ac electrical conductivity measurements

The temperature and frequency dependence of dielectric constant (ε'), dielectric loss (ε''), loss tangent ($\tan\delta$), ac electrical conductivity (σ_{ac}) and electric modulus were investigated for MIS Schottky diode.

The complex permittivity can be defined in the following complex form [17,18],

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

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

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

where Y^*, C and G are the measured admittance, capacitance and conductance of the dielectric and ω is the angular frequency ($\omega = 2\pi f$) of the applied electric field [19].

The dielectric constant which is the real part of the complex is calculated at the various frequencies by using the measured capacitance values at the strong accumulation region from the relation [20,21],

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

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 ($\varepsilon_o = 8.85 \times 10^{-14}$ F/cm). In the strong accumulation region, the maximum value of the MIS Schottky diode capacitance corresponds to the insulator capacitance ($C_{ox} = \varepsilon' C_o = \varepsilon'\varepsilon_o A/d$). The dielectric loss ($\varepsilon''$) which is the imaginary part of the complex permittivity is calculated at the various frequencies by using the measured conductance values at strong accumulation region from the relation [1–3],

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

The loss tangent ($\tan\delta$) can be expressed as follows [17,18,20–22],

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

The values of ac electrical conductivity (σ_{ac}) can be written as [15,17,23],

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

The complex impedance (Z^*) and complex electric modulus (M^*) formalisms were discussed by various authors [15,19]. Analysis of the complex permittivity (ε^*) data within the Z^* formalism ($Z^* = 1/Y^* = 1/j\omega C_o\varepsilon^*$) is commonly used to separate the bulk and the surface phenomena and to determine the bulk dc conductivity of the material [19,23]. The complex impedance or the complex permittivity ($\varepsilon^* = 1/M^*$) data were transformed into the M^* formalism using the following relation [15,19,24]

$$M^* = j\omega C_o Z^* \tag{7}$$

or

$$M^* = \frac{1}{\varepsilon^*} = M' + jM'' = \frac{\varepsilon'}{\varepsilon'^2 + \varepsilon''^2} + j\frac{\varepsilon''}{\varepsilon'^2 + \varepsilon''^2} \tag{8}$$

The real component M' and the imaginary component M'' were calculated from ε' and ε''.

The temperature dependence of the dielectric constant (ε'), dielectric loss (ε''), loss tangent ($\tan\delta$) at different frequencies for MIS Schottky diode is shown in Fig. 2a, b and c, respectively. The variation of the ε' and ε'' with frequency are small at low temperatures and at high frequencies. In the absence of an electric field, the charge carriers that bind to different localized states would show different dipole orientations. An electron can hop between a pair of these centers under the action of an ac field, leading to the reorientation of an electric dipole. This process would give an increase to a change in the dielectric constant. Hence the increase in the dielectric constant with decreasing frequency can be attributed to the dipole effect.

As can be seen from these figures, ε', ε'' and $\tan\delta$ increase as the temperature is increased [22,25–29]. As the temperature rises, imperfections/disorders are created in the lattice and the mobility of the majority charge carriers (ions and electrons) increases. The combined effect gives an increase in the values of ε' and ε'' with increasing temperature. This may be possibly due to the ion jump, the orientation and space charge effect resulting from the increased concentrations of the charge carriers. Furthermore, the increase in temperature induced an expansion of molecules which causes some increase in the electronic polarization and hence an increase in the ε' and ε'' of the dielectric material [30–32].

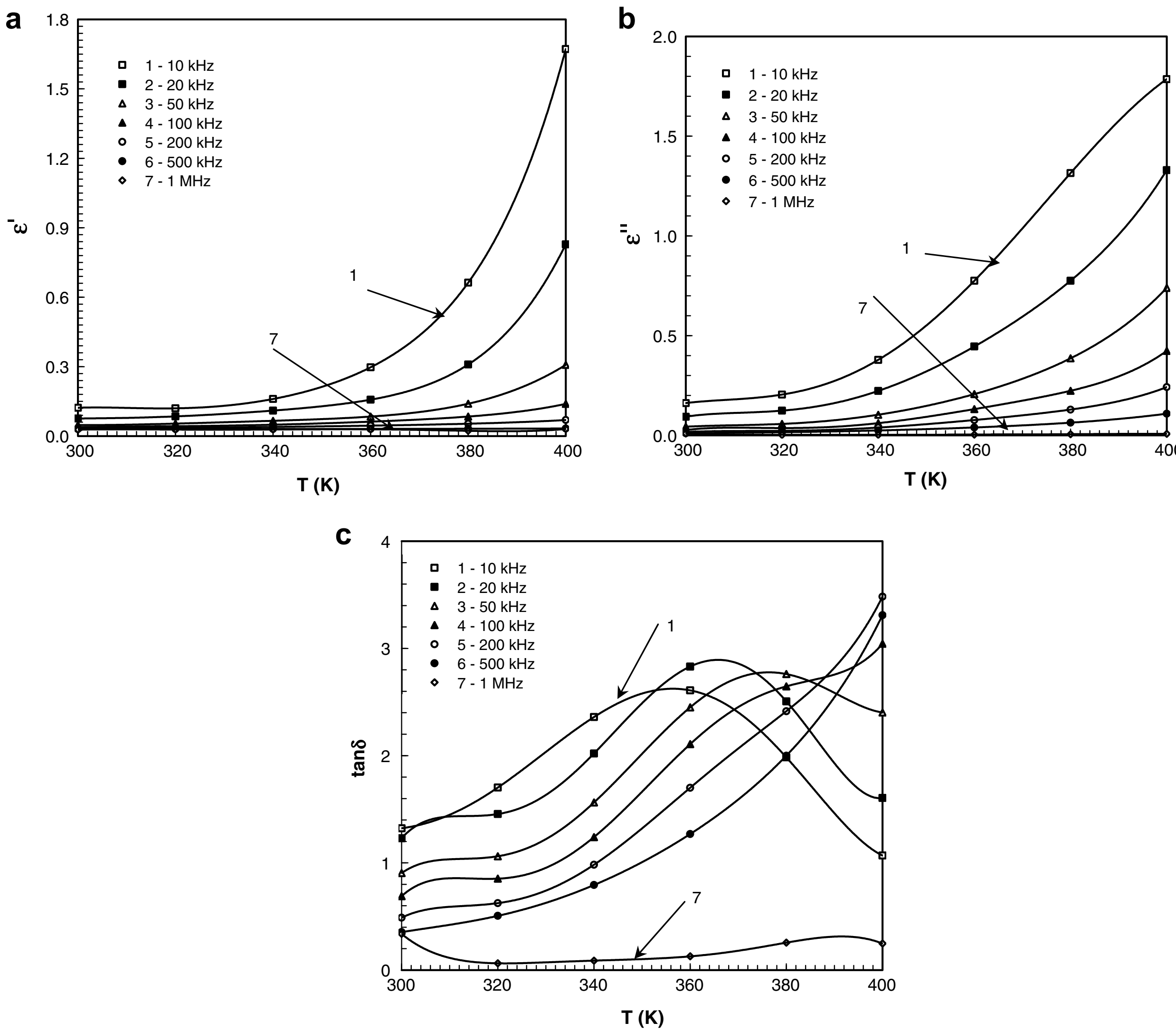

Fig. 2. Temperature dependence of the (a) ε', (b) ε'' and (c) $\tan\delta$ at different frequencies for MIS Schottky diode.

The rate of increase, as the temperature causes a loosening of the rigid structure, results in an increase in dipole orientation and hence an increase in ε', ε'' and $\tan\delta$. These results show that the studied MIS Schottky diode possess better dielectric properties at temperatures lesser than room temperature. The variation of the ε', ε'' and $\tan\delta$ with temperature is a general trend in ionic solids. It may be due to space charge polarization caused by impurities or interstitials in the materials. Moreover in narrow band semiconductors, the charge carriers are not free to move but are trapped causing a polarization. With increasing temperature, the number of charge carriers increases exponentially and thus produces further space charge polarization and hence leads to a rapid increase in the dielectric constant ε'. Of course, both types of charge carriers n and p contribute to the polarization. However, the p-type contribution is negligible where the dominant charge carriers are electrons as shown previously [15,25,26].

Fig. 3 shows the temperature dependence of ac electrical conductivity (σ_{ac}) at different frequencies for MIS Schottky diode. It is clear that the conductivity increases with increasing temperature and frequency. Similar results have been reported in the literature [15,23,24,28,33,34]. It is suggested that the process of dielectric polarization in MIS Schottky diode takes place through a mechanism similar to the conduction process. According to the references [23,24,32,33], the increase of the electrical conductivity at high temperature is attributed to the impurities, which locate at the grain boundaries. These impurities lie below the bottom of the conduction band.

A linear relation between the total conductivity and the inverse absolute temperature could be written as

$$\sigma = \sigma_o \exp(-E_a/kT) \tag{9}$$

where σ_o represents the composite constant, k the Boltzmann constant and E_a, is the apparent activation energy. Fig. 4 shows the Arrhenius plots for the temperature dependence of ac conductivity $\sigma_{ac}(T)$ measured at different frequencies under accumulation bias in the temperature range of 300–400 K.

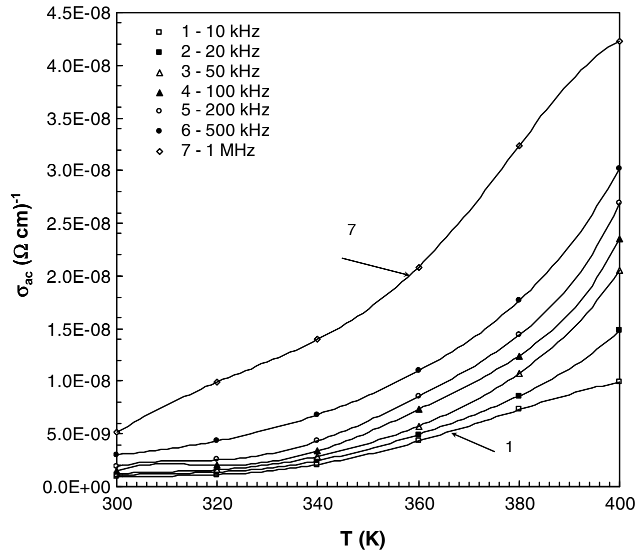

Fig. 3. Temperature dependence of ac electrical conductivity (σ_{ac}) at different frequencies for MIS Schottky diode.

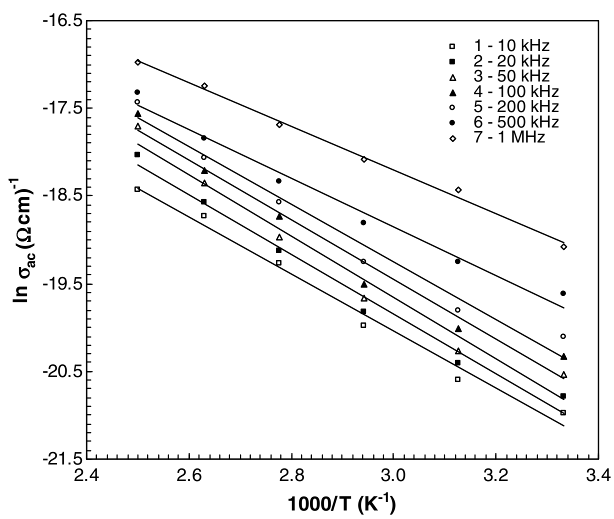

Fig. 4. Arrhenius plot of ac electrical conductivity for MIS Schottky diode.

As shown in Fig. 4 a plot of $\ln\sigma$ versus $1000/T$ is a straight line. The activation energy (E_a) values obtained from the slope at different frequency are given in Table 1. As can be seen in Table 1, the activation energy increases with increasing frequency. Similar results have been reported in the literature [15,27,28,32,35–37]. The higher activation energy that is observed in the high-temperature region may be due to the sum of the energies required for the generation of the charge carriers and their motion into vacancies [38].

Fig. 5a and b shows the real part of M' and the imaginary part of M'' of electric modulus M^* versus temperature for MIS Schottky diode at several frequencies. As can be seen in Fig. 5a, the M' decreases with increasing temperature while increases with increasing frequency. On the other hand, Fig. 5b shows that the M'' increases with increasing frequency. Similar studies have been reported in literature [15,19,24,39].

Table 1
The activation energy (E_a) and the composite constant (σ_o) for different frequency ranges

f (kHz)	E_a (eV)	σ_o $(\Omega\,\text{cm})^{-1}$
10	0.026	2.436×10^{-6}
20	0.025	5.081×10^{-6}
50	0.025	1.040×10^{-5}
100	0.025	9.732×10^{-6}
200	0.026	8.048×10^{-6}
500	0.031	2.592×10^{-6}
1000	0.035	1.308×10^{-6}

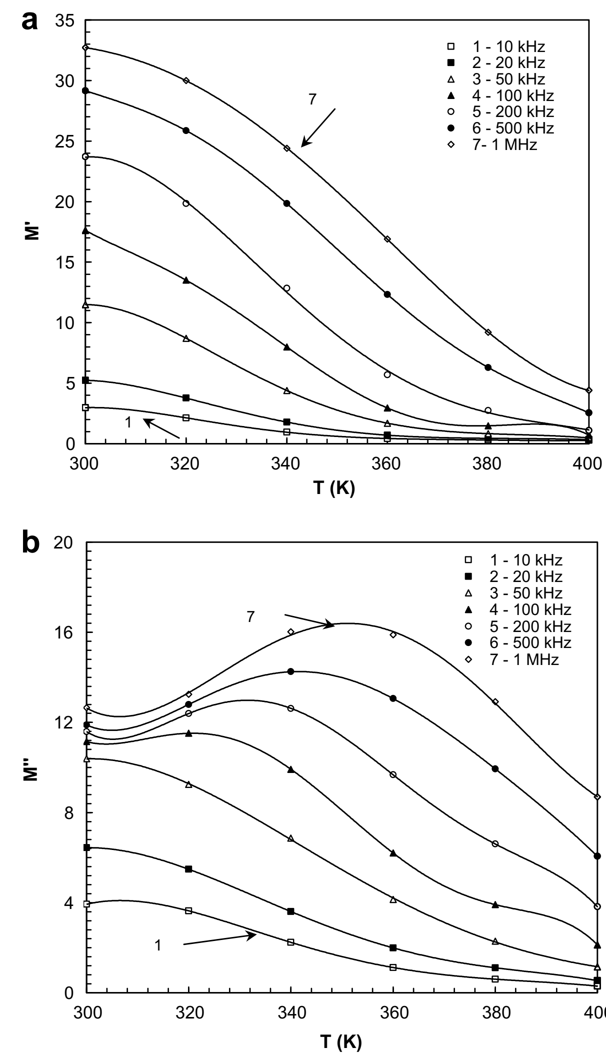

Fig. 5. (a) Real part M' and (b) imaginary part M'' of electric modulus M^*, versus temperature over a measured frequency range of 10 kHz–1 MHz for MIS Schottky diode.

4. Conclusions

Frequency and temperature dependence of dielectric properties and ac electrical conductivity of $Al/SiO_2/p\text{-}Si$

(MIS) type Schottky diode have been studied in detail in the temperature (300–400 K) and frequency (10 kHz–1 MHz) range. The values of capacitance (C) and conductance (G/ω) decrease with increasing frequency while increase with increasing temperature. The increase in C and G/ω with temperature may be due to ionic conduction. The values of dielectric constant (ε') and dielectric loss (ε'') increase with increasing temperature. Ac electrical conductivity (σ_{ac}) increase with increasing temperature. The variation of the conductivity as a function of temperature and frequency reveals non-adiabatic hopping of charge carriers between impurity sites in the low-dispersion region. The activation energy decreases with an increase in frequency. The observed frequency dependent conductance behaviour suggests that the conduction mechanism in MIS type Schottky diodes may be due to the hopping of charge carriers between distributed defects/localized states. The behaviour of dielectric properties especially depends on temperature, frequency, interfacial insulator layer and the density of space charges. Since the presence of the interfacial insulator layer, interface states and series resistance cause the deviation of the electrical and dielectric characteristics, that is, the MIS type Schottky diodes do not show the ideal capacitance and conductance behaviour.

Acknowledgement

This work is supported by Turkish Prime Ministry State Planning Organization project number 2001K120590.

References

[1] S.M. Sze, Physics of Semiconductor Devices, second ed., Wiley, New York, 1981.
[2] E.H. Rhoderick, R.H. Williams, Metal–Semiconductor Contacts, second ed., Oxford University Press, Oxford, 1988.
[3] E.H. Nicollian, J.R. Brews, MOS Physics and Technology, John Wiley and Sons, New York, 1982.
[4] J.H. Werner, Appl. Phys. A 47 (1988) 291.
[5] M.K. Hudait, S.B. Krupanidhi, Solid-State Electron. 44 (2000) 1089.
[6] W. Schottky, Naturwissenchaften 26 (1938) 843.
[7] N.F. Mott, Proc. Cambridge Philos. Soc. 34 (1983) 568.
[8] P. Chattopadhyay, Solid State Electron. 37 (1994) 1759.
[9] A. Singh, Solid-State Electron. 28 (3) (1985) 223.
[10] P. Cova, A. Singh, R.A. Masut, J. Appl. Phys. 82 (1997) 5217.
[11] H. Deuling, E. Klausmann, A. Goetzberger, Solid-State Electron. 15 (5) (1972) 559.
[12] R. Castagne, A. Vapaille, Surf. Sci. 28 (1) (1971) 157.
[13] U. Kelberlau, R. Kassing, Solid-State Electron. 22 (1) (1979) 37.
[14] E.H. Nicollian, A. Goetzberger, Appl. Phys. Lett. 7 (1965) 216.
[15] K. Prabakar, S.K. Narayandass, D. Mangalaraj, Phys. Status Solidi (a) 199 (3) (2003) 507.
[16] B. Akkal, Z. Benamara, B. Gruzza, L. Bideux, Vacuum 57 (2000) 219.
[17] C.P. Symth, Dielectric Behaviour and Structure, McGraw-Hill, New York, 1955.
[18] Vera V. Daniel, Dielectric Relaxation, Academic Press, London, 1967.
[19] A. Tataroğlu, Microelectron. Eng. 83 (2006) 2551.
[20] M. Popescu, I. Bunget, Physics of Solid Dielectrics, Elsevier, Amsterdam, 1984.
[21] A. Chelkowski, Dielectric Physics, Elsevier, Amsterdam, 1980.
[22] A. Tataroğlu, Ş. Altındal, M.M. Bülbül, Microelectron. Eng. 81 (2005) 140.
[23] M.S. Mattsson, G.A. Niklasson, K. Forsgren, A. Harsta, J. Appl. Phys. 85 (4) (1999) 2185.
[24] M.D. Migahed, M. Ishra, T. Fahmy, A. Barakat, J. Phys. Chem. Solids 65 (2004) 1121.
[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. Polym. Sci. 34 (1996) 425.
[27] M.A. Osman, M.A. Hefni, R.M. Mahfouz, M.M. Ahmad, Physica B 301 (2001) 318.
[28] A.S.Md.S. Rahman, M.H. Islam, C.A. Hogarth, Int. J. Electron. 62 (2) (1987) 167.
[29] C.V. Kannan, S. Ganesamoorthy, C. Subramanian, P. Ramasamy, Phys. Status Solidi (a) 196 (2) (2003) 465.
[30] M.R. Ranga Raju, R.N.P. Choudhary, S. Ram, Phys. Status Solidi (b) 239 (2) (2003) 480.
[31] V. Singh, A.R. Kulkarni, T.R. Rama Mohan, J. Appl. Polym. Sci. 90 (2003) 3602.
[32] D. Maurya, J. Kumar, Shripal, J. Phys. Chem. Solids 66 (2005) 1614.
[33] A.A. Sattar, S.A. Rahman, Phys. Status Solidi (a) 200 (2) (2003) 415.
[34] A.S. Riad, M.T. Korayem, T.G. Abdel-Malik, Physica B 270 (1999) 140.
[35] P. Suguna, D. Mangalaraj, Sa.K. Narayandass, P. Meena, Phys. Status Solidi (a) 155 (1996) 405.
[36] R. Arora, A. Kumar, Phys. Status Solidi (a) 115 (1989) 307.
[37] A.A. Dakhel, J. Phys. Chem. Solids 65 (2004) 1765.
[38] P. Meena, C. Balasubramanian, Sa.K. Narayandass, D. Mangalaraj, Phys. Status Solidi (a) 135 (1993) 207.
[39] S.P. Szu, C.Y. Lin, Mater. Chem. Phys. 82 (2003) 295.