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Effects of swift heavy ion irradiation on the electrical characteristics of Au/n-GaAs Schottky diodes

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Abstract

Metal-semiconductor diode of Au/n-GaAs is studied under the irradiation of swift heavy ion (SHI) beam (80 MeV $^{16}O^{6+}$), using *in situ* current–voltage characterization technique. The diode parameters like ideality factor, barrier height, and leakage current are observed to vary with irradiation fluence. Significantly, the diode performance improves at a high fluence of 2×10^{13} ions cm^{-2} with a large decrease of reverse leakage current in comparison to the original as deposited sample. The Schottky barrier height (SBH) also increases with fluence. At a high irradiation fluence of 5×10^{13} ions cm^{-2} the SBH (0.62 ± 0.01 eV) is much larger than that of the as deposited sample (0.55 ± 0.01 eV). The diode parameters remain stable over a large range of irradiation up to fluence of 8×10^{13} ions cm^{-2}. A prominent annealing effect of the swift ion beam owing to moderate electronic excitation and high ratio of electronic energy loss to the nuclear loss is found to be responsible for the improvement in diode characteristics.

Keywords: Schottky diodes; *in situ* I–V; Barrier height; Reverse leakage current; Energy loss

1. Introduction

Metal-semiconductor (M-S) interfaces form an integral part of any semiconductor device structure and thus, their studies attract considerable interests. They also form an important research tool for characterization of materials. Studies of high-energy ion beam modification of semiconductor devices are helpful in simulating their performance in irradiation environments and in outer space where they are continuously subjected to bombardment by stream of energetic particles. GaAs is a direct band gap semiconductor and has great technological importance due to its applications in detectors, high-speed semiconductor devices and in optoelectronics.

Metal-semiconductor Schottky diodes are very sensitive to the quality of the interface formed at the contact between the metal and semiconductor surface. Any mechanism that modifies the properties of the interface such as the introduction of an interfacial layer [1–4], annealing [5,6], irradiation with gamma rays [7,8], protons [9–14] and neutrons [14–16], ion implantation, [17–19] and high-energy ion beam irradiation [20–26] are found to alter the characteristics of the barrier. The Schottky barrier height (SBH) forms a very important parameter of the diode as it controls the electrical transport across the barrier. Some analyses have been reported on the studies of high-energy ion beam modification of M-S interfaces [22–26]. However, the deeper understanding of the basic nature of such interactions still remains incomplete. Normally, the SBH is found to decrease at high irradiation fluence (above 1×10^{13} ions cm^{-2}) in comparison to that of the as deposited sample [22,23]. Increase in SBH has been observed at a relatively lower dose of ion irradiation around 1×10^{12} ions cm^{-2} [21]. In comparison to such results, a new behavior was observed in our experiment with 80 MeV $^{16}O^{6+}$ ions. In order to avoid any sample-to-sample variation [27] in diode properties, an *in situ* current–voltage (I–V) characterization technique has been used. The diode characteristics have been studied over a large range of ion irradiation fluencies from 5×10^{9} to 8×10^{13} ions cm^{-2} and at

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close intervals for systematic and detailed analysis of ion beam induced modification on diode performance. The modifications observed in device characteristics are explained on the basis of interaction mechanism of SHI with solid.

2. Experimental

The Schottky diodes were fabricated on single-side polished *n*-type GaAs (Si-doped) wafer of doping concentration 5×10^{15} atoms cm^{-3}. Prior to deposition the wafer was chemically cleaned. For fabrication of Ohmic contact Au–Ge eutectic alloy was deposited by resistive heating in high vacuum environment (10^{-7} Torr), and then annealed at 430 °C for 5 min. On the same polished side of the wafer, circular Au Schottky contact of diameter 2 mm was deposited in ultra high vacuum chamber (10^{-8} Torr) by electron beam evaporation. Deposition rate was maintained at 0.1 Å/s and thickness of the film grown was 150 nm as monitored by a quartz crystal thickness monitor.

The ion beam irradiation experiment was performed using 80 MeV $^{16}O^{6+}$ ions from the 15UD Pelletron Accelerator at the Inter-University Accelerator Centre, New Delhi [28]. The irradiation chamber was maintained at a high vacuum of 5×10^{-6} mbar and the diode was irradiated from the contact side. The ion beam current was maintained constant at a low value of 3 nA to avoid excessive sample heating. Electrical contacts were made for *in situ* I–V measurement and connections were taken out of the chamber using vacuum feed-throughs for shielded coaxial cables. I–V measurement was performed using programmable Keithley 2400 source meter at various ion fluencies by temporarily stopping the ion beam after the particular irradiation fluence.

3. Results and discussion

There are various mechanisms for current transport across the metal-semiconductor Schottky barrier: thermionic emission, thermionic field emission, field emission, and recombination-generation. In case of moderately doped semiconductor used in our experiment (at ordinary temperature), thermionic emission is the dominant phenomenon of conduction across the barrier. Thus, the experimental I–V data are best fitted by the thermionic emission model, which follows the equation [29],

$$I = I_S \exp\left(\frac{qV}{nkT}\right)\left[1 - \exp\left(\frac{-qV}{kT}\right)\right] \quad (1)$$

where, I_s denotes saturation current, n is the ideality factor of the diode, q is electronic charge, and k is Boltzmann's constant. The ideality factor n in the equation indicates the deviation of experimental I–V characteristics from thermionic emission model. Saturation current I_s is given by

$$I_S = AA^*T^2 \exp\left(\frac{-q\phi_B}{kT}\right) \quad (2)$$

where, A denotes contact area of the diode, A^* is Richardson's constant (8.16 A/cm^{2}K^2 for GaAs) and Φ_B is the apparent

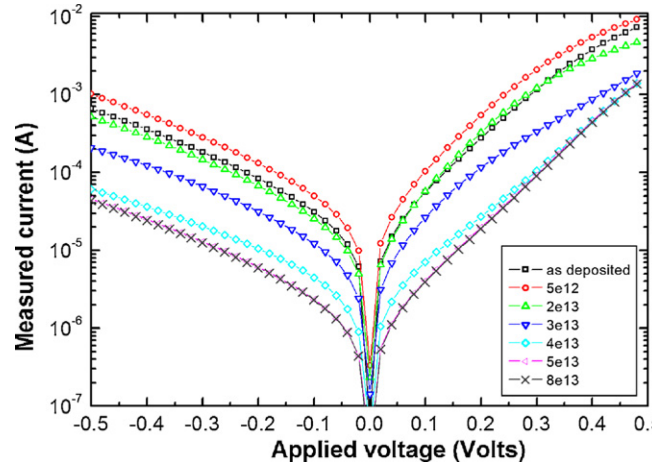

Fig. 1. I–V Characteristics of as deposited and 80 MeV $^{16}O^{6+}$ ion irradiated Au/n-GaAs Schottky diode with irradiation fluence.

barrier height. The diode parameters are extracted from semi-logarithmic plot of current–voltage characteristics. Ideality factor is obtained from the slope of the linear portion in ln (I) versus V plot, and saturation current (I_s) is calculated from the y-intercept. Then, Φ_B is determined using Eq. (2).

The current–voltage characteristics (on semilogarithmic scale) for as deposited and irradiated Au/n-GaAs diode with irradiation fluence up to 8×10^{13} ions cm^{-2} are shown in Fig. 1. Only a few selected fluencies are shown for clarity of the plot. Fig. 2 shows the corresponding values of SBH and ideality factor at various ion irradiation fluencies up to 8×10^{13} ions cm^{-2}.

The characteristics of the diode like SBH and reverse leakage current (I_R) are found to vary as a function of the ion irradiation fluence. Significantly, a large increase in the SBH is observed at high fluence of 5×10^{13} ions cm^{-2} relative to that observed for the as deposited sample. There is also a large reduction in the value of I_R measured at this high ion irradiation fluence showing an improvement in diode performance in comparison to the unirradiated sample. Such observation is

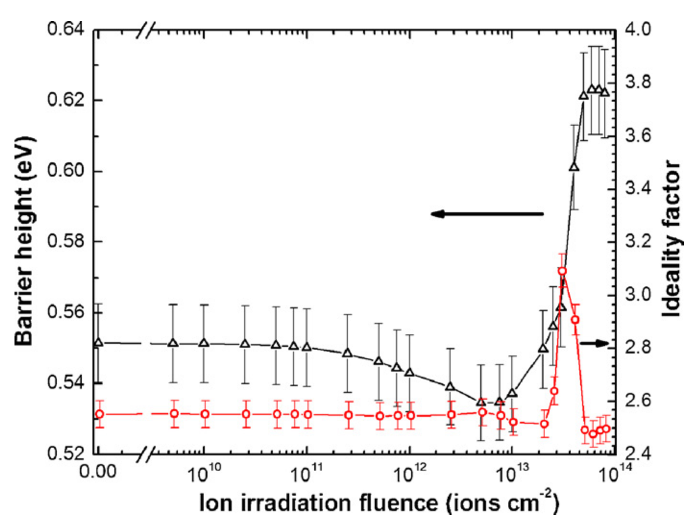

Fig. 2. Variation of Schottky barrier height and ideality factor with ion irradiation fluence.

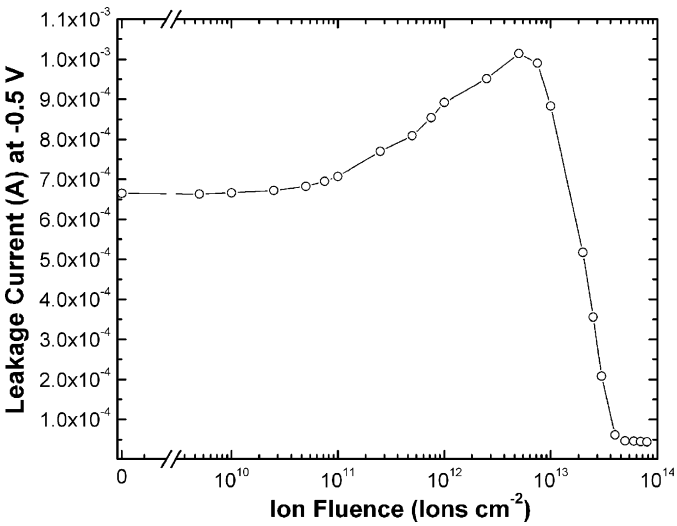

Fig. 3. Variation of leakage current with ion irradiation fluence.

relatively new in view of the results available in the literature. The earlier studies on SHI irradiation found a decrease in SBH (compared to as deposited sample) at high fluence of more than 1×10^{13} ions cm^{-2} [22,23], and increase in SBH was normally found at lower fluence of about 1×10^{12} ions cm^{-2} [21].

In the present experiment the SBH for as deposited diode is found to be 0.55 ± 0.01 eV, which remains constant up to irradiation fluence of 5×10^{12} ions cm^{-2}. On further irradiation the SBH increases and attains the maximum value of 0.62 ± 0.01 eV at a fluence of 5×10^{13} ions cm^{-2}. After this irradiation fluence the SBH remains unchanged up to a high fluence of 8×10^{13} ions cm^{-2}. Interesting change is observed in the reverse leakage current of the diode as shown in Fig. 3. Leakage current (I_R) at -0.5 V for unirradiated diode is 6.65×10^{-4} A. Its value is found to increase with ion fluence to 1.01×10^{-3} A at fluence of 5×10^{12} ions cm^{-2}. Thereafter, I_R decreases with irradiation to 2.08×10^{-4} A at fluence of 3×10^{13} ions cm^{-2} and finally it decreases to 4.36×10^{-5} A at 8×10^{13} ions cm^{-2}. The leakage current of the diode at the highest irradiation fluence of 8×10^{13} ions cm^{-2} is about 15 times smaller than that of the as deposited sample. The SBH of 0.62 ± 0.01 eV is also much larger than initial value of 0.55 ± 0.01 eV observed for the unirradiated sample. This indicates an improvement in diode performance at such a high fluence using the high-energy oxygen ion beam.

The ideality factor (n) for the as deposited sample is 2.55. Under ion irradiation, this diode parameter is found to remain in the range of 2.48–2.63, except for the higher values of 3.09 and 2.9 at 3×10^{13} and 4×10^{13} ions cm^{-2} respectively.

To understand the modification induced by SHI beam on device characteristics, the basic phenomenon of interaction of energetic ion with solid must be considered. As the swift ion enters the target it transfers its energy through:

(1) nuclear energy loss (S_n) which results from elastic interaction of incoming ion with target nuclei, and;
(2) electronic energy loss (S_e) due to inelastic interaction of ion with electron cloud of the target.

The electronic loss is the dominant phenomenon at high energies (MeV range) when velocity of the projectile ion is comparable to the Bohr velocity of the electrons in the orbit. The energy loss of 80 MeV oxygen ions in the Au/n-GaAs Schottky structure was calculated using the standard Monte Carlo simulation program SRIM 2006 [30]. The energetic ion crosses the M-S interface and moves into a depth of more than 45 μm inside the GaAs substrate. Thus, the ion traverses far away from the interface. According to the simulation, after passing through 150 nm thick Au layer the energy of the ion reduces to 79.5 MeV. At this energy the values of S_e and S_n are respectively, 3.1×10^2 and 2.15×10^{-1} eV/Å in Gold, and 1.32×10^2 and 8.18×10^{-2} eV/Å in GaAs. Thus, the mean values of S_e and S_n at the M-S interface are 2.21×10^2 and 1.48×10^{-1} eV/Å respectively, which indicates that the electronic energy loss is nearly 1500 times the nuclear loss. Thus, the interaction is largely dominated by electronic energy loss.

The nuclear energy loss mainly causes displacement of target atoms leading to the creation of defects like vacancies and interstitials, and this can increase the density of states at M-S interface. The electronic energy loss leads to excitation of electrons in the target, and during the relaxation of these electrons various phenomena like mixing may occur at the M-S interface, and other complex defects may be formed [31,32]. A partial annealing of defects due to ions with high electronic energy loss has also been observed. There are some studies on GaAs showing such type of interaction with ion beam [33,34].

The properties of Schottky barrier are very sensitive to the quality of the interface formed at the contact between metal and semiconductor surface. The SBH is drastically influenced by the density of states at the M-S interface. The irradiation of SHI beam leads to modification of interface state density (D_s) at the M-S interface, and alters the transport properties across the barrier [22–24]. The swift ion transfers its energy as it enters the target and this energy loss at the M-S interface as it passes through the structure leads to change in barrier characteristics. The Au layer is not affected by electronic loss due to strong screening of charges in metals.

The value of SBH is 0.55 ± 0.01 eV for the as deposited Au/n-GaAs Schottky diode. This is relatively low in comparison to that observed for ideal contact on n-GaAs [35]. The lower value of SBH observed may be due to the presence of an interfacial layer such as an oxide incorporated during the fabrication process. This may increase the density of interface states and can result in its slight immunity against ion irradiation. The irradiation of energetic ion beam alters the properties of the M-S interface through creation or annealing of defects and modifies D_s at the interface. However, due to the presence of a significant density of interface states in the as deposited diode, such change is not apparent up to some level of irradiation. Thus, the diode parameters remain largely unaltered up to ion fluence of 5×10^{12} ions cm^{-2}. Above the fluence of 5×10^{12} ions cm^{-2}, an effective annealing of defects takes place at M-S interface due to high S_e of the incoming ion leading to reduction in density of interface states. The effect of annealing is more prominent in the case of ions with high values of electronic energy loss, and such phenomenon will appear above some level of irradiation fluence when the effective cylinders of influence of incoming ions may begin to overlap. The SBH increases to 0.56 ± 0.01 eV at 3×10^{13} ions cm^{-2} and to 0.60 ± 0.01 eV at 4×10^{13} ions cm^{-2}. On further irradiation, the SBH increases to a maximum of 0.62 ± 0.01 eV at 5×10^{13} ions cm^{-2} and this value remains unchanged up to irradiation fluence of 8×10^{13} ions cm^{-2}. It is found that ion irradiation results in improved Schottky barrier characteristics due to deactivation of dopants in the near interface region [20,21]. Such effect is primarily observed in near interface deposition of ions. In our case, the SHI crosses the M-S interface and traverses deep inside the substrate far from the interface. The electronic energy loss happens to be the dominant phenomenon and leads to modification of the electronic states at the M-S interface, which leads to the modifications in diode properties.

The reverse leakage current (I_R) also shows a corresponding change with irradiation fluence. Increase in SBH is associated with a decrease in the leakage current. There is not much change in the leakage current up to a fluence of 1×10^{11} ions cm^{-2}. With increasing fluence, I_R increases to a maximum of 1.01×10^{-3} A at 5×10^{12} ions cm^{-2}. With increase in density of interface states the possibilities for leakage paths across the M-S interface also increase. At higher fluencies above 1×10^{13} ions cm^{-2}, an annealing effect due to the ion beam irradiation results in the reduction of D_s at the interface. This leads to decrease in the reverse leakage current showing an improved diode performance at a high irradiation fluence of 4×10^{13} to 8×10^{13} ions cm^{-2}.

The ideality factor of the diode (n) has a value of 2.55 for as deposited sample, which remains close to this initial value (2.48–2.63) on ion irradiation except for the larger values at fluencies of 3×10^{13} and 4×10^{13} ions cm^{-2}. A large increase in SBH (0.56 ± 0.01 to 0.62 ± 0.01) eV with irradiation fluence occurs (3×10^{13}–5×10^{13} ions cm^{-2}), corresponding decrease in ideality factor (3.09–2.49) is observed. Ideality factor of the diode shows deviation of current transport from ideal thermionic emission, its value should be one for ideal thermionic model. Increase in value of the ideality factor indicates increase in the contribution due to field emission, thermionic field emission, and recombination-generation processes. Increase in the interface states may increase possibility of these current transport phenomena across the barrier. In the range of irradiation fluence from 3×10^{13} to 5×10^{13} ions cm^{-2}, effective annealing due to irradiation by ion beam having moderate S_e and large S_e/S_n ratio leads to reduction in the interfacial state density. Thus, increase in SBH and decrease in ideality is observed. Above a fluence of 5×10^{13} (up to 8×10^{13}) ions cm^{-2}, a near equilibrium between the competing processes of defect creation and annihilation due to SHI beam gets established. Thus, the diode characteristics are observed to remain almost stable in this range.

The results obtained in the experiment with 80 MeV $^{16}O^{6+}$ show a prominent annealing effect of swift ion beam which leads to increase in SBH and large reduction in leakage current of the diode at high ion fluence. The 80 MeV $^{16}O^{6+}$ ion used in the present experiment is associated with a high S_e to S_n ratio (1500), and low value of nuclear energy loss at the M-S interface (1.48×10^{-1} eV/Å). The small value of S_n results in less defect creation due to nuclear energy loss, and the moderately high electronic energy loss lead to prominent annealing of defects at M-S interface. This gives rise to the observed improvements in the Schottky barrier height and leakage current of the diode.

4. Conclusion

Au/n-GaAs Schottky diodes have been studied by *in situ* I–V characterization during irradiation by 80 MeV $^{16}O^{6+}$ up to fluence of 8×10^{13} ions cm^{-2}. The diode parameters are found to depend on the fluence of ion irradiation. Large increase in the SBH and decrease in reverse leakage current was observed indicating an improvement in the diode performance at high irradiation fluence (5×10^{13} ions cm^{-2}). On further irradiation, the diode parameters remained stable up to ion fluence of 8×10^{13} ions cm^{-2}. A prominent annealing effect of the SHI beam owing to its moderate value of S_e and high S_e/S_n ratio is found to be responsible for the improvement in diode properties.

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References

[1] Y. Ding, S.A. Campbell, Appl. Phys. Lett. 89 (2006) 093508.
[2] S.D. Lin, C.P. Lee, J. Appl. Phys. 90 (2001) 5666.
[3] A.R. Vearey-Roberts, D.A. Evans, Appl. Phys. Lett. 86 (2005), 072105.
[4] S. Fujieda, Appl. Phys. Lett. 61 (1992) 288.
[5] H. Xu, S. Belkouch, C. Aktik, Appl. Phys. Lett. 66 (1995) 2125.
[6] T. Sands, W.K. Chan, C.C. Chang, E.W. Chase, V.G. Keramidas, Appl. Phys. Lett. 52 (1998) 1338.
[7] S. Karatas, A. Turut, S. Altındal, Nucl. Instrum. Methods Phys. Res., Sect. A 555 (2005) 260.
[8] A. Tataroglu, S. Altindal, Nucl. Instrum. Methods Phys. Res., Sect. B 252 (2006) 257.
[9] J.F. Barbot, E. Ntsoenzok, C. Blanchard, J. Vernois, D.B. Isabelle, Nucl. Instrum. Methods Phys. Res., Sect. B 95 (1995) 213.
[10] S.A. Goodman, F.D. Auret, W.E. Meyer, Nucl. Instrum. Methods Phys. Res., Sect. B 90 (1994) 349.
[11] S. Arulkumaran, J. Arokiaraj, N. Dharmarasu, J. Kumar, Nucl. Instrum. Methods Phys. Res., Sect. B 119 (1996) 519.
[12] F.D. Auret, S.A. Goodman, M. Hayes, M.J. Legodi, H.A. van Laarhoven, Appl. Phys. Lett. 79 (2001) 3074.
[13] S. Nigam, J. Kim, F. Ren, G.Y. Chung, M.F. MacMillan, R. Dwivedi, T.N. Fogarty, R. Wilkins, K.K. Allums, C.R. Abernathy, S.J. Peartona, J.R. Williams, Appl. Phys. Lett 81 (2002) 2385.
[14] S. Sciortino, F. Hartjes, S. Lagomarsino, F. Nava, M. Brianzi, V. Cindro, C. Lanzieri, M. Moll, P. Vanni, Nucl. Instrum. Methods Phys. Res., Sect. A 552 (2005) 138.

[15] F.D. Auret, A. Wilson, S.A. Goodman, G. Myburg, W.E. Meyer, Nucl. Instrum. Methods Phys. Res., Sect. B 90 (1994) 387.
[16] J.M. Borrego, R.J. Gutmann, Appl. Phys. Lett. 28 (1976) 280.
[17] S. Ashok, H. Krautle, H. Beneking, Appl. Phys. Lett. 45 (1984) 433.
[18] R. Singh, S. Ashok, Appl. Phys. Lett. 47 (1985) 426.
[19] H.C. Chien, S. Ashok, J. Appl. Phys. 60 (1986) 2886.
[20] F. Roccaforte, S. Libertino, V. Raineri, A. Ruggiero, V. Massimino, L. Calcagno, J. Appl. Phys. 99 (2006), 013515.
[21] F. Roccaforte, S. Libertino, F. Giannazzo, C. Bongiorno, F. La Via, V. Raineri, J. Appl. Phys. 97 (2005) 123502.
[22] S. Kumar, D. Kanjilal, Nucl. Instrum. Methods Phys. Res., Sect. B 248 (2006) 109.
[23] R. Singh, S.K. Arora, D. Kanjilal, Mater. Sci. Semicond. Process. 4 (2001) 425.
[24] R. Singh, S.K. Arora, J.P. Singh, D. Kanjilal, Radiat Eff. Defects Solids 157 (2002) 367.
[25] S. Kumar, Y.S. Katharria, D. Sugam Kumar, Kanjilal, J. Appl. Phys. 100 (2006) 113373.
[26] P. Jayavel, M. Udhayasankar, J. Kumar, K. Asokan, D. Kanjilal, Nucl. Instrum. Methods Phys. Res., Sect. B 156 (1999) 110.
[27] R.T. Tung, Mater. Sci. Eng., R 35 (2001).
[28] D. Kanjilal, S. Chopra, M.M. Narayanan, I.S. Iyer, V. Jha, R. Joshi, S.K. Dutta, Nucl. Instrum. Methods Phys. Res., Sect. A 328 (1993) 97.
[29] S.M. Sze, Physics of Semiconductor Devices, Wiley, New York, 1981.
[30] J.F. Ziegler, J.P. Biersack, U. Littmarc, The Stopping and Range of Ions in Matter, Pergamon, New York, 1985.
[31] P. Stampfli, Nucl. Instrum. Methods Phys. Res., Sect. B 107 (1998) 138.
[32] J.P. Singh, R. Singh, D. Kanjilal, N.C. Mishra, V. Ganesan, J. Appl. Phys. 87 (2000) 2742.
[33] M. Mikou, R. Carin, P. Bogdanski, R. Madelon, Nucl. Instrum. Methods Phys. Res., Sect. B 107 (1996) 246.
[34] T. Bachmann, E. Wendler, W. Wesch, O. Herre, R.J. Wilson, C. Jeynes, R.M. Gwilliam, B.J. Sealy, Nucl. Instrum. Methods Phys. Res., Sect. B 99 (1995) 619.
[35] J.R. Waldrop, Appl. Phys. Lett. 44 (1984) 1002.