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

Article Type: Original Paper

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

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 60Co -ray irradiation. The capacitance values measured under both reverse and forward bias at 500 kHz have been corrected for the effect of series resistance and excess capacaitance to obtain the real capacitance of the diode. The effects of 60Co -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 60Co -ray irradiation. This has been attributed to a decrease in the net ionized dopant concentration that occurred as a result of 60Co -ray irradiation. Some contact parameters such as barrier height , interface state density and series resistance were calculated from the C-V and G-V characteristics of the diode before and after irradiation. It was seen that the and values decreased after the applied radiation, while the value increased.

Response to Technical Check Results

Comments:

1) A maximum of 6 keywords should be provided.

It was done as requested.

2) Reference list must conform strictly to the guide for authors. For journal articles, please adhere to the following order: surname followed by initials, year, article title, abbreviated journal name, volume/issue number and page span.

It was done as requested.

3) Please cite and list references strictly according to the Guide for Authors. Citations of references in the text for single author should be indicated by the author's name together with the year of publication. For references with two authors both authors' names and the year of publication and for references with three or more authors, first author's name followed by 'et al.' and the year of publication should be cited.

It was done as requested.

4) The order of the figures and tables at the end of the manuscript should be: figure captions page, tables, and figures. Please revise.

It was done as requested.

Reviewer #1 :

Abstract

1. On my opinion, sentences "have been corrected for the effect of series resistance (Rs) and excess cpacaitance (C0) to obtain the real capacitance of the diode" and "The C-V and G-V characteristics of the diode indicate very strong irradiation dependence." are unnecessary.

The related sentences in abstract has been removed as requested.

Introduction

1. The introduction does not clearly state the problem and includes repetition of some information.

It is made as referee request.

2. The report Trefilova et al.2001 does not contain the information about 4H-SiC Shottky rectifiers.
(In reviewered manuscript: "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).")

The related reference in introduction and reference list has been removed. **Furthermore, the related reference has been rearranged in red.**

3. Some mistakes are present (e.g, "Ocak et al. (Ocak et al., 2010) reported the effect of 60Co <gamma>-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.")

Electron irradiation has been changed as " ^{60}Co gamma irradiation" **in red**

Results and Discussion

1.The experiment conditions ("at 500 kHz, at room temperature and in dark") should not be repeated so often in the Section "Results and Discussion".

The related sentences in the section have been removed as requested.

2. The accuracy of the parameter determination is absent in the manuscript (both in the text and in the Table 1.) and so many digits after the decimal point is used.

Two digits after the decimal point have been rearranged in text and Table 1.

3. The measured capacitance and conductance in accumulation are used in eq. (1), but Fig.4 is plotted for accumulation, depletion and inversion region.

   The Fig.4 ***has been revised as requested.***

4. The authors can not talk about "with increasing irradiation" or "while the irradiation dose increases" because only one dose (11.4 kGy) is used.

"with increasing irradiation" or "while the irradiation dose increases" sentences have been rearranged as "after 11.4 kGy" in full-length text

5. If "<epsilon>i<epsilon>0" is used in equations then <epsilon>i=3.2 and <epsilon>s=11.8, not <epsilon>i=3.2<epsilon>0 and <epsilon>s=11.8<epsilon>0. And "<epsilon>i<epsilon>0" must be used in (5) and (10).

Eq. (5), (8), (10) and C_{org} has been rearranged without <epsilon>0. Because it was received as $\varepsilon_S = 11.8\varepsilon_0$ for Si and $\varepsilon_i = 3.2\varepsilon_0$

6. It can be seen (Fig5,a) that Cc,acc changed after irradiation. Therefore dorg must change too (from 21 nm to ~25 nm). But reason of this phenomenon is not discussed in manuscript.

"There is a discrepancy in the values of $C_{c,acc}$ before and after 11.4 kGy in Fig. 5(a) due to the effect of interface states. The interface states have a passivation after 11.4 kGy irradiation and interface states cannot follow the ac signal. This makes the contribution of interface state capacitance to the total capacitance small.." sentence has been added in page 8 in red.

7. The method for correcting non-linear 1/C2-V characteristics does not explained in detail and the nature of the excess capacitance is not

discussed.

"This non-linearity of the C^{-2} versus V curve at high frequency ($f \geq 500$ kHz) can be explained on the basis of assumption that only some of the interface states (N_{ss}) follow the applied ac signal. The N_{ss} yield an excess capacitance (C_0).That is, the existence of non-linearity can be referred to the C_0 at the metal/semiconductor interface and to the existence of the two various type impurities levels as a result of bias-dependent charging occuring from deeper traps or surface states (N_{ss}) (Türüt et al., 1995)." Sentence has been added in page 10 (in red)

8. The unclear procedure is used:
Step1: Dependence C vs (Vd(!!)-V) is plotted and C0 is determinated;
Step 2: Dependence 1/(CC-C0)2 vs V is plotted and Vd (!!!) is determinated.

Step 1:

"The values of excess capacitance (C_0) have been determined from intercept of the (C_c) vs. $(V_d - V)^{-1/2}$ plots" sentences have been added in text in red.

Step 2:

"V_0 is the diffusion potential at zero bias determined from the extrapolation of the linear reverse bias $C_c^{-2} - V$ plot to the V axis. The V_d value has been determined from V_0 plus kT/q." sentences have been added in text in red.

9. Equation (8) is incorrect and EF is not "the energy difference between the bulk Fermi level and valance band" for n-Si.

Eq. (7) and (9) have been rearranged and "V_n is the potential difference between the Fermi energy level (E_F) and the bottom of the conduction band in the neutral region of n-Si" sentence has been added in text in page 10 in red. Furthermore, E_F section in Table 1 has been changed as V_n

10. The term "kT/q" should be present in (7) if accuracy about mV is used for <PHI>b determination.

"The V_d value has been determined from V_0 plus kT/q." sentence has been added in text in page 9 in red.

11. The authors have not indicated completely how the results relate to earlier research.

It is given the results of our sample because we have obtained similar results to previous studies.

Figures

1. The range of the axes on the Fig. 2, 3, 4, 6 can be chosen better.

The range of the axes on all the figures has been rearranged.

References

1. Several references are not accurate completely (e.g. Ger, 2008): some journals use paper number instead pages.

All references have been checked according to "Guide for Authors" of the journal

Reviewer #2 :

First of all there are some format problems with the paper. The figures are not consistent, some of them have the y-axis in the middle of the x-axis, others have it at the left side of the x-axis. The ones with the y-axis in the middle should be converted to the standard format with the y-axis at the left end of the x-axis.

All figures has been rearranged as requested.

I have not gone through all the references checking if the coordinates are correct, but found that Gülü 2008a has the wrong volume number, 4 instead of 41. I strongly recommend that the authors thoroughly check the reference list.

The volume number of reference related to "Güllü 2008a" has been changed as 4 instead of 41. Furthermore, All references have been checked according to "Guide for Authors" of the journal.

There are few grammar/style problems. For example on page 8 in line 13 it should be ". has a peak" instead of ".consists of a peak".

"consists of a peak" has been changed as ". have a peak" on page 8 in line 13 in red. Furthermore, All manuscript has been checked in terms of few grammar/style problems.

The main problem is that the paper presents lot of equations and calculated values, but it is short on discussion. For example they mention that there is a peak in Figure 4 but there is no explanation given for that.

It is clear from Fig. 4 that the values of R_s are very effective especially in the depletion region. The absence of a peak in G-V curve (Fig. 3) means that series resistance produced the dominant loss, completely masking the interface trap loss (Nicollian and Brews, 1982). Correction for series resistance is particularly important in conductance measurements according to Eq. (1) (Nicollian and Brews, 1982 (not given in text). Also, after correction for series resistance, the peaks correspond to the depletion area of the device and its existence verifies the presence of interface traps (given in page 9)

As requested of Reviewer 1, Fig. 4 has been rearranged in accumulaion region. Becasuse the measured capacitance and conductance in accumulation are used in eq. (1). Consequently, the revised Fig. 4 has not include a peak. Therefore, the explanations that mentioned above for Reviewer 2 has not included in text.

They say that the interface traps passivate (sic) with increasing irradiation dose, but no discussion is offered why it is happening.

Firstly , "the interface traps passivate (sic) with increasing irradiation dose" sentence has been changed as "the interface states have a passivation after 11.4 kGy irradiation."

Another statement say that the ionized donor density decreases with irradiation dose due to the recombination-generation through the interface states in the interface and cites Gülü 2008a. I looked up this paper and did not find a detailed explanation that backs up the above statement.

This explanation has been given in Güllü 2008a (the last paragraf in page 6) and Güllü 2008b (the last sentences of results and discussion) for p-Si. Hence, It has been made the similar explanation for our sample (related to n-Si). *The reduction of ionized carrier doping density after radiation is valid for each two types of Si*

Also, this seems to somewhat contradictory to the previous statement that the interface states decrease with the irradiation. Usually, the apparent decrease of the doping concentration in semiconductors is due to traps created by displacement damage. In this case there is no displacement so I would like to see some more detailed explanation.

"Radiation creates the permanent effects on semiconductor device characteristics. It makes defects and defect clusters in semiconductor which can act as recombination-generation centers. These centers reduce the carrier doping concentration (Nicollian and Brews, 1982)." *sentence has been added in page 12* ***in red.***

There is one thing that really disturbs me. The authors cite Gülü 2008a, which is a paper on a similar experiment (although the organic material is different) but they never mention that this paper presented quite different results. Especially, Gülü 2008a found that the Schottky barrier decreases with irradiation and the serial resistance increase. These are just the opposite what this paper's authors found. I would accept this result with some discussion but the fact that they forgot to mention the discrepancies is troubling.

Firstly, Our article have only the capacitance-conductance-voltage measurements of the sample before and after irradition but the above mentioned explanations (referee report) relate to current-voltage measurements of the sample.

If we look at the article of Güllü 2008a, we see "... the capacitance of the device decreases significantly after gamma irradiation. (in page 6)". Consequently, this paper presented quite same results with our paper because it is seen that the capacitance of the device decreases after gamma irradition in our paper.

"Some researchers (Gür et al., 2008, Mamor et al., 2007; Fonash et al., 1981; Grussell et al., 1980) also reported that particle or gamma irradiation induces defects in the band gap which influences the free carrier concentration and leads to

an increase and decrease in the barrier height in p-type and n-type semiconductors, respectively." sentence has been added in page 12 (in red)

References (Mamor et al., 2007; Fonash et al., 1981; Grussell et al., 1980) have been added in reference section.

Another problem I have with the paper is that they used only one dose for the irradiation and then they make statements like this and that increases/decreases with increasing radiation. They can only make a statement between non-irradiated and irradiates samples. How do they know that for example the series resistance does not have a maximum or minimum as the function of the radiation dose?

"with increasing irradiation" or "while the irradiation dose increases" sentences have been rearranged as "after 11.4 kGy irradiation" in full-length text

What I would like to see in the revised manuscript is:

* Additional measurements done with several doses (it is really easy just irradiate, measure, irradiate, measure, etc.) to show the trends.

The radiation source used in our Resarch Center is out of order. We have waited for the enhancement of source of radiation source for 3 months in our Research Center, but it is unclear when the enhancement of source will increase.

We would like to specify that knowledge of the influence of radiation damage on the Schottky barrier diodes (SBDs) performance is a fundamental field of research, having technological relevance for many applications in semiconductor electronic devices.

We ask that the evaluation of our article in this way

* Much more discussion of the mechanisms that lead to these changes, even detailed speculations would do.

It is made as referee request.

* An explanation why their results are the opposite of what was presented in Gülü 2008a.

It is made as referee request.

*	Review the reference list for errors.

All references have been checked according to "Guide for Authors" of the journal.

*	Thoroughly read the manuscript for grammar mistakes or odd sounding sentences.

It is made as referee request.

^{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 effects of ^{60}Co γ-ray irradiation on the electrical characteristics of a (PMI)/n-Si Schottky diode were investigated. 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, HfO_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. 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 determine the particle irradiation effect on the 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).

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 ^{60}Co gamma 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. (Kim et al., 2004) and Nigam et al. (Nigam et al., 2002), respectively.

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 dose 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 after 11.4 kGy irradiation dose. 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. It is seen from Fig. 3 that the values of the conductance increase with increasing voltage before and after irradiation and decrease after 11.4 kGy irradiation dose. 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 11.4 kGy irradiation dose have been calculated through relation (Nicollian and Brews, 1982):

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

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

Fig. 4 shows 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. It is clearly seen in Fig. 4 that the values of the series resistance (R_s) increase after 11.4 kGy irradiation dose. The series resistance as a function of voltage gives a peak in approximately the same voltage range. It is also clear from Fig. 4 that the values of R_s are very effective especially in the depletion region. The absence of a peak in *G-V* curve (Fig. 3) means that series resistance produced the dominant loss, completely masking the interface trap loss (Nicollian and Brews, 1982). Correction for series resistance is particularly important in conductance measurements according to Eq. (1) (Nicollian and Brews, 1982). The values of series resistance of the Au/PMI/n-Si Schottky diode at the accumulation region before and after irradiation 11.4 kGy have 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):

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

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 11.4 kGy irradiation dose. There is a discrepancy in the values of $C_{c,acc}$ before and after 11.4 kGy in Fig. 5(a) due to the effect of interface states. The interface states have a passivation after 11.4 kGy irradiation and interface states cannot follow the ac signal. This makes the contribution of interface state capacitance to the total capacitance small. 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 have 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):

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

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 $\left(C_{org} = \varepsilon_i A / d_{ox}\right)$, 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 27.18 x 10^{-11} and 3.95 x 10^{-11} eV^{-1} cm^{-2} before and after 11.4 kGy irradiation dose, respectively. These values are also given in Table 1. As shown in Table 1, the density of interface states (N_{ss}) decreases after 11.4 kGy irradiation dose. On the other hand, it is seen that the interface states have a passivation after 11.4 kGy irradiation.

V_0 is the diffusion potential at zero bias determined from the extrapolation of the linear reverse bias $C_c^{-2} - V$ plot to the V axis. The V_d value has been determined from V_0 plus kT/q. Fig. 6 represents the corrected capacitance (C_c) vs.

$(V_d - V)^{-1/2}$ characteristics of the Au/PMI/n-Si Schottky diode before and after γ – irradiation. This non-linearity of the C^{-2} versus V curve at high frequency ($f \geq 500$ kHz) can be explained on the basis of assumption that only some of the interface states (N_{ss}) follow the applied ac signal. The N_{ss} yield an excess capacitance (C_0).That is, the existence of non-linearity can be referred to the C_0 at the metal/semiconductor interface and to the existence of the two various type impurities levels as a result of bias-dependent charging occuring from deeper traps or surface states (N_{ss}) (Türüt et al., 1995). The values of excess capacitance (C_0) have been determined from intercept of the (C_c) vs. $(V_d - V)^{-1/2}$ plots before and after γ – irradiation as 1.61 x 10^{-11} and 5.61 x 10^{-11} F, respectively. As can be seen from Fig. 6, after 11.4 kGy irradiation dose, 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 11.4 kGy irradiation dose. In n type semiconductor based Schottky junction, the depletion layer capacitance is given by (Sze, 1981; Rhoderick and Williams, 1988):

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

and

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

(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):

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

where V_n is the potential difference between the Fermi energy level (E_F) and the bottom of the conduction band in the neutral region of n-Si and $\Delta\Phi_B$ is the image force lowering and given by (Sze, 1981; Rhoderick and Williams, 1988):

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

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):

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

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 diffusion 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 1.22 eV and 1.08 eV for Au/PMI/n-Si diode before and after 11.4 kGy irradiation dose, respectively. The N_D value was found as 5.04 x 10^{15} cm^{-3} and 4.08 x 10^{15} cm^{-3} for Au/PMI/n-Si Schottky diode before and after 11.4 kGy irradiation dose from the slope of the extrapolated $1/(C_c - C_0)^2$ lines with the voltage axis. Radiation creates the permanent effects on semiconductor device characteristics. It makes defects and defect clusters in semiconductor which can act as recombination-generation centers. These centers reduce the carrier doping concentration (Nicollian and Brews, 1982). The decrease in the ionized donor density (N_D) after 11.4 kGy 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 V_n, $\Delta\Phi_B$ 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 V_n have been determined as 23.0 meV and 0.21 eV before irradiation, respectively. The values of $\Delta\Phi_B$ and V_n have been determined as 21.2 meV and 0.22 eV after 11.4 kGy irradiation dose, respectively. Therefore, the barrier height value (Φ_B) 1.41 eV and 1.28 eV for Au/PMI/n-Si Schottky diode before and after 11.4 kGy irradiation dose 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 11.4 kGy irradiation dose. The decrease in the barrier height (Φ_B) after irradiation is mainly due to the decrease in the diffusion potential (V_d). Some researchers (Gür et al., 2008, Mamor et al., 2007; Fonash et al., 1981; Grussell et al., 1980) also reported that particle or gamma irradiation induces defects in the band gap which influences the free carrier concentration and leads to an increase and decrease in the barrier height in p-type and n-type semiconductors, respectively.

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):

$$W_D = \sqrt{\frac{2\varepsilon_s}{qN_D}V_d} \qquad (10)$$

the W_D value was found to be about 5.63 x 10^{-5} cm and 5.89 x 10^{-5} cm for Au/PMI/n-Si Schottky diode before and after 11.4 kGy irradiation dose.

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.

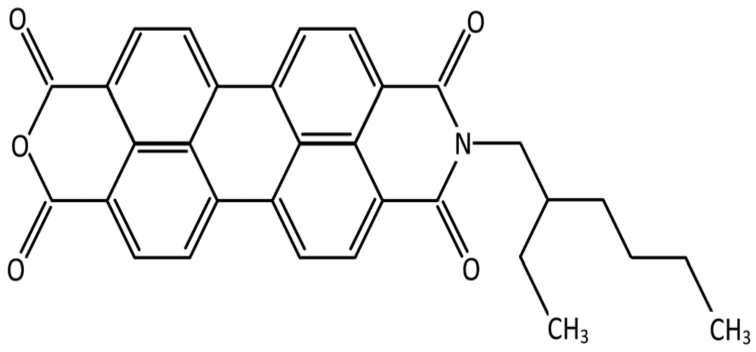
Figure 4. Variation of the series resistance (R_s) of the Au/PMI/n-Si Schottky diode Schottky diode with the applied bias voltage before and after irradiation.

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.

(a)



b)

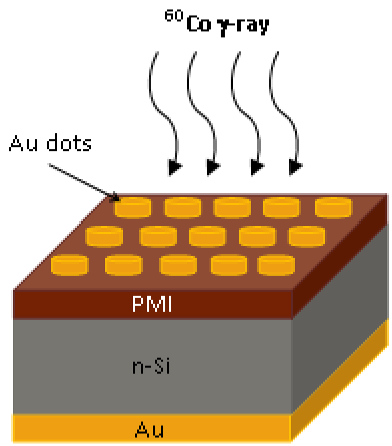


Fig. 1

Figure

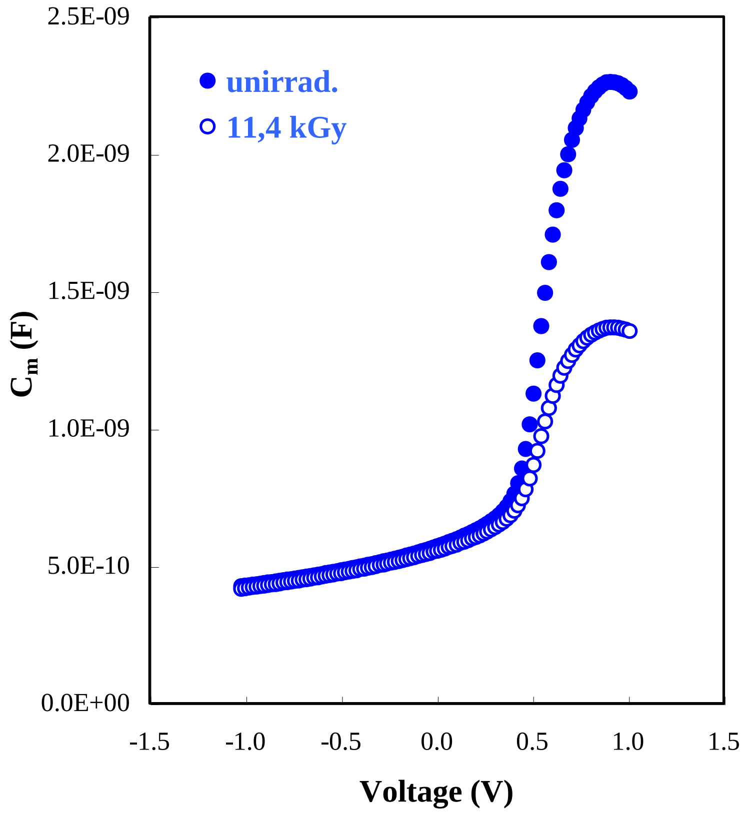

unirrad.
11,4 kGy
2.5E-09
2.0E-09
1.5E-09
1.0E-09
5.0E-10
0.0E+00
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
C_m (F)
Voltage (V)

Fig. 2

Figure

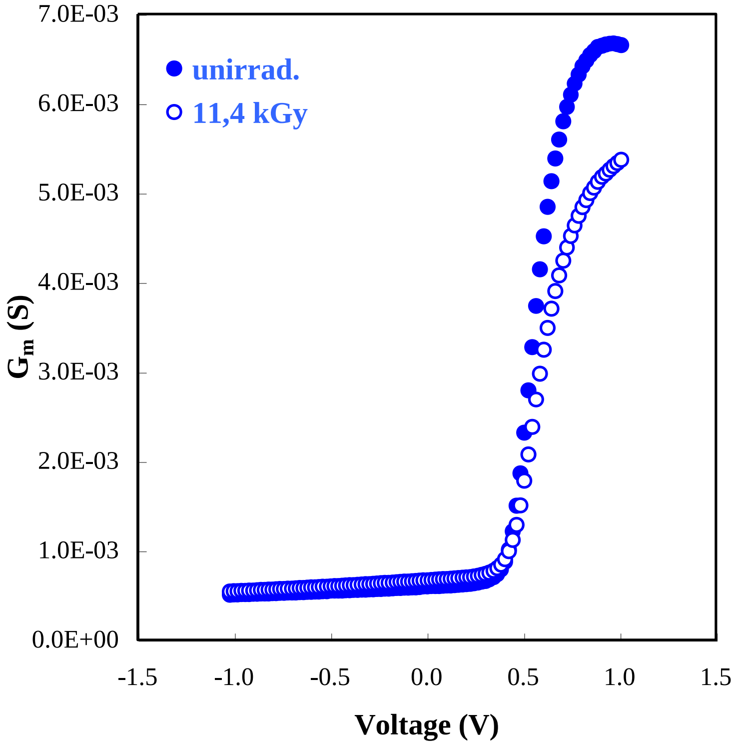
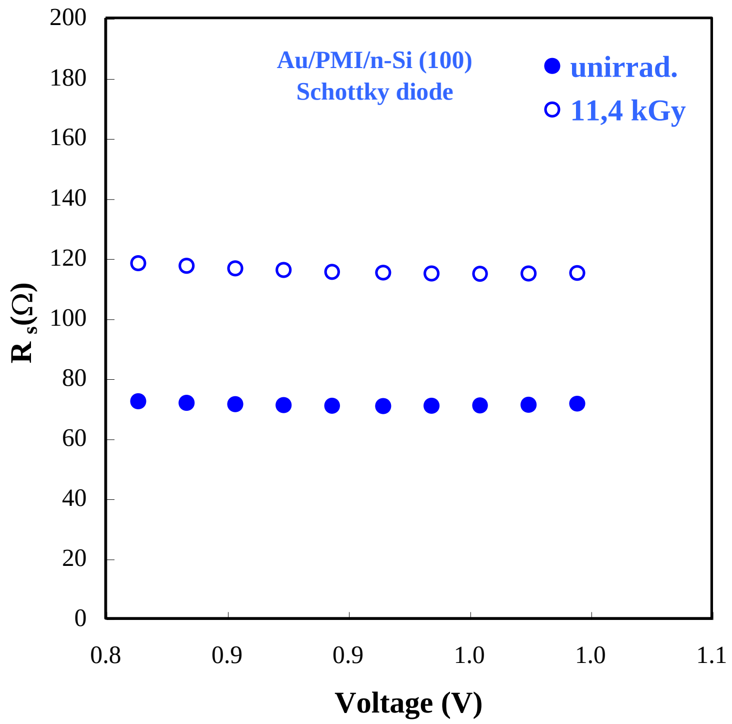

7.0E-03
6.0E-03
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
0.0E+00
G_m (S)
unirrad.
11,4 kGy
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Voltage (V)

Fig. 3

Figure



Au/PMI/n-Si (100)
Schottky diode
unirrad.
11,4 kGy
$R_s(\Omega)$
Voltage (V)
200
180
160
140
120
100
80
60
40
20
0
0.8
0.9
0.9
1.0
1.0
1.1

Fig. 4

Figure

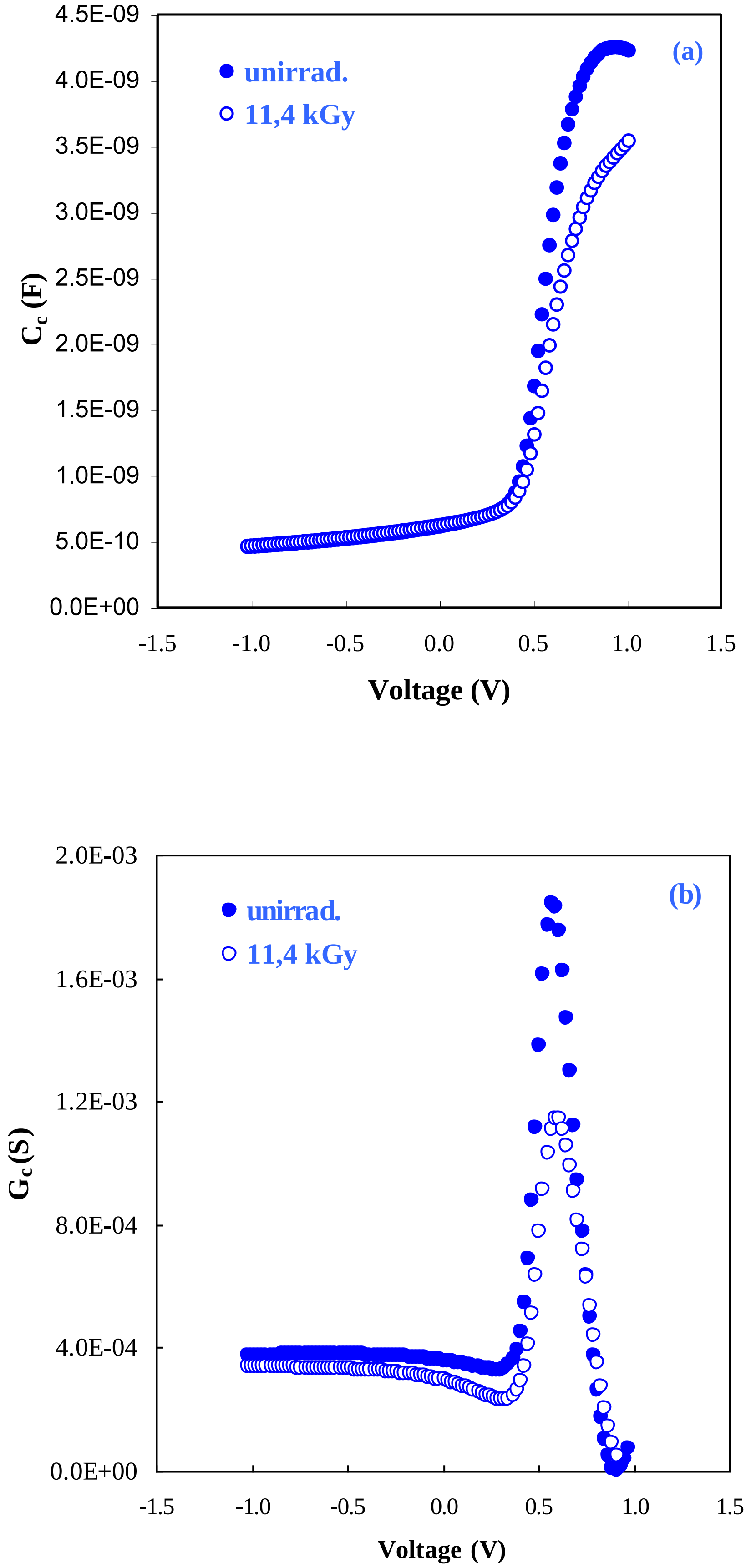

(a)
unirrad.
11,4 kGy
C_c (F)
Voltage (V)
4.5E-09
4.0E-09
3.5E-09
3.0E-09
2.5E-09
2.0E-09
1.5E-09
1.0E-09
5.0E-10
0.0E+00
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
(b)
unirrad.
11,4 kGy
G_c (S)
Voltage (V)
2.0E-03
1.6E-03
1.2E-03
8.0E-04
4.0E-04
0.0E+00
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5

Fig. 5

Figure

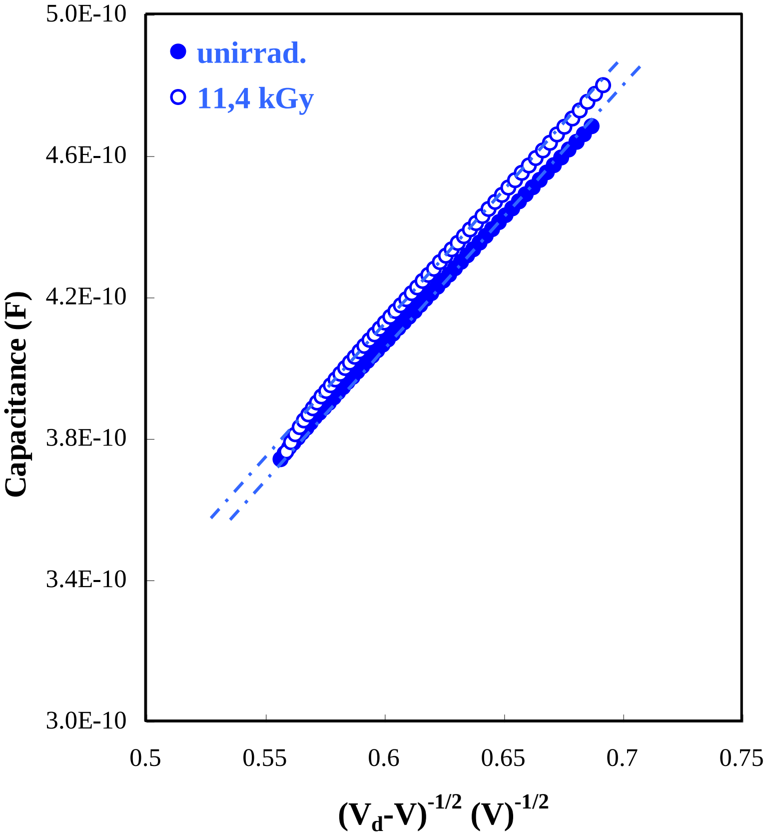

5.0E-10
4.6E-10
4.2E-10
3.8E-10
3.4E-10
3.0E-10
Capacitance (F)
unirrad.
11,4 kGy
0.5
0.55
0.6
0.65
0.7
0.75
$(V_d\text{-}V)^{-1/2}$ $(V)^{-1/2}$

Fig. 6

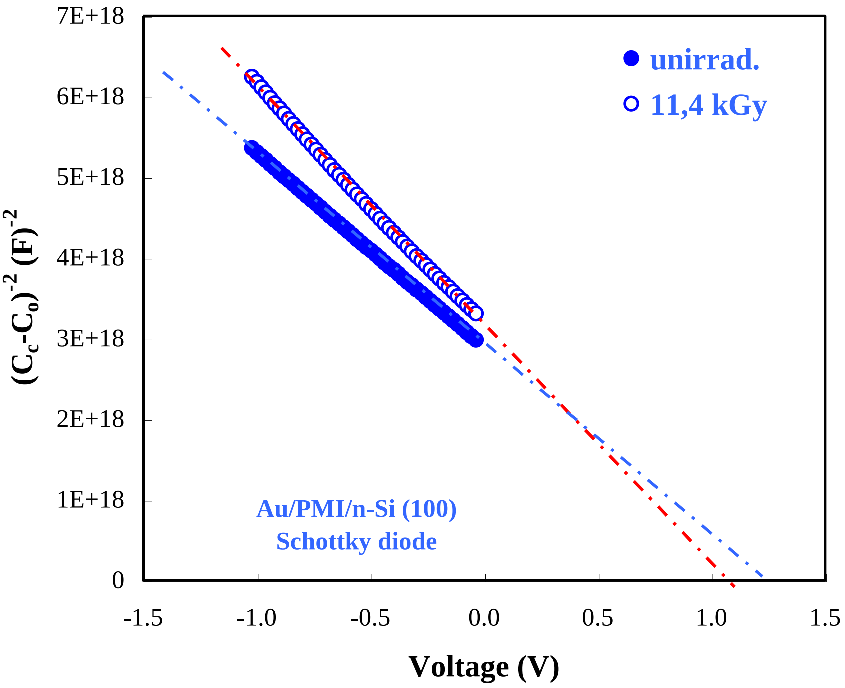

7E+18
6E+18
5E+18
4E+18
3E+18
2E+18
1E+18
0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
$(C_c-C_o)^{-2}$ (F)$^{-2}$
Voltage (V)
unirrad.
11,4 kGy
Au/PMI/n-Si (100)
Schottky diode

Fig. 7

Table Captions

Table 1. The experimental values of the Au/PMI/n-Si Schottky diode obtained capacitance/conductance-voltage characteristics before and after 11.4 kGy γ-ray irradiation

Table

Table 1

	N_D ($x10^{15}$ cm^{-3})	V_n (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.	5.04	0.21	1.22	5.63	23.0	1.41	70.3	27.18
11.4 kGy	4.08	0.22	1.08	5.89	21.2	1.28	114.2	3.95