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Research Article

Electrical Response of CdS Thin Film and CdS/Si Heterojunction to Gamma Radiation

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Gamma irradiation method has been used to change the electrical properties of CdS thin film. A specific dose of γ-irradiation increases the activation energy of CdS thin film. In addition, γ-irradiation was used to change the sign of Hall coefficient, R_H, of CdS thin film from negative to positive irrespective of temperature. The Hall mobility mechanism shows noticeable change after γ-irradiation from decreasing to increasing with raising the temperature. In depth, analysis was done using capacitance-voltage measurement in order to realize the modification in the CdS/Si junction band gap after γ-irradiation. Several parameters were also studied such as charge carrier concentration, N_D, and flat band potential, V_{fb}. The γ-irradiation was found to increase the concentration of the deep traps within the band gap of the CdS/Si heterojunction.

1. Introduction

Cadmium sulfide (CdS), with typical II–VI semiconductor properties, is a basic object of nanotechnology where the modification of their electrical and optical properties provides nanomaterials with unique application in the fields of electronics and optoelectronic devices [1–3]. The electrical properties of II–VI semiconductor compounds are drastically affected by impurities and native defects, which can be controlled by several techniques such as gamma irradiation [4–7].

The irradiation creates a wide variety of defect states in the material system by ionization or excitation processes which form new electronic configuration coordinates that cause a change in electrical response of the material and consequently its physical properties [8, 9]. These changes are strongly dependent on the exposure dose.

Several methods are reported for the preparation of CdS using relatively simple, inexpensive, and scalable technique [10–12]. Hydrothermal method is one of the newest chemical methods which achieved these requirements to produce CdS in large area of industrial applications [13]. Thin films active devices now occupy a prominent place in research and solid-state technology. The optimization of CdS films characteristics has created a need for a better understanding of its electrical properties, which have been investigated intensively, while few studies on gamma irradiation have been available in the literature [8, 14, 15]. The novelty of this study is to modify the electrical properties of CdS thin films by exposing them to specific doses of gamma irradiation, which makes change in dc electrical conductivity, carrier concentration, Hall mobility, Hall coefficient, and flat band potential.

2. Experimental

Thin films of CdS have been prepared by electron beam evaporation method using vacuum coating unit (Edwards modal number E306) at a pressure of about 5.3×10^{-3} Pa on well-cleaned glass substrate (soda-lime glass) and Si wafer (p-type) in order to form CdS/Si heterojunction. The starting nanostructured CdS powder was prepared by hydrothermal process, which has been explained elsewhere [16]. All chemicals used in the present work were of analytical grade without any further purification. The chemical composition and structure

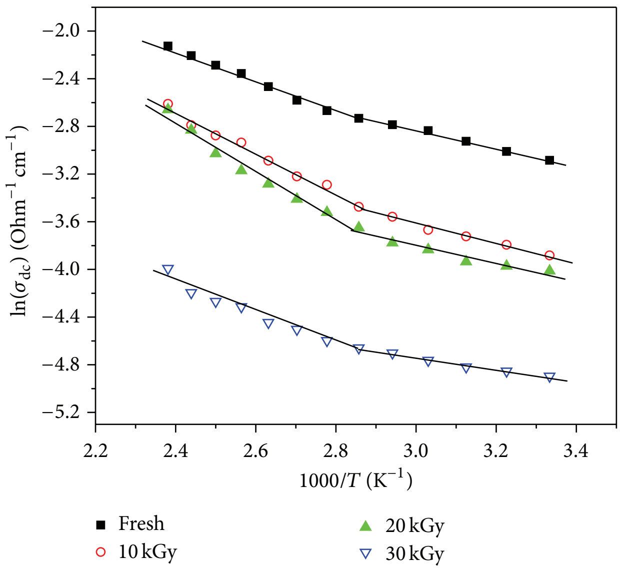


Figure 1: Temperature dependence of the dc conductivity, σ_{dc}, for the investigated CdS thin film before and after γ-irradiation with different doses.

phase of the powder and as-deposited thin film samples were investigated using EDX and XRD techniques, respectively. The analysis confirmed the homogeneity and nanostructural nature of the CdS thin films as explained elsewhere [16].

A Cobalt-60 Indian Gamma cell GC4000A was used for irradiating the thin film samples at 10, 20, and 30 kGy (accumulative doses) and electrical measurements were analyzed before and after irradiation. For the dc conductivity and Hall Effect measurements the prepared films have a rectangular shape and four electrodes were made by silver paste on the four sides. A Keithly-617 electrometer and Oxford cryostat (DN1710) connected to automatic temperature controller were used for measuring the resistance of the thin film samples under vacuum and within temperature range of 300–420 K. Hall coefficient was measured in the same temperature range and under the effect of magnetic field up to 3.2 kG. The capacitance-voltage (C-V) measurements of CdS/Si heterojunction were obtained at constant frequency of 10^6 Hz using a computer controlled LRC bridge model HIOKI 3535 in the same temperature range from 300 to 420 K.

3. Results and Discussion

3.1. dc Electrical Conductivity. The variation of dc electrical conductivity (σ_{dc}) as a function of temperature (300–420 K) for CdS thin film was recorded prior to and after γ-irradiation ranging from 10 to 30 kGy and shown in Figure 1. The graph showed an increase in the dc conductivity over the entire temperature range but in two different conduction mechanisms. This means that the conduction in this film is through an activated process having dual transport mechanisms at high and relatively lower temperatures range. At high temperature range from about 350 to 420 K, the conduction is due to the thermally activated conduction of electron in the potential barrier and the next relation can express σ_{dc}:

Table 1: The value of radiation dose, dc conductivity (σ_{dc}), and activation energy (ΔE_1 and ΔE_2).

Dose	σ_{dc} (at 340 K) (Ohm^{-1} cm^{-1})	ΔE_1 (eV)	ΔE_2 (eV)
Fresh	6.17×10^{-2}	0.262	0.151
10 kGy	2.85×10^{-2}	0.338	0.166
20 kGy	2.29×10^{-2}	0.427	0.172
30 kGy	9.08×10^{-3}	0.260	0.101

$$\sigma_{dc} = \sigma_o \exp\left(\frac{-\Delta E_1}{k_B T}\right), \tag{1}$$

where σ_o is the preexponential factor, ΔE_1 is the dc activation energy, and k_B is the Boltzmann constant, while at relativity low temperature from about 300 to 350 K the conduction is due to transition of charge carriers between the localized states by hopping near the Fermi level [17] and σ_{dc} can be given by the following relation:

$$\sigma_{dc} = \sigma_1 \exp\left(\frac{-\Delta E_2}{k_B T}\right), \tag{2}$$

where σ_1 is the preexponential factor and ΔE_2 is the activation energy. Table 1 shows the values of σ_{dc} at 340 K, ΔE_1, and ΔE_2. The activation energy was calculated from the slope of the curve shown in Figure 1. From this table we can observe that σ_{dc} decreases with increasing γ-irradiation doses. On the other hand, ΔE_1 and ΔE_2 increase firstly with doses up to 20 KGy and then decrease at γ dose of 30 KGy. This increment in both ΔE_1 and ΔE_2 with γ-irradiation up to 20 KGy can be attributed to the increase in defect states within the band gap especially at the edges of the extended states and near the Fermi level, respectively [17]. Further increase in the γ-dose (30 KGy) can cause rearrangement in the chemical bonds in the system [18, 19]. Therefore, the energy splitting between the states of the valence and conduction bands will change and in consequence both ΔE_1 and ΔE_2 are changed.

3.2. Hall Coefficient. The temperature dependence of the Hall coefficient, R_H, for fresh and irradiated CdS thin films is displayed in Figure 2. The experimental R_H values were calculated in temperature range from 300 to 420 K and under constant applied magnetic field of $B = 3.2$ kG using the following relation:

$$R_H = \frac{V_H d}{IB}, \tag{3}$$

where V_H is the transverse voltage difference, d is the thickness of the film, I is the longitudinal current, and B is the perpendicular applied magnetic field. It is found that the Hall coefficient of fresh CdS sample is negative irrespective of temperature, which indicates that the fresh sample is n-type semiconductor material and the electrons are the majority carriers while holes are the minority carriers as illustrated in

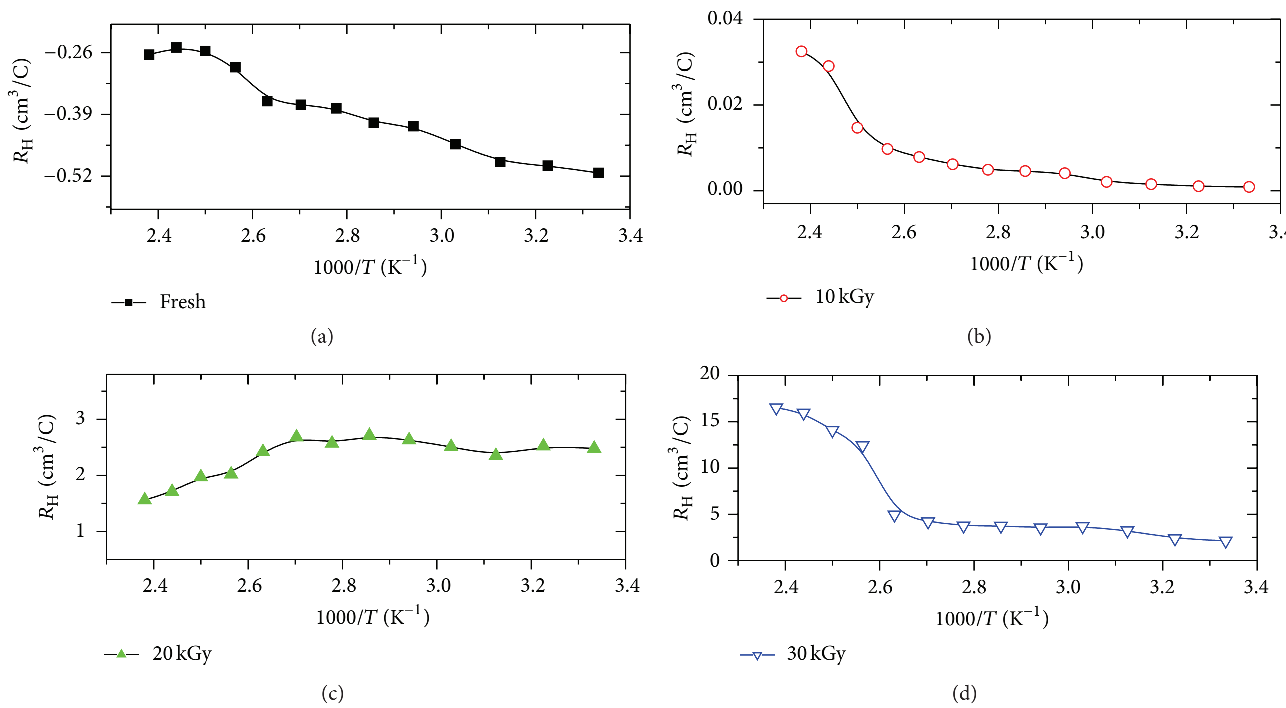


Figure 2: Temperature dependence of Hall coefficient, R_H, for the investigated CdS thin film (a) before and (b–d) after γ-irradiation with different doses.

Figure 2(a). With irradiation, the sign of R_H is changed from negative to positive irrespective of temperature as shown in Figures 2(b)–2(d). This means that the γ-irradiation changes the carrier concentration in the CdS sample. In other words, the defects which are generated and the rearrangement in the chemical bonds in the CdS system caused by γ-irradiation change the number of the free charge carriers, electrons, and holes, in the sample and consequently the semiconductor type of CdS film, from n-type to p-type. This has been clarified after calculating the charge carriers number N and Hall mobility coefficients μ_H. First, N was calculated using the following relation [20]:

$$N = \frac{1}{eR_H}, \tag{4}$$

where e is the electron charge and R_H is the Hall coefficient. Figure 3 shows the charge carriers concentration of the fresh and irradiated CdS film in the temperature range from 300 to 420 K. From the data shown in Figure 3 it can be inferred that the charge carriers have different behavior with temperature and different transport mechanisms [21, 22]. Moreover, this behavior changed completely after specific dose of γ-irradiation as shown in Figure 3(c), where the slope changed from negative to positive.

Second, the Hall mobility μ_H was calculated using the well-known relation [23]:

$$\mu_H = \sigma_{dc} R_H, \tag{5}$$

where σ_{dc} is the dc conductivity. Figure 4 shows the temperature dependence of Hall mobility for the fresh and irradiated CdS thin film in the temperature range from 300 to 420 K. This figure illustrates the clear changes in the Hall mobility mechanism with temperature after γ-irradiation from decreasing to increasing with raising the temperature. For the fresh CdS sample (Figure 4(a)), with increasing temperature, the carriers are scattered by an increasing number of thermally generated acoustic phonons and the mobility decreases with temperature, while for irradiated samples (Figures 4(b)–4(d)), the increase of the mobility with temperatures can be explained by an increase in the thermal velocity of the free carriers. In addition, the defects created by γ-radiation, which act as dopants and ionized scattering centers [24], will cause a smaller deflection in the carriers (Rutherford Scattering). Furthermore, it can be noted that the mobility of the charge carriers increases with the increase of γ-doses.

3.3. C-V Measurements. Figure 5 shows Mott-Schottky plots ($1/C^2$ versus V) of fresh and irradiated CdS thin film (Schottky contact) deposited on p-type Si wafer surface. The ambient temperature was varied from 300 to 420 K at constant frequency of 10^6 Hz. This plot illustrates a strong dependence of the behavior of $1/C^2$ on heating temperature. In the temperature range from 310 up to 420 K the plot shows almost a linear relationship with a positive slope according to an n-type semiconductor, while at room temperature, 300 K, there are three main features which protrude (marked by (1), (2), and (3) in Figure 5(a)). In the first feature, the slope of the curves changes positively with the applied bias voltages up to ≈2 V, while in the second feature, the capacitance remains nearly constant with the applied bias voltages in the range from about 2 up to 3.5 V for the fresh sample (marked by

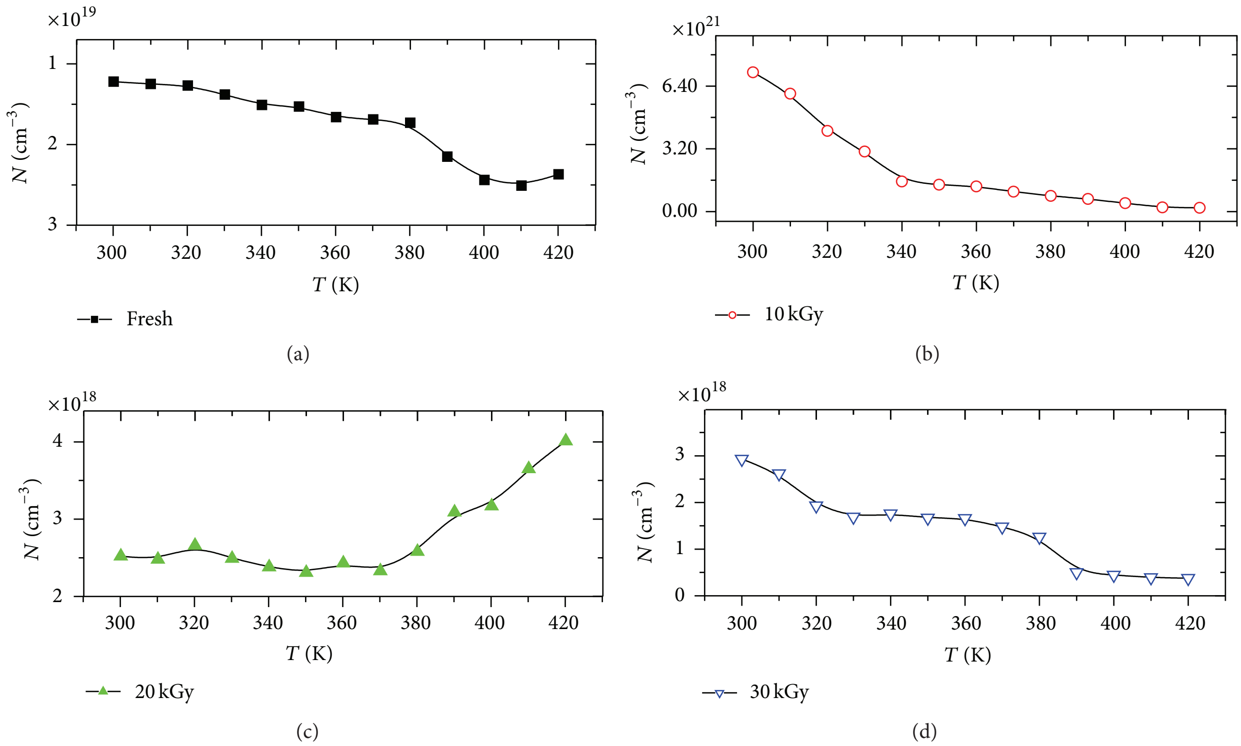


FIGURE 3: Temperature dependence of carrier concentration, N, for the investigated CdS thin film (a) before and (b–d) after γ-irradiation with different doses.

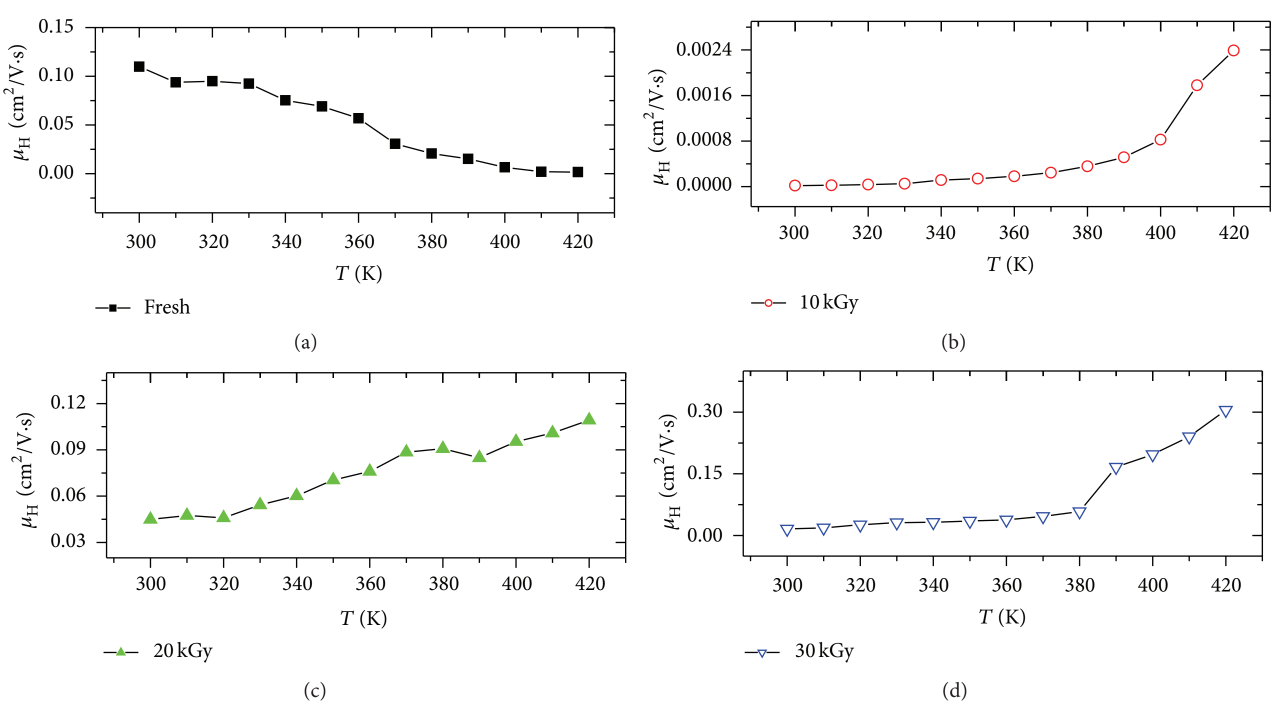
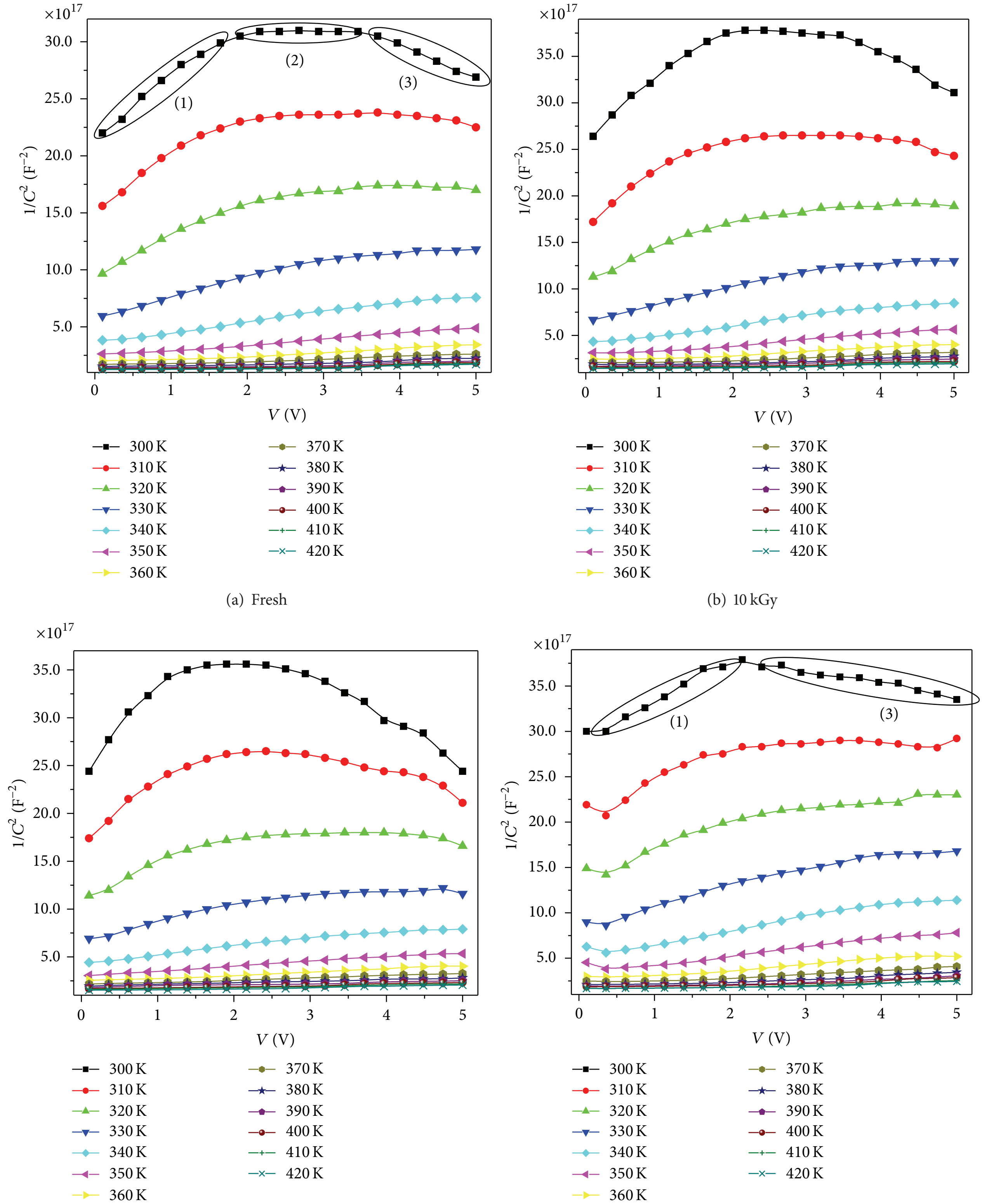


FIGURE 4: Temperature dependence of Hall mobility, μ_H, for the investigated CdS thin film (a) before and (b–d) after γ-irradiation with different doses.



(a) Fresh

(b) 10 kGy

(c) 20 kGy

(d) 30 kGy

Figure 5: Temperature dependence of Mott-Schottky plot for the investigated CdS/Si heterojunction at different temperature (a) before and (b–d) after γ-irradiation with different doses.

(2) in Figure 5(a)) and this range decreases with increasing irradiation dose until it vanished at 30 kGy (Figure 5(d)). In the third feature, the slope of the curves changes to negative sign with the applied bias voltages from 3.5 up to 5 V and this range increases with increase in the irradiation dose (marked by (3) in Figure 5(d)).

The change in the capacitance behavior with the applied bias voltages and irradiation doses, at room temperature, can be explained by the influence of the high concentration of deep traps within the band gap of the CdS semiconductor material [25]. Depending on their occupational status, they contribute or do not contribute to the measured capacitance [26]. A change in bias voltage and/or irradiation dose causes a shift of the Fermi energy level. Consequently, the occupation state of the deep traps within an energy range close to the Fermi level changes which results in a variation in the net doping concentration and, therefore, a change in the slope of the C-V characteristics [27], while raising the temperature above the room temperature limits the impact of these deep traps within the band gap and the slope behavior of the capacitance becomes almost constant with applied bias voltages.

The charge carrier concentration and flat band potential are defined by Mott-Schottky relationship in the linear part of $1/C^2$ versus V plot:

$$\frac{1}{C^2} = \frac{2}{N_D e \varepsilon \varepsilon_0 A^2}\left[(V - V_{fb}) - \frac{kT}{e}\right], \quad (6)$$

where N_D is the charge carrier concentration, e is the electron charge, ε is the dielectric constant, ε_0 is the permittivity of free space, A is the electrode surface area, and V_{fb} is the flat band potential, which is the applied potential at which the semiconductor energy bands are flat. Therefore, V_{fb} can be determined from the intercept on V axis and the value of N_D from the slope by knowing ε and A.

Figures 6 and 7 show the variation of charge carrier concentration and the flat band potential, respectively, with temperature for fresh and irradiated Schottky contact sample. As shown in these figures it can be observed that both the charge carrier concentration and negativity of the flat potential increase with the temperature and decrease with γ-irradiation doses. It is well known that the flat band potential is the potential (or voltage) at which the band bending disappears and the thickness of the space charge layer is (theoretically) zero and the capacity becomes infinitely large. In our case, we have found that both the charge carrier concentration and negativity of the flat potential increase with the temperature and decrease with γ-irradiation. This means that the γ-irradiation works against temperature; that is, space charge layer thickness decreases with irradiation doses and hence the flat potential.

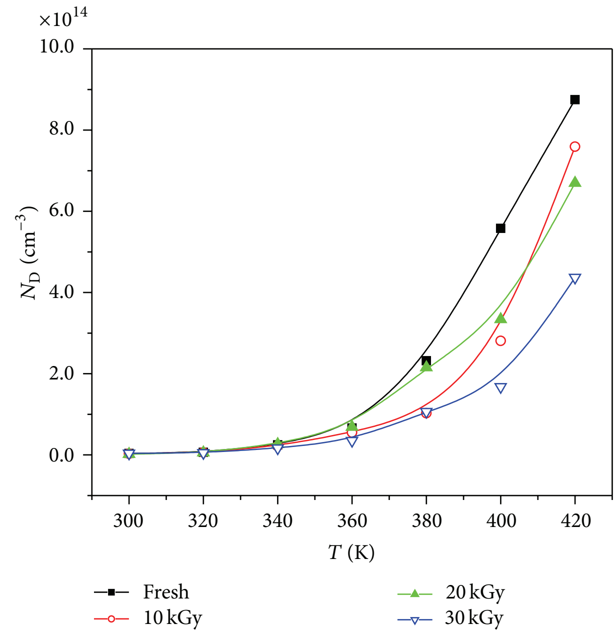


Figure 6: Temperature dependence of charge carrier concentration for the investigated CdS/Si heterojunction before and after γ-irradiation with different doses.

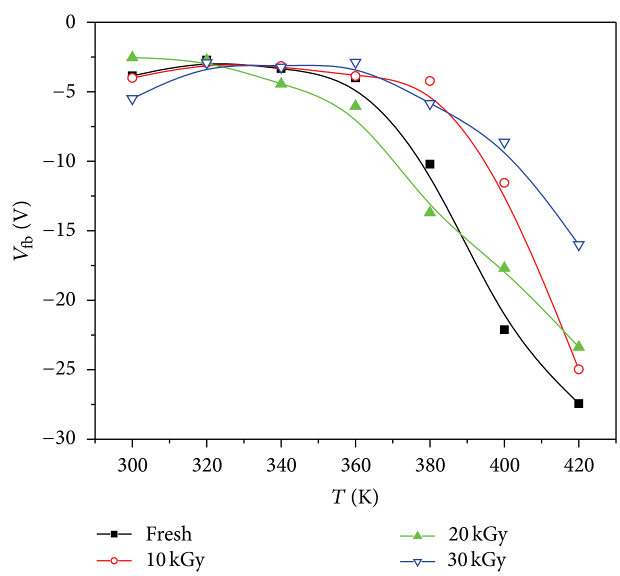


Figure 7: Temperature dependence of flat potential for the investigated CdS/Si heterojunction before and after γ-irradiation with different doses.

4. Conclusion

The obtained results confirmed that γ-irradiation could be used to modify the dc electrical conductivity and activation energy of CdS thin film. Doses of 10 and 20 KGy increase both ΔE_1 and ΔE_2, while σ_{dc} decreases with doses up to 30 KGy. Measuring R_H values of CdS thin film sample confirmed the possibility to change the number of free charge carriers (electrons and holes) in the sample and consequently the type from n-type to p-type. Moreover, γ-irradiation changes the Hall mobility mechanism with raising the temperature from decreasing before irradiation to increasing after irradiation. In addition, based on the results obtained from measuring C-V of CdS/Si Schottky contact, the γ-irradiation strongly affects the net doping concentration within the band gap of the CdS/Si heterojunction. The charge carrier concentration and flat band potential were affected also by γ-irradiation.

Competing Interests

The authors declare that they have no competing interests.

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