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Effect of temperature and electron irradiation on the *I–V* characteristics of Au/CdTe Schottky diodes

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Abstract

The results of the studies on the effect of temperature and 8 MeV electron irradiation on the current–voltage (*I–V*) characteristics of the Au/CdTe Schottky diodes are presented in this article. Schottky diodes were prepared by evaporating Au onto n-type CdTe films electrodeposited onto stainless steel substrates. The forward and reverse current–voltage characteristics of these diodes were studied as a function of temperature. The diodes were subjected to 8 MeV electron irradiation at various doses and their effect on the *I–V* characteristics was studied. Some intrinsic and contact properties such as barrier height, ideality factor, and series resistance were calculated from the *I–V* characteristics. Diode ideality factor of the junctions were greater than unity. The ideality factor and the series resistance R_s increase with decrease in temperature. The conduction seems to be predominantly due to thermionic emission–diffusion mechanism. The resistance was found to increase with increasing dose. The leakage current, ideality factor and barrier height were found to be unaffected by electron irradiation up to, a dose of about 40 kGy.

Keywords: CdTe; Schottky diode; *I–V* characteristics; Electron irradiation; Electrodeposition

1. Introduction

Cadmium telluride (CdTe) is an attractive low cost thin film photovoltaic material (Wysocki and Rapport, 1960; Anthony et al., 1985). The direct band gap of 1.45 eV, high optical absorption coefficient and reasonable mobility-lifetime product for both electrons and holes, make CdTe an attractive material for use in photovoltaic applications. CdTe thin films can be prepared by different techniques such as thermal evaporation, close spaced sublimation, metal oxide chemical vapour deposition (MOCVD), molecular-beam epitaxy (MBE), electrodeposition and sputtering. Among these methods electrodeposition is the simplest and most economical method of preparation of thin films for large area solar cell applications (Mathew et al., 1999; Mathew, 2003).

Metal/CdTe interfaces play an important role in optoelectronic devices such as infra red detectors and sensors in thermal imaging (Chand and Kumar, 1995), solar cells etc. (Dharmadasa et al., 1982). A clear understanding of the physical principles underlying the properties of these interfaces is therefore essential in order to develop practical devices based on this semiconductor material. The dominant charge transport mechanisms in Au/CdTe devices have been identified as thermionic emission over the barrier, Poole–Frenkel, and space charge limited conduction (Gurumurthy et al., 1999; Van Meirhaeghe et al., 1991; Mathew et al., 2000). Analysis of current–voltage (*I–V*) characteristics of Schottky devices allows us to understand different aspects of current transport. Temperature dependence of *I–V* characteristics of the Au/CdTe Schottky

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barrier diode in the temperature range 210–310 K has been taken up in the present study.

Light weight CdTe solar cells on flexible metallic substrates can be attractive for space applications. Stability against particle irradiation is essential for long term suitability of solar cells for space applications. Batzner et al. (2001) have studied the effect of low energy protons and high energy electrons on CdTe/CdS solar cells and found that the devices were stable against irradiation. In the space environment, the devices are constantly subjected to electron bombardment of high (MeV) energy. Electron irradiation is known to have less degradation effect than neutron irradiation of similar energy and dose, but have higher damage coefficient than for gamma rays (Zoutendyk et al., 1988). Radiation causes ionization and atomic displacement in semiconductors. Solar cells are damaged principally by the displacement of atoms from native sites to form defects. The effect of 8 MeV electron irradiation on the I–V characteristics of Au/CdTe diodes has been studied and reported in this article.

2. Experimental

CdTe films of about one micron thickness have been grown by electrodeposition technique on to clean thin stainless steel (SS) substrates. The electrolyte was a 1 M $CdSO_4$ containing 100–200 μM TeO_2. The solution was continuously stirred at the rate of 50–100 rpm and the temperature of the electrolyte was maintained at around 80–90 °C. The films were deposited at a potential of −1050 to −1070 mV with respect to a Hg/Hg_2SO_4 reference electrode. Prior to the addition of TeO_2 the electrolyte was purified by electrochemical method. Schottky diodes were formed by depositing gold dots of 100 nm thickness through a mask on to the films at a pressure lower than 10^{-5} torr. The contact area used is 0.0167 cm^2. I–V measurements of the SS/CdTe/Au diodes have been performed using a computer interfaced Keithley 236 source/measure unit. The temperature dependent I–V measurements of the diode were performed in the range of 210–310 K using a cryostat connected to the temperature controller unit of DLS-2000 system. X-ray diffraction (XRD) measurements were carried out using a BRUKER axs D8 ADVANCE diffractometer with CuKα radiation ($\lambda = 1.5406$ Å). The SS/CdTe/Au diodes were irradiated with 8 MeV electrons from the Microtron accelerator for various doses from the SS substrate side as the range of the 8 MeV electrons in stainless steel (6.5 mm) is much higher than the substrate thickness (60 μm). The doses absorbed by the samples have been calibrated using chemical dosimeters. The I–V characteristics of the irradiated diode were also measured in the temperature range 210–300 K.

3. Results and discussion

XRD pattern of the CdTe thin film is shown in Fig. 1. It is found that the CdTe film is polycrystalline with a strong preference for the (1 1 1) plane and matches with face-centered cubic F-43m. The average particle size estimated from the FWHM of the (1 1 1) peak using the Scherer formula (Cullity, 1967) is about 55 nm. Typical I–V characteristics measured in dark for Au/CdTe device at various temperatures are shown in Fig. 2. The current through a Schottky barrier diode under a forward bias 'V' is given by the relation (Sze, 1981),

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

where I_s is the reverse saturation current given by

$$I_s = A_d A^{**} T^2 \exp\left(\frac{-q\phi_b}{kT}\right) \tag{2}$$

Here A_d is the diode area, $A^{**} = 12\ \mathrm{A\,cm^{-2}\,K^{-2}}$ is the effective Richardson constant, T is the temperature, k is the Boltzmann constant, q is the electronic charge, Φ_b is the barrier height (in eV) and 'n' is the ideality factor.

3.1. Temperature effects

The ideality factor, 'n' can be obtained from Eq. (1) as

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

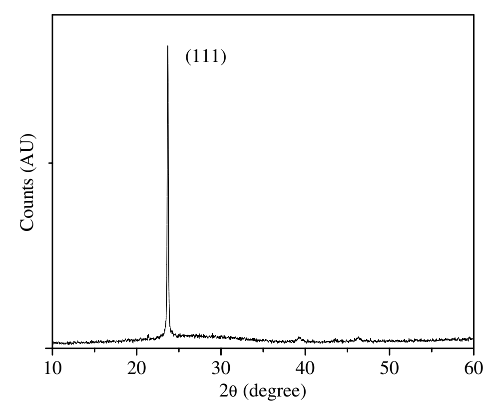

Fig. 1. X-ray diffractogram of the CdTe thin film.

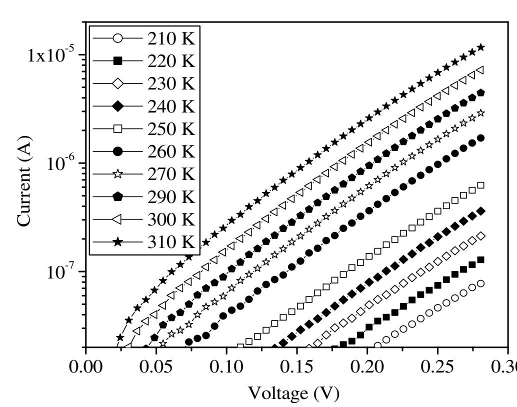

Fig. 2. Current–voltage characteristics of Au/CdTe Schottky diode at various temperatures in the range 210–310 K.

The diode ideality factor, 'n' was calculated from the I–V characteristics in the region 0.08 V to 0.2 V, and the reverse saturation current I_s was obtained by extrapolating the straight line portion of I–V curve to $V = 0$.

The barrier height Φ_b can be calculated using the relationship

$$\phi_b = (kT/q)\ln(A_d A^{**} T^2/I_s) \tag{4}$$

$$\ln\left(\frac{I_s}{T^2}\right) = \ln(A_d A^{**}) - \frac{q\phi_B}{kT} \tag{5}$$

In order to identify the dominant current transport mechanisms through the junction, $\ln(I_s)$ was plotted as a function of inverse temperature (Richardson plot) and is shown in Fig. 3. The variation is found to be linear in the entire range. This indicates that thermionic emission is the dominant mechanism of charge transport (Van Meirhaeghe et al., 1991). The barrier height (Φ_b) and the Richardson constant (A^{**}) were calculated from the slope and the intercept of the Richardson plot. The value of A^{**} obtained was 0.076×10^{-4} A cm^{-2} K^{-2} which is much lower than the theoretical value of 12 A cm^{-2} K^{-2} for n-CdTe. The A^{**} value obtained from the temperature dependence of the I–V characteristics may be affected by lateral inhomogeneity of the barrier (Gumus et al., 2002). The reverse current measurements can also be used to extract Φ_b (Raynaud et al., 2002). In reverse bias, the current $I_r = I_s$ and hence, the plot of $\ln(I_r/T^2)$ versus $1/T$ gives Φ_b. The value of Φ_b thus obtained is 0.22 eV which is different from the Φ_b value obtained using forward current characteristics. This suggests that the transport mechanism in the reverse bias is different from that in forward bias which is supported by the fact that the reverse current exceeds the value of 'I_s'.

The diode ideality factor 'n' of the junctions studied in the present work were larger than unity. An ideality factor greater than unity is generally attributed to the presence of a bias dependent Schottky barrier height. Image forces, tunneling, generation–recombination, interface impurities and interfacial oxide layer are possible factors which could lead to a higher ideality factor (Chand and Kumar, 1995).

For depletion region dominated current transport, Arrhenius plot of I_s should yield an activation energy approximately equal to half the band gap of CdTe and 'n' values should lie between 1 to well above 2 (Bayhan and Ercelebi, 1997).

For a thermally activated phenomenon, I_s is expressed as

$$I_s = I_{s0}\exp(-E_a/kT) \tag{6}$$

where E_a is the thermal activation energy of the process.

If the current transport is due to diffusion 'n' is equal to 1 and the activation energy is equal to the band gap of the semiconductor (Marshal et al., 1998). If the current is controlled by tunneling mechanism, the ideality factor must be much greater than 1 and the slope of the $\ln(I)$–V plot should be constant with temperature (Van Meirhaeghe et al., 1991; Bayhan and Ercelebi, 1997). In the present studies activation energy was found to be 0.39 eV which is much lower than the CdTe band gap suggesting that all the three mechanisms mentioned above are not the dominant mechanisms of current transport. The increase in ideality factor might be due to other effects such as inhomogeneities of thickness and non-uniformity of the interfacial charges (Tugluoglu et al., 2004). Therefore, the thermionic emission mechanism may be the dominant mechanism for current transport at this range as suggested by the observed linearity in $\ln(I)$–V plots (Fig. 2) (Chand and Kumar, 1995). For Au/CdTe diodes prepared by electrodepositon, Poole–Frenkel conduction was identified as the dominant transport mechanism in the 100–380 K regions (Mathew et al., 2000). However, in the present studies, the data fits better for thermionic conduction than for the Poole–Frenkel mechanism.

Ideality factor calculated from the I–V characteristics at various temperatures as a function of temperature is shown in Fig. 4. The change in barrier height Φ_b with temperature is shown in Fig. 5. Similar variations for the irradiated samples are also shown in these figures. 'n' is found to decrease with increasing temperature and the decrease is steeper at lower temperatures. Φ_b was found to increase with increasing temperature. The ideality factor of an

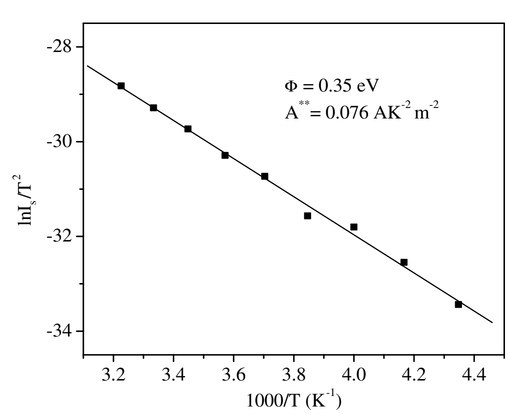

Fig. 3. Richardson plot of Au/CdTe Schottky diode.

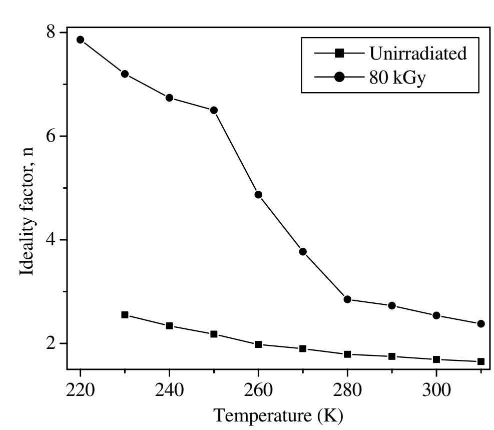

Fig. 4. Variation of ideality factor with temperature.

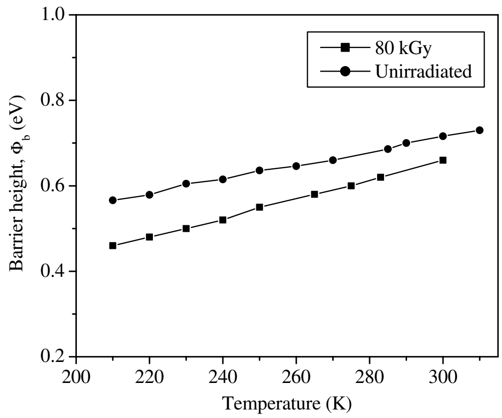

Fig. 5. Variation of barrier height (Φ_b) with temperature.

inhomogeneous Schottky barrier diode with a distribution of low Schottky barrier heights may increase with a decrease in temperature (Tung, 1992; Sullivan et al., 1991). The Schottky barrier consists of laterally inhomogeneous patches of different barrier heights. Since current transport across the metal/semiconductor interface is a temperature-activated process, at low temperature electrons are able to surmount the lower barriers and therefore the current transport will be dominated by current flowing through the patches of lower Schottky barrier height and a larger ideality factor (Gumus et al., 2002; Raynaud et al., 2002). As the temperature increases, more and more electrons have sufficient energy to surmount the higher barrier.

The neutral region (between the depletion region and back contact) of the semiconductor offers a higher resistance and a significant voltage drop occurs in this region. This amounts to a reduction of the voltage across the barrier region which can be accounted for by replacing the voltage by V–IR in Eq. (1). In such a situation a plot of ln(I) versus V deviates from a straight line at high forward voltages. The value of R_s can be determined independently from the I vs V plot in the high forward bias region. Fig. 6 shows the series resistance values calculated from forward I–V characteristics as a function of temperature. The R_s values vary exponentially with temperature and the value decreases from 595 kΩ to 4.7 kΩ in the temperature range

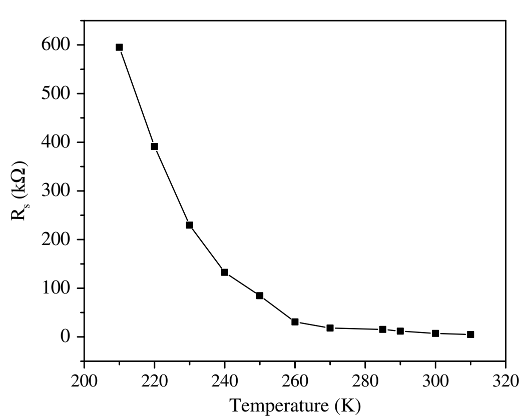

Fig. 6. Variation of series resistance (R_s) with temperature.

210–310 K. The decrease of R_s with increasing temperature is attributed to the factors responsible for increase of n and/or to the freeze out of free carriers at low temperatures (Tugluoglu et al., 2004).

3.2. Irradiation effects

Fig. 7 shows the room temperature I–V characteristics of Au/CdTe Schottky diode before and after irradiation with different electron doses. It is seen that the effect of irradiation is more pronounced at higher voltages than at lower voltages. The main effect of irradiation is a reduction in forward current with increasing dose. The nature of the I–V characteristics indicates that the resistivity of the material has increased after irradiation.

The diode parameters calculated from the I–V characteristics are given in Table 1. The ideality factor 'n', reverse saturation current I_s, series resistance R_s and barrier height $\Phi_b$extracted from the pre-irradiation forward bias characteristics were 1.85, 2.39×10^{-8} A, 4.11 kΩ and 0.705 eV respectively. Fig. 8 shows the ideality factor and barrier height as a function of electron dose. A small decrease in 'n' was noted up to a dose of 10 kGy, above 10 kGy 'n' started to increase with increasing dose. Change in ideality factor indicates that current transport mechanisms other than thermionic emission are present.

The changes in minority carrier life time will dominate I_s at relatively low doses. The life time of the minority carriers

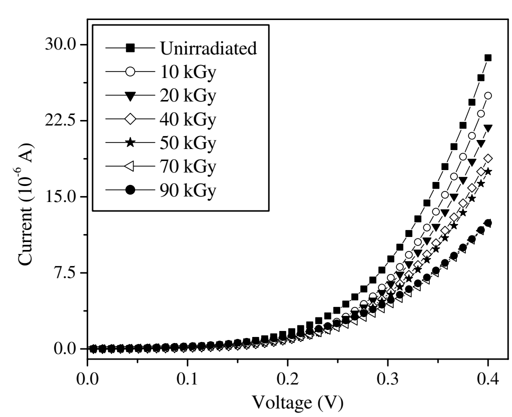

Fig. 7. Forward I–V characteristics of a typical Au/CdTe diode at different electron irradiation doses.

Table 1
The change in Au/CdTe diode parameters with electron irradiation dose

Dose (kGy)	n	I_s (A)	R_s (kΩ)	Φ_b (eV)
0	1.85	2.39×10^{-8}	4.11	0.705
10	1.82	1.39×10^{-8}	4.52	0.719
20	1.85	1.46×10^{-8}	5.29	0.718
40	1.87	1.48×10^{-8}	6.19	0.718
70	2.27	3.26×10^{-8}	10.63	0.697
90	2.31	5.21×10^{-8}	11.05	0.685

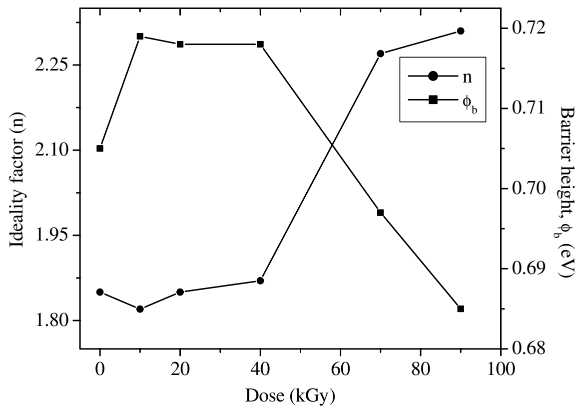

Fig. 8. Ideality factor and barrier height of Au/CdTe diode as a function of dose.

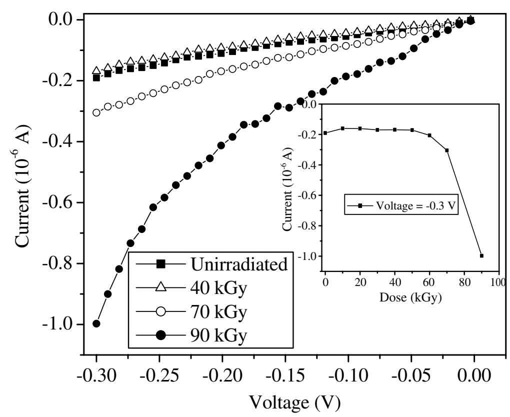

Fig. 9. Reverse I–V characteristics of a typical Au/CdTe diode at different electron irradiation doses. The variation of reverse current with dose at −0.3 V is shown in the inset.

is shortened by radiation-induced crystal lattice defects which act as trapping or recombination centers for the carriers. As the life time decreases, the diffusion length decreases, and the reverse current increases (Olesen, 1966). It can be seen from the table that I_s decreases at lower doses and for doses higher than 40 kGy I_s shows a tendency to increase.

The barrier height Φ_b also shows the same trend as that of I_s. A slight decrease in Φ_b was observed for doses above 40 kGy. Irradiation may introduce defects at the Au/CdTe interface leading to a reduction in Schottky barrier height. Decrease in barrier height indicate a change in electrical properties of the interface, including the possibility of chemical intermixing, which can change the location of Fermi energy level pinning for the Schottky contact. An increase in series resistance 'R_s' was found for all doses, indicating that the product of the mobility and the free carrier concentration has reduced. The reduction in mobility is due to the introduction of defect centers on irradiation which act as scattering centers. The free carrier concentration will be reduced if deep traps are introduced into the material associated with point defect displacement damage. Free carriers in the crystal lattice are captured by the defect centers resulting in decreased carrier density. The density of radiation-induced defect centers increases with increasing fluence leading to increased carrier removal.

The reverse I–V characteristics of the Au/CdTe diode before and after irradiation with 8 MeV electrons of different doses are shown in Fig. 9. The inset shows the variation of reverse current with dose at a reverse bias of 0.3 V. The reverse current remained approximately constant up to a dose of 50 kGy and significant increase in reverse current is observed for doses above 70 kGy.

The forward I–V characteristics of the Au/CdTe diode, after irradiating with a dose of 80 kGy was measured over the temperature range 210–310 K. 'n' and Φ_b were calculated from the I–V characteristics using Eqs. (3) and (4) respectively. The variation of 'n' and Φ_b with temperature are shown in Figs. 4 and 5. The barrier height is found to increase with increase in temperature similar to the unirradiated diode. 'n' initially increases marginally with decrease in temperature, but significantly at low temperatures. This indicates that after irradiation, the current transport mechanism at low temperature has deviated from thermionic-emission diffusion. This may be due to the introduction of irradiation-induced defects at the interface.

The main factors which stimulate degradation of semiconductor devices are generation, transformation and migration of lattice defects and impurities. Electrons near threshold energy (<500 keV) mainly produce isolated vacancies and interstitials called Frenkel pairs. High energy electrons produce clusters of displaced atoms and vacancies in addition to Frenkel pairs. The creation of defects results in a change in the carrier concentration, minority carrier life time and carrier mobility. In CdTe, Cd atoms can be displaced by electrons of energy greater than 235 keV while, both Cd and Te atoms are displaced by electrons of energy greater than 340 keV (Bryant et al., 1968, 1971). The atomic displacement energy for cadmium and Te are 5.6 eV and 7.8 eV respectively (Bryant and Cox, 1968). The Cd and Te interstitials are quite mobile above room temperature and thus vacancies of either Cd or Te or these vacancies and impurity complexes account for the dominant electrically active defects (Taguchi and Inuishi, 1980).

Taguchi et al. have found that irradiation by electrons results in a decrease in electron concentration (Taguchi and Inuishi, 1980). If radiation produces acceptor type defects with energy levels below the Fermi level in n-type material, the defects will capture electrons from the conduction band, decreasing the equilibrium electron concentration. The irradiation of materials by high energy particles is known to introduce lattice defects and the semiconductor properties are sensitive to defect concentrations (Goodman et al., 1999). However, in the electrodeposited CdTe films, the effect of irradiation, at least up to a dose of about 40 kGy, is not very significant. This makes CdTe, prepared by electrodeposition a promising material for space grade thin film solar cells.

4. Conclusion

The following conclusions can be reached from the studies on the effect of temperature and electron irradiation on the *I–V* characteristics of the Au/CdTe Schottky diodes.

1. The dominant conduction mechanism in the forward bias region seems to be thermionic emission–diffusion while in the reverse bias condition some other mechanism may be responsible.
2. The ideality factor and the series resistance R_s increase with a decrease in temperature.
3. The electron irradiation up to a dose of 40 kGy does not make significant changes in ideality factor, Schottky barrier height and series resistance.
4. However, at doses of above 70 kGy a significant increase in the reverse current is observed.
5. The degradation of the device parameters at higher doses is due to the creation of radiation-induced defects at the metal semiconductor interface through the change in carrier concentration, minority carrier life time and carrier mobility.
6. The polycrystalline CdTe thin film based devices seem to be stable against electron radiation at least at lower doses.

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References

Anthony, T.C., Fahrenbruck, A.L., Peters, M.C., Bube, R.H., 1985. Electrical properties of CdTe films and junctions. J. Appl. Phys. 57, 400–410.

Batzner, D.L., Romeo, A., Dobeli, M., Weinert, K., Zogg, H., Tiwari, A.N., 2001. Radiation hardness of CdTe/CdS solar cells. Presented at the 17th PVSEC, Munich, OA9.3.

Bayhan, H., Ercelebi, C., 1997. Electrical characterization of vacuum-deposited n-CdS/p-CdTe heterojunction devices. Semicond. Sci. Technol. 12 (5), 600–608.

Bryant, F.J., Cox, A.F.J., 1968. Atomic displacement energies for binary semiconductors. J. Phys. C (Proc. Phys. Soc.) 1 (2), 1734–1736.

Bryant, F.J., Cox, A.F.J., Webster, E., 1968. Atomic displacements and the nature of band edge radiative emission in cadmium telluride. J. Phys. C (Proc. Phys. Soc.) 1 (2), 1737–1745.

Bryant, F.J., Totterdell, D.H.J., Hangston, W.E., 1971. Identification of edge and exciton emission centres in CdTe. J. Phys. C: Solid State Phys. 4, 641–653.

Chand, S., Kumar, J., 1995. Current–voltage characteristics and barrier parameters of Pd_2Si/p-Si (1 1 1) Schottky diodes in a wide temperature range. Semicond. Sci. Technol. 10, 1680–1688.

Cullity, B.D., 1967. Elements of X-Ray Diffraction, second ed. Addison-Wesley, California, p. 99.

Dharmadasa, I.M., Roberts, G.G., Petty, M.C., 1982. Electrical properties of Au/n-CdTe Schottky diodes. J. Phys. D. Appl. Phys. 15, 901–910.

Goodman, S.A., Auret, F.D., Plessis, M.du., Meyer, W.E., 1999. The influence of high energy alpha-particle irradiation on the spectral and defect properties of a Si photovoltaic detector. Semicond. Sci. Technol. 14, 323–326.

Gumus, A., Turut, A., Yalcin, N., 2002. Temperature dependent barrier characteristics of CrNiCo alloy Schottky contacts on n-type molecular-beam epitaxy GaAs. J. Appl. Phys. 91 (1), 245–250.

Gurumurthy, S., Bhat, H.L., Kumar, V., 1999. Excellent rectifying characteristics in Au/n-CdTe diodes upon exposure to rf nitrogen plasma. Semicond. Sci. Technol. 14, 909–914.

Marshal, L.F., Pallares, J., Correig, X., Orpella, A., Bardes, D., Alcubilla, R., 1998. Current transport mechanisms in n-type amorphous silicon–carbon on p-type crystalline silicon (a-$Si_{0.8}C_{0.2}$:H/c-Si) heterojunction diodes. Semicond. Sci. Technol. 13, 1148–1153.

Mathew, X., 2003. Opto-electronic properties of an Au/CdTe device. Semicond. Sci. Technol. 18, 1–6.

Mathew, X., Sebastian, P.J., Sanchez, A., Campos, J., 1999. Structural and opto-electronic properties of electrodeposited CdTe on stainless steel foil. Solar Energy Mater. Solar Cells 59, 99–114.

Mathew, X., Enrique, J.P., Sebastian, P.J., Pattabi, M., Sanchez-Juarez, A., Campos, J., McClure, J.C., Singh, V.P., 2000. Charge transport mechanism in a typical Au/CdTe Schottky diode. Solar Energy Mater. Solar Cells 63, 355–365.

Olesen, H.L., 1966. Radiation Effects on Electronic Systems. Plenum, New York, p. 72.

Raynaud, C., Isoird, K., Lazar, M., Johnson, C.M., Wright, N., 2002. Barrier height determination of SiC Schottky diodes by capacitance and current–voltage measurements. J. Appl. Phys. 91 (12), 9841–9847.

Sullivan, J.P., Tung, R.T., Pinto, M.R., Graham, W.R., 1991. Electron transport of inhomogeneous Schottky barriers: a numerical study. J. Appl. Phys. 70, 7403–7424.

Sze, S.M., 1981. Physics of Semiconductor Devices, second ed. Wiley Interscience, New York, pp. 255–262.

Taguchi, T., Inuishi, Y., 1980. Radiation-induced defects and their annealing behaviour in cadmium telluride. J. Appl. Phys. 51 (9), 4757–4769.

Tugluoglu, N., Karadeniz, S., Sahin, M., Safak, H., 2004. Temperature dependence of current–voltage characteristics of Ag/p-SnSe Schottky diodes. Appl. Surf. Sci. 233, 320–327.

Tung, R.T., 1992. Electron transport at metal–semiconductor interfaces: general theory. Phys. Rev. B 45, 13509–13523.

Van Meirhaeghe, R.L., Van de Walle, R., Laflere, W.H., Cardon, F., 1991. On the relationship between the surface composition of the substrate and the Schottky barrier height in Au/n-CdTe contacts. J. Appl. Phys. 70 (4), 2200–2203.

Wysocki, J.J., Rapport, R., 1960. Effect of temperature on photovoltaic solar energy conversion. J. Appl. Phys. 31 (3), 571–578.

Zoutendyk, J.A., Goben, C.A., Berdent, D.F., 1988. Comparison of the degradation effects of heavy ion, electron and Cobalt 60 irradiation in an advanced bipolar process. IEEE Trans. Nucl. Sci. 35 (6), 1428–1431.