Radiation Effects & Defects in Solids, 2002, Vol. 157, pp. 367–374

IN SITU CURRENT-VOLTAGE CHARACTERIZATION OF SWIFT HEAVY ION IRRADIATED Au/n-GaAs SCHOTTKY DIODE AT LOW TEMPERATURE

R. SINGH*, S. K. ARORA, J. P. SINGH and D. KANJILAL

Nuclear Science Centre, Aruna Asaf Ali Marg, New Delhi – 110 067, India

(Received 15 March 2001; In final form 9 July 2001)

A Au/n-GaAs(100) Schottky diode was irradiated at 80 K by a 180 MeV $^{107}Ag^{14+}$ ion beam. *In situ* current-voltage (I–V) characterization of the diode was performed at various irradiation fluences ranging from 1×10^{10} to 1×10^{13} ions cm^{-2}. The semiconductor was heavily doped (carrier concentration $= 1 \times 10^{18}$ cm^{-3}), hence thermionic field emission was assumed to be the dominant current transport mechanism in the diode. Systematic variations in various parameters of the Schottky diode like characteristic energy E_0, ideality factor n, reverse saturation current I_S, flatband barrier height Φ_{bf} and reverse leakage current I_R have been observed with respect to the irradiation fluence. The nuclear and electronic energy losses of the swift heavy ion affect the interface state density at the metal-semiconductor interface resulting in observed variations in Schottky diode parameters.

Keywords: Swift heavy ion irradiation; Schottky barrier height; Thermionic field emission; Metal-semiconductor interface; Nuclear and electronic energy loss.

PACS: 61.80.Jh; 73.30.+y; 73.40.Gk

1 INTRODUCTION

The studies on the effect of swift heavy ion irradiation on the electrical transport behavior of Schottky diodes are important for application as well as fundamental understanding of the phenomenon. There are a few reports of low energy irradiation works on Schottky diodes [1–4]. But not much work has been performed on high energy heavy ion irradiation of Schottky diodes. These investigations are important from the space applications point of view because in outer space the electronic devices are exposed to cosmic radiation, comprising a variety of high energy particles, which may degrade their performance over years of operation [5, 6]. Apart from this, a few of the works indicate the usefulness of high energy irradiation in reducing the minority carrier lifetime in GaAs and thus producing very short

* Corresponding author. E-mail: rajendra@nsc.ernet.in; Tel: +91-11-6893955; Fax: +91-11-6893666
ISSN 1029-0150 print; ISSN 1029-4953 online
DOI: 10.1080/1042015021000031965

switching times of the electronic switches [7, 8]. Furthermore, these studies shed light on the basic ion-solid interaction processes, and their influence on various properties of semiconductors [9].

In the present study we report the influence of 180 MeV $^{107}Ag^{14+}$ ion irradiation on the current-voltage (I–V) characteristics of a Au/n-GaAs(100) Schottky diode at low temperature (80 K). The I–V characteristics of the diode were recorded *in situ* after irradiation by 180 MeV $^{107}Ag^{14+}$ ions at various irradiation fluences. The dominant current transport process in the diode at low temperature and heavily doped condition was assumed to be due to thermionic field emission mechanism. The effect of 180 MeV $^{107}Ag^{14+}$ irradiation on various diode parameters like the characteristic energy E_0, ideality factor n, reverse saturation current I_S, flatband barrier height Φ_{bf} and reverse leakage current I_R with irradiation fluence was studied.

2 EXPERIMENT

The Schottky diode was fabricated on a heavily silicon doped (dopant concentration $N_d = 1 \times 10^{18}\,\mathrm{cm}^{-3}$) GaAs(100) substrate. Prior to back ohmic contact and Schottky contact deposition, the wafer was properly cleaned and etched. The cleaning was done by dipping the GaAs wafer sequentially in trichloroethylene, methanol and acetone for 5 min each. Then the sample was etched in 15% HCl for 1 min duration to remove the native oxide from the surface. After this the sample was inserted in a cryopump operated high vacuum chamber for Au:Ge back ohmic contact deposition with a thickness of 100 nm. The base chamber pressure was 1×10^{-7} mbar. The Au:Ge contact was annealed at 430°C for 5 min in flowing argon ambient. Afterannealing in argon atmosphere, a 2 mm diameter Au contact with a thickness of 100 nm was deposited on the polished side of the wafer to obtain a Schottky diode.

The irradiation was performed by a 180 MeV $^{107}Ag^{14+}$ ion beam from the 15 UD Pelletron accelerator at Nuclear Science Centre, New Delhi [10]. The vacuum in the irradiation chamber was 1×10^{-6} mbar. For irradiation the Au/n-GaAs Schottky diode was mounted on a liquid nitrogen cooled copper sample holder. The temperature of the sample holder was maintained at (80 ± 0.5) K using a Lakeshore temperature controller. The diode was irradiated from the Au contact side and its I–V characteristics were recorded at various fluences (ranging from 5×10^{10} to $1 \times 10^{13}\,\mathrm{ions\,cm}^{-2}$) by stopping the beam after each fluence. The two contacts from the diode were taken out from the irradiation chamber through shielded coaxial cables using an electrical feed-through attached to the target ladder. The I–V characteristics were measured using Keithley's voltage source (model 230) and pico-ammeter (model 386).

3 RESULTS AND DISCUSSION

In a Schottky diode the current transport occurs through various mechanisms like thermionic emission (TE), recombination-generation, thermionic field emission (TFE) and field emission (FE) [11]. At low temperature and high carrier concentration in the semiconductor, thermionic field emission or field emission becomes the dominant current transport process. In our case, for a pristine sample the carrier concentration in n-GaAs was $1 \times 10^{18}\,\mathrm{cm}^{-3}$ and sample temperature was 80 K and hence thermionic field emission will be the dominant current transport process. In the case of TF emission, the current-voltage relationship is given by [11–13]:

$$I = I_S \exp(qV/E_0) \tag{1}$$

where I_S is the reverse saturation current, q is the electric charge, V is the applied voltage, and E_0 is the characteristic energy or tunneling parameter expressed as:

$$E_0 = E_{00} \coth(E_{00}/kT) \tag{2}$$

with

$$E_{00} = qh/4\pi(N_d/m^*\varepsilon_s)^{1/2} \tag{3}$$

Here m^*, ε_s and N_d are the tunneling effective mass, the static dielectric constant of the semiconductor and the dopant concentration respectively, and k is Boltzmann's constant. The pre-exponential term I_S is a complicated function of the temperature, barrier height and semiconductor parameters, and is given graphically as a function of kT/qE_{00} by Crowell and Rideout [13].

In our case $N_d = 1 \times 10^{18}\,\mathrm{cm}^{-3}$, so $E_{00} = 19.75$ meV and $E_0 = 19.88$ meV. In this case $kT/qE_{00} < 1$, and hence TF emission will be the dominant current transport process in our Schottky diode [11]. The experimental value of E_0 may also be evaluated from the slope in the log(I) *vs.* V graph. From the interception on the Y-axis, I_S may be known.

Figure 1 shows the semilogarithmic plot of the I-V characteristics of our Au/n-GaAs Schottky diode at various fluences. These curves were linearly fitted using Eq. (1) and the parameters E_0 and I_S were extracted. The tunneling parameter E_0 is related to the ideality factor n through the relation,

$$n = qE_0/kT \tag{4}$$

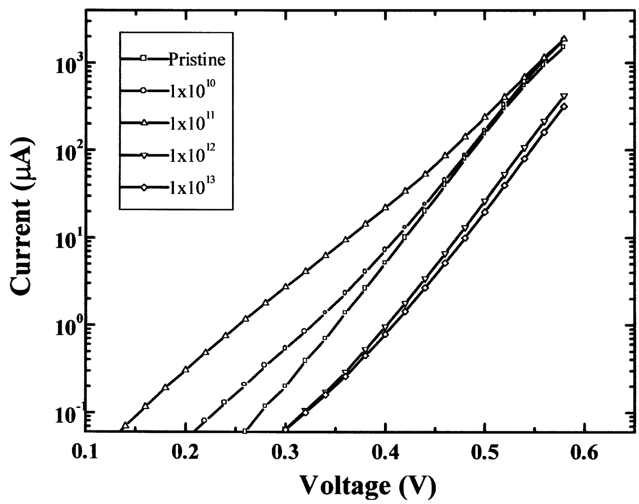

FIGURE 1 Forward I-V characteristics of a Au/n-GaAs Schottky diode at various fluence values of a 180 MeV $^{107}Ag^{14+}$ ion beam. (Irradiation temperature = 80 K and Schottky contact diameter = 2 mm).

The variation in E_0 with irradiation fluence is shown in Figure 2. The value of E_0 for the unirradiated diode is 30.8 meV. After irradiation the value of E_0 increases with fluence upto a fluence value of 5×10^{11} ions cm^{-2}. Its value is 46.3 meV for the fluence value of 5×10^{11} ions cm^{-2}. A sharp decrease is observed at a fluence value of 1×10^{12} ions cm^{-2} where the value of E_0 drops to 30.3 meV. After that it remains almost constant upto a fluence of 1×10^{13} ions cm^{-2}. The variation in ideality factor n will also follow the same trend because it is linearly related to E_0 through Eq. (4).

Another parameter of interest is the barrier height Φ_{b0} of a Schottky diode which depends on the electric field across the metal-semiconductor (MS) contact and consequently on the applied bias voltage. In order to compare different Schottky contacts it is therefore necessary to specify standard field conditions. It is well established that the flatband barrier height is the fundamental barrier height which should be used when comparing experiments with theory [14, 15]. Under this condition the semiconductor bands are flat, which precludes tunneling and image force lowering from affecting the I–V characteristics. The flatband barrier height can be calculated from the ideality coefficient and the zero-bias barrier Φ_{b0} according to [14]

$$\Phi_{bf} = n\Phi_{b0} - (n-1)(kT/q)\ln(N_C/N_D) \tag{5}$$

where Φ_{bf} is the flatband barrier height, N_C is the effective density of states in the conduction band, and N_D is the ionized donor density. The flatband barrier height is independent of the current transport mechanism. Therefore it can be determined also for heavily doped diodes where tunneling contributes significantly to the total current resulting in an ideality coefficient larger than 1 [14].

In this case the flatband barrier height for unirradiated diode is (1.02 ± 0.01) eV. It increases with the fluence until it reaches a value of (1.30 ± 0.02) eV for the fluence value of 5×10^{11} ions cm^{-2}. After that there is a sharp fall in the flatband barrier height to a value of (1.06 ± 0.02) eV at a fluence of 1×10^{12} ions cm^{-2}. Then it remains almost constant upto a fluence of 1×10^{13} ions cm^{-2}. The variation in flatband barrier height with irradiation fluence of 180 MeV $^{107}Ag^{14+}$ ion beam is shown in Figure 3. Similarly the variations in

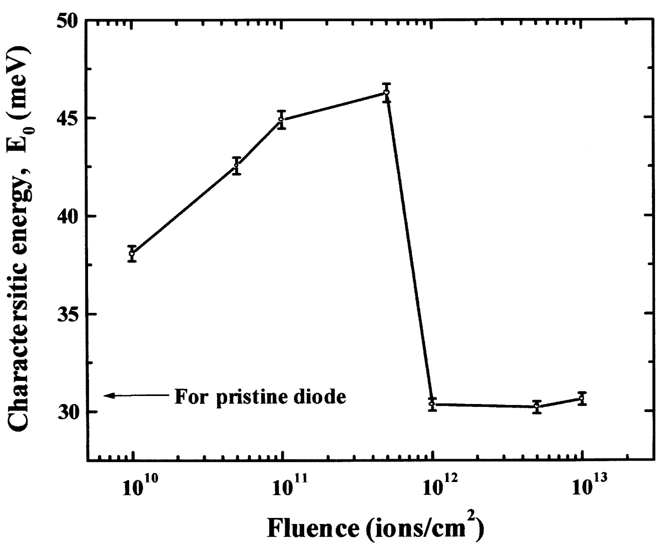

FIGURE 2 Characteristic energy E_0 as a function of fluence for a Au/n-GaAs Schottky diode.

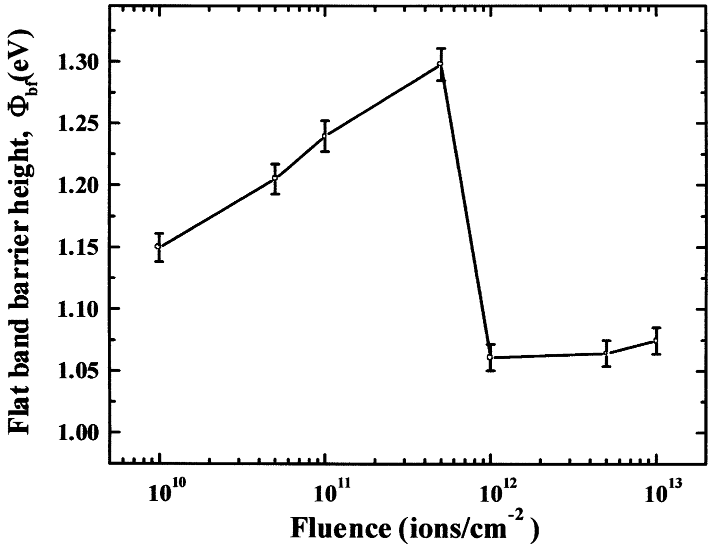

FIGURE 3 The variation of flatband barrier height Φ_{bf} with fluence for a Au/n-GaAs Schottky diode.

reverse saturation current I_S and reverse leakage current I_R have also been studied. Table I shows a compilation of the values of E_0, n, Φ_b, I_S and I_R at various fluences for the Schottky diode.

The parameter E_0 is connected with the transmission probability of electrons across the Schottky barrier [16]. It characterizes the electric field at the semiconductor surface at a given bias through the carrier concentration and the dielectric constant. Hence it characterizes the barrier shape and width at a given bias. It also characterizes the density of states through the effective mass. Therefore any mechanism which enhances the electric field or the density of states at MS interface, or affects the energy bands in the near-interface region, may increase the TF emission, and so the value of E_0. Mechanisms increasing the electric field at the MS interface may be geometrical inhomogeneities as crystal defects, surface roughness, a local pile up of dopant atoms (*e.g.* around crystal defects), the interface charge including the fixed one and that of interface states. The density of states may also be influenced by the quality of the interface. Further on, multi-step tunneling via interface states also yields

TABLE I Measured E_0, ideality factor n, reverse saturation current I_S, reverse leakage current I_R at 0.5 V and flatband barrier height Φ_{bf} at various fluence values of a 180 MeV $^{107}Ag^{14+}$ ion beam impinging onto a Au/n-GaAs Schottky diode

Fluence (ions cm^{-2})	*Characteristic Energy E_0 (meV)*	*Ideality factor, n*	*Reverse saturation current, I_S (A)*	*Reverse leakage current (0.5 V) I_R (A)*	*Flatband barrier height, $q\Phi_{bf}$ (eV)*
0	30.76	4.46	11.9	2.24	1.02
1×10^{10}	38.07	5.52	229	2.26	1.15
5×10^{10}	42.55	6.17	1520	2.57	1.21
1×10^{11}	44.89	6.51	3330	2.82	1.24
5×10^{11}	46.27	6.71	2190	1.32	1.29
1×10^{12}	30.34	4.40	0.193	0.38	1.06
5×10^{12}	30.2	4.38	0.147	0.32	1.06
1×10^{13}	30.62	4.44	0.172	0.31	1.07

high apparent E_{00} [17]. In case of swift heavy ion irradiation, the enhancement in interface state density at the MS interface mainly controls the value of parameter E_0.

Now to understand the observed modifications in the Schottky barrier diode properties, it is important to analyze the possible implications of ion transport through the sample. When 180 MeV $^{107}Ag^{14+}$ ion passes through the Schottky diode, it loses energy via two mechanisms: 1) nuclear energy loss S_n resulting from elastic collisions of the ion with the target atoms causing their displacement from the regular lattice sites, and 2) electronic energy loss S_e which results due to ionization/excitation of electrons inside the solid. For 180 MeV $^{107}Ag^{14+}$ ion, the variation of S_n and S_e as a function of depth inside the sample has been shown in Figure 4. It is evident from Figure 4 that at the MS interface region S_e is the dominant energy loss mechanism ($S_e/S_n \approx 300$). The S_n becomes dominant only at the end of the ion range, which is about 15.8 µm. Hence the ion reaches deep inside the substrate far away from the MS interface. All the energy loss calculations have been performed using standard Monte Carlo simulation program called SRIM98 [18]. Now at the MS interface the S_n value is 0.063 keV/nm while S_e is 18.6 keV/nm (in the GaAs substrate). The S_n causes creation of defects like vacancies, interstitials etc. at the interface [19] and this will lead to an increase in the interface state density D_S. Now according to the Fermi level pinning model of Bardeen, when the interface density D_S is very high, the Schottky barrier height (SBH) of SBD on an n-type semiconductor in the so-called Bardeen limit is given by

$$\Phi_{bB} = (E_g/q - \Phi_0) - \Delta\Phi \tag{6}$$

where E_g is the energy gap of the semiconductor, $q\Phi_0$ is the energy level coincidence with the Fermi level before the metal-semiconductor contact was formed, and $q\Phi$ is the lowering of the Schottky barrier due to the image force. On the other hand, when D_S is zero, then the SBH of a SBD on an n-type semiconductor in the so-called Schottky limit is given by

$$\Phi_{bS} = \Phi_m - \chi - \Delta\Phi \tag{7}$$

where Φ_m is the work function of the metal and $q\chi$ is the electron affinity of the semiconductor. According to Ref. [20], $q\Phi_0 = 0.53 \pm 0.33$ eV, $q\chi = 4.07$ eV, $E_g = 1.51$ eV, $q\Phi = 0.08$ eV

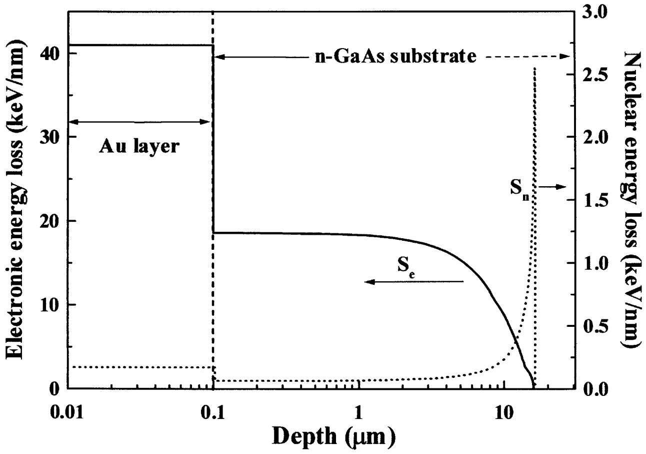

FIGURE 4 The electronic and nuclear energy losses of 180 MeV $^{107}Ag^{14+}$ ions as a function of depth inside a Au/n-GaAs Schottky diode.

for GaAs at $T = 80$ K, and $q\Phi_m = 4.8$ eV for Au. Using these values we obtain, $q\Phi_{bB} = 0.90 \pm 0.33$ eV and $q\Phi_{bS} = 0.65$ eV. This means that when the interface state density D_S increases from the Schottky limit to the Bardeen limit, the SBH increases from 0.65 eV to 0.90 ± 0.33 eV. As mentioned earlier, when a swift heavy ion passes through the MS interface it creates various kinds of defects causing the enhancement in the interface state density D_S. Due to this increase in D_S, the SBD goes more towards the Bardeen limit causing enhancement in the SBH. In fact the SBH of a Au/n-GaAs Schottky diode increases from a value of 1.02 eV for the pristine sample to 1.29 eV for the irradiated sample having an irradiation fluence of 5×10^{11} cm^{-2}. The corresponding values of the characteristic energy E_0 are 30.8 meV and 46.7 meV, respectively. The increase in E_0 is due to multistep tunneling via the interface states as mentioned earlier. As the irradiation fluence increases, the interface state density D_S also increases causing an enhancement in E_0. At a fluence of 1×10^{12} ions cm^{-2}, the values of SBH and E_0 decreases to 1.06 eV and 30.3 meV, respectively. After this fluence their values do not change much and at a final fluence of 1×10^{13} ions cm^{-2}, the values of SBH and E_0 are 1.07 eV and 30.6 meV, respectively. This indicates that there is a decrease in the interface state density D_S. Now it is evident from Figure 4 that at the MS interface S_e value is about 300 times larger than S_n. This high value of S_e may cause partial annealing of the defects created by S_n leading to a decrease of interface state density D_S. In fact in some recent studies regarding the effect of swift heavy ion irradiation on GaAs, it has been observed that the high electronic energy loss results in slight annealing of the defects [9, 21]. In the present case, we speculate that after a fluence of 1×10^{12} ions cm^{-2} the rate of creation of defects by S_n and rate of annealing of defects by S_e may become equal resulting in constancy of SBH and E_0 with respect to fluence.

4 SUMMARY

In this experiment a Au/n-GaAs Schottky diode was irradiated by a 180 MeV $^{107}Ag^{14+}$ beam at a sample temperature of 80 K. *In situ* I–V characterization of the diode was carried out with respect to the irradiation of fluence (ranging from 1×10^{10} to 1×10^{13} ions cm^{-2}). Due to low temperature and high carrier concentration in the semiconductor, thermionic field emission theory was applied to explain the I–V behavior of the diode. Systematic variations in various parameters like E_0, n, I_S, I_R and Φ_{bf} have been observed. The initial increase in the values of SBH and E_0 up to a fluence of 5×10^{11} ions cm^{-2} has been attributed to the increase of interface state density due to nuclear energy loss of the swift heavy ions at the MS interface. After this fluence, SBH and E_0 decrease sharply and then remain constant upto a fluence of 1×10^{13} ions cm^{-2}. This is due to the large electronic energy loss at the MS interface that causes partial annealing of the already existing defects.

Acknowledgements

The authors are thankful to the Pelletron Group of Nuclear Science Centre for providing a stable ion beam during the experiment. The help received from F. Singh and Ravi Kumar during the experiment is gratefully acknowledged.

References

[1] Ejimanya, J.I., (1986). *Solid State Electron.*, **29**, 841.
[2] Thurzo, I., Hrubcin, L., Bartos, J. and Pincik, E., (1993). *Nucl. Instrum. Methods*, **B83** 145.
[3] Arulkumaran, S., Arokiaraj, J., Dharamrasu, N. and Kumar, J., (1996). *Nucl. Instrum. Methods*, **B119**, 519.

[4] Dharamrasu, N., Arulkumaran, S., Sumathi, R.R., Jayavel, P., Kumar, J., Magudapathy, P. and Nair, K.G.M., (1998). *Nucl. Instrum. Methods*, **B140**, 119.
[5] Auret, F.D., Goodman, S.A., Erasmus, R., Meyer, W.E. and Myburg, G., (1996). *Nucl. Instrum. Methods*, **B119**, 51.
[6] Carlone, C., Parenteau, M. and Khanna, S.M., (1998). *J. Appl. Phys.*, **83**, 5164.
[7] Lambsdorff, M., Klingenstein, M., Kuhl, J., Moglestue, C. and Rosenzweig, J., (1991). *Appl. Phys. Lett.*, **58**, 1410.
[8] Lambsdorff, M., Kuhl, J., Rosenzweig, J., Axmann, A. and Schneider, J., (1991). *Appl. Phys. Lett.*, **58**, 1881.
[9] Mikou, M., Carin, R., Bogdanski, P. and Madelon, R., (1996). *Nucl. Instrum. Methods*, **B107**, 246.
[10] Kanjilal, D., Chopra, S., Narayanan, M.M., Iyer, I.S., Jha, V., Joshi, R. and Datta, S.K., (1993). *Nucl. Instrum. Methods*, **A238**, 97.
[11] Rhoderick, E.H. and Williams, R.H., *Metal Semiconductor Contacts*, (Oxford, New York, 1988), 2nd ed., p. 109.
[12] Padovani F.A., and Stratton, R., (1966). *Solid State Electron.* **9**, 695.
[13] Crowell, C.R. and Rideout, V., (1969). *Solid State Electron.*, **12**, 189.
[14] Hubers, H.W. and Roser, H.P., (1998). *J. Appl. Phys.*, **84**, 5326.
[15] Langer, L.F., Young, R.W. and Sugerman, A., (1983). *IEEE Electron Device Lett.*, **EDL-4**, 320.
[16] Horvath, Zs J., (1996). *Solid State Electron.*, **39**, 176.
[17] Yu, L.S., Liu, Q.Z., Xing, Q.J., Qiao, D.J., Lau, S.S. and Redwing, J., (1998). *J. Appl. Phys.*, **84**, 2099.
[18] Ziegler, J.F., Biersack, J.P. and Littmark, U., *The Stopping and Ranges of Ions in Matter*, (Pergamon, New York, 1985).
[19] Levalois, M., Bogdanski, P. and Toulemonde, M., (1992). *Nucl. Instrum. Methods*, **B63**, 14.
[20] Sze, S.M., *Physics of Semiconductor Devices*, (John Wiley & Sons, New York, 1981), 2nd ed., p. 275.
[21] Bachmann, T., Wendler, E., Wesch, W., Wilson, O. R.J., Jeynes, C., Gwilliam, R.M. and Sealy, B.J., (1995). *Nucl. Instrum. Methods*, **B99**, 619.