Radiation effects on dielectric properties of MIS structure with Si_3N_4 thin film prepared by r.f. magnetron sputtering

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The effects of gamma-radiation on the dielectric properties of $Au/Si_3N_4/n\text{-}Si/Au$ (MIS) structure with Si_3N_4 thin film prepared by r.f. magnetron sputtering were investigated by using capacitance-voltage and conductance-voltage measurements. The capacitance (C) and conductance (G) measurements were performed at five different frequency values (1, 10, 100, 500 and 1000 kHz) before and after irradiation in the radiation dose range of 2 kGy to 100 kGy. The dielectric parameters of the MIS structure such as dielectric constant (ε'), dielectric loss (ε''), loss tangent ($\tan\delta$), ac conductivity (σ_{ac}) and electric modulus (M) were calculated from these measurements. The measured value of C and G decreases with increase in radiation dose and frequency. After irradiation, the decrease in capacitance is due to the irradiation-induced defects at the interface. Also, the calculated value of the ε' and ε'' decreases with the increase of radiation dose and frequency. In addition, while the value of σ_{ac} decreases with the increasing radiation dose, it increases with the increasing frequency. As a result, the dielectric parameters of the structure are quite sensitive to radiation.

1. Introduction

The metal-insulator-semiconductor (MIS) and metal-oxide-semiconductor (MOS) structures due to the dielectric property of insulator/oxide layer constitute a kind of capacitor. These structures consist of an oxide film layer sandwiched between a semiconductor substrate and a metal plate. The insulator/oxide layer is an important part that is incorporated in the MIS/MOS structure that is in turn an important device used in large-scale integration [1-3].

The most sensitive part of these structures to ionizing radiation is the interfacial oxide layer. Ionizing radiation such as γ-ray, x-ray, proton, electron and neutron interact with the oxide layer of structure, and electron-hole pairs are created by the deposited energy [4-15]. The creation of electron-hole pairs depends on the energy of the ionizing radiation. Some of this pairs recombine in the oxide layer. Some of the transporting holes fall into relatively deep long-lived trap states when the holes reach the Si interface. The radiation-induced interface traps at the Si/Oxide interface are localized states with energy levels in the Si band-gap [5-7].

Also, the radiation-induced defects (such as oxide-trap charge, interface-trap charge, fixed-oxide charge and mobile ionic charge) acting as recombination centers trapping the generated carriers have significant effect on semiconductor device performance.

These defects can cause increasing in the density of generation-recombination traps, decreasing in the lifetime charge carriers, and reducing in free charge carrier mobility.

The main purpose in this study is to investigate gamma-radiation effects on dielectric properties of the fabricated MIS structure. Therefore, all measurements were performed at five different frequency values before and after gamma irradiation dose.

2. Experimental detail

$Au/Si_3N_4/n\text{-}Si$ (MIS) structure was fabricated on phosphorus doped (n-type) single crystal Si substrate with a 2″ diameter, 300μm thickness, (100) orientation, and 0.5 Ω.cm resistivity. Detailed fabrication procedures of the $Au/Si_3N_4/n\text{-}Si$ (MIS) device have been given in our previous study [15].

The MIS structure was irradiated by using a ^{60}Co gamma-ray source with a dose rate of 0.69 kGy/h. The capacitance (C) and conductance (G) measurements were carried out at five various frequency values (1, 10, 100, 500 and 1000 kHz) before and after irradiation in the radiation dose range of 2 kGy to 100 kGy. The dielectric parameters of the MIS were calculated from these measurements.

3. Results and discussion

3.1. Capacitance-voltage (C-V) and conductance-voltage (G/ω-V) characteristics

Before and after various cumulative irradiation doses, the C-V and G/ω-V measurements of the MIS structure were performed at five different frequency values (1, 10, 100, 500 and 1000 kHz). Fig. 1(a) and (b) show the measured C-V and G/ω-V curves of the MIS structure as a function of frequency before and after gamma irradiation. As seen in Fig. 1(a) and (b), the value of C and G decrease with the increasing radiation dose at each frequency value [15-21]. The decrease in capacitance and conductance with dose can be attributed to the production of the lattice defects in the form of vacancies, defect clusters, and dislocation loops near the Si/Si_3N_4 interface. Also, capacitance reduction with radiation may be explained by the changes in electric dipole moments of the insulator layer.
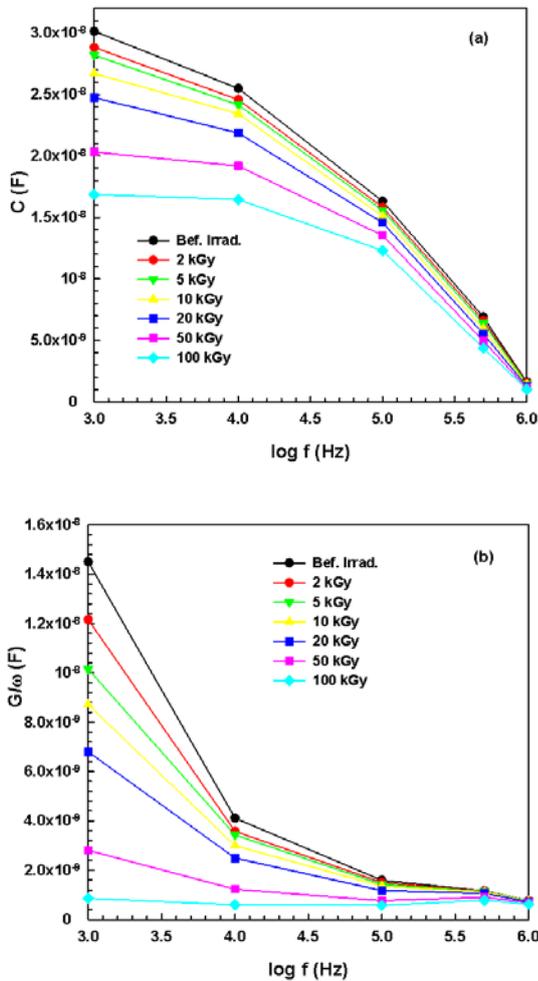
Fig. 1. (a) Capacitance and (b) conductance curves as a function of frequency of the MIS structure before and after irradiation at various doses.

In addition, the value of C and G decreases with the increasing frequency. The frequency dependence of the capacitance indicates the existence of interface states (N_{ss}) at metal-semiconductor interface. As the frequency is increased, the capacitance decreases to the same limit, as the charges on the defects no longer have time to rearrange in response to the applied voltage. At the sufficiently high frequencies, the N_{ss} cannot follow the ac signal. Therefore, the contribution of interface states capacitance to the total capacitance can be neglected [2,3].

3.2. Dielectric characteristics

The values of dielectric parameters such as dielectric constant (ε'), dielectric loss (ε''), etc. are obtained from the admittance (capacitance and conductance) measurements.

The admittance is a complex form written as,

$$Y^* = G + i\omega C \tag{1}$$

where C and G are the measured capacitance and conductance values of the device, and i is the square root of -1.

The complex permittivity (ε^*) formalism is employed to define the dielectric characteristics. In the case of admittance measurements, the ε^* formalism is expressed as,

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

where C_o ($=\varepsilon_o A/d_{ox}$) is capacitance of an empty capacitor and ω is the electric field angular frequency.

Also, the complex permittivity can be defined in the following complex form [22-26]:

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \tag{3}$$

where ε' and ε'' are the real and the imaginary part of complex permittivity of dielectric materials. Moreover, the ε' and ε'' are expressed as the dielectric constant and loss. The dielectric constant is a measure of the energy stored from the applied electric field in the device and identifies the strength of alignment of dipoles in the dielectric. The dielectric loss is the energy dissipated in the dielectric. In other words, the energy loss is called the dielectric loss, which always accompanies time-varying electric fields.

The dielectric constant (ε') is calculated using the measured capacitance values from the relation,

$$\varepsilon' = \frac{C_m}{C_o} \tag{4}$$

The dielectric loss (ε'') is calculated using the measured conductance values from the relation,

$$\varepsilon^{"} = \frac{G_m}{\omega C_o} \qquad (5)$$

when an alternating voltage is applied to an ideal dielectric material, current flows 90º out of phase with the applied voltage. The dissipation factor or loss tangent (tanδ) is the tangent of the angle by which the current deviates from the ideal of 90º. The loss tangent is given by,

$$\tan \delta = \frac{\varepsilon^{"}}{\varepsilon^{'}} \qquad (6)$$

The complex conductivity (σ^*) with the real part representing the in-phase conductivity, which means the current capable of following the field, and the imaginary part representing the out-of-phase conductivity can be expressed as follows,

$$\sigma^* = i\varepsilon_o\omega\varepsilon^* = i\varepsilon_o\omega(\varepsilon^{'} - i\varepsilon^{"}) = \varepsilon_o\omega\varepsilon^{"} + i\varepsilon_o\omega\varepsilon^{'} \quad (7)$$

The alternating current (ac) conductivity expressed as real part of σ^* is calculated from the dielectric loss values according to the relation

$$\sigma_{ac} = \omega C \tan\delta(d/A) = \varepsilon_o\omega\varepsilon^{"} \qquad (8)$$

The electrical modulus (M) corresponds to the relaxation of the electric field in the material when the electric displacement remains constant. The modulus was introduced to describe the dielectric response of non-conducting materials. The electric modulus is expressed in the complex modulus formalism (M^*). The complex electrical modulus is expressed as follows [27-32],

$$M^* = \frac{1}{\varepsilon^*} = M^{'} + iM^{"} \qquad (9)$$

where $M^{'}$ and $M^{"}$ are the real and the imaginary parts of complex modulus. The real and imaginary parts are calculated using the following expressions:

$$M^{'} = \frac{\varepsilon^{'}}{\varepsilon^{'2} + \varepsilon^{"2}}$$

and

$$M^{"} = \frac{\varepsilon^{"}}{\varepsilon^{'2} + \varepsilon^{"2}} \qquad (10)$$
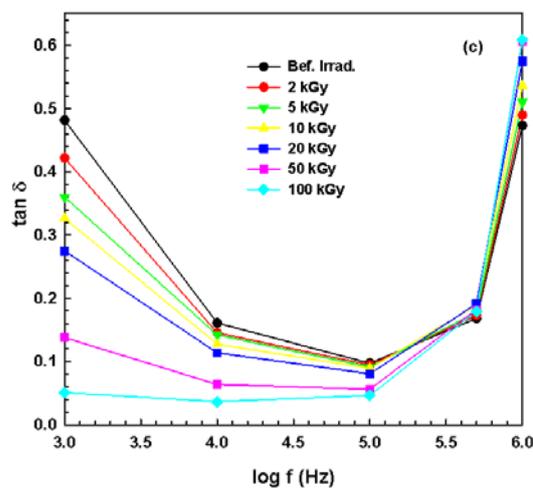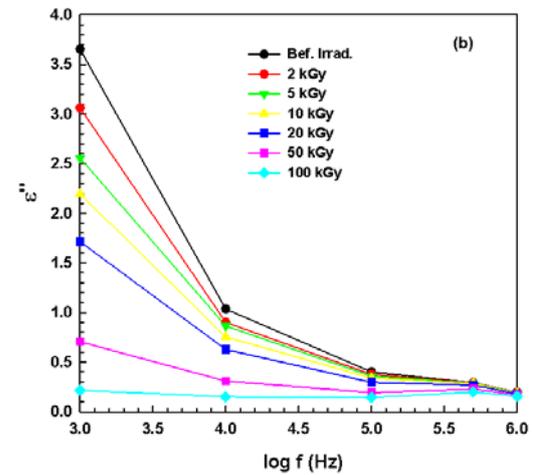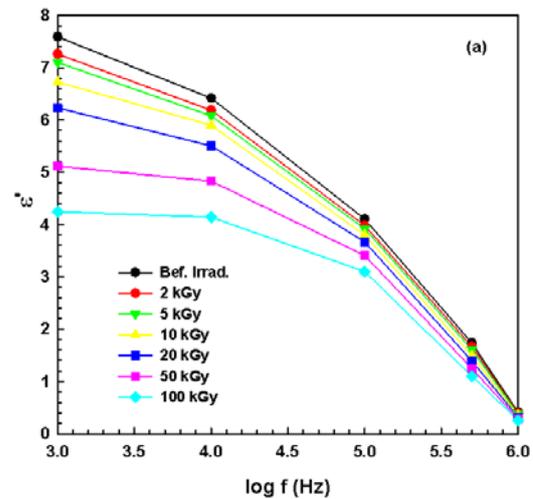
Fig. 2. The plots of (a) $\varepsilon^{'}$, (b) $\varepsilon^{"}$ and (c) tanδ as a function of frequency before and after gamma irradiation.

The capacitance and conductance measurements were used to analyze the effects of the irradiation dose on the dielectric characteristics of the MIS structure. Fig. 2(a), (b) and (c) show the plots of the dielectric constant (ε'), dielectric loss (ε'') and loss tangent (tanδ) of the MIS structure as a function of frequency before and after gamma irradiation, respectively. As seen in Fig. 2 (a) and (b), the values of ε' and ε'' decrease with the increasing radiation dose and the increasing frequency. The decrease in the dielectric constant with dose can be attributed to the decrease in carrier polarization indicating that charge carriers move by discontinuous hopping movements between localized sites [17,33-37]. Moreover, the dielectric constant is directly proportional to the number of dipoles. The decrease in dielectric constant and capacitance with increase in dose is probably due to the decrease in the number of dipoles with irradiation dose. In addition, the decrease in ε' and ε'' with the increasing 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 [37-41]. As seen in Fig. 2 (c), the value of loss tangent (tanδ) decreases with increase in the irradiation dose at each frequency. The decrease in loss tangent may be attributed to the particular distribution of charges at interface and atomic displacements. Also, the loss tangent at each irradiation dose decreases in the frequency range of 10 kHz-100 kHz and increases in the frequency range of 100 kHz-1000 kHz.
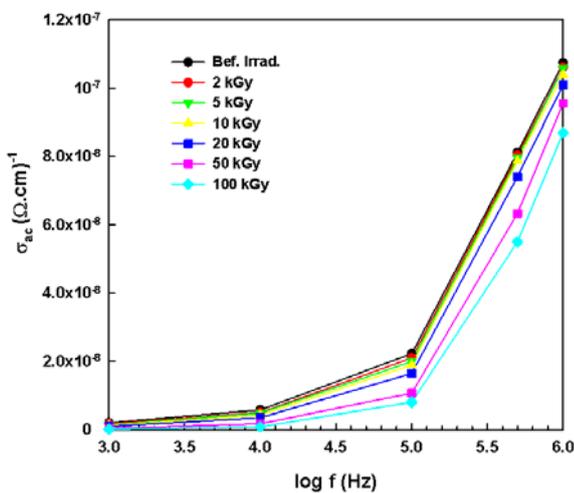
Fig. 3. Variation of the ac conductivity (σ_{ac}) as a function of frequency before and after gamma irradiation.

Fig. 3 shows the variation of ac conductivity (σ_{ac}) as a function of frequency before and after gamma irradiation. As seen in Fig. 3, the value of σ_{ac} decreases with the increasing radiation dose. The decrease in ac conductivity may be attributed to the charge centers created because of the breaking of lattice bounds and a decrease in the conduction of residual current and the conduction of

absorption current [42-44]. Also, the observed decrease in conductivity is caused by a decrease in the conduction of residual current and the conduction of absorption current. In addition, the value of σ_{ac} increases with increase in the frequency. The frequency dependence of conductivity arises due to mobile charge carriers.

Fig. 4 (a) and (b) the variation of real part (M') and imaginary part (M'') of complex modulus (M^*) as a function of frequency before and after gamma irradiation, respectively. As seen in Fig. 4(a) and (b), the value of M' and M'' increase with the increasing radiation at each frequency. Furthermore, the value of M' and M'' increase with the increasing frequency. The increase in M' and M'' may be related to a lack of restoring force governing the mobility of charge carriers under the action of an induced electric field.
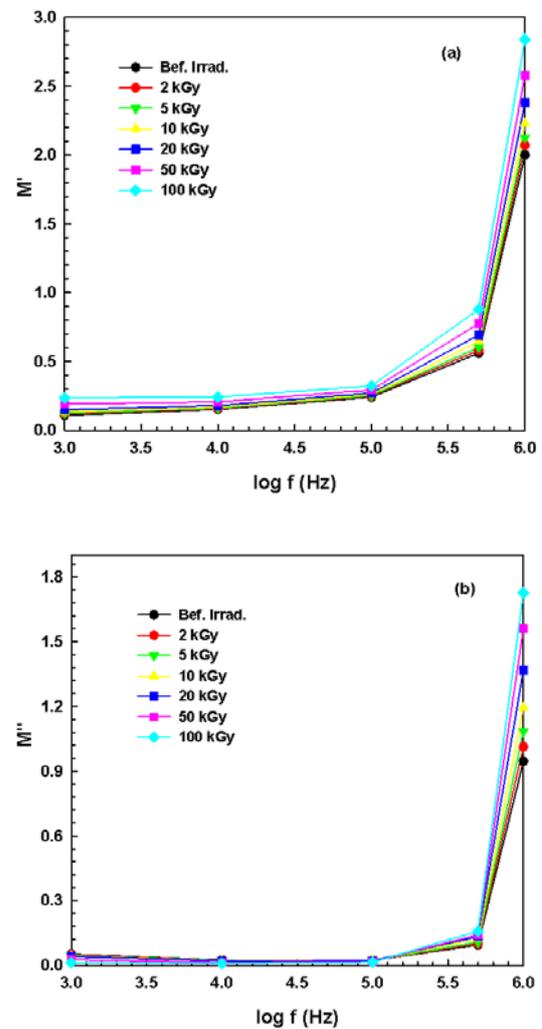
Fig. 4. Variation of (a) real part M' and (b) imaginary part M'' of complex modulus (M^*) as a function of frequency before and after gamma irradiation.

4. Conclusions

In the present study, gamma-radiation effects on the dielectric characteristics of the MIS structure have been

investigated. The obtained experimental results indicate that the capacitance and conductance decrease with the increasing irradiation dose due to the irradiation-induced defects at the interface. As irradiation dose increased, the value of dielectric constant and loss decreases due to the charge carriers caused by irradiation and the change in dipole moment. In addition, it has been observed that the value of ac conductivity decreases with increase radiation dose due to charge centers created. Whereas, the ac conductivity increases with increase in frequency. The results reveal that the dielectric parameters of the MIS structure were strongly affected by the gamma radiation.

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