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^{60}Co gamma irradiation effects on the the capacitance and conductance characteristics of Au/PMI/n-Si Schottky diodes

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Abstract

In this work, the perylene-monoimide (PMI)/n-Si (100) Schottky structures were fabricated by spin coating process. We have studied the capacitance-voltage (*C–V*) and conductance-voltage (*G-V*) characteristics of the Au/PMI/n-Si diodes at 500 kHz before and after ^{60}Co γ-ray irradiation. The capacitance values measured under both reverse and forward bias at 500 kHz have been corrected for the effect of series resistance (R_s) and excess capacaitance (C_0) to obtain the real capacitance of the diode. The effects of ^{60}Co γ-ray irradiation on the electrical characteristics of a (PMI)/n-Si Schottky diode were investigated. The *C–V* and *G-V* characteristics of the diode indicate very strong irradiation dependence. A decrease in the capacitance and conductance has been observed after ^{60}Co γ-ray irradiation. This has been attributed to a decrease in the net ionized dopant concentration that occurred as a result of ^{60}Co γ-ray irradiation. Some contact parameters such as barrier height (Φ_B), interface state density $(N_{ss})$and series resistance (R_s) were calculated from the *C–V* and *G-V* characteristics of the diode before and after irradiation. It was seen that the Φ_B and N_{ss} values decreased after the applied radiation, while the R_s value increased.

Keywords: Gamma irradiation, perylene monoimide, spin coating process, barrier height, interface state density, series resistance.

1. Introduction

Metal-semiconductor (MS) Schottky diodes are a necessary part of all semiconductor electronic and optoelectronic devices (Sze, 1981; Rhoderick and Williams, 1988). The existence of an interfacial layer such as SiO_2, SnO_2 and TiO_2 transform the MS Schottky diode into a metal-insulator-semiconductor (MIS) or metal-oxide-semiconductor (MOS) device (Nicollian and Brews, 1982) and can have a strong influence on the values of diode parameters and can modify the electrical properties of MIS structure. The electrical properties of metal-semiconductor (MS) Schottky diodes can also be modified by organic interfacial layers such as perylene monoimide, rubrene and so on when these organic interfacial layers are added between the inorganic semiconductor and metal. Furthermore, the studies of the modification due to irradiation for many applications in semiconductor devices mentioned above are of both scientific interest and technological importance (Ma, 1989; Atanassova et al., 2001; Ta et al., 2010).

Semiconductor devices are the most sensitive to the radiation induced damages caused by energetic γ-rays, electrons, protons, and neutrons. These damages can have an effect on the electrical properties of the devices and therefore on their performances. It is very important to understand the particle irradiation impact on semiconductor devices due to the need for usage of these devices in radiation environments (Ma, 1989; Atanassova et al., 2001; Ta et al., 2010; Ergin et al., 2010). Radiation effects on MOS or MIS structures have attracted large attention during the last decades (Atanassova et al., 2001; Ta et al., 2010; Ergin et al., 2010) but reports related to gamma irradiation effects on electrical properties of the metal-organic interfacial layer- inorganic semiconductor diode are in rare.

Many researchers have studied the effect of gamma radiation on the electrical properties of organic compound interfacial layer (Ocak et al., 2010; Güllü et al, 2008a) and oxide/insulator films (MOS, MIS) (Changshi, 2004; Kaschieva et al., 2002; Kaschieva et al., 2003; Ma and Barker, 1974; Tuğluoğlu, 2007; Tuğluoğlu et al. 2004; Tugay et al. 2012), and metal electrode (Güllü et al. 2008b) deposited on inorganic semiconductors. The effect of gamma radiation on high-k oxide in MOS structures has also been reported in the literature (Ma, 1989; Atanassova et al., 2001; Ta et al., 2010; Ergin et al., 2010). Recently, some researchers have begun to investigate the influence of electron irradiation on the electrical properties of organic compound interfacial layer (Aydoğan et al. 2011a; Çınar et al., 2009; Aydoğan et al., 2011b; Güllü et al., 2008c), oxide films (MOS) (Kaschieva et al., 2003; Laha et al., 2011; Laha et al., 2012a; Laha et al., 2012b), and metal electrode (Gür et al., 2008; Uğurel et al., 2008) deposited on inorganic semiconductors.

Aydoğan et al. (Aydoğan et al. 2011a) investigated the effect of 12 MeV-electron irradiation on the electrical characteristics of the Au/Aniline Blue (AB)/n-Si/Al device at room temperature. They determined the values of the Schottky barrier heights from the *C-V* characteristics as 0.76 and 0.79 eV at 500 kHz before and after electron irradiation, respectively. Ocak et al. (Ocak et al., 2010) reported the effect of ^{60}Co γ-ray irradiation on the electrical characteristics of the Sn/ZnOA/n-Si device at room temperature. They calculated the values of the Schottky barrier heights from the *C-V* characteristics as 0.98 and 0.88 eV at 500 kHz before and after electron irradiation, respectively. Güllü et al. (Güllü et al., 2008c) fabricated a Pb/Rh101/p-Si/Al structure and obtained the effect of 6 MeV-electron irradiation on the electrical characteristics of the structure. The values of the barrier heights obtained from the reverse bias C^{-2}–V characteristics at 500 kHz frequencies have been found as 0.82 and

1.10 eV for before and after irradiation, respectively. The effects of high dose gamma ray irradiation and high-energy proton irradiation on 4H-SiC Schottky rectifiers have also been investigated by Kim et al. and Nigam et al., respectively, (Nigam et al., 2002; Trefilova et al. 2001).

Considerable efforts have been devoted to the investigation of organic semiconductor devices because of their promising applications, low-cost manufacturing and easy processing. Among organic semiconductor, perylene and its derivatives have attracted considerable interest because of their wide range of applications in optoelectronic devices such as field effect transistors (FETs) (Malenfant et al., 2002), organic light emitting diodes (OLEDs) (Yoshida et al., 1996; Suzuki and Hoshino, 1996), dye sensitized solar cells (DSSCs) (Zafer et al., 2007), photovoltaic devices (Kuş et al., 2008), and Schottky diode (Yüksel et al., 2011; Tuğluoğlu et al., 2012a; Tuğluoğlu et al., 2012b).

In previous study (Tuğluoğlu et al., 2012a) we have investigated the electrical and interface state properties of Au/perylene-monoimide (PMI)/n-Si Schottky barrier diode by capacitance–voltage (*C*–*V*) measurements at room temperature. To the best of our knowledge there has been no report on the *C-V* and *G-V* characteristics of PMI/n-Si (100) Schottky diodes after ^{60}Co γ-ray irradiation. Therefore, to show the effect of gamma irradiation on the electrical characteristics of Au/PMI/n-Si (100) Schottky diode, an attempt has been made to determine the characteristics parameters of PMI/n-Si (1 0 0) Schottky diodes from the *C-V* and *G-V* measurements before and after 11.4 kGy irradiation dose.

2. Experimental Procedures

In this study, an n-type P-doped Si semiconductor wafer with (1 0 0) surface orientation, 380 μm thickness and 20 Ω cm resistivity was used. The n-Si wafer is initially degreased with organic solvents like trichloroethylene, acetone and methanol by means of ultrasonic agitation in sequence for 5 min each to remove contaminants and rinsed in deionised water and then dried in N_2 flow. Before making contacts,the n-Si wafer was chemically cleaned using the RCA cleaning procedure (i.e. a 10 min boil in NH_3+H_2O_2+6H_2O followed by a 10 min boil in HCl+H_2O_2+6H_2O) with the final dip in diluted HF for 60 s, and then rinsed in deionized water of resistivity of 18 MΩ cm with ultrasonic vibration and dried by high purity nitrogen. The ohmic contact was made by evaporating the Au on the back of the n-Si substrate, and then it was annealed at 450 ^{o}C for 3 min in N_2 atmosphere. The native oxide on the front surface of the substrate was removed in HF+10H_2O solution and then it was rinsed in de-ionized water for 60 s and was dried in N_2 atmosphere before forming an organic layer on the n-type Si substrate. The PMI organic film to the front surface of the n-Si wafer was formed by a spin coating method at a spinning rate of 1000 rpm for 60 s with a Laurell Spin Coater. The molecular structure of PMI is given in Fig. 1(a). Then, by evaporating Au metal on the PMI at 10^{-6} Torr, the Au/PMI/n-Si/Au device was fabricated (diode area = 3.14×10^{-2} cm^2). The schematic representation of the device is shown in Fig. 1(b). The PMI layer thickness was estimated to be about 21 nm from measurement of the interfacial layer capacitance in the accumulation region from capacitance-voltage characteristic at 500 kHz. The capacitance-voltage (*C*-*V*) and conductance-voltage (*G*-*V*) measurements by using HP 4192A LF impedance analyzer (5 Hz -13 MHz) were performed before and after ^{60}Co γ-ray source irradiation with the dose of 0.7 kGy/h at 500 kHz, at room temperature and in dark. Total dose was 11.4 kGy.

3. Results and Discussion

The effect of interface state density can be eliminated when the $C-V$ curve is measured at sufficiently high frequency ($f \geq$ 500 kHz), since the charges at the interface states cannot follow an ac signal (Rhoderick and Williams, 1988; Ocak et al., 2010; Aydoğan et al., 2011a; Tuğluoğlu and Karadeniz, 2012a). In this case, the interface states are in equilibrium with the semiconductor (Rhoderick and Williams, 1988; Ocak et al., 2010; Aydoğan et al., 2011a; Tuğluoğlu and Karadeniz, 2012a). Fig. 2 represents the measured capacitance-voltage (*C-V*) characteristics before and after 11.4 kGy ^{60}Co γ-ray irradiation at 500 kHz frequency for Au/PMI/n-Si Schottky diode at room temperature and in dark. As shown in Fig. 2, the $C-V$ plots before and after ^{60}Co γ-ray irradiation have three regimes of accumulation–depletion–inversion region, verifying a typical metal-insulator-semiconductor (MIS) type Schottky barrier diode behavior. The *C-V* plots show a significant difference after 11.4 kGy irradiation especially in the depletion and accumulation regions. It is seen from Fig. 2 that the values of the capacitance increase with increasing voltage before and after irradiation and decrease with irradiation. Fig. 3 represents the measured conductance (*G*) characteristics versus gate bias (*V*) before and after 11.4 kGy ^{60}Co γ-ray irradiation for Au/PMI/n-Si Schottky diode at 500 kHz and at room temperature. It is seen from Fig. 3 that the values of the conductance increase with increasing voltage before and after irradiation and decrease with irradiation. This irradiation effect can be referred to the decrease in the net ionized dopant concentration with irradiation (Güllü et al., 2008b; Uğurel et al., 2008).

One of the important parameters of the device is its series resistance. The series resistance of Au/PMI/n-Si Schottky diode can be determined from the measured *C-V* and *G-V* measurements in the accumulation region at high frequency ($f \geq$ 500 kHz). The values of series resistance (R_s) before and after irradiation has been calculated through relation (Nicollian and Brews, 1982):

$$R_s = \frac{G_{m,acc}}{G_{m,acc}^2 + \left(\omega C_{m,acc}\right)^2} \tag{1}$$

where $C_{m,acc}$ and $G_{m,acc}$ are the measured capacitance and conductance in accumulation.

Fig. 4 show the voltage dependence of the series resistance (R_s) determined from Eq. (1) before and after 11.4 kGy ^{60}Co γ-ray irradiation. This voltage dependence of R_s is the result of voltage dependent charges such as interface trapped charge, fixed oxide charge, oxide trapped charge and mobile oxide charge and also at the grain boundaries of PMI/n-Si structures. As seen in Fig. 4, the value of the series resistance (R_s) increases and with increasing irradiation. The series resistance as a function of voltage gives a peak in approximately the same voltage range. The values of series resistance of the Au/PMI/n-Si Schottky diode at the accumulation region before and after irradiation 11.4 kGy has been determined as 70.33 and 114.20 Ω, respectively. These values are also given in Table 1.

These R_s values are utilized to correct the measured *C-V* and $G-V$ curves. The corrected capacitance C_c and equivalent parallel conductance G_c for series resistance were evaluated form the relations (Nicollian and Brews, 1982):

$$C_c = \frac{\left(G_m^2 + \omega^2 C_m^2\right)C_m}{a^2 + \omega^2 C_m^2} \ , \ G_c = \frac{\left(G_m^2 + \omega^2 C_m^2\right)a}{a^2 + \omega^2 C_m^2} \ , \ a = G_m - \left(G_m^2 + \omega^2 C_m^2\right)R_s \qquad (2)$$

where C_m and G_m are the measured capacitance and conductance. Figs. 5(a) and 5(b) represent the voltage dependence of the corrected capacitance C_c and conductance G_c characteristics before and after irradiation at 500 kHz and at room temperature. As can be seen from Figs. 5(b), it is clearly seen that the $G_c - V$ characteristics of Au/PMI/n-Si Schottky diode consists of a peak. These peaks correspond to the depletion area of the device. The value of interface traps density (N_{ss}) is determined from this peak value. This peak was observed before and after 11.4 kGy irradiation.

From C-V and $G/\omega - V$ measurements in accumulation region, the organic layer capacitance C_{org} was calculated through relation (Nicollian and Brews, 1982):

$$C_{org} = C_{c,acc}\left[1 + \left(\frac{G_{c,acc}}{\omega C_{c,acc}}\right)^2\right] \qquad (3)$$

where $C_{c,acc}$ and $G_{c,acc}$ are the corrected capacitance and conductance in accumulation region. The organic layer (PMI) thickness d_{org} calculated from high frequency (500 kHz) C-V data in accumulation region using Eq. (3) for corrected organic layer capacitance $\left(C_{org} = \varepsilon_i \varepsilon_0 A / d_{ox}\right)$, where $\varepsilon_i = 3.2\varepsilon_0$ (Tuğluoğlu and Karadeniz, 2012a) and ε_0 are the permittivity of the interfacial organic layer and free space, has been determined to be about 21 nm.

A number of different methods have been used to measure N_{ss} from the capacitive and conductive response of the interface states to a small external ac signal. The application of a single-frequency approximation method (Hill and Coleman, 1980) allows estimation of the density of interface states from the G-V measurements.

A fast and reliable way to determine the density of interface states (N_{ss}) is the Hill-Coleman method (Hill and Coleman, 1980) and confirmed by our research group (Tuğluoğlu, 2007; Tuğluoğlu and Karadeniz, 2012a). According to this method, N_{ss} can be determined using the following formula:

$$N_{ss} = \frac{2}{qA} \frac{G_{c,\max} / \omega}{[(G_{c,\max} / \omega C_{org})^2 + (1 - C_c / C_{org})^2]} \tag{4}$$

where q is the elementary electrical charge, ω is the angular frequency, A is the area of the diode, C_{org} is the capacitance of organic layer in accumulation region of $C_c - V$ curves, $G_{c,\max}$ conforms to maximum corrected *G-V* curve; C_c is capacitance of the diodes corresponding to $G_{c,\max}$. This method was applied on *G-V* curves of the frequency of 500 kHz. The peaks correspond to the depletion area of the device and its existence verifies the presence of interface traps (Tuğluoğlu, 2007; Tuğluoğlu and Karadeniz, 2012a; Trefilova, et al., 2001). The value of N_{ss} has been determined using Eq. (4) as 27.18x10^{-11} and 3.95 x10^{-11} eV^{-1} cm^{-2} before and after irradiation, respectively. These values are also given in Table 1. As shown in Table 1, the density of interface states (N_{ss}) decreases with increasing irradiation. On the other hand, it is seen that the interface traps passivate while the irradiation dose increases.

Fig. 6 represents the capacitance (*C*) vs. $(V_d - V)^{-1/2}$ characteristics of the Au/PMI/n-Si Schottky diode before and after $\gamma -$irradiation. The values of excess capacitance (C_0) have been determined from intercept of the (*C*) vs. $(V_d - V)^{-1/2}$ plots before and after $\gamma -$irradiation as 1.611 x 10^{-11} and 5.613 x 10^{-11} F, respectively. As can be seen from Fig. 6, as $\gamma -$irradiation increases, the excess capacitance increases.

The excess capacitance is a useful quantity for correcting non-linear $1/C^2 - V$ characteristics of the Au/PMI/n-Si Schottky diode.

Fig. 7 represents the reverse $1/(C_c - C_0)^2$ vs. V plots of the Au/PMI/n-Si Schottky diode before and after irradiation. In n type semiconductor based Schottky junction, the depletion layer capacitance is given by (Sze, 1981; Rhoderick and Williams, 1988):

$$C^{-2} = 2(V_d + V)/ q\varepsilon_s A^2 N_D \tag{5}$$

and

$$\frac{\partial(1/C^2)}{\partial V} = \frac{2}{A^2 \varepsilon_s \varepsilon_0 q N_D}$$

(6) where A is the area of device, C is the capacitance in the depletion region, V_d is the diffusion potential at zero bias, N_D is the ionized traps like-donor which is determined from the slope of $1/(C_c - C_0)^2$ plot, ε_s is the permittivity of the semiconductor ($\varepsilon_S = 11.8\varepsilon_0$ for Si) and ε_0 is the vacuum permittivity (ε_0 =8.85 x 10^{-12} F/m) (Sze, 1981).

The barrier height is determined from the following relation (Sze, 1981; Rhoderick and Williams, 1988):

$$\Phi_B = V_d + E_F - \Delta\Phi_B \tag{7}$$

where E_F is the energy difference between the bulk Fermi level and valance band edge and $\Delta\Phi_B$ is the image force lowering and given by (Sze, 1981; Rhoderick and Williams, 1988):

$$\Delta\Phi_B = \left(\frac{qE_m}{4\pi\varepsilon_s\varepsilon_0}\right)^{1/2}, \qquad E_m = \left(\frac{2qV_d N_D}{\varepsilon_s\varepsilon_0}\right) \tag{8}$$

where E_m is the maximum electric field. The value of barrier height of Φ_B can be readily calculated with the use of the following standart relations (Sze, 1981; Rhoderick and Williams, 1988):

$$E_F = \frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right), \qquad N_C = 4.82x10^{15}T^{3/2}\left(\frac{m_e^*}{m_0}\right)^{3/2} \tag{9}$$

where N_C is the effective density of states conductance band of n-Si ($N_C = 2.8$ x 10^{19} cm^{-3}) (Sze, 1981).

Initially, we extract the diffussion potential (V_d) from the extrapolation of $1/(C_c - C_0)^2$ plot to the voltage axis. The value of V_d was calculated as 1.225 eV and 1.086 eV at 500 kHz at room temperature (300 K) for Au/PMI/n-Si diode before and after irradiation, respectively. The N_D value was found as 5.042 x 10^{15} cm^{-3} and 4.085 x 10^{15} cm^{-3} for Au/PMI/n-Si Schottky diode before and after irradiation from the slope of the extrapolated $1/(C_c - C_0)^2$ lines with the voltage axis. The decrease in the ionized donor density (N_D) with the increase in the irradiation dose is due to generation–recombination through the interface states in the interface (Güllü et al., 2008a; Güllü et al., 2008b). After calculating the values of V_d and N_D, the values of E_F, $\Delta\Phi_B$ and Φ_B can be readily obtained from Eqs. (9), (8), and (7). All calculations are also given in Table 1. The values of $\Delta\Phi_B$ and E_F have been determined as 23.0 meV and 0.215 eV before irradiation, respectively. The values of $\Delta\Phi_B$ and E_F have been determined as 21.2 meV and 0.221 eV after irradiation, respectively. Therefore, the barrier height value (Φ_B) 1.418 eV and 1.286 eV for Au/PMI/n-Si Schottky diode before and after irradiation was calculated using Eq. (7), respectively. The barrier height obtained from $1/(C_c - C_0)^2$ characteristic at 500 kHz before irradiation is higher than the value obtained from $1/(C_c - C_0)^2$ characteristics after irradiation. The decrease in the barrier height (Φ_B) after irradiation is mainly due to the decrease in the diffusion potential (V_d). The width of the depletion layer (W_D) has been deduced from the donor doping density N_D and the diffusion voltage V_d using the following expression (Sze, 1981; Rhoderick and Williams, 1988):

$$W_D = \sqrt{\frac{2\varepsilon_s}{qN_D} V_d} \tag{10}$$

the W_D value was found to be about 5.634 x 10^{-5} cm and 5.892 x 10^{-5} cm for Au/PMI/n-Si Schottky diode before and after irradiation.

4. Conclusion

The forward and reverse-bias *C-V* and *G-V* characteristics of Au/PMI/n-Si Schottky diode were measured before and after 11.4 kGy irradiation dose at room temperature, 500 kHz, and in dark. A decrease in the capacitance and conductance was observed after ^{60}Co γ-ray irradiation. This has been attributed to a decrease in the net ionized dopant concentration that occurred as a result of ^{60}Co γ-ray irradiation. It was determined that the characteristic parameters of the Au/PMI/n-Si Schottky diode are very sensitive to 11.4 kGy ^{60}Co γ-ray irradiation. It was seen that the Φ_B and N_{ss} values decreased after the applied radiation, while the R_s value increased.

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Research Highlights

1- A investigation of electrical properties of the contacts due to irradiation has been reported.

2- The C-V and G-V of the PMI/n-Si Schottky structures has been reported before and after irradiation.

3- The values of Φ_b, N_{ss}, and R_s of contacts before and after irradiation have been obtained and compared.

4- Series resistance effects on organic-inorganic Schottky diodes have been investigated.

5- Interface state density effects on organic-inorganic Schottky diodes have been investigated.

Figure Captions

Figure 1. (a) Molecular structure of a perylene-monoimide organic compound. (b) Cross-sectional view of Au/PMI/n-Si Schottky diode for electrical characterization.

Figure 2. The measured capacitance-voltage $(C_m - V)$ plots of the Au/perylene-monoimide/n-Si Schottky diode at 500 kHz before and after irradiation.

Figure 3. The measured conductance-voltage $(G_m - V)$ plots of the Au/perylene-monoimide/n-Si Schottky diode at 500 kHz before and after irradiation.

Figure 4. Variation of the series resistance (R_s) of the Au/PMI/n-Si Schottky diode Schottky diode with the applied bias voltage before and after irradiation.

Figure 5. (a) The corrected capacitance-voltage $(C_c - V)$ and (b) conductance-voltage $(G_c - V)$ plots of the Au/perylene-monoimide/n-Si Schottky diode at 500 kHz before and after irradiation.

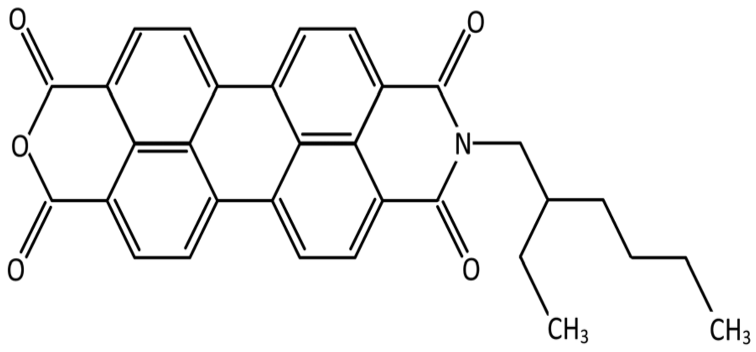
Figure 6. The capacitance (*C*) vs. $(V_d - V)^{-1/2}$ plots of Au/PMI/n-Si Schottky diode at 500 kHz before and after irradiation.

Figure 7. The $1/(C_c - C_0)^2$ vs. *V* plots of the Au/PMI/n-Si Schottky diode at 500 kHz before and after irradiation.

Table 1

	N_D (x10^{15} cm^{-3})	E_F (eV)	V_d (eV)	W_d (x10^{-5}cm)	$\Delta\Phi_B$ (meV)	Φ_B (eV)	R_s (Ω)	N_{ss} ($x10^{11} eV^{-1} cm^{-2}$)
Unirrad.	5.042	0.215	1.225	5.634	23.0	1.418	70.3	27.18
11.4 kGy	4.085	0.221	1.086	5.892	21.2	1.286	114.2	3.95

(a)



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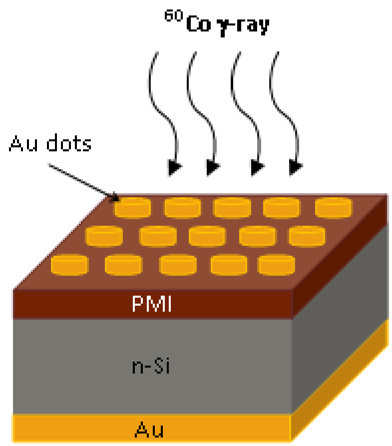


Fig. 1

Figure 2.doc

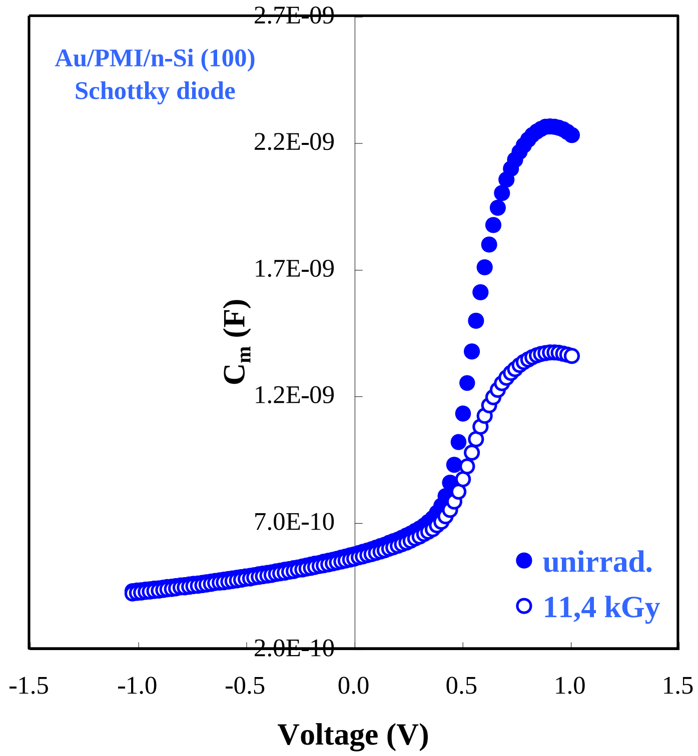


Fig. 2

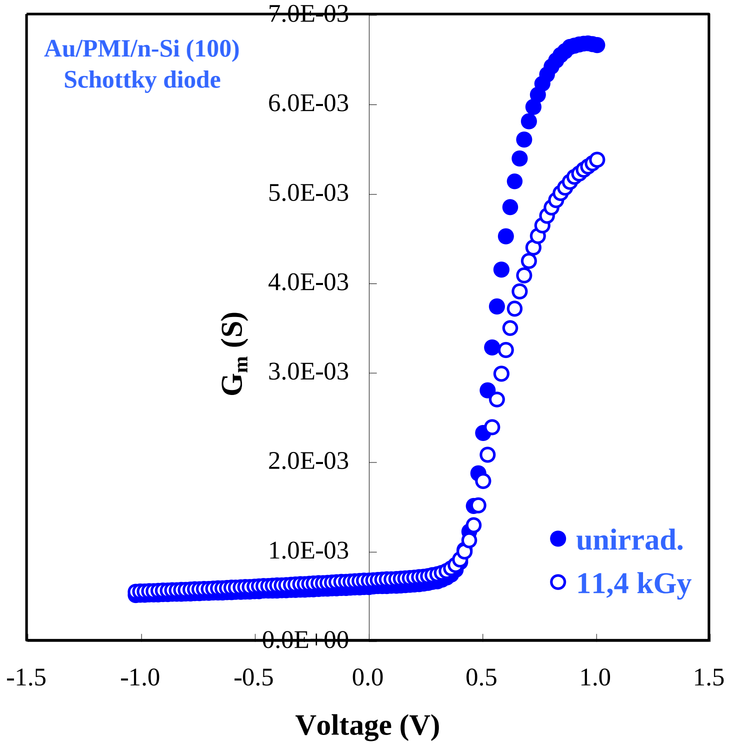

Au/PMI/n-Si (100)
Schottky diode
7.0E-03
6.0E-03
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
0.0E+00
G_m (S)
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Voltage (V)
unirrad.
11,4 kGy

Fig. 3

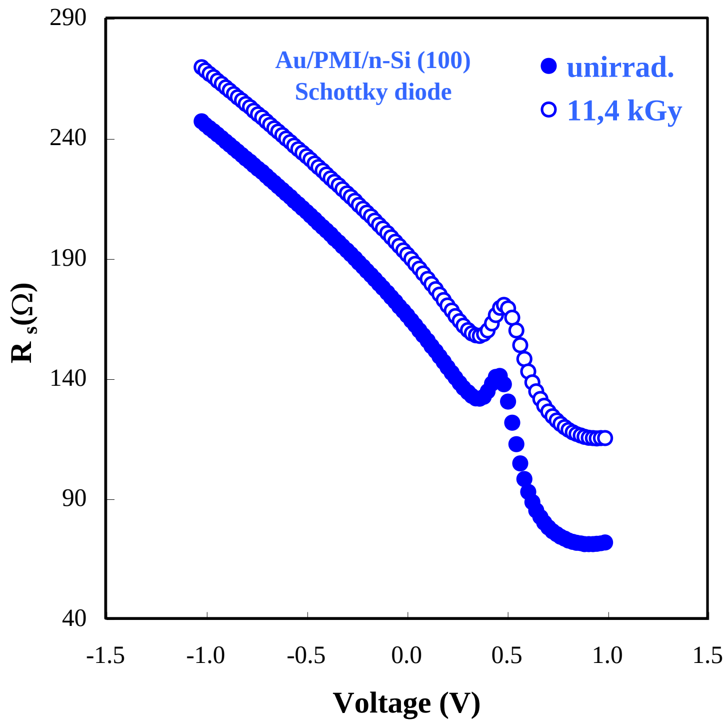
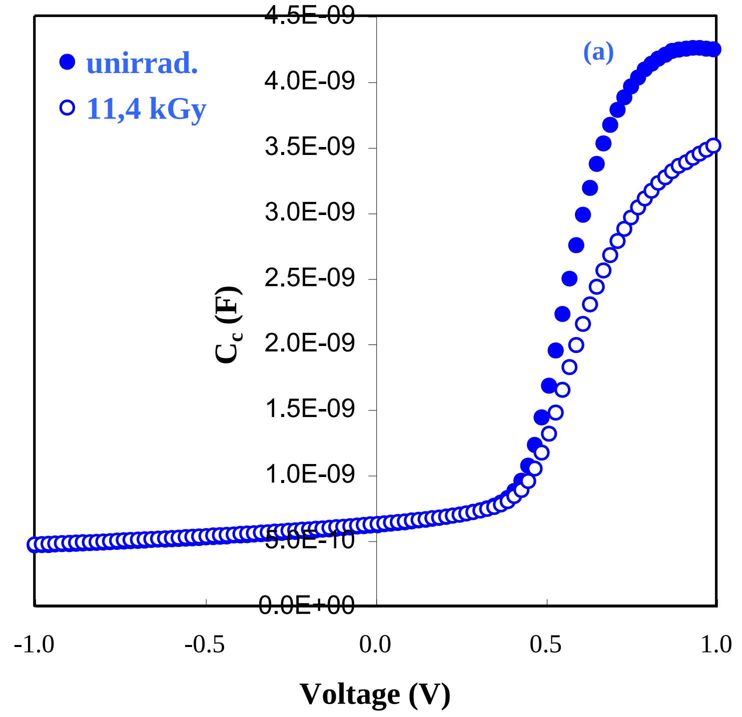

Au/PMI/n-Si (100)
Schottky diode
unirrad.
11,4 kGy
$R_s(\Omega)$
290
240
190
140
90
40
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Voltage (V)

Fig. 4


unirrad.
11,4 kGy
(a)
4.5E-09
4.0E-09
3.5E-09
3.0E-09
2.5E-09
2.0E-09
1.5E-09
1.0E-09
5.0E-10
0.0E+00
C_c (F)
-1.0
-0.5
0.0
0.5
1.0
Voltage (V)

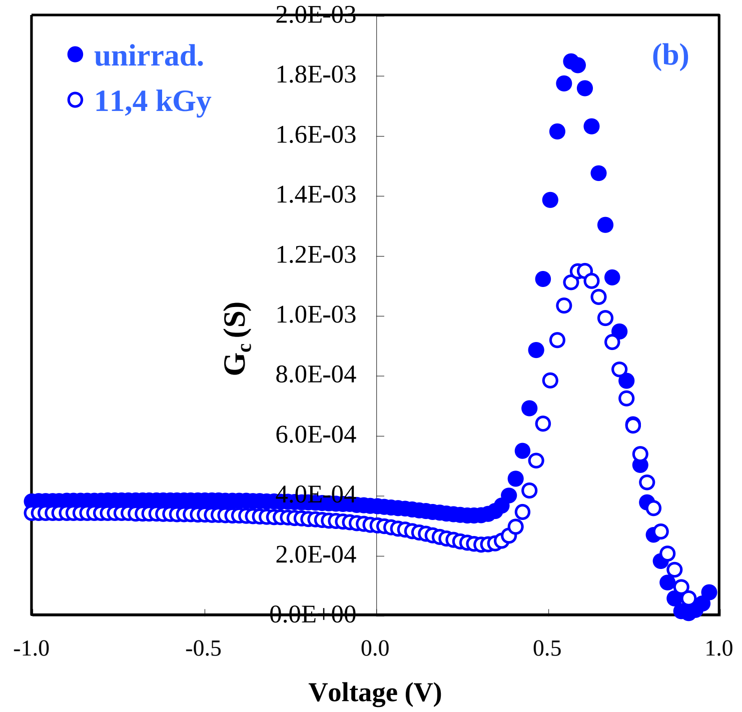

unirrad.
11,4 kGy
(b)
2.0E-03
1.8E-03
1.6E-03
1.4E-03
1.2E-03
1.0E-03
8.0E-04
6.0E-04
4.0E-04
2.0E-04
0.0E+00
G_c (S)
-1.0
-0.5
0.0
0.5
1.0
Voltage (V)

Fig. 5

Figure 6.doc

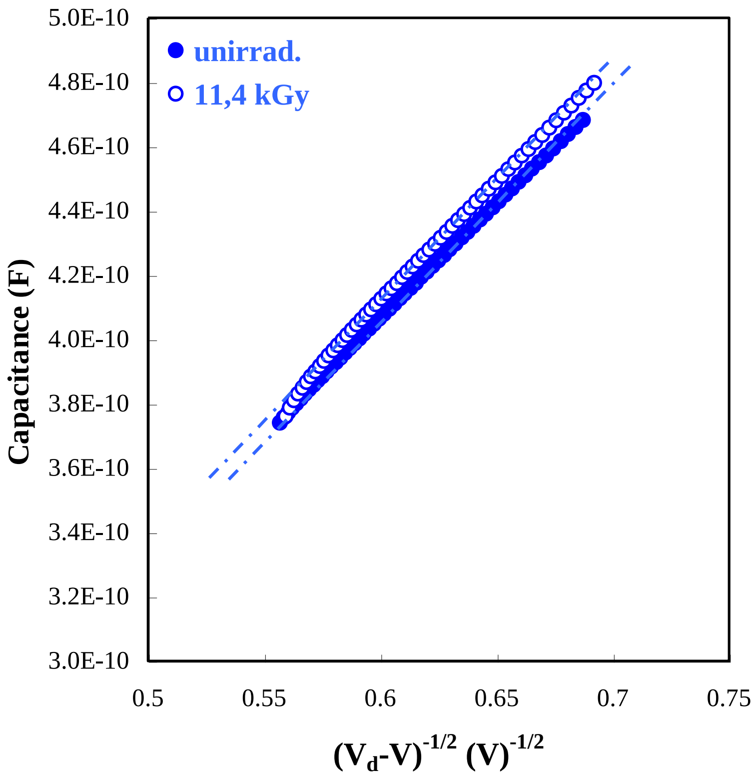


Fig. 6

Figure 7.doc

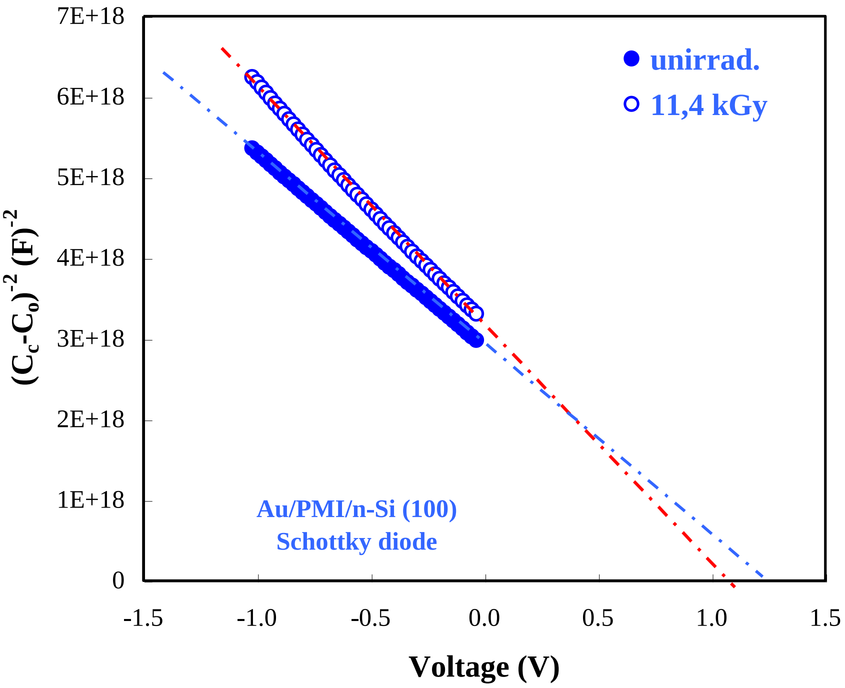


Fig. 7