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# $\gamma$-Irradiation-induced changes at the electrical characteristics of Sn/p–Si Schottky contacts

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**Abstract**

We studied electrical parameters of Sn/p–Si Schottky barrier diodes (SBDs) by using in situ current–voltage (*I–V*) and capacitance–voltage (*C–V)* measurements under $\gamma$-irradiation at room temperature. The devices were held under zero bias during $\gamma$-irradiation with dose rate 0.25 kGy/h, and the total dose range was 0–45 kGy. Irradiation results indicated that these devices may have applications as radiation sensors in order to detect the low-energy $\gamma$ radiation.


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*Keywords:* Radiation effect; Schottky barrier diode; Barrier inhomogeneity

## 1. Introduction

The studies of the modification in semiconductor devices due to irradiation are of both technological importance and scientific interest [1]. When any radiation, such as $\gamma$-radiation as well as electron, neutron, proton and alpha particles with energies in the range of 1 keV to hundreds of MeV passes through the semiconductor device it may occur at different events [2]. High-energy radiation penetrates the metal–semiconductor (MS) interface and causes damage deep below the interface. Low-energy radiation causes severe lattice damage in the form of vacancies, interstitials and defect complexes at the near interface of the device [3–7]. The irradiation-induced electrically active defects act either as traps or recombination centers in the semiconductors, depending on the capture cross-sections of the electrons and holes [1]. The defects created at the interface using low-energy $\gamma$-irradiation reduce the semiconductor-free carrier density, whereas recombination centers introduce generation–recombination current in rectifying devices [4,8]. Similarly, the defects result in changing the property of the material at the surface or deep into the surface depending upon the energy of the irradiation [1,2].

In the past decade, the radiation response of MS contacts has been found to alter significantly when the structures are exposed to pre-irradiation processes at determined doses [1,8–14]. Radiation doses greater than a kilogray (kGy) (1 Gray = 100 Rad) exposure may cause strong changes in the electrical characteristics of MS structures. It has been also shown that the particle or $\gamma$-irradiations induce defects in the bandgap, which affects the free carrier concentration and leads to an increase and decrease of barrier height in p- and n-type semiconductors, respectively [15–17]. The 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 the semiconductor electronic devices [17]. Hence, it is very much essential to evaluate the effect of irradiation and identify the degradation mechanism to understand the failure mechanisms [6].

In this study, we present the investigation of the current–voltage (*I–V*) and capacitance–voltage (*C–V*) characteristics of Sn/p–Si SBD irradiated by $\gamma$-radiation with 60 keV at various doses. Our aim is to compare the earlier results

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on Sn/Si Schottky diodes with new results based on $\gamma$-irradiation effects on the diodes at room temperature. Therefore, using Am-241 with low-energy photons (60 keV) we studied probable effects of $\gamma$-irradiation on Sn/Si contact. However, Karatas et al. [10] investigated effects of the high energy (1.2 MeV) radiation produced by Co-60 on the Sn/Si contacts. We showed that the reverse bias current of the Sn/p–Si contact changed with increasing irradiation with low energy (60 keV).

## 2. Experimental details

The metallization processes and ohmic back contact formation for Sn/p-type Si SBDs were performed as follows: the samples were prepared by using the polished p-type Si wafer with [1 0 0] orientation. Free carrier concentration of $N_A = 1.09 \times 10^{15}\,\mathrm{cm}^{-3}$ for the p-type Si wafer was calculated from the $C$–$V$ measurements The wafer was chemically cleaned using the RCA cleaning procedure (i.e, 10 min boil in $NH_4 + H_2O_2 + 6H_2O$ followed by 10 min boil in $HCl + H_2O_2 + 6H_2O$). The native oxide on the front surface of the substrate was removed in HF:$H_20$ (1:10) solution and finally was rinsed in de-ionized water for 30 s. Then, low-resistivity ohmic back contact to p-Si wafer was made using Al, followed by a temperature treatment at 570 °C for 3 min in $N_2$ atmosphere. The thickness of the Al film was 1000–1400 Å. The Schottky contacts were formed by evaporation of Sn dots with a diameter of about 1.0 mm (diode area is $A = 7.82 \times 10^{-3}\,\mathrm{cm}^2$). The thickness of the Sn film was 800–1200 Å. All evaporation processes were carried out in a vacuum coating unit of about $10^{-6}$ mbar. $\gamma$-radiation with 60 keV energy from an Am-241 point source was used for the irradiation on Sn/p–Si contact. The device was irradiated from the top (Schottky metal) metal side with various $\gamma$-irradiation doses (5, 11, 22, 34, 45 kGy) at room temperature as seen in Fig. 1.

In this study, we used a dose-rate meter having scales of μR/h, mR/h and R/h produced by Cekmece Nuclear Research and Education Center, made in Turkey, in order to measure the dose rate of radiation source. We measured a radiation dose of 30 mR/h for Am-241. Then, this

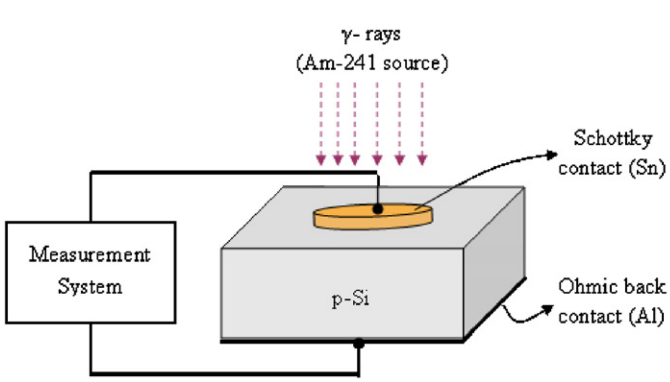


Fig. 1. Experimental setup for in situ measurements and irradiation process of the Sn/p–Si Schottky barrier diode.

value was transformed to 0.25 kGy/h using the relationship given by

$$1\,\mathrm{R/h} = 2.45\,\mathrm{Gy/s},$$

where R is Röntgen, h is hour, Gy is Gray, and s is second.

During the irradiation process no bias voltage was applied to the device. The $I$–$V$ and $C$–$V$ measurements of the irradiated device were carried out by stopping the irradiation by a Keithley 487 Picoammeter/Voltage Source and HP model 4192A LF impedance analyzer at room temperature under dark conditions. In addition, we wore protective clothes against the radiation and used a Pb block as radiation shielding during the electrical measurements.

## 3. Results and discussion

### 3.1. Analysis of current–voltage characteristics

The current through a SBD under a bias $V$ is given by the relation [18,19],

$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \tag{1}$$

where $I_0$ is the reverse saturation current given with

$$I_0 = AA^{**}T^2 \exp\left(-\frac{q\Phi_{B,I-V}}{kT}\right). \tag{2}$$

Here $A$ is the diode area, $A^{**} = 32\,\mathrm{A\,cm^{-2}\,K^{-2}}$ is the Richardson constant, $T$ is the temperature, $k$ is the Boltzmann constant, $q$ is the electronic charge, $\Phi_{B,I\text{–}V}$ is the barrier height and $n$ is the ideality factor.

From Eqs. (1) and (2), the ideality factor $n$ and barrier height $\Phi_{B,I\text{–}V}$ can be written, respectively, as

$$n = \frac{q}{kT}\frac{\mathrm{d}V}{\mathrm{d}\ln(I)} \tag{3}$$

and

$$\Phi_{B,I-V} = \frac{kT}{q}\ln\left(\frac{AA^{**}T^2}{I_0}\right). \tag{4}$$

From the slope of $\ln I$ vs. $V$ curve in Eq. (3), the value of ideality factors are calculated. $I_0$ is determined from the intercept of $\ln I$ vs. $V$ curve on the $y$-axis. Putting these values of $I_0$ in Eq. (4), the values of SBHs were calculated.

The $I$–$V$ characteristics have been measured for as-deposited and irradiated samples at various doses ranging from 5 to 45 kGy. Fig. 2 shows the room-temperature $I$–$V$ characteristics of as-deposited and irradiated diodes. As seen from the Fig. 2, there is a great linearity in the region of the moderate currents, in contrast to higher currents that show curvature due to a series resistance on a logarithmic scale for both samples. It is observed that the forward bias $I$–$V$ curves of the device exposed to $\gamma$-irradiation shift towards high voltage side in comparison to the as-deposited ones. The $\ln I$–$V$ curves did not show a significant difference among the measurements obtained in the range of radiation dose 22–45 kGy. Here, it can be thought that

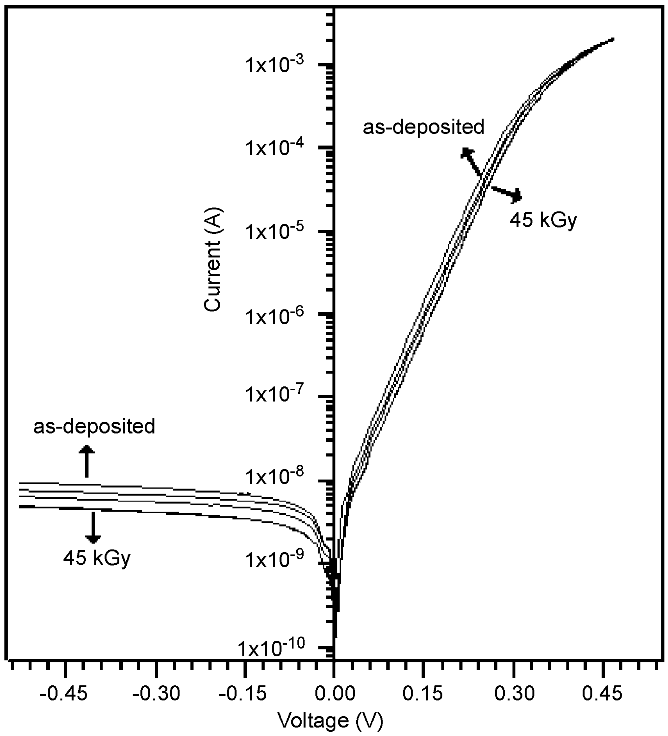


Fig. 2. The $I$–$V$ characteristics of as-deposited and irradiated Sn/p–Si Schottky barrier diode with various $\gamma$-irradiation doses (5, 11, 22, 34, 45 kGy).

the $\gamma$ radiation effect exposes to saturation by depending upon radiation energy and dose in this irradiation dose range. Also, as seen from Fig. 2, the value of the reverse current was observed to decrease with the increase in the radiation dose up to a level 45 kGy. This radiation-induced enhancement observed in the reverse bias current could be ascribed to the decrease in the interfacial defect density [11]. The values of ideality factor, barrier height, reverse saturation current and series resistance obtained from $I$–$V$ characteristics of as-deposited and irradiated device have been given in the Table 1 as a function of irradiation dose rate. As seen in Table 1 and Fig. 3, the barrier height of Sn/p–Si SBD increases with increasing irradiation dose. Recently, by some researchers [15–17] it has been shown that the irradiation processes on the MS structures induces defects in the bandgap, which affects the free carrier concentration and leads to an increase (or decrease) of barrier height in p-type (or n-type) semiconductors. Therefore, the increase in the barrier height after $\gamma$-irradiation can be correlated with the modification of concentration of free carriers at the Sn/p–Si interface induced by the $\gamma$-irradiation [17]. Additionally, the increase in the value of barrier height with increasing irradiation dose can be explained by reduction in carrier concentration (see Table 1) in the depletion region of Sn/p–Si Schottky diode through the occurrence of traps and recombination centers associated with radiation damage. Similarly, it can clearly be seen that ideality factor of the device increases also with increasing irradiation dose in Table 1 and Fig. 3. Similar trends have already been reported recently for contacts on other MS structures and have been explained by assuming inhomogeneities at the interface [10,17].

According to Jayavel et al. [8], the ideality factor increases due to the inhomogeneity of the interface that depends upon $\gamma$-irradiation-induced damage. It shows that the current flow mechanism can be due to other mechanisms. The image–force effect, recombination–generation, and tunneling may be other possible mechanisms that could lead to an ideality factor greater than unity [11]. Additionally, the increase of the ideality factor indicates an increase in defect density at the interface with increasing $\gamma$-irradiation dose and/or the increase of the ideality factor is due to the lateral inhomogeneity of barrier height [10]. As a result, the obtained results from $I$–$V$ characteristics of as-deposited and irradiated Sn/p–Si SBD have been attributed to the presence of a very thin oxide layer between the metal and the semiconductor [9,20,21].

In order to get further insights into the conduction mechanism of reverse characteristics through the irradiated contact, we calculated the reverse saturation current of $\gamma$-irradiated diode and the result is shown in Table 1. Obviously, there is a decrease with the increasing irradiation dose. The decrease in reverse current with increasing irradiation dose may be likely that deep levels can act as recombination centers and often play the role of carrier recombination in the reverse characteristics [17].

As seen in Table 1, the values of series resistance calculated from Cheung's function [22] decrease with the increasing irradiation dose. The value of the series resistance decreases with the increasing radiation dose. Recently, Tataroglu and Altindal [23] attributed that the trap charges have enough energy to escape from the traps located between the metal and semiconductor interface in the Si bandgap. Additionally, for an irradiated device this decrease may be attributed to the generation of radiation-induced defect states in the energy gap and compensates the free carriers in the substrate [24].

### 3.2. Analysis of capacitance–voltage characteristics

In Schottky diodes, the depletion layer capacitance per unit area can be expressed as [18,25]

$$C = \frac{\varepsilon A}{W} = \sqrt{\frac{q\varepsilon_s N_A A^2}{2\left(V_{bi} - V - \frac{kT}{q}\right)}}, \tag{5}$$

where $\varepsilon_s$ is the dielectric constant of the semiconductor, $A$ is the area of the Schottky diode, $W$ is the depletion layer depth, $V_{bi}$ is the built-in potential, $N_A$ is the density of ionized acceptor atoms and $V$ is the applied reverse bias voltage. Using Eq. (5) the value of $N_A$ may be written as

$$N_A = \frac{2}{q\varepsilon_s}\left[\frac{-1}{\mathrm{d}(A^2/C^2)/\mathrm{d}V}\right]. \tag{6}$$

Table 1
The various parameters obtained from $I$–$V$ and $C$–$V$ characteristics of as-deposited and irradiated Sn/p–Si Schottky barrier diode with various $\gamma$-irradiation doses (5, 11, 22, 34, 45 kGy)

| Irradiation deposited (kGy) | $\Phi_{B,I-V}$ (eV) | $\Phi_{B,C-V}$ (eV) | $n$ | $I_0$ (nA) | NA ( $\times 10^{15}\,cm^{-3}$) | $R_s$ (ohm) |
|---|---|---|---|---|---|---|
| As-deposited | 0.754 | 0.750 | 1.042 | 2.34 | 1.09 | 54.4 |
| 5 | 0.762 | 0.763 | 1.051 | 1.74 | 1.06 | 50.1 |
| 11 | 0.765 | 0.765 | 1.053 | 1.52 | 1.07 | 49.5 |
| 32 | 0.771 | 0.769 | 1.060 | 1.19 | 1.06 | 48.5 |
| 34 | 0.772 | 0.769 | 1.062 | 1.19 | 1.06 | 48.3 |
| 45 | 0.771 | 0.768 | 1.061 | 1.19 | 1.06 | 48.8 |

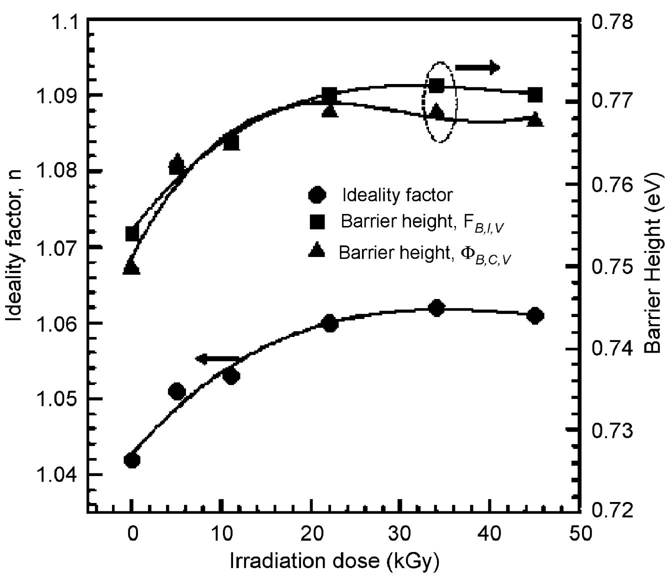


Fig. 3. The variation of $n$, $\Phi_{B,I-V}$ and $\Phi_{B,C-V}$ of the Sn/p–Si Schottky barrier diode as a function of $\gamma$-irradiation doses (5, 11, 22, 34, 45 kGy).

Hence from the slope of $1/C^2$ vs. $V$ curve the value of ionized acceptor density $N_A$ or free carrier concentration can be calculated. The Schottky barrier height $\Phi_B(\Phi_{B-C})$ can be obtained by the relation

$$\Phi_{B,C-V} = V_{bi} + \frac{kT}{q}\ln\left(\frac{N_V}{N_A}\right), \tag{7}$$

where $N_V$ is the effective concentration of states in the valance band. From the intercept of the $1/C^2$ vs. $V$ curve on the voltage axis, the value of the $\Phi_{B,C-V}$ is calculated.

Fig. 4 shows the $C$ vs. $V$ characteristics of as-deposited and irradiated Sn/p–Si Schottky contacts. As seen in Fig. 4, the capacitance of the device decreased as a function of $\gamma$-irradiation dose and the $C$–$V$ curves did not show a significant difference among the measurements obtained in the range of radiation dose 22–45 kGy. According to Refs. [10,26], it may be due to the change in dielectric constant at the MS interface or, according to Ref. [27], this may be due to decrease in the net ionized dopant concentration (see Table 1) by depending on increasing irradiation dose.

Fig. 5 shows the $C^{-2}$ vs. $V$ characteristics of as-deposited and irradiated Sn/p–Si Schottky contact. The $C^{-2}$–$V$ plots with increase in the irradiation dose move towards the

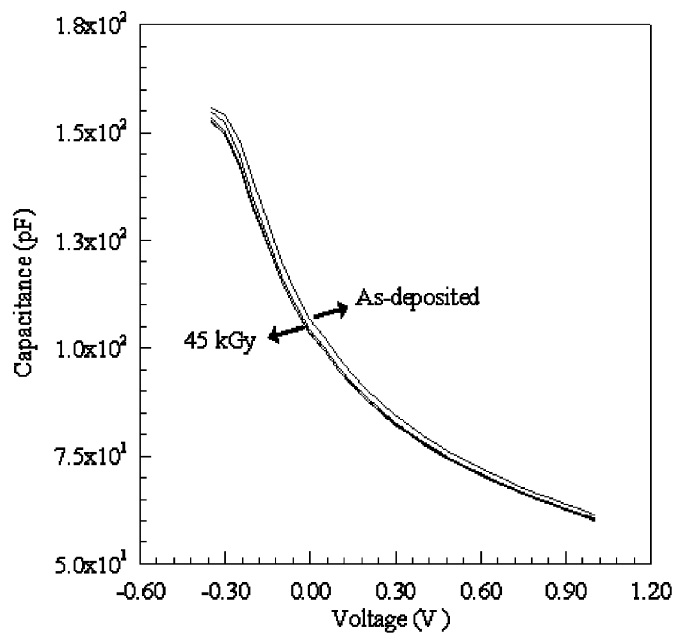


Fig. 4. The $C$–$V$ characteristics of as-deposited and irradiated Sn/p–Si Schottky barrier diode with various $\gamma$-irradiation doses (5, 11, 22, 34, 45 kGy).

upper side. Explanations related to this trend have been shown above. The barrier height $\Phi_{B-C}$ of the device for each irradiation dose was calculated using Eq. (7) from the intercept on the voltage axis of the $C^{-2}$–$V$ plots. The obtained values of the Schottky barrier height $\Phi_{B,C-V}$ are given in Table 1, and the change in the barrier height as a function of irradiation dose is shown also in Fig. 3. Here, the figure shows that the values of $\Phi_{B,C-V}$ increase with the increase in the irradiation dose. The increase in the barrier height $\Phi_{B,C-V}$ is mainly due to the increase in the diffusion potential (see Fig. 5) [10]. As seen from Fig. 3, the variation in the barrier height $\Phi_{B,C-V}$ obtained from the $C$–$V$ characteristics is parallel with the change in the $\Phi_{B,I-V}$ and also, one can be obtained nearly equal to the values of the other the barrier height obtained from both measurement tools with small errors. Crowell and Rideout [28] attributed the difference observed in value of the barrier height calculated from $I$–$V$ and $C$–$V$ methods for Si and GaAs to the effect of thermionic field emission on the charge transport through the MS interface. Also, this

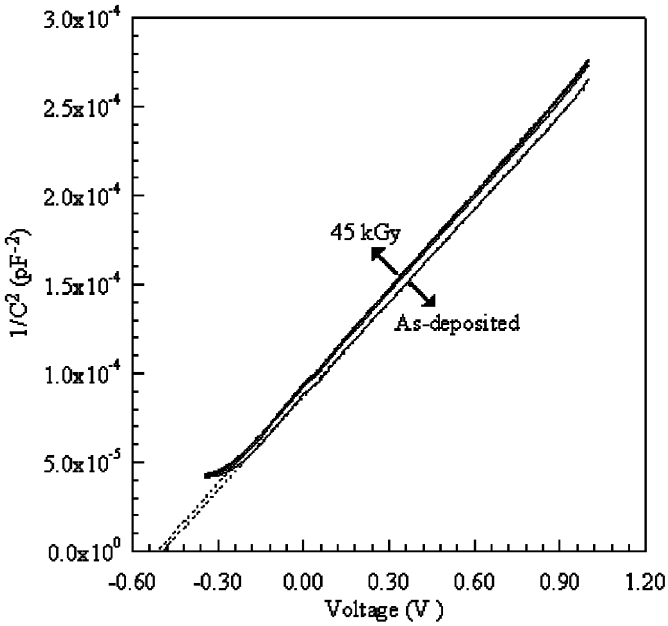


Fig. 5. The $1/C^2-V$ characteristics of as-deposited and irradiated Sn/p–Si Schottky barrier diode with various $\gamma$-irradiation doses (5, 11, 22, 34, 45 kGy).

discrepancy can be explained by the existence of excess capacitance of devices due to an interfacial insulator layer or surface states in the semiconductor, and other explanation is of existence of SBH inhomogeneities [29]. Additionally, it may be meant that the close values of barrier height from both methods are homogeneous of MS interface. The ionized acceptor concentration values $N_A$ obtained from $C$–$V$ measurements as a function of the $\gamma$-irradiation dose are shown in Table 1. The decrease in ionized acceptor density with increase in the irradiation dose is due to generation–recombination through the interface states in the MS interface [10]. According to Ref. [10], when the bias injects holes that recombine with the electrons already present in the depletion region, the density of mobile carriers is reduced as a result and the space charge is enhanced further.

## 4. Conclusion

In conclusion, we have investigated the electrical parameters of the Sn/p–Si SBDs by using $I$–$V$ and $C$–$V$ characteristics under $\gamma$-irradiation at room temperature. The devices were held at a zero bias during $\gamma$-irradiation with the dose rate 0.25 kGy/h. The basic diode parameters such as ideality factor, barrier height, series resistance and reverse saturation current were extracted from electrical measurements as a function of the irradiation dose. The results indicated that $\gamma$-irradiation induced an increase in the effective Schottky barrier height extracted from both $I$–$V$ and $C$–$V$ measurements. Also, it was seen that the ideality factor increased with the increasing $\gamma$-irradiation doses. The increase in the Schottky barrier height and ideality factor of the device has been argued by different researchers [9–11,15–17,20,21], with their different explanations related to subject. We have also observed that the reverse bias current of the Sn/Si contact exceedingly decreased with increasing irradiation dose with low energy (60 keV). The basic results as related to the $\gamma$-irradiation have indicated that this device may have application as a radiation sensor in order to detect low-energy $\gamma$ radiation.


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