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Gamma-ray irradiation effects on the interface states of MIS structures

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ABSTRACT

Gamma-ray irradiation effects on the interface states of Au/SiO_2/n-Si (MIS) structures have been determined from capacitance–voltage (*C–V*) and conductance–voltage (*G/ω–V*) measurements. The MIS structures were irradiated with gamma-rays at doses up to 100 kGy. The C–V and *G/ω–V* characteristics were measured at high frequency (1 MHz) and room temperature before and after ^{60}Co γ-ray irradiation. The obtained results showed that the barrier height (Φ_b) decreases with increasing radiation dose, while the interface states (N_{ss}) and depletion layer width (W_D) increase with the increase in radiation dose obtained from reverse bias *C–V* measurements. After γ irradiation, the decrease in capacitance and conductance of MIS structure result in the increase in the semiconductor depletion width. In addition, the voltage dependency of the series resistance (R_s) profile for various radiation doses was obtained from admittance-based measurement method. In addition, the high frequency (1 MHz) capacitance and conductance values measured under both reverse and forward bias have been corrected for the effect of R_s to obtain the real capacitance of MIS structure. Experimental results indicate that the total dose radiation hardness of MIS structures may be limited by the decisive properties of the SiO_2/Si interface to radiation-induced damage.

1. Introduction

The presence of an interfacial insulator layer in metal–insulator–semiconductor (MIS) and metal–oxide–semiconductor (MOS) structures makes them rather sensitive to irradiation. Most of the radiation-induced damages are located at or near the Si/SiO_2 interface. Trapped charge and impurities at or near Si/SiO_2 interface degrade the radiation response and long-term reliability of MIS and MOS electronics. Historically, four general categories of defects have been recognized as significant contributors to MIS degradation. These are oxide-trap charge, interface-trap charge, fixed-oxide charge, and mobile ionic charge [1–3]. Improvements in MIS and MOS processing techniques and reductions in contamination during manufacturing have significantly reduced the amounts of fixed-oxide charge and mobile ionic charge typically found in advanced MIS and MOS technologies. However, oxide and interface-trap charge remain topics of great importance to MIS radiation response and long-term reliability [1,2]. Recently, extensive studies have been carried out and shown that radiation has two primary effects on MIS structures: positive charge accumulation in the oxide and creation of new electron states at the Si/SiO_2 interface [4–14].

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.

Ionizing radiation damages MIS structures primary through building up positive charges (holes) in the oxide layer, and trapping negative charges (electrons) at the interface of MIS structures. Although some of the radiation-generated electron–hole pairs in the oxide recombine, the applied gate voltage sweeps most of the mobile electrons out of the gate oxide. The radiation-generated holes (are less mobile than the electrons) become trapped in the oxide (SiO_2) for positive gate bias where they contribute to a trapped positive oxide charge. They may be also trapped at the SiO_2 interface for negative gate bias where they act to trap electrons [1,15].

Da Silva et al. [6], Ma [7] and Winokur et al. [8] were among the first to make a systematic observation of the after-irradiation behavior of radiation-induced interface states (N_{ss}) at the semiconductor–insulator interface in MIS structures. Especially there are two important effects of radiation to be considered: (a) the transient effects due to the electron–hole pair generation and (b) permanent effect due to the bombardment of devices with radiation, causing changes in the crystal lattice. The radiation-generated holes may diffuse in the insulator, but are less mobile than the electrons; many stationary holes traps are also present.

In order to achieve a better understanding of the effect of ^{60}Co γ-ray irradiation on the interface states of Au/SnO_2/n-Si MIS structures, we measured both reverse and forward bias

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capacitance–voltage (C–V) and conductance–voltage (G/ω–V) characteristics as a function of dose rate at room temperature. The structures are stressed with a zero-bias during γ-ray irradiation with the dose rate of 2.12 kGy/h and total dose range was 0–100 kGy. Also, we report on the bias dependence of the series resistance (R_s) profile for various radiation doses. In addition, experimental results for the diodes are compared with results published for these type semiconductor devices.

2. Experimental detail

The $Au/SiO_2/n$-Si (MIS) structures used in this study were fabricated using n-type (P-doped) single crystals silicon wafer with ⟨1 0 0⟩ surface orientation having thickness of 350 μm, 2 in. diameter and 2 Ω cm resistivity. For the fabrication a process, Si wafer was degreased in organic solvent of $CHCICCI_2$, 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 $6HNO_3$: 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 $\sim 2 \times 10^{-6}$ Torr in vacuum pump system and the evaporated Au was sintered. The oxidations are carried out in a resistance-heated furnace in dry oxygen with a flow rate of a 1.5 l/min and the oxide layer thickness is grown at the temperatures of 750 °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 for through a metal shadow mask in a liquid nitrogen trapped vacuum system in a vacuum of $\sim 2 \times 10^{-6}$ Torr. The interfacial oxide layer thickness was estimated to be about 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 to 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 of 2.12 kGy/h and total dose range was 0–100 kGy at 1 MHz under dark condition 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

The analysis of the C–V characteristics was realized using the expression for the bias dependence of the depletion layer capacitance, C, of the MIS and MOS structures. In MIS structures the depletion layer capacitance is given as follows [2,16,17]

$$C^{-2} = \frac{2(V_0 + V)}{\varepsilon_s \varepsilon_0 q A^2 N_D} \tag{1}$$

$$\frac{d(C^{-2})}{dV} = \frac{2}{\varepsilon_s \varepsilon_0 q A^2 N_D} \tag{2}$$

where A is the diode area, ε_s is the dielectric constant of semiconductor ($11.8\varepsilon_0$ for Si), ε_0 is the dielectric constant of vacuum (8.85×10^{-14} F cm^{-1}), N_D is equivalent to the free electron concentration when all shallow donor levels are ionized, q is the electronic charge, V is the applied bias and V_0 is the intercept of C^{-2} vs V plot

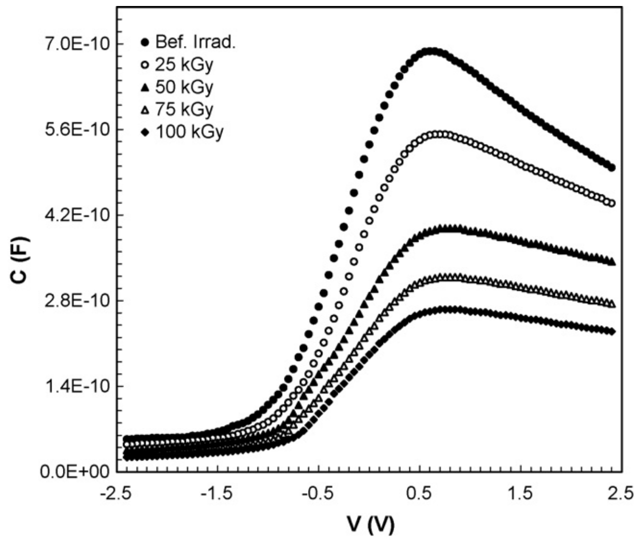

Fig. 1. The C–V characteristics of the MIS structure at 1 MHz before and after γ-ray radiation.

with the voltage axis and is given by

$$V_0 = \frac{V_D - kT}{q} \tag{3}$$

where V_D is the diffusion potential, T is the absolute temperature in K and k is the Boltzmann's constant. The value of the barrier height (Φ_b) can be obtained by the relation,

$$\Phi_b = V_D + E_F - \Delta\Phi_b = V_D + \left(\frac{kT}{q}\right) \ln\left(\frac{N_C}{N_D}\right) - \Delta\Phi_b \tag{4}$$

where E_F is the energy difference between the bulk Fermi level and conductance band edge, N_C is the effective density of states in conduction band and $\Delta\Phi_b$ is the image force barrier lowering and can be obtained from the well-known relationship in Refs. [16–19].

Fig. 1 shows a typical C–V relation obtained from the measurement at high frequency of 1 MHz and room temperature before and after γ-ray irradiation, which manifests the presence of the trapping centers [14,18–20]. It is clear that for n-type substrate, holes accumulate underneath SiO_2 at negative gate bias.

A slight shift of the C–V data from inversion toward the accumulation region decreases with the increase in radiation dose. By analyzing the high frequency curves in Fig. 1, it is clearly seen the decreasing values of the capacitance with increasing radiation dose and the stretch-out of the C–V curves under the influence of irradiation, reflecting the generation of oxide charge due to electron–hole pair generation by the radiation [1,5,15]. The decrease in C with increase in dose especially at reverse bias results in the increase in the semiconductor depletion width. Also, the C–V measurements at high frequency are relatively easily and rapidly carried out, and these measurements can yield interesting and meaningful results to show the negligibility of excess capacitance.

Fig. 2 shows the reciprocal of the squared capacitance per unit area as a function of the bias before and after γ-ray irradiation between 0 and 100 kGy. As can be seen in Fig. 2, the C^{-2}–V plots are linear in the wide voltage region when C–V measurements are carried out at sufficiently high frequency (such that carrier life time τ is much larger than $1/2\pi f$). This linearity of the curve is attributed to the uniformity of the N_D in the depletion region, indicating the interface states cannot follow ac signal at high frequencies.

In Fig. 2, it is clear that the intercept of the C^{-2} vs V characteristics changes with increasing radiation dose. These radiation dependent experimental C–V measurements revealed that, in the γ-irradiated structures, the barrier height Φ_b increases with increase in radi-

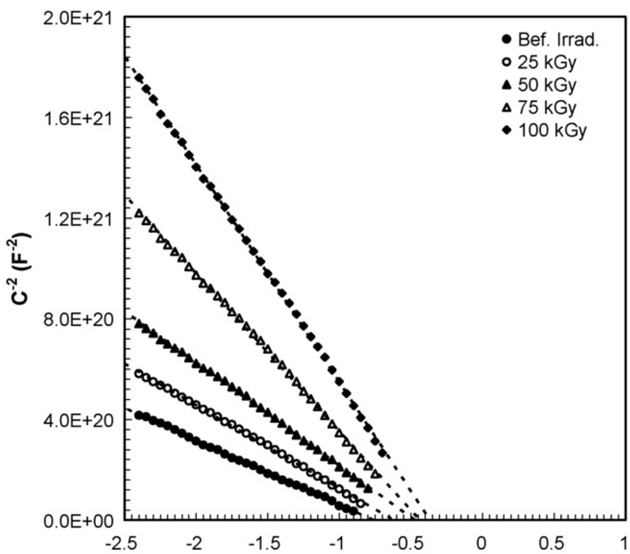

Fig. 2. C^{-2}–V characteristics for the MIS structure at 1 MHz before and after γ-ray radiation.

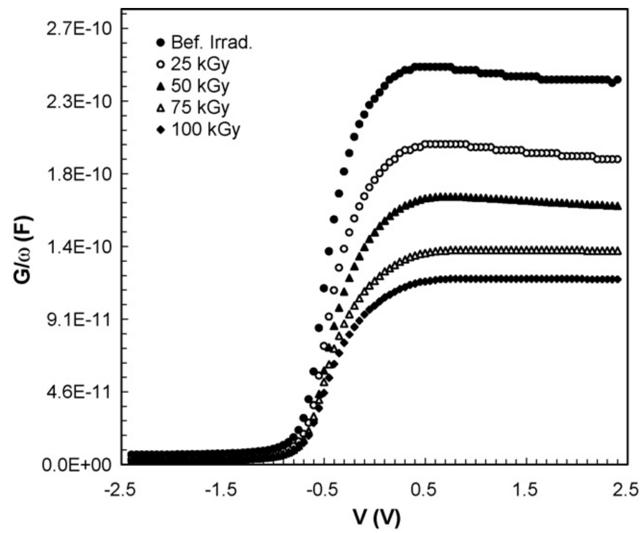

Fig. 3. The G/ω–V characteristics of the MIS structure before and after γ-ray radiation at 1 MHz.

ation dose [4,12,21]. The decrease in barrier height, Φ_b, obtained from the experimental C^{-2}–V plots, is due to a decrease in V_0 shown in Fig. 2. As shown in Table 1, before and after exposure of 100 kGy dose, the C–V measurements revealed that the values of Φ_b changes from 1.018 to 0.657 eV and the donor concentration from 7.573×10^{14} to 2.248×10^{14} cm^{-3}. The C–V technique measures the barrier height of MIS structure taking averages over the whole area. As shown in Table 1, the obtained values of the mean density of interface states (N_{ss}) between insulator and semiconductor (SiO_2/Si) interface increase with increasing radiation dose. This result is assumed to be due to the traps created by irradiation in insulator layer. In addition, the buildup of interface states may be related to the inhomogeneous hole distribution that is trapped at the interface following the hole transport. The trapped inhomogeneous hole distribution can lead to fluctuations in surface potential and an increase in interface state density. As the dose is increased, holes may be trapped farther from the interface, but only that charge trapped close to the interface is effective in producing strong surface potential fluctuations that can result in an increase in the density of interface states [22,23].

The relationship of the theoretical carrier doping density N'_D (=2.083×10^{15} cm^{-3}) and the experimental carrier doping density N_D is known as $c_2 \cong N_D/N'_D$. Thus, the mean density of N_{ss} were calculated from C–V characteristics at 1 MHz frequency for different radiation doses by using the equation [24–27],

$$c_2 = -\frac{2}{q\varepsilon_s N_D \left[\mathrm{d}(C^{-2})/\mathrm{d}V\right]} \cong \frac{N_D}{N'_D} = \frac{\varepsilon_i}{\varepsilon_i + q\delta N_{ss}} \tag{5}$$

where the interfacial insulator layer thickness, δ, is 80 Å, the dielectric constant of interfacial insulator layer is $\varepsilon_i = 3.8\varepsilon_0$ for SiO_2 and the value of c_2 is taken from Table 1. Also, the calculated values of V_0, V_D, N_D, E_F, W_D, $\Delta\Phi_b$, Φ_b, c_2 and N_{ss} obtained from C^{-2}–V plot at different radiation dose ranges, are presented in Table 1.

As shown in Table 1, the donor concentration (N_D) decreases with increasing radiation dose. The decrease in donor doping density with increase in radiation dose is due to generation and recombination through the interface states SiO_2/Si interface. Furthermore, the reverse bias injects holes that recombine with the electrons already present in the depletion region. The interface state capacitance appears directly in parallel with the depletion capacitance, and this results in a higher total value of the capacitance for diodes than if no interface states were present [12,27–31].

The conductance technique [2,16,17,24,25] is based on the conductance losses resulting from the exchange of majority carriers between the interface states and majority carrier band of the semiconductor when a small ac signal is applied to the MIS structures [32]. The applied ac signal causes the Fermi level to oscillate about the mean positions governed by the dc bias, when the MIS structure is in the depletion. Fig. 3 shows the measured conductance–voltage (G/ω–V) characteristics of the MIS structure at various radiation doses between 0 and 100 kGy. The values of conductance decrease with increasing radiation dose. This behaviour 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 of the irradiation.

There are several methods to extract the series resistance of MIS and MOS structures in literature [33–35]. In this study we have used the conductance method developed by Nicollian and Goetzberger [32,33]. The real series resistance (R_s) of MIS structures can be subtracted from the measured capacitance (C_m) and conductance (G_m) in strong accumulation region at high frequency ($f \geq 500$ kHz) [10,15,25,30]. In addition, the voltage and frequency dependence of the series resistance profile can be obtained from the C–V and G/ω–V curves. The measured impedance (Z_{ma}) at strong accumulation of MIS structure using the parallel RC circuit [2,16,25] is equivalent to

Table 1
Electrical parameters of Au/SiO_2/n-Si (MIS) structure obtained from C^{-2}–V plot before and after radiation between 0 and 100 kGy.

Radiation (kGy)	V_0 (V)	V_D (eV)	N_D ($\times 10^{14}$ cm^{-3})	E_F (eV)	W_D ($\times 10^{-4}$ cm)	(Φ_b (meV)	Φ_b (eV)	c_2	N_{ss} (eV^{-1} cm^{-2})
Bef. irrad.	0.764	0.790	7.573	0.241	1.167	12.850	1.018	0.364	4.599×10^{12}
25	0.622	0.648	5.865	0.247	1.201	11.470	0.884	0.282	6.704×10^{12}
50	0.472	0.498	4.749	0.253	1.170	10.190	0.740	0.228	8.896×10^{12}
75	0.436	0.462	3.103	0.264	1.394	8.989	0.717	0.149	1.501×10^{13}
100	0.367	0.393	2.248	0.272	1.511	7.964	0.657	0.108	2.172×10^{13}

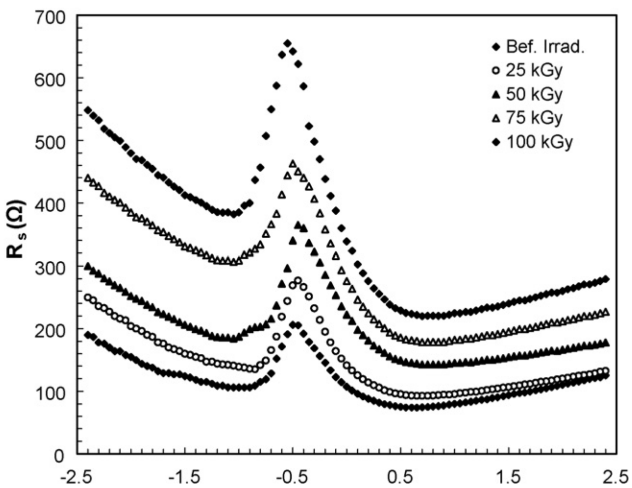

Fig. 4. Series resistance (R_s) vs gate bias under different irradiation doses at 1 MHz.

the total circuit impedance as

$$Z_{ma} = \frac{1}{G_{ma} + j\omega C_{ma}} \tag{6}$$

Comparing the real and imaginary part of the impedance, the series resistance is given by [16,33–35]

$$R_s = \frac{G_m}{G_m^2 + (\omega C_m)^2} \tag{7}$$

where C_m and G_m represent the measured capacitance and conductance in strong accumulation region, respectively and ω is the angular frequency. The series resistance is an important parameter to determine the noise ratio of device in terms of radiation dose. The values of R_s were calculated from Eq. (7) according to Ref. [32] and are given in Fig. 4. The values of R_s increase with increasing dose rate. However, the exposure of studied sample to the ^{60}Co (γ-ray) irradiation were not chance the relation between voltage and R_s. The use of Eq. (7) produces a series resistance dependence on voltage. As seen in Fig. 4, in the inversion region, the value of the series resistance increases with increasing voltage and in the depletion regions, about −1 to 0 V, gives a peak [12,21,36,37]. This voltage dependence of R_s is the result of voltage-dependent charges such as interface charge, fixed-oxide charge, oxide-trapped charge and mobile oxide charge.

The obtained series resistance values are used to correct the measured *C–V* and *G/ω–V* curves. As can be seen in Figs. 1 and 3, the measured capacitance C_m and conductance G_m are dependent on radiation dose especially at forward bias. In order to obtain the real diode capacitance C_c and conductance G_c/ω, the capacitance and conductance at 1 MHz measured under reverse and forward bias were corrected for removing the effect of series resistance using following equations. The corrected capacitance C_c and conductance G_c are calculated from the relations [16]

$$C_c = \frac{\left[G_m^2 + (\omega C_m)^2\right] C_m}{a^2 + (\omega C_m)^2} \tag{8}$$

and

$$G_c = \frac{G_m^2 + (\omega C_m)^2 a}{a^2 + (\omega C_m)^2} \tag{9}$$

where $a = G_m - \left[G_m^2 + (\omega C_m)^2\right] R_s$.When the correction is made on the *C–V* and *G/ω–V* curves, the values of the corrected capacitance C_c and conductance G_c/ω before irradiation change under forward and reverse biases are seen in Fig. 5(a) and (b), respectively.

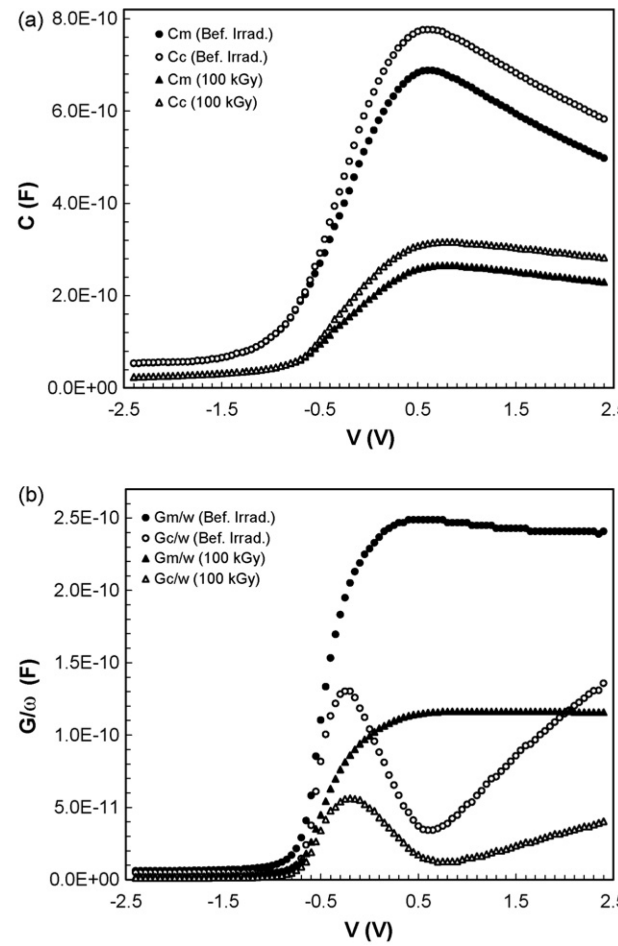

Fig. 5. The voltage dependent plots of the corrected (a) capacitance and (b) conductance curves before and after (100 kGy) irradiation at 1 MHz.

As seen in these figures, while the values of corrected capacitance are greater than the measured values of capacitance, the values of corrected conductance are smaller than the measured values because of elimination of the series resistance effect. As seen from Fig. 5(b), the plots of the corrected conductance give a peak, proving that the charge transfer can take place through the interface. These peaks correspond to the depletion area of the structure.

4. Conclusion

In summary, we have studied γ-ray irradiation effects on the electrical properties of Au/SiO_2/n-Si (MIS) structures when the structures are exposed to doses of ionizing radiation up to 100 kGy. The obtained experimental results show a decrease in the change in capacitance and conductance due to the irradiation-induced defects at the SiO_2/n-Si interface. Exposure to increasing cumulative γ-ray doses was found to have the following effects: (a) a manifested decreases in the barrier height obtained from the reverse bias *C–V* measurements, (b) increases in the series resistance R_s obtained from *C–V* and *G/ω–V* measurements and (c) increase in the interface states N_{ss} with the increase in radiation dose. The value of capacitance and conductance of the irradiated MIS structure is found to decrease for all the doses due to the irradiation-induced donor like defects which responsible for carrier removal at the interface.

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