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Influences of irradiation on the *C–V* and *G/ ω –V* characteristics of Si_3N_4 MIS capacitors

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ABSTRACT

The effects of gamma-ray exposures on the electrical characteristics of Silicon Nitride (Si_3N_4) metal–insulator–semiconductor (MIS) structures have been investigated at room temperature. The MIS structures were irradiated with the GAMMACELL 220 Co-60 radioactive source. The distributions of interface states and series resistance were determined from the C–V and G/ω-V characteristics by taking into account the irradiation-dependent the barrier height. Both the values of series resistance, interface states and barrier heights enhanced with increasing dose. Experimental results demonstrate that gamma-ray irradiations have the significant effects on electrical characteristics of Si_3N_4 MIS structures.

Keywords: Radiation effects, Si_3N_4 MIS capacitor, Interface states, Series resistance.

1. Introduction

Metal Insulator Semiconductors (MIS) are technologically important devices that have many electronic applications such as transistors, photovoltaic, radiation sensors etc. The suitability and usability of MIS devices in technological applications depends on the device characteristics, which are directly related to the gate insulators and their interfaces with the underlying semiconductors [1]. Owing to several possible sources of errors, the electrical characteristics of MIS capacitors deviate from their expected ideal behaviors. These errors may be related to such parameters as the interface-state densities *(D_{it})* and series resistances *(R_s)*. Therefore, these parameters should be taken into account in relevant calculations.

On the other hand, semiconductor based devices such as Schottky barrier diodes (SBDs), metal-insulator/oxide-semiconductor (MIS or MOS) structures and solar cells have been used in many satellites and played important roles in a wide range of communications, broadcast, meteorological, scientific research, space development applications and other industrial areas. Development of electronic sensors, MS or MIS structures with stable performance in strongly ionizing radiation fields is also essential to improving the reliability of atomic power plants and nuclear fusion systems [2]. It is well known that MIS devices are extremely sensitive to ionizing radiation, and the radiation response of these devices has been found to change significantly due to the variations on the D_{it} and R_s. However it has been reported that the radiation induced flat- band voltage shift of the nitride based structure is smaller than that of the MOS/MIS structure, and the radiation hardness has been improved [3, 4]. Silicon nitride (Si_3N_4) is one of the promising nitride films with high dielectric constant low surface state density and thermal stability underlying silicon substrate [1, 5, 6]. Therefore, the purpose of the present work is to investigate effects of irradiation on Si_3N_4 MIS devices. In order to investigate influences of irradiation on these electrical characteristics of Si_3N_4 MIS capacitors, the samples were irradiated by using the Co-60 gamma ray source from 5 Gy to 10 Gy. The electrical characteristics of the device were investigated from high frequency (1 MHz) *C-V* and

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G/ω-V measurements and discussed for different exposure doses.

2. Experimental

Silicon nitride (Si_3N_4) films with a thickness of 100 nm were deposited by plasma enhanced chemical vapor deposition (PECVD) at 13.56MHz on p-type (100) Si substrate using a gas mixture of ammonia (NH_3) and silane (SiH_4). The plasma power and growth temperature were fixed at 10 W and 250 ^{0}C, respectively. The pressure in the chamber remained at 500 mTorr. To study the response of MIS devices to irradiation over a range of doses, MIS samples were irradiated using a Co-60 gamma-ray source for 5 Gy and 10 Gy. Capacitance-voltage *(C-V)* and conductance-voltage *(G/ω-V)* measurements were performed at high frequency (1 MHz) before and after gamma irradiation by using an Impedance Analyzer in dark environment at room temperature.

3. Results and Discussion

Fig. 1 demonstrates the *C-V* characteristics of Si_3N_4 MIS capacitor under different irradiation doses. The fabricated devices exhibit characteristic MIS type behavior with three known distinct regimes as accumulation, depletion and inversion for all measurements. Ionizing radiation such as gamma rays and X-rays generates defects, interface trap and oxide trap-charges in MIS structure [7]. Hence, ionizing radiation causes a shift in flat band and mid-gap voltage. The shifts of the C-V curves are to the left side after irradiation as seen in Fig. 1. The behaviors of capacitances can be caused by the enhancement of trapped charge densities such as interface trapped charges and oxide trapped charge in MIS device generated by irradiation [8, 9]. In addition, the measured capacitances slightly decrease with increasing irradiation doses and this may be due to series resistance, contribution of interface states capacitance generated by irradiation to measured capacitance and/or the leakage through the oxide is responsible for the slight decrease of the *C–V* curves in accumulation region [10, 11].

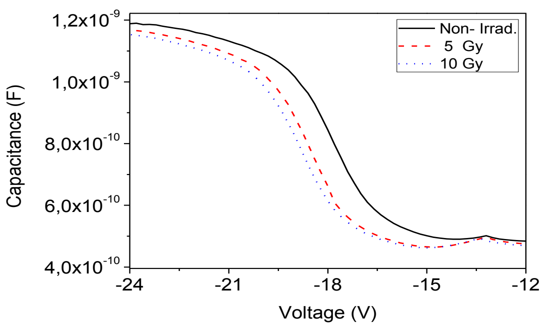

Fig.1. The measured C–V curves of Si_3N_4 MIS capacitor before and after gamma radiation at different doses.

Fig. 2 shows the *G/ω-V* characteristics of Si_3N_4 MIS capacitor under different irradiation doses. The conductance method [12, 13] is based on the conductance losses resulting from the exchange of majority carriers and the interface states when a small voltage signal is applied to the MIS devices. Therefore they are important characteristics in order to determine the interface defects distributions of MIS devices. As seen in Fig. 2, the conductance characteristics decrease whole regions with increasing the irradiation doses, indicating that variations of the lattice defects in the form of vacancies, defect clusters in the interface between insulator and semiconductor layers [14]. In addition the voltage shifts toward negative voltage axis with increasing irradiation dose were observed from Fig. 2. This behavior may be related to the changes in the distribution of interface states, and series resistance characteristics of devices.

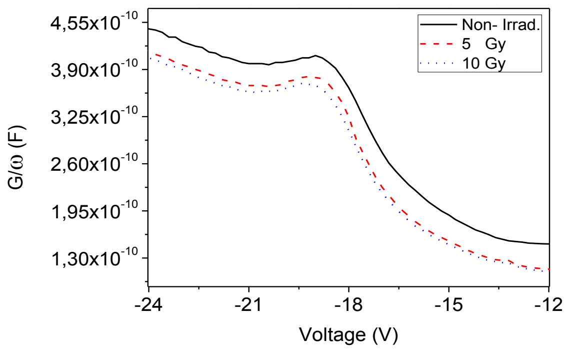

Fig.2. The measured G/ω-V curves of Si_3N_4 MIS capacitor before and after gamma radiation at different doses.

The real series resistances of the MIS structure can be calculated from the measured capacitance (C_{ma}) and conductance (G_{ma}) in the strong accumulation region at high frequencies [5, 12, 15]:

$$R_s = \frac{G_{ma}}{(G_{ma})^2 + (\omega C_{ma})^2} \quad (1)$$

where ω is the angular frequency, and C_{ma} and G_{ma} are defined as the measured capacitance and conductance in the strong accumulation region, respectively. Calculated R_s values are given in Table 1 and slightly rise in the R_s values with increasing irradiation dose have been observed, due to the reordering and restructuring of radiation-induced defects in the MIS capacitors. These obtained R_s values were used to correct the measured *G/ω-V* and *C-V* characteristics of the devices.

In order to remove the effects of R_s on the measured capacitance (C_m) and conductance (G_m) characteristics and evaluate the real interface trap density D_{it} of Si_3N_4 MIS device before and after irradiation, *C–V* and *G/ω–V* curves were corrected by the obtained R_s values. The corrected capacitance C_c and conductance G_c were calculated from following equations [5, 12, 15]:

$$C_c = \frac{[(G_m)^2 + (\omega C_m)^2]C_m}{a^2 + (\omega C_m)^2} \tag{2}$$

and

$$G_c = \frac{[(G_m)^2 + (\omega C_m)^2]a}{a^2 + (\omega C_m)^2} \tag{3}$$

Where $a = (G_m) - [(G_m)^2 + (\omega C_m)^2]R_s$, ω is the angular frequency, $(2\pi f)$, G_m and C_m are measured conductance and capacitance, respectively. The distributions of C_c and G_c/ω as a function biases are seen in Fig. 3 (a) and (b) before and after irradiation, respectively. These figures show the corrected conductance and capacitance characteristics have significant change compared to the measured values. Capacitance increases while conductance decreases after corrections. These behaviors demonstrate that the series resistances were masking the real *C-V* and *G/ω-V* characteristics and the peaks in the corresponding depletion edge give an evidence on the interaction between interface states and majority carriers of semiconductors [15, 16].

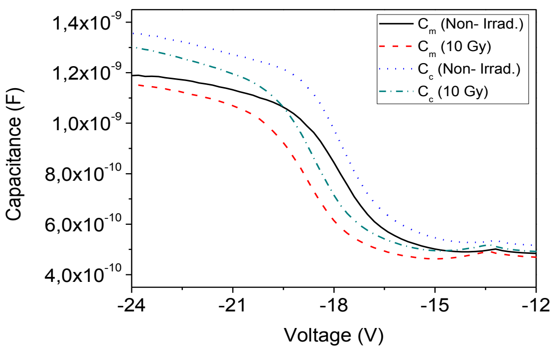

Fig.3.(a) The correction effects on the C-V characteristics of Si_3N_4 MIS capacitors.

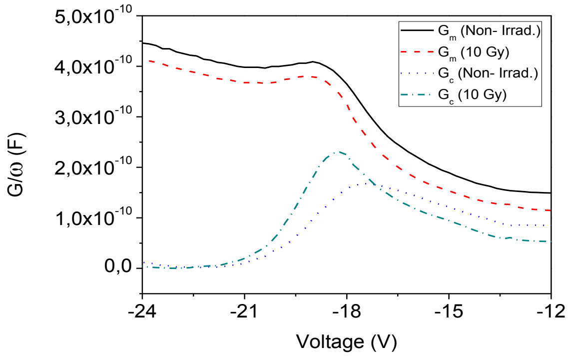

Fig.3.(b) The correction effects on the G/ω-V characteristics of Si_3N_4 MIS capacitors.

It is well-known that the distributions of interface states are important parameter to examine effects of radiation on MIS structures. Several suggested methods [7, 9, 11] can be used to determine D_{it}. Among these, Hill-Coleman method [17] is fast and reliable one in order to determine the density of interface states. Thus, D_{it} can be calculated by Eq. 4:

$$D_{it} = \frac{2}{Aq} \frac{G_{c,max}/\omega}{(G_{c,max}/\omega C_{ox})^2 + (1 - C_c/C_{ox})^2} \tag{4}$$

where, *q* is the electrical charge, *A* is the front contact area MIS capacitor, C_{ox} is the capacitance of oxide layer in accumulation region of C_c–*V* curve for non-irradiated devices, $G_{c,max}/\omega$ is peak values of corrected *G/ω–V* curve, C_c is corrected capacitance of the MIS capacitor corresponding to $G_{c,max}/\omega$. The densities of interface states calculated by using Eq. 4 prior to and after irradiation were given in Table 1. It is seen that D_{it} values increase with increasing in irradiation dose. This is due to the increasing in defects concentrations on MIS devices by irradiation. However, the calculated D_{it} values of MIS devices are about order of 10^{12} eV^{-1} cm^{-1}. This order of D_{it} values is not high enough to pin Fermi level of Si substrate corrupting device operation.

Table 1. *Some electrical characteristics of Si_3N_4 MIS devices under irradiation.*

Dose (Gy)	R_s (Ohm)	$G_{c\,max}$ x 10^{-10} (F)	C_c x 10^{-10} (F)	D_{it} x 10^{12} ($eV^{-1}cm^{-2}$)	V_D (eV)	φ_B (eV)
0	414	1.68	8.04	1.44	19.1	19.0
5	421	1.91	8.15	1.65	19.8	19.6
10	435	2.31	7.91	1.77	21.3	21.1

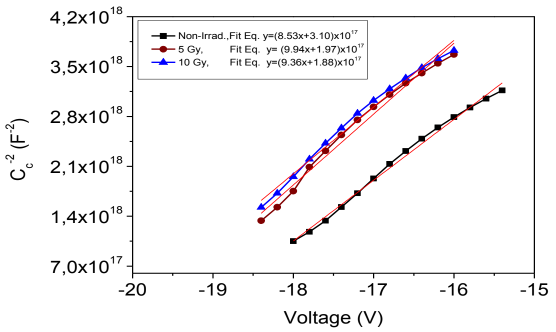

Fig. 4. The C_c^{-2}–V characteristics for the Si_3N_4MIS capacitor before and after gamma irradiation.

The irradiation dependent barrier height (ϕ_B) of devices can be calculated from reverse voltage C_c^{-2} –V characteristics seen in Fig. 4 by following the relation [1, 12, 18]:

$$\phi_B = V_0 + \frac{kT}{q} + E_F - \Delta\phi_B = V_D + \frac{kT}{q}\ln\left(\frac{N_V}{N_a}\right) - \Delta\phi_B \qquad (5)$$

where E_F is the energy difference between the bulk Fermi level and valance band edge, N_V is the effective density of states in valance band. V_0 (= V_D- kT/q) is the intercept of the C_c^{-2} vs. V plot with the voltage axis prior to and after irradiation, V_D is the diffusion potential and $\Delta\phi_B$ is the image force barrier lowering and can be calculated from the following Eq.6 [1]:

$$\Delta\phi_B = \sqrt{\frac{qE_m}{4\pi\varepsilon_s\varepsilon_0}} \qquad (6)$$

where $E_m = \sqrt{2qV_D N_a / \varepsilon_0\varepsilon_s}$ is the maximum electric field detailed in literature [19]. The intercept of C_c^{-2} vs. V plot calculated from linear fit equation of C_c^{-2} vs. V in Fig. 4, is negative voltage value for non-irradiated sample which indicates that a fairly large number of positive charges are trapped in devices structure due to fabrication process. In addition, the calculated barrier heights respect to radiation doses are tabulated in Table 1. The increases in barrier height have been observed. This is due to an increase in diffusion potential, V_d. Devices had wide-barrier height decrease charge injection from the substrate into the dielectric and thus the tunneling effects into the structure may decrease resulting from higher value of barrier height.

4. Conclusion

The variations in the measured *C-V* and *G/ω-V* characteristics have been observed after irradiation, owing to generated defect densities and trapped charges in the device structure. In addition, the real conductance values increase with increasing the radiation dose, while the experimental conductance value decrease with increasing radiation dose and the corrected capacitance is also different from experimental measurements. These obtained results demonstrate that the series resistance is a crucial factor which can mask the real device characteristics for device behavior. Additionally, the barrier heights of devices increase with increasing the irradiation and this behavior may be attributed the changes in diffusion potential.

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