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Barrier modification of Au/n-GaAs Schottky diode by swift heavy ion irradiation

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Abstract

The effect of swift heavy ion (72.5 MeV $^{58}Ni^{6+}$) irradiation on Au/n-GaAs Schottky barrier characteristics is studied using in situ current–voltage measurements. Diode parameters are found to vary as a function of ion irradiation fluence. The Schottky barrier height (SBH) is found to be 0.55(±0.01) eV for the as deposited diode, which decreases with ion irradiation fluence. The SBH decreases to a value of 0.49(±0.01) eV at the highest ion irradiation fluence of 5×10^{13} ions cm^{-2}. The ideality factor is found to be 2.48 for unirradiated diode, and it increases with irradiation to a value of 4.63 at the highest fluence. The modification in Schottky barrier characteristics is discussed considering the energy loss mechanism of swift heavy ion at the metal–semiconductor interface.

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1. Introduction

Metal–semiconductor (M–S) contacts form an important and essential part of any semiconductor device structure and their studies are vital to the development of technology. The basic understanding of Schottky barrier formation at such an interface has been an issue of considerable research interest at present. Models have been proposed which highlight the role of the semiconductor band gap electronic states in the Fermi level pinning mechanism at such interface. Such electronic states could be either metal-induced [1,2] or induced by defects [3]. As the Schottky barrier height (SBH) controls the electrical transport across the M–S interface, it is a very significant parameter for successful device operation. The performance of these devices is influenced to a large extent by the quality of interface formed at the contact between the metal and semiconductor surface. The density of states at the M–S interface and their energy distribution can largely influence device characteristics.

Irradiation with energetic ion beam can modify the properties of the M–S interface, and lead to changes in the SBH and the current transport properties across the barrier. Such studies are interesting due to the technological potential of ion beam techniques in device fabrication and in tailoring the properties of semiconductor material and semiconductor-devices. There is also a physics motivation towards better understanding of the fundamental processes involved in ion–solid interaction.

There are some reports on the study of the effect of swift heavy ion (SHI) irradiation on the characteristics of metal–semiconductor interface [4–10]. At large energies, the electronic energy loss is much greater than the nuclear loss, and the modification of M–S interface will be dominated by the electronic energy loss phenomenon. Some studies have also been conducted on the interaction of metal–semiconductor

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interface with ions at low energies [11–14]. Such analyses show a variation in Schottky barrier characteristics with fluence of ions.

In the present work, the diode characteristics have been analyzed over a large range of ion fluence from 5×10^9 to 5×10^{13} ions cm^{-2} and at close intervals for a detailed analysis of ion beam induced modifications on the characteristics of the diode. The changes in Schottky barrier properties are discussed with the energy loss mechanism of swift heavy ion at the M–S interface.

2. Experimental

Single side polished n-type GaAs (Si-doped) wafer of doping concentration 5×10^{15} atoms cm^{-3} was used for fabrication of Schottky barrier diode. The polished side was used for deposition of both Ohmic and Schottky contacts. Prior to deposition, the wafer was chemically cleaned thoroughly. It was treated with trichloroethylene, acetone and methanol sequentially for 10 min each. After that samples were deoxidized by etching in 10% HCl solution for 1 min, and thoroughly rinsed in deionized water. Au–Ge (88:12) eutectic alloy was used for making Ohmic contact of diameter 2 mm, deposited in high vacuum (10^{-7} torr) by resistive heating. Samples were then annealed in argon atmosphere at 430 °C for 5 min. After chemical cleaning, Au Schottky contact of diameter 2 mm and thickness 150 nm was deposited by electron gun evaporation in ultra high vacuum (10^{-8} torr) at a rate of deposition of 0.1 Å s^{-1} monitored by quartz crystal monitor.

The irradiation was performed with $^{58}Ni^{6+}$ ions of energy 72.5 MeV. The 15UD Pelletron accelerator facility at the Inter-University Accelerator Centre, New Delhi [15] was used to obtain the ion beam. The diode was mounted on the target ladder inside the irradiation chamber, in a high vacuum of 5×10^{-6} mbar. The irradiation was performed at room temperature on the Au-contact by masking the Ohmic contact. During the entire ion irradiation experiment, beam current was 4 nA. It is observed that some sample-to-sample variations are always involved in the diode characteristics like SBH and ideality factor, even with diodes fabricated on the same material and in identical environment [16,17]. The effect of ion irradiation depends on the initial or virgin state of the sample like temperature, vacuum, etc. By using in situ technique, the true effect exclusively due to ion irradiation is observed maintaining identical experimental conditions during irradiation and without any unwanted contributions due to sample variations. In situ current–voltage (I–V) characteristics were measured at various ion irradiation fluences from 5×10^9 to 5×10^{13} ions cm^{-2}, by stopping the ion beam after the particular irradiation fluence.

The contacts from the diode were taken out from the irradiation chamber by using vacuum feed-throughs for shielded coaxial cables. The I–V characterization was performed using programmable Keithley 2400 source meter.

3. Results and discussion

The current transport across the M–S Schottky barrier takes place through various mechanisms like thermionic emission, thermionic field emission, field emission, and recombination–generation. For moderately doped semiconductor at ordinary temperature of the experiment, thermionic emission happens to be the dominant phenomenon of current transport across the M–S barrier. The experimental current–voltage data are thus analyzed using the thermionic emission model of conduction across the barrier [18]

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

where, I_s denotes the saturation current and n is the ideality factor of the diode; q is the electronic charge and k is Boltzmann's constant. Ideality factor in the expression accounts for deviation of the experimental I–V characteristics from the ideal thermionic emission current. Saturation current I_s is given by the relationship

$$I_s = AA^*T^2 \exp\left(\frac{-q\Phi_B}{kT}\right), \qquad (2)$$

where, A is the contact area of diode, A^* is the Richardson constant (8.16 A/cm^2 K^2 for GaAs) and Φ_B denotes the apparent barrier height. To extract diode parameters, ln (I) is plotted versus applied voltage. From the slope of the linear portion in ln (I) versus V plot, ideality factor is obtained and saturation current (I_s) is evaluated from the y-intercept. From I_s, Φ_B is determined using Eq. (2).

Fig. 1. shows the current–voltage characteristics (semi-logarithmic scale) for pristine and irradiated Au/n-GaAs diode with irradiation fluences up to 5×10^{13} ions cm^{-2}, where only few selected fluences are shown for clarity. The corresponding values of Schottky barrier height (SBH) and ideality factor are shown in Fig. 2.

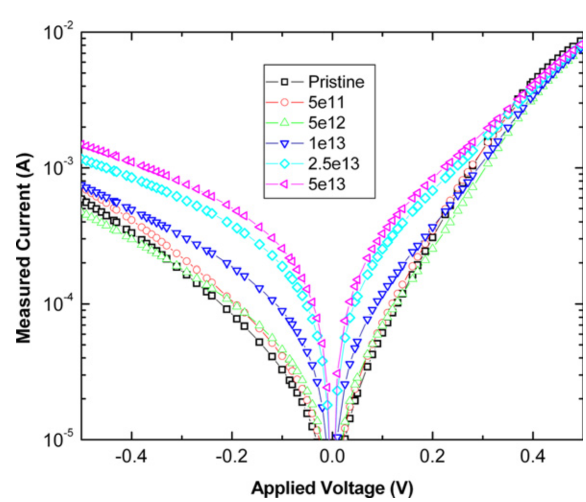

Fig. 1. I–V Characteristics of Pristine and 72.5 MeV $^{58}Ni^{6+}$ irradiated Au/n-GaAs SBD at various ion fluences.

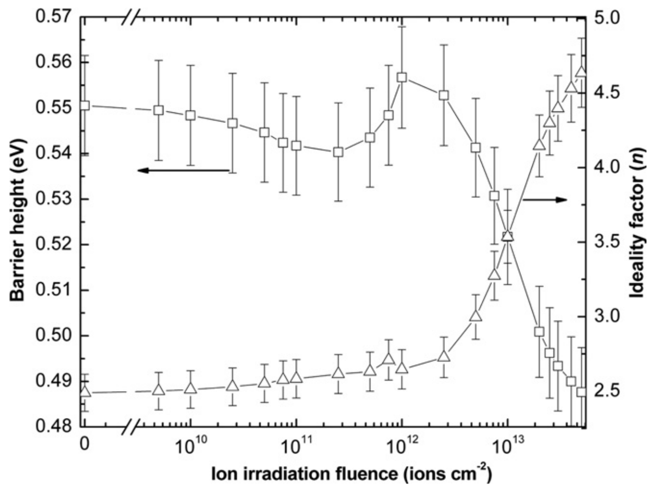

Fig. 2. Variation of SBH and ideality factor with irradiation fluence.

The SBH for pristine diode is found to be 0.55(±0.01) eV, which remains almost unchanged up to irradiation fluence of 1×10^{12} ions cm^{-2}. At higher irradiation fluences, the SBH decreases to 0.50(±0.01) eV at 2×10^{13} ions cm^{-2} and 0.49(±0.01) eV at 5×10^{13} ions cm^{-2}.

The ideality factor (n) is found to be 2.48 for pristine sample, which increases with irradiation fluence to 2.7 at 7.5×10^{11} ions cm^{-2}. At higher ion irradiation fluence, n increases to 3.53 at 1×10^{13} ions cm^{-2} and 4.63 at 5×10^{13} ions cm^{-2}.

Modification in the reverse leakage current (I_R) of the diode due to the ion irradiation is shown in Fig. 3. Leakage current at −0.5 V for pristine diode is 5.88×10^{-4} A. Its value is found to increase with ion fluence up to 2.5×10^{11} ions cm^{-2}. Slight decrease in I_R is observed around 5×10^{11} to 1×10^{12} ions cm^{-2} at which the value is 3.83×10^{-4} A. It then increases with irradiation fluence to 7.47×10^{-4} A at 1×10^{13} ions cm^{-2} and 1.5×10^{-3} A at 5×10^{13} ions cm^{-2}, respectively.

The modification of M–S Schottky barrier characteristics due to interaction with swift heavy ion beam can be understood by considering the basic phenomena of energy loss of the ion as it passes through the M–S interface. The energetic ion loses its energy inside the solid mainly through the processes of (1) Nuclear energy loss (S_n) due to elastic scattering by the target nuclei, and (2) Electronic energy loss (S_e) due to inelastic interaction with the target electrons. The electronic loss dominates at high energies whereas the nuclear loss becomes dominant only at low energy. The energy loss of the 72.5 MeV $^{58}Ni^{6+}$ ions inside the target is shown as a function of depth in Fig. 4. The energetic ion crosses the interface and moves to about 12 μm deep inside the GaAs substrate far away from the M–S interface. According to calculation performed with standard Monte Carlo simulation program SRIM 2006 [19], after passing through the 150 nm thick gold film, the energy of the ion is 69 MeV. At this energy the values of S_n and S_e in gold are respectively, 8.24 eV/Å and 2.22×10^3 eV/Å. The corresponding values in GaAs are 3.14 eV/Å and 1.05×10^3 eV/Å. Thus the mean values of nuclear energy loss and electronic energy loss at the M–S interface are 5.69 eV/Å and 1.64×10^3 eV/Å, respectively. The value of electronic loss is thus nearly 290 times that of the nuclear energy loss at the M–S interface. Electronic energy loss thus happens to be the dominant mechanism. As is well known, the nuclear energy loss mainly causes displacement of target atoms leading to defects like vacancies and interstitials, and this can increase the density of states at M–S interface. The electronic energy loss causes excitations of target electrons, and during the relaxation of these electrons various defects like vacancies, interstitials, mixing at the M–S interface, and other complex defects are created [20,21]. These defects have their energy levels lying deep inside the band gap of the semiconductor, which leads to the introduction of interface states at metal–semiconductor interface, which modifies the current transport properties

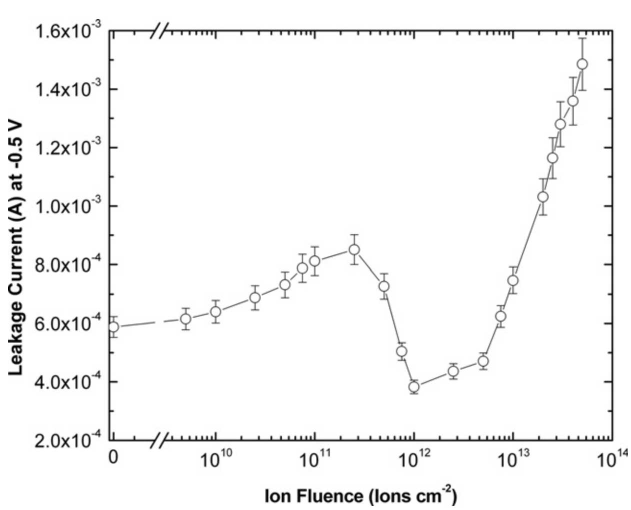

Fig. 3. Variation of leakage current with ion fluence.

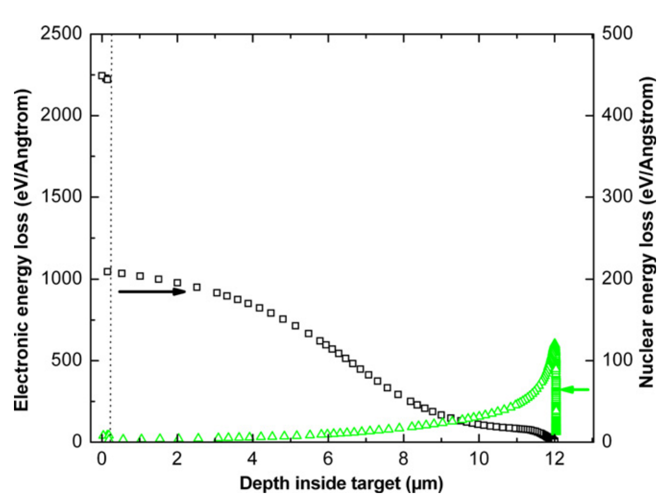

Fig. 4. Energy loss of 72.5 MeV $^{58}Ni^{6+}$ ion inside Au/n-GaAs as function of depth.

across the M–S barrier. The gold layer is unaffected by electronic loss due to strong screening of charges in metals.

It is found that ion irradiation results in an improved Schottky barrier characteristics due to the deactivation of dopants in the near interface region [7,9]. Such effect is predominantly observed in case of near interface deposition of ions. In our experiment, the swift heavy ion crosses the M–S interface and traverses deep inside the substrate (GaAs) far from the interface region. For ions at such high energies, electronic energy loss happens to be the dominant phenomenon and lead to the modification of electronic states at the M–S interface. This results in the observed variations in diode properties.

The SBH is drastically influenced by the density of interface states (D_s) at M–S interface. The original Schottky model predicts the effective height of the barrier in case of ideal M–S interface where no interfacial states are present. With increasing density of states at the M–S interface, the value of SBH approaches the Bardeen limit [22], which considers very high density of states at the M–S interface.

The value of SBH for the pristine Au/n-GaAs Schottky diode is found to be 0.55($\pm$0.01) eV, which is low in comparison to the value observed in case of ideal metal contact on n-type GaAs [23]. The lower value of SBH observed in the pristine sample may be ascribed to the presence of an interfacial layer such as an oxide incorporated during the fabrication process or in course of surface treatment. This increases the density of interface states and alters the electric field across the M–S interface resulting in reduction of the effective barrier height in comparison to ideal contact. The presence of a significant density of interface states in the pristine sample results in its slight immunity against ion irradiation. The interaction with energetic ion beam leads to modification in the density of states at the M–S interface. If large D_s are already present, the modification induced by ion beam irradiation may remain unapparent up to some irradiation fluence. Thus the diode characteristics remain nearly unchanged up at low irradiation fluences. On further irradiation when ion fluences are in overlapping range (more than 1×10^{12} ions cm^{-2}) defect combination or agglomeration of defects starts which drastically influence the Schottky barrier diode characteristics. This leads to increase in the density of states at the M–S interface and the apparent decrease in the Schottky barrier height at high irradiation fluences. With increase in fluence, the SBH is observed to decrease with irradiation to a value of 0.49($\pm$0.01) eV at 5×10^{13} ions cm^{-2}.

The ideality factor (n) is found to be 2.48 for the pristine sample, and increases with fluence to 2.7 at 7.5×10^{11} ions cm^{-2}. On further irradiation it increases with ion fluence. The ideality factor of the diode accounts for the deviation of current transport from ideal thermionic emission model. The increase in value of n shows more contribution due to field emission, thermionic field emission, and recombination–generation currents. The possibilities of these current transport processes may increase with the density of states at the M–S interface. The reverse leakage current (I_R) shows the same trend as ideality factor. With increase in the density of states at the M–S interface the possibilities for leakage paths may increase. Leakage current increases with increase in the irradiation fluence. It shows that the ion irradiation induced defects are responsible for this behavior. As the ion fluence increases, ion irradiation induced defects increase, hence the tunneling through these defect states also increases, which results in an increased value of the ideality factor.

4. Conclusion

The modifications induced in the barrier characteristics of Au/n-GaAs Schottky structure by irradiation with swift heavy ion beam (72.5 MeV $^{58}Ni^{6+}$) are analyzed at various ion fluences. In situ *I–V* measurements are performed to study the effect of ion irradiation on the properties of the diode. Diode parameters are observed to vary as function of ion fluence. The barrier height of the diode found to be 0.55($\pm$0.01) eV for pristine reduced to 0.49($\pm$0.01) eV at irradiation fluence of 5×10^{13} ions cm^{-2}. The ideality factor is observed to increase with irradiation fluence. At the M–S interface, the interactions with swift heavy ions induce the creation of defects and changes in the density of states, which lead to modification in the current transport properties through the Schottky barrier.

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