Investigation of the effects of gamma-ray irradiation on electrical characteristics of MOS capacitors

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The effects of gamma(γ)-ray irradiation on the electrical characteristics of metal-oxide-semiconductor (MOS) capacitors were investigated. The MOS capacitor was exposed to a ^{60}Co γ-radiation source with a dose rate of 0.69 kGy/h and was irradiated with gamma rays at doses up to 100 kGy. Capacitance-voltage (C-V) and conductance-voltage (G/ω-V) characteristics were analyzed before and after exposure to gamma irradiation at high frequency (1 MHz) and room temperature. These characteristics of the gamma irradiated capacitor have shown the changes in the capacitance and conductance values, respectively with gamma irradiation dose. A decrease in the C and G/ω was observed when the irradiation dose increased. Also, the capacitance and conductance curves measured at 100 kGy were corrected to decrease the effects of the series resistance (R_s). Furthermore, the values of interface states (N_{ss}) were determined using Hill-Coleman method. The N_{ss} decreases with the increasing radiation dose.

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1. Introduction

The presence of an interfacial oxide layer in metal-oxide-semiconductor (MOS) structures makes them rather sensitive to irradiation. Most of the radiation-induced damages are located at or near the semiconductor/oxide interface. Trapped charge and impurities at or near semiconductor/oxide interface degrade the radiation response and long-term reliability of MOS electronics [1-10]. The exposure of these structures to high-level particles (such as x-rays, γ-rays, β-particles, α-particles, etc) results in a considerable amount of lattice defects. These defects act as recombination centers trapping the generated carriers. These defects that act as recombination centers or minority/majority carrier trapping centers cause degradation of the diode performance and applications.

Ionizing radiation damages MOS structures primary through building up positive charges (holes) in the oxide layer, and trapping negative charges (electrons) at the interface of MOS 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 for positive gate bias where they contribute to a trapped positive oxide charge. They may be also trapped at the oxide interface for negative gate bias where they act to trap electrons [1,2].

Tin dioxide films (SnO_2) have very interesting physical properties such as high electrical conductivity coupled with fairly large optical transmission in the visible region, low resistivity, a wide band gap high transmittance to visible radiation and reflect infrared. Due to its advantageous properties SnO_2 is material used in numerous optoelectronics and sensor technology, such as transparent electrodes, gas detectors, far-infrared detectors, high efficiency solar cells, and lithium ion batteries. There are several methods to prepare SnO_2 films such as electron beam evaporation, thermal evaporation of oxide powders, chemical vapor deposition (CVD), ac-dc magnetron sputtering, spray deposition, sol-gel, etc. Among them, the spray deposition process present an easy way to integrate SnO_2 devices into the Si technology, since it offers the possibility of good control of the deposition parameters, low processing temperatures and low production costs [11-14].

In this work, we present results of a study on the effect of gamma-ray irradiation on the electrical characteristics of Au/SnO_2/n-Si (MOS) capacitor. After each radiation dose, we report on the changes in electrical characteristics evaluated using forward and reverse bias voltage capacitance (C) and conductance (G/ω) measurements.

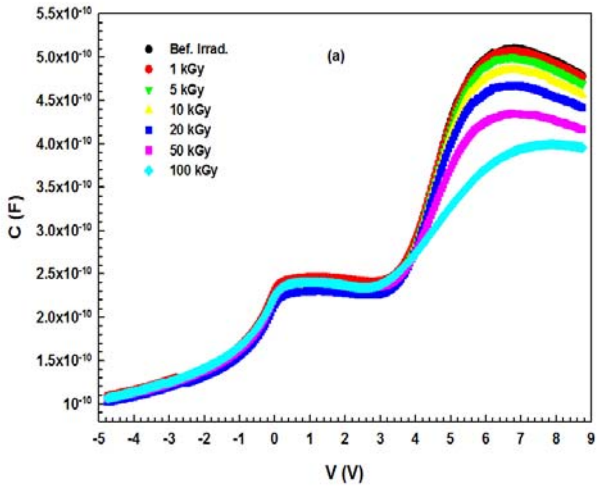
2. Experimental detail

The MOS (Au/SnO_2/n-Si) capacitors used in this work were fabricated using n-type (P-doped) single crystals silicon wafer with (111) surface orientation, 280 µm thickness, 5.08 cm diameter and 1-5 Ω.cm resistivity. The silicon wafer was degreased for 5 min. in boiling trichloroethylene, acetone and ethanol consecutively and then etched in: first H_2SO_4, H_2O_2 and 20%HF solution, then 6HNO_3: 1HF: 35H_2O and 20%HF solution for 4 min. After each cleaning step, the wafer was rinsed thoroughly in de-ionized water of 18 MΩ-cm resistivity. In order to remove any native thin oxide layer on the Si surface, the samples were dipped in HF: H_2O (1:10) about 20 s and finally the wafer were rinsed in de-ionized water for 10 min. using ultrasonic bath. After surface cleaning, high purity Au metal (99.999%) with thickness of 2000 Å was thermally evaporated from the tungsten filament onto the whole back surface of the wafer in liquid nitrogen trapped oil-free ultra-high vacuum system in the pressure of $\sim 1\times10^{-6}$ Torr. In order to form low-resistivity ohmic contact, the Au coated n-Si wafer was annealed at about 500 °C for 5 min in flowing dry nitrogen (N_2) in a quartz tube furnace. Immediately after the formation of ohmic contact, a thin layer of SnO_2 was grown on the Si substrate by spraying a solution consisting of 32.21 wt% of ethyl alcohol (C_2H_5OH), 40.35 wt% of de-ionized water (H_2O) and 27.44 wt% of stannic chloride ($SnCl_4.5H_2O$), which was maintained at a constant temperature of 400 °C. The temperature of the substrates was monitored by chromel-alumel thermocouple fixed on top surface of the substrate. The variation of the substrate temperature during spray was maintained within ±2 °C with the help of a temperature controller. The rate of spraying was kept at about 30 cc/min by controlling the carrier gas flow-meter. N_2 was used as the carrier gas. After spraying process, circular dots of 2 mm in diameter Au rectifying contacts with 1500 Å thickness were deposited onto the SnO_2 surface of the Si wafer through a metal shadow mask in liquid nitrogen trapped oil-free ultra-high vacuum system in the pressure of $\sim 1\times10^{-6}$ Torr. Both the thickness of metal layer and deposition rates were monitored with the help of a digital quartz crystal thickness monitor. The deposition rates were about 1-3 Å/s. The wafer was mounted on a copper holder with the help of silver paste and the electrical contacts were made to the upper electrodes by the use of tiny silver coated wires with silver paste.

The MOS capacitor was irradiated with γ-rays (^{60}Co) in the dose range of 0-100 kGy at the dose-rate of 0.69 kGy/h. During irradiation no biasing to the capacitor was applied. The capacitance-voltage (C-V) and conductance-voltage (G/ω-V) measurements were carried out using an HP 4192A LF impedance analyzer at high frequency (1 MHz) and room temperature.

3. Results and discussion

The values of capacitance (C) and conductance (G/ω) of the MOS (Au/SnO_2/n-Si) capacitor were measured before and after γ-ray irradiation at room temperature and 1 MHz. Fig. 1(a) and 1(b) show the measured capacitance and conductance as a function of gate voltage both before irradiation and after six different gamma doses. By analyzing the high frequency curves in Fig. 1(a) and 1(b), two apparent effects can be distinguished: (a) shifting of the maximum of the capacitance and conductance values toward the positive bias voltage at accumulation region and stretch-out of the C-V and G/ω curves, reflecting the generation of oxide charge due to electron-hole pair generation by the radiation and (b) the decreasing values of the capacitance and conductance with the increasing dose of ionizing radiation [1-3,10,15-17]. In addition, the decreasing values of the capacitance and conductance can be attributed to a decrease in the density of interface trapped charge at semiconductor/oxide interface created by gamma irradiation. Also, the C-V and G/ω-V measurements at high frequency (~ 1 MHz) are relatively easily and rapidly carried out, and these measurements can yield interesting and meaningful results to show the negligibility of excess capacitance [10,18].



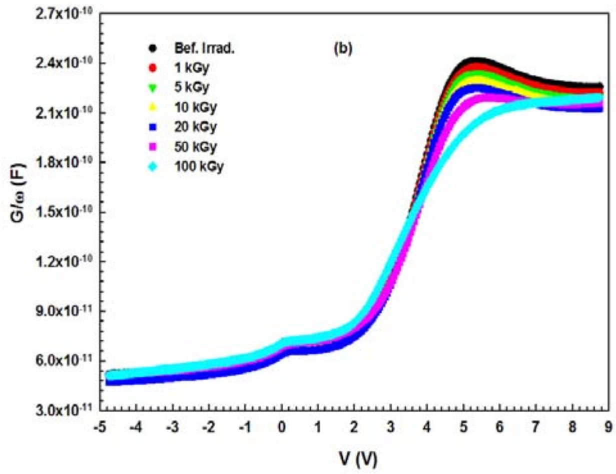


Fig. 1. C-V and G/ω-V curves of the MOS capacitor measured before and after gamma irradiation.

There are several methods to extract the series resistance of MOS structure in literature [19-21]. In this study we have used the conductance method developed by Nicollian and Goetzberger [21,22]. The real series resistance (R_s) can be subtracted from the measured capacitance (C_{ma}) and conductance (G_{ma}) in strong accumulation region at high frequency (f ≥500 kHz). 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 MOS structure using the parallel RC circuit [22,23] is equivalent to the total circuit impedance as

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

Comparing the real and imaginary part of the impedance, the series resistance is given by [19-24]

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

The capacitance of interfacial oxide layer C_{ox} is related to series resistance by

$$C_{ma} = \frac{C_{ox}}{(1+\omega^2 R_s^2 C_{ox}^2)} \tag{3}$$

From this relation, C_{ox} is obtained as

$$C_{ox} = C_{ma}\left[1+(\frac{G_{ma}}{\omega C_{ma}})^2\right] = \frac{\varepsilon_i \varepsilon_o A}{d_{ox}} \tag{4}$$

where, $\varepsilon_i = 7\varepsilon_o$ and ε_o are the permittivities of the oxide layer and free space. The oxide layer thickness d_{ox} calculated for the MOS capacitor using the Eq. (4) was found to be about 500 Å.

The series resistance is an important parameter to determine the noise ratio of device in terms of radiation dose. The values of R_s of the un-irradiated and gamma irradiated MOS capacitor were calculated from Eq. (2) and are given in Fig. 2. As can be seen in Fig. 2, the values of R_s increase with the increasing irradiation dose at forward bias voltage. In addition, The R_s vs voltage curves give a peak in the depletion region, while remain almost constant in the accumulation region. These values of R_s indicate that special attention should be given to the effects of series resistance in the application of the C-V and G/ω-V measurements.

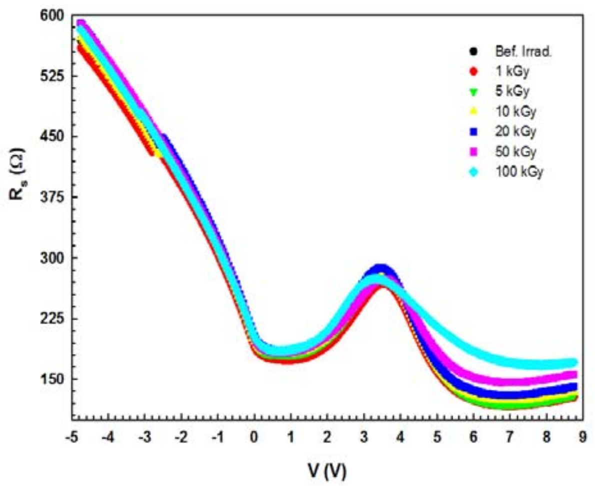


Fig. 2. Series resistance (R_s) vs gate bias voltage under different irradiation doses at 1 MHz.

The obtained series resistance values are used to correct the measured C-V and G/ω-V curves. In order to obtain the real capacitance C_c and conductance G_c/ω, the values of capacitance and conductance measured after irradiation were corrected for removing the effect of series resistance using following equations. The corrected capacitance and conductance are calculated from the relations [23]

$$C_c = \frac{\left[G_m^2 + (\omega C_m)^2\right] C_m}{a^2 + (\omega C_m)^2} \tag{5}$$

and

$$G_c = \frac{[G_m^2 + (\omega C_m)^2]a}{a^2 + (\omega C_m)^2} \tag{6}$$

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 after irradiation are seen in Fig. 2(a) and (b), respectively.

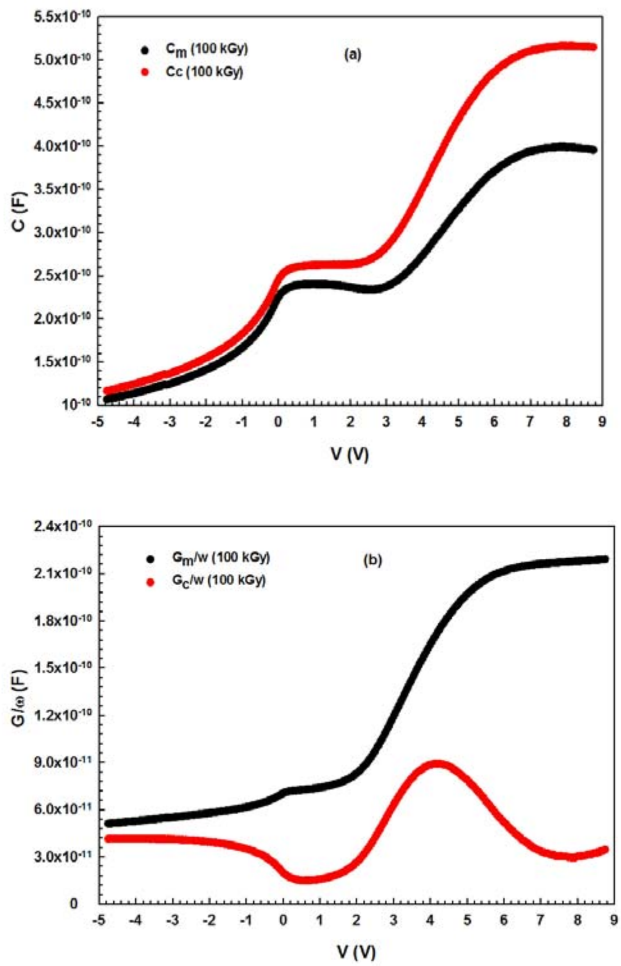


Fig. 3. The voltage dependent plots of the corrected (a) capacitance and (b) conductance curves after irradiation (100 kGy).

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 shown in Fig. 2(b), the plot of the corrected conductance gives a peak after irradiation (at 100 kGy) in the depletion region which proves that the charge transfer can take place through the interface. Also, the corrected conductance peak is related to the interface traps. In addition, the increase in corrected conductance between 0 and 4 V was attributed to movement of the metal Fermi level above the conductance band edge of the Si substrate.

In addition, there are several methods for the calculation of the density of interface states (N_{ss}) [19]. In this study, we have used the Hill-Coleman method [25] to obtain the N_{ss}. According to this method, the density of interface states can be calculated by using the following equation:

$$N_{ss} = \frac{2}{qA} \frac{(G_m / \omega)_{\max}}{((G_m / \omega)_{\max} C_{ox})^2 + (1 - C_m / C_{ox})^2)} \tag{7}$$

where, A is the area of rectifier contact, ω is the angular frequency, $(G_m/\omega)_{max}$ is the maximum measured conductance value. C_{ox} is the capacitance of interfacial oxide layer in strong accumulation region and C_m is the capacitance value, which corresponding to the $(G_m/\omega)_{max}$ value. The values of N_{ss} were calculated from Eq. (7) and are given in Fig. 4. As shown in Fig. 4, the N_{ss} decreases with the increasing irradiation dose. These changes have been attributed to the decrease in recombination centre and the existence of an interfacial oxide layer between SnO_2 and semiconductor [4,10,26-28].

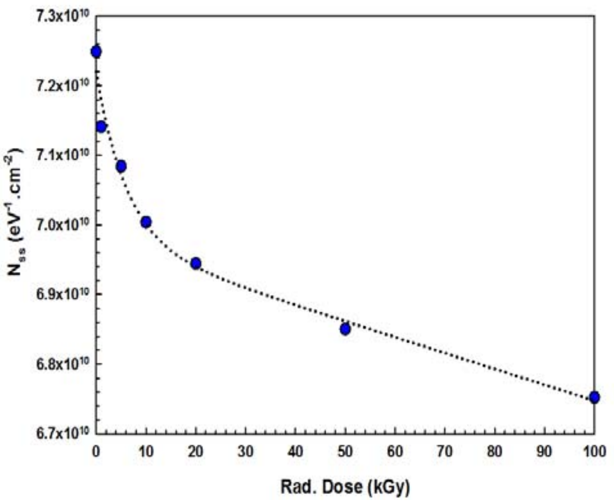


Fig. 4. The density of interface states (N_{ss}) as a function of radiation dose of MOS capacitor.

4. Conclusions

To investigate the radiation effects on the electrical characteristics of MOS (Au/SnO_2/n-Si) capacitor using C-V and G/ω-V measurements, MOS capacitor was exposed to a γ-radiation source at dose rate of 0.69 kGy/h. Experimental results show a decrease in the change in capacitance and conductance due to the irradiation-induced defects at the interface. Exposure to increasing cumulative γ-ray doses was found to have the following effects: (i) increases in the series resistance R_s obtained from C-V and G/ω-V measurements and (ii) decreases in the interface states N_{ss} with increasing radiation dose. As a result, the capacitance and conductance of the irradiated MOS capacitor are found to decrease for the entire radiation doses due to both the neutralization of some part of the positive oxide charges and the irradiation-induced donor-like defects, responsible for carrier removal at the interface during the gamma irradiation.

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