γ-ray irradiation effects on dielectric properties of Au/SiO_2/n-Si (MIS) structures

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The effects of γ-ray irradiation on the dielectric properties of Au/SiO_2/n-Si (MIS) structures were investigated. Structures were exposed to a ^{60}Co γ-radiation source with a dose rate of 2.12 kGy/h. The dielectric constant (ε'), dielectric loss (ε''), loss factor (tanδ) and ac electrical conductivity (σ_{ac}) were calculated from the C-V and G/ω-V measurements and plotted as a function of radiation dose at high frequency (1 MHz). A decrease in the ε' and ε'' was observed as the irradiation dose was increased. The decrease in the magnitudes of the ε' and ε'' of irradiated MIS structures is explained on the basis of Maxwell-Wagner interfacial polarization. The obtained data from the C-V and G/ω-V measurements suggest that these structures may be used in radiation dosimetry applications.

(Received October 18, 2010; accepted April 11, 2011)

Keywords: Radiation effects, MIS structures, Dielectric properties, Conductivity, Electric modulus

1. Introduction

It is now a well known fact that the exposure of any metal/insulator or oxide/semiconductor (MIS or MOS) structures to ionizing radiations (such as X-rays, gamma rays, beta particles, alpha particles, etc) produces changes in the microstructural properties of the material, which in turn affects the optical, electrical and dielectric properties. In addition to their main applications in microelectronics, MIS and MOS structures are susceptible to ionizing radiation and are presently being used as dosimeter for monitoring radiation doses in various applications such as space and nuclear industry researches [1-9]. Numerous efforts have recently been made to investigate the influence of gamma radiation on thin films and their structures of different metal oxides and polymers, in order to find out the suitability of using thin films and their structures of different metal oxides and polymers as gamma radiation dosimeters [1-6].

From the observed changes in the C-V and G/ω-V characteristics of MIS structure, it can be concluded that for any ionizing radiation with a photon energy greater than the band gap of the SiO2 (9 eV) a not positive trapped charge builds up in insulator/oxide region of MIS structures. In MIS and MOS structures, the interfacial insulator layer is an important part of the structure. Therefore, from both scientific and the technological aspects, it is of great interest to understand the effects of high levels of ionizing radiation at or near the Si/SiO2 interface. It has been reported that the most important effects occurring when MIS structures are exposed to ionizing radiation are the introduction of a fixed positive space charge in the interfacial insulator layer and the creation of new surface states at Si/SiO_2 interface on some occasions [5,7].

These structures 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. Furthermore, to improve the radiation resistance of MIS and MOS structures, the widespread γ-ray irradiation dose is necessary for understanding the effects of radiation on their electrical characteristics [10-15]. The origins of the radiation-induced defects are not clearly understood and further studies are necessary to clarify the atomic structure of the defects. The fundamental studies on radiation-induced defects in Si have extensively been carried out by Bourgoin et al. [16] and Kimerling [17]. Goetzberger [18] argued that the charge trapped within 30 Å of the interface could produce fluctuations in surface potential capable of trapping electrons and holes.

In this work, we present the results of a study of the γ-ray irradiation on the dielectric properties and electrical conductivity of MIS structure at room temperature. The ε', ε'', tanδ and σac are determined from capacitance-voltage (C-V) and conductance-voltage (G/ω-V) measurements for MIS structures before and after gamma irradiation of doses up to a total dose of 100 kGy at 1 MHz and room temperature under dark condition. The observed change in dielectric properties can be understood by considering the displacement damage introduced by irradiation.

2. Experimental details

The Au/SiO_2/n-Si (MIS) structures used in this study were fabricated using n-type (P-doped) single crystals silicon wafer with <100> surface orientation having thickness of 350 μm, with 5.08×10^{-2} m (2 inches) diameter and 0.02 Ω.m resistivity. For the fabrication process, Si wafer was degreased in organic solvents of $CHClCCl_2$, CH_3COCH and CH_3OH consecutively and then etched in a sequence of H_2SO_4 an H_2O_2, 20% HF, a solution of $6HNO_3$: 1 HF: 35 H_2O, 20% HF and finally quenched in de-ionized 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 gold (Au) 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 $\sim2\times10^{-6}$ Torr in vacuum pump system and the evaporated Au was sintered. The oxidation steps are carried out in a resistance-heated furnace in dry oxygen with a flow rate of a 1.5 lt/min and the oxide layer thickness is grown at the temperature of 750 ^{o}C during 1.5 h. To form the Schottky contacts, the circular dots of ~2 mm diameter and ~2000 Å thick Au are deposited onto the oxidized surface of the wafer through a metal shadow mask in a liquid nitrogen trapped vacuum system in a vacuum of $\sim2\times10^{-6}$ Torr. The interfacial oxide layer thickness was estimated to be about $8\text{x}10^{-9}$ m (80 Å) from high frequency (1 MHz) measurement of the interface oxide capacitance in the strong accumulation region for MIS structures.

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. The C-V and G/ω-V measurements were performed before and after ^{60}Co γ-ray source irradiation with the dose rate of 2.12 kGy/h and total dose range was 0-100 kGy at 1 MHz and room temperature under dark condition. 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. Capacitance and conductance versus radiation dose

The measurements of capacitance (C) and conductance (G/ω) as a function of radiation dose of the MIS structure at 1 MHz and room temperature are shown in Fig. 1(a) and (b), respectively. As shown in Fig. 1(a) and (b), the C and G/ω decrease with the increasing radiation dose. During the irradiation, the induced defects decrease the majority carrier concentration in the depletion region. The decrease in the C and G/ω are also attributed to the decrease in the dielectric permittivity of the depletion layer [8,20,21]. This result is attributed to the production of the lattice defects in the form of vacancies, defect clusters, and dislocation loops near the SiO_2/Si interface due to the increase in the irradiation.

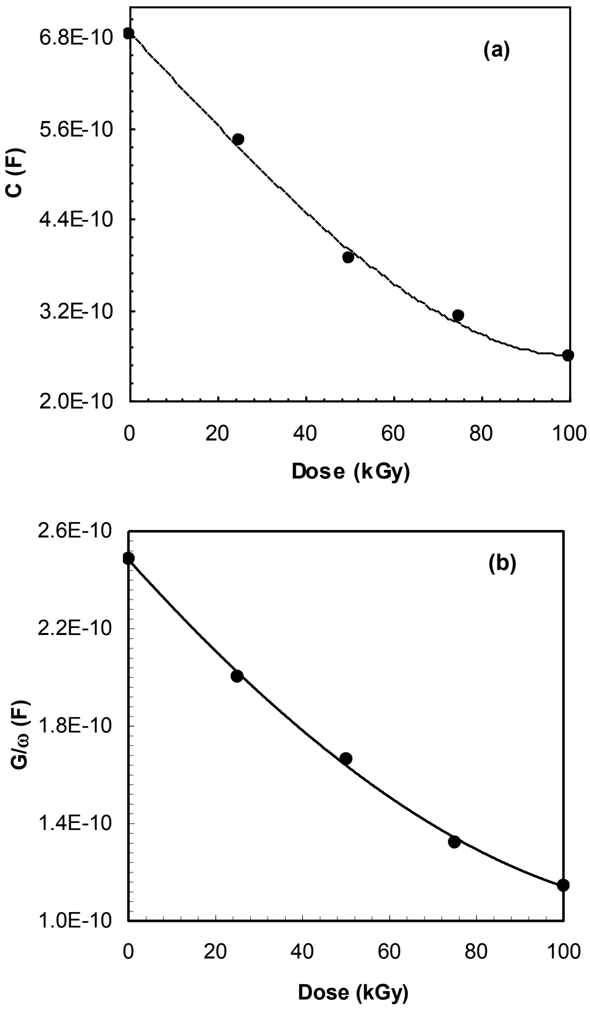

Fig. 1. Plot of capacitance (C) and conductance (G/ω) versus radiation dose at 1 MHz.

3.2. The effects of γ-radiation on the dielectric properties

The γ-ray dose dependence of dielectric constant (ε'), dielectric loss (ε''), loss factor (tanδ), ac electrical conductivity (σ_{ac}) and electric modulus are studied for MIS structure at 1 MHz.

The complex permittivity can be defined in the following complex form [22,23],

$$\varepsilon^{*}(\omega)=\varepsilon^{'}(\omega)-i\varepsilon^{''}(\omega) \quad (1)$$

where ε' and ε'' are the real and the imaginary parts 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:

$$\varepsilon^* = \frac{Y^*}{i\omega C_0} = \frac{C}{C_0} - i\frac{G}{\omega C_0} \quad (2)$$

where Y^*, C and G are the measured admittance, capacitance and conductance of the dielectric, respectively, and ω is the angular frequency (ω=2πf) of the applied electric field [24].

It turns out the effect of conductivity can highly be suppressed when the data are presented in the modulus representation. The electric modulus approach began when the reciprocal complex permittivity was discussed as an electrical analogue to the mechanical shear modulus [24]. From the physical point of view, the electrical modulus corresponds to the relaxation of the electric field in the material when the electric displacement remains constant. Therefore, the modulus represents the real dielectric relaxation process [25,26]. The complex modulus $M^*(\omega)$ was introduced to describe the dielectric response of non-conducting materials. This formalism has been applied also to materials with non-zero conductivity. The starting point for further consideration is the definition of the dielectric modulus: [24,27].

$$M^*(\omega) = \frac{1}{\varepsilon^*} = M'(\omega) + iM''(\omega) \quad (3)$$

$$M'(\omega) = \frac{\varepsilon'(\omega)}{\varepsilon'(\omega)^2 + \varepsilon''(\omega)^2}$$

and

$$M''(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)^2 + \varepsilon''(\omega)^2} \quad (4)$$

where M' and M'' are the real and imaginary parts of complex modulus. Based on Eq. (4) we have changed the form of presentation of the dielectric data from $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ to $M'(\omega)$ and $M''(\omega)$.

The real part of the complex permittivity, the dielectric constant (ε'), at various frequencies is calculated using the measured capacitance values at the strong accumulation region from the relation [28-30],

$$\varepsilon'(\omega) = \frac{C}{C_0} \quad (5)$$

where C_o is capacitance of an empty capacitor. $C_0 = \varepsilon_0 (A/d)$; 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 (ε_o = 8.85×10^{-14} F/cm). In the strong accumulation region, the maximal capacitance of MIS structure corresponds to the insulator capacitance (C_{ox}) $(C_{ac} = C_{0x} = \varepsilon' \varepsilon_0 A/d)$; where ε' is the dielectric constant of interfacial insulator layer ($\varepsilon' = \varepsilon_i = 3.8\varepsilon_o$).

The imaginary part of the complex permittivity, the dielectric loss (ε''), at various frequencies is calculated using the measured conductance values from the relation,

$$\varepsilon''(\omega) = \frac{G}{\omega C_0} \quad (6)$$

The dissipation factor or loss tangent (tanδ) can be expressed as follows [22,23,28-30],

$$\tan\delta = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \quad (7)$$

The ac conductivity of all samples has been calculated from the dielectric losses according to the following relation

$$\sigma^* = \varepsilon_0 \omega \varepsilon'' + i\varepsilon_0 \omega \varepsilon' \quad (8)$$

The real part of $\sigma^*(\omega)$ is given by

$$\sigma_{ac} = \omega C \tan\delta (d/A) = \varepsilon_0 \omega \varepsilon'' \quad (9)$$

Fig. 2(a), (b) and (c) show the variation of the dielectric constant (ε'), dielectric loss (ε'') and loss factor (tanδ) of the MIS structure with radiation dose at 1 MHz and room temperature, respectively. As show in Fig. 2(a) and (b), the ε' and ε'' decrease with the increasing radiation dose. Since the successive increase in the charge density causes the depletion layer to widen, the values of the capacitance decrease. Thus, this decrease in the capacitance values with the increasing dose indicates that the ionization is taking place on radiation exposure and in turn leading to changes in the permittivity of the materials [31,32].

The observed change in dielectric properties can be understood by considering the displacement damage introduced by irradiation results in the decrease in the values of ε' and ε''. As shown in Fig. 2(c), the tanδ increases with the increasing radiation dose. The observed increase in tanδ, and thus decrease in conductivity, are caused by a decrease in the conduction of residual current and the conduction of absorption current [33].

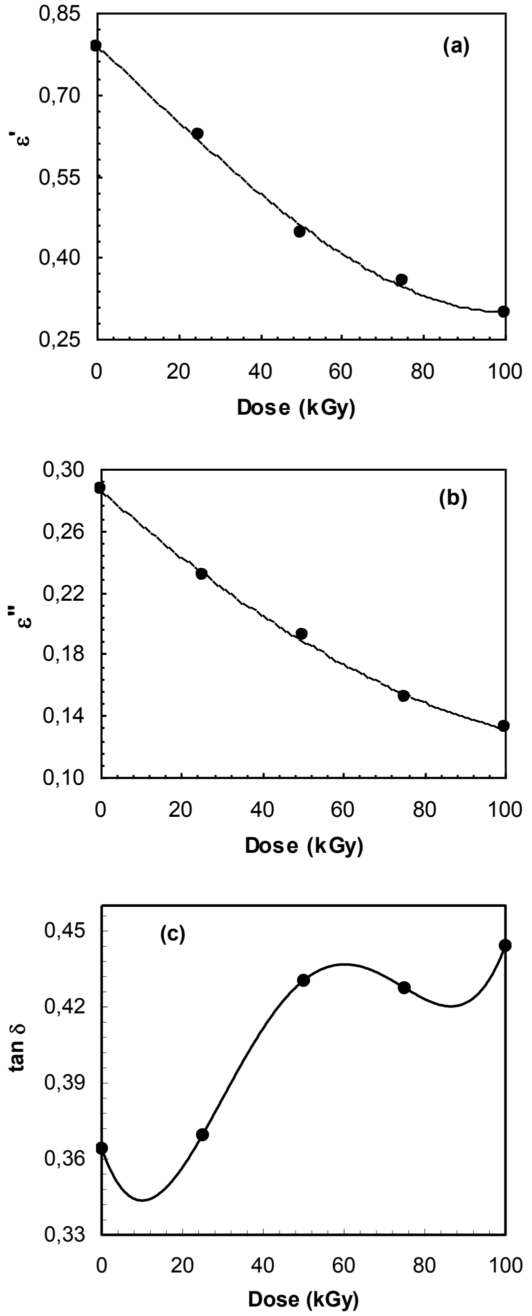

Fig. 2. Radiation dependence of the (a) ε', (b) ε'' and (c) $\tan\delta$ at 1 MHz for MIS structure.

The radiation dependence of ac electrical conductivity (σ_{ac}) for MIS structure at 1 MHz is given in Fig. 3. As shown in Fig. 3, the σ_{ac} decreases with the increasing radiation dose. The decrease in conductivity as a result of irradiation may be attributed to the charge centers created because of the breaking of lattice bounds. The oscillation of charge centers gives rise to circulatory currents under the influence of an externally applied voltage. Slow vibrations arise because of the large mass of positive charge carriers whereas free electrons generate circulatory currents. These circulatory currents develop an inductive behavior in the dielectric, which may be responsible for the observed small decrease in the conductivity [34,35].

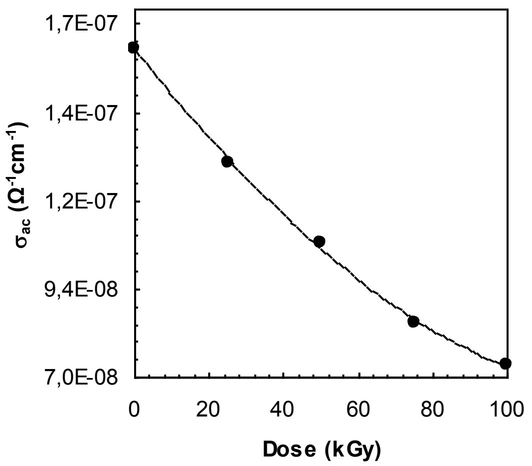

Fig. 3. Radiation dependence of ac electrical conductivity (σ_{ac}) at 1 MHz for MIS structure.

Fig. 4(a) and (b) show the real (M') and the imaginary (M'') parts of electric modulus M^* versus radiation dose at 1 MHz. As can be seen in Fig. 4(a) and 4(b), the M' and M'' increase with the increasing radiation dose. Similar studies have been reported in literature [8,36-38].

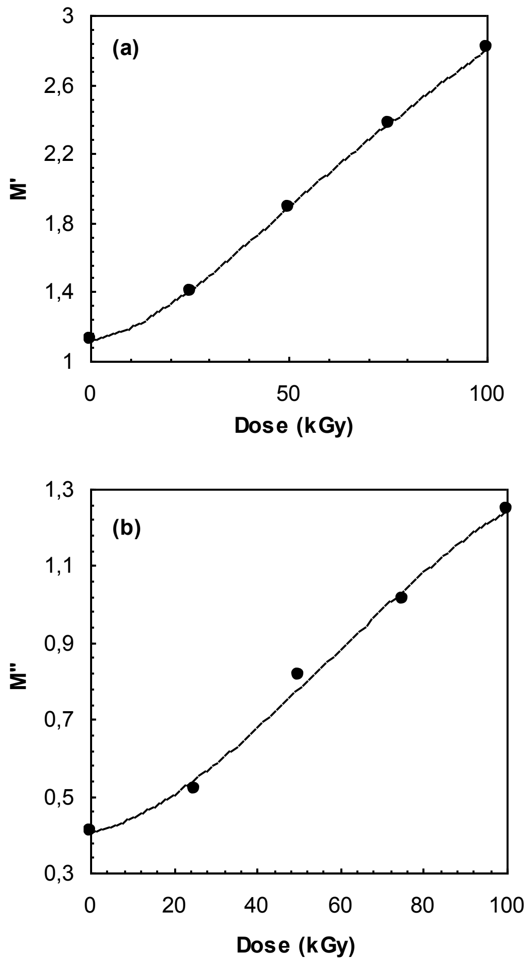

Fig. 4. Radiation dependence of (a) real part M' and (b) imaginary part M'' of electric modulus M^* at 1 MHz for MIS structure.

4. Conclusions

The study of the effect of ^{60}Co γ-irradiation on dielectric properties of MIS structure indicates that the irradiation induces structural changes that lead to the creation of mobile charge carriers. The values of $\varepsilon^{'}$ and $\varepsilon^{''}$ are strongly dependent on irradiation dose and decrease with the increasing radiation dose. This decrease in $\varepsilon^{'}$ and $\varepsilon^{''}$ can be attributed the charge carriers or dipolar molecules formed from structural modifications caused by irradiation and the Maxwell-Wagner interfacial polarization. The decrease in ac electrical conductivity with the radiation dose may be attributed to charge centers created because of the breaking of lattice bounds. As a result, the structure could be useful for an application in radiation dosimetry.

Acknowledgments

This work is supported by Gazi University Scientific Research Project (BAP), FEF. 05/2010-16.

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