Recovery of Electrical Characteristics of Au/n-Si Schottky Junction Under ^{60}Co Gamma Irradiation

Shammi Verma, Kumsi C. Praveen, Achamma Bobby, and Dinakar Kanjilal

***Abstract*—The electrical transport characteristics of a Au/n-Si metal–semiconductor Schottky barrier junction under exposure to ^{60}Co gamma rays have been reported in this paper. The role of energy loss mechanisms in the Schottky junction due to gamma irradiation is studied using the current–voltage $(I-V)$ and capacitance–voltage $(C-V)$ measurements. The electrical characteristics were measured at various doses of gamma by incrementally increasing the exposure from 0.85 Mrad (Si) to 340 Mrad (Si) to systematically study the dose effects on electrical transport across the Schottky interface. After irradiation, the ideality factor was found to decrease initially up to a dose of 17 Mrad (Si), and thereafter, it started increasing. At a dose of 340 Mrad (Si), the characteristics of the Schottky interface were found to recover toward the pristine characteristics. The recovery effect is attributed to annealing of interface defects due to the electronic energy loss S_e of gamma ray photons.**

***Index Terms*—Defect annealing, gamma irradiation, I–V and C–V characteristics, Schottky barrier interface.**

I. Introduction

The modern micro- and nano-electronic devices have either rectifying metal–semiconductor (M–S) contacts, generally known as Schottky contacts or non-rectifying M–S contacts, called ohmic contacts as an essential part. The rectifying Schottky junctions serve as an integral part of multi-layered device structures like solar cells, spintronics devices, memory devices, high electron mobility transistors (HEMTs), etc. The interface of the Schottky device plays a crucial role in determining the eventual characteristics of the device. The interface properties depend on the choice of metal and semiconductor work functions, the interface density of states, the semiconductor cleaning and device fabrication protocols etc., [1], [2]. The technological interest is to have a controlled barrier, called Schottky Barrier (SB) of different heights depending upon the specific application. The SB devices are commonly used in radiation rich environments, e.g., in spacecraft and as detectors in nuclear and particle physics experiments. The reliability of these M–S contacts is, therefore, a major concern for the devices having M–S contacts. Other than radiation hardness testing and reliability issues of the M–S contacts, they provide a fundamental and experimentally excellent tool to study the interaction and effect of the ionizing radiation at the interface.

Swift heavy ions (SHI), low energy ions and cosmic radiation (alpha particles, protons, electrons, neutrons, and gamma rays) are the various types of radiations which affect the devices to different extents and through different mechanisms. It is well known that a highly energetic ion while interacting with a material, losses its energy predominantly to target material initially by inelastic collisions (electronic energy loss, S_e) near the entrance and then by elastic collisions (nuclear energy loss, S_n) near the end of ion range. The two kinds of energy loss mechanisms affect the interfaces in different ways. While the nuclear energy loss causes point defects at the interface, the electronic energy loss is known to create complex defect zones in material and also causes annealing of the defects. There are a large number of research papers available on the ion implantation and irradiation studies on Schottky interfaces [3], [4]. Previous investigations [5] of our group have reported that 100 MeV Ni ion irradiation exhibits annealing effects on electrical properties of Pt/n-Si SB diodes. This annealing was attributed to overlapping of the damaged regions caused by high electronic energy loss of the incident ions. In order to understand the annealing behavior due to electronic energy loss, similar Schottky interfaces were irradiated with gamma radiation up to a high total dose of 340 Mrad (Si). The gamma radiation does not have nuclear energy loss component and the displacement damage is caused only by the secondary electrons produced during gamma interaction. This study is a systematic correlation of electronic energy loss due to swift heavy ion irradiation and gamma irradiation. The dose intervals considered in the present investigation are equivalent to those of 100 MeV Ni ion fluences reported in our previous paper [5] to study the separate effect of S_e on defect evolution in the material. The effect of gamma irradiation on SB diode is studied by extracting the electrical parameters such as ideality factor (η), Schottky barrier height (Φ_B), leakage current and series resistance (R_s) from the current–voltage $(I–V)$ and capacitance-voltage $(C–V)$ characteristics before and after gamma irradiation. The irradiation results are presented and the effects of gamma irradiation on electrical transport of Schottky contacts are discussed in the paper.

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II. Experimental Details

A. Wafer Cleaning and Contact Depositions

Schottky barrier junctions were fabricated on double side polished n-type Si ⟨100⟩ wafer of resistivity 1 Ω-cm (with

$N_D \sim 10^{15}$ cm^{-3}). The wafer was properly cleaned and etched according to the standard silicon wafer cleaning procedure. In order to degrease the wafer, it was boiled for 5 min consecutively in TCE (tri-cholroethylene), acetone and propanol each. After giving a rinse in ultrapure de-ionized (DI) water (resistivity 18 MΩ.cm), the wafer is etched in a solution of DI water + HF acid (20 : 1) for removal of native oxide from the Si surface. Finally, the wafer was dried in a convection oven at 90 °C for about 15 minutes. An ohmic metal contact was deposited with 250 nm aluminum film on one side of Si wafer by thermal evaporation. On the other side of the wafer, Schottky contacts were made by depositing 50 nm of 5N pure Au metal as 2 mm diameter circular dots using photo-lithographic technique. The Au metal was deposited by thermal evaporation method under a high vacuum of the order of 10^{-7} mbar.

B. Gamma Irradiation

The devices were irradiated in "Gamma chamber 1200" located at Inter University Accelerator Centre (IUAC) in New Delhi, India. The gamma chamber 1200 consists of a compact and shielded ^{60}Co gamma irradiator with controlled modes of operation. The ^{60}Co source emits gamma photons of two different energies, 1.17 and 1.33 MeV. Thus the average gamma photon energy is 1.25 MeV. The ^{60}Co source strength was approximately 8.5 kGy/hr (~240 rad/s) during the experiment. The ^{60}Co gamma dose is measured in "Mrad" with silicon as the target material.

C. I–V, C–V Measurements

The effect of gamma irradiation on Schottky diode was studied by incrementally adding the gamma doses, starting from 0.85 Mrad (Si) up to a total dose of 340 Mrad (Si). The I–V and C–V measurements were performed after every dose and all the electrical tests were measured "not in-flux and remote tests". According to MIL-STD 750E standards, method 1019.5 [6], after every gamma dose the devices were taken out of the gamma chamber and the electrical measurements were immediately performed (within 15 minutes) to avoid post-irradiation time dependent annealing effects. As specified in standard procedure, all the measurements have been performed at an ambient temperature (~25 °C). The current–voltage characteristics were carried out using 2400 Keithley source meter and C–V measurements were carried out using Boonton-7200 capacitance meter. These instruments were programmed using LabVIEW program and the instruments were interfaced to the computer using standard IEEE 488 (GPIB) interfacing. The schematic diagram for device structure and electrical measurement set-up are shown in Fig. 1.

III. Results

The experimentally measured I–V and C–V characteristics of Au/n-Si SB interface for different total doses of gamma radiation are shown in Figs. 2 and 3 respectively.

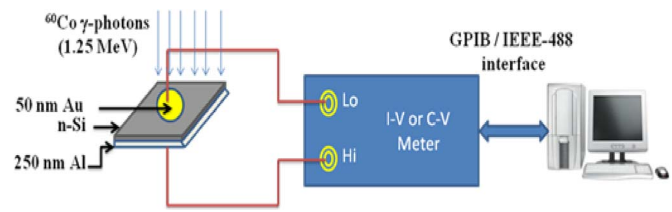

Fig. 1. The schematic diagram of M–S Schottky device structure and electrical measurement set-up.

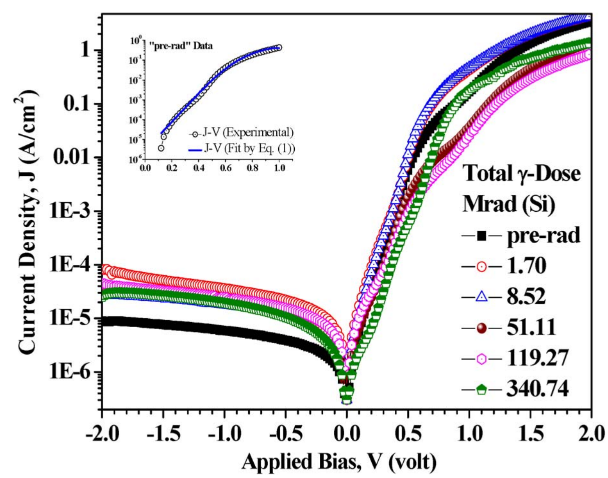

Fig. 2. The current–voltage characteristics of Au/n-Si SBD exposed to different doses of gamma radiation. For brevity, I–V curves for only a few doses are shown in the figure. The fitting to experimental data of forward pre-rad I–V curve has been shown in inset.

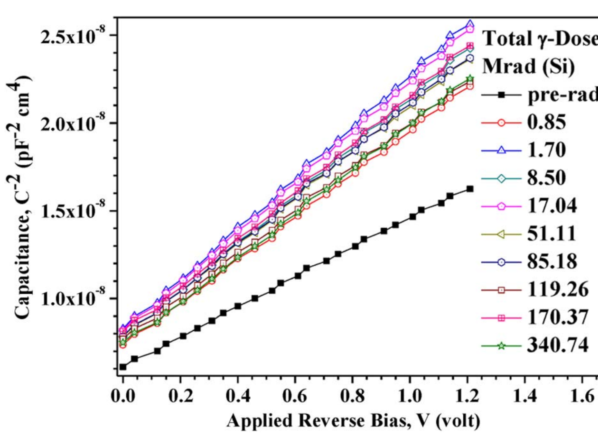

Fig. 3. The C^{-2} versus V characteristics of Au/n-Si SBD for different gamma doses.

A. Current–Voltage Characteristics

Fig. 2 shows the plots of forward- and reverse-biased current–voltage characteristics. The terminals of the SB diode were floating during gamma irradiation so that the charges can be accumulated near the interface and in the bulk of the device. There is an increase in the reverse leakage current of the SB diode with gamma irradiation dose. The effect of gamma radiation on current transport across these SB interfaces is determined from the forward current–voltage characteristics. To evaluate the ideality factor and Schottky barrier height (SBH) of the SB diode, the current–voltage characteristics

TABLE I
THE DIODE PARAMETERS OF Au/n-Si SCHOTTKY BARRIER CONTACTS FOR DIFFERENT DOSES OF GAMMA IRRADIATION

SI. No.	Gamma Dose (Mrad (Si))	Ideality Factor (η)	SBH Φ_B (eV)	SBH Φ_B^{CV} (eV)	Saturation Current(J_s) (μA/cm^2)	Series Resistance R_s(Ω)	Donor Concentration N_D ($\times10^{14}$ cm^{-3})
1	Pre-rad	2.36	0.770	1.01	1.07	21	14
2	0.85	2.34	0.745	0.88	3.07	19	9.66
3	1.70	2.32	0.748	0.86	2.76	20	8.17
4	8.50	2.17	0.760	0.86	1.77	26	8.65
5	17.04	2.09	0.766	0.86	1.42	70	8.32
6	51.11	2.87	0.761	0.88	1.71	419	8.99
7	85.18	3.31	0.742	0.88	3.61	726	8.94
8	119.26	3.79	0.741	0.91	3.66	754	9.64
9	170.37	3.77	0.761	0.88	1.75	1718	8.71
10	340.74	2.83	0.792	0.87	0.52	153	9.34

were fitted to the standard thermionic emission equation for Schottky diode [7]:

$$\boldsymbol{J} = \boldsymbol{J}_s \left[e^{\frac{qV_D}{\eta k_B T}} - 1 \right] \tag{1}$$

where $J = I/A$ is the current density, I is the diode current and A is the active device area (0.0314 cm^2). $V_D = V - I \cdot R_s$ is the voltage across device under test (DUT) i.e., the SB diode, q is electron charge, k_B is Boltzmann constant, T is ambient temperature, V is applied voltage and R_s is the series resistance of diode. The parameter η is the ideality factor which is a measure of deviation from ideal thermionic transport ($\eta = 1$) mechanism.

$J_s (= I_s/A)$ denotes the reverse saturation current density and is given by:

$$J_s = A^* T^2 e^{\left(\frac{-q\varphi_B}{K_B T}\right)} \tag{2}$$

where A^* is Richardson constant (equal to 110 A cm^{-2} K^{-2} for n-type Si) and Φ_B is effective SBH at zero bias condition.

In order to determine the Φ_B, η, R_s and J_s we have employed an iteration method using SIGMA Plot 5.0 software. Here Φ_B, η, R_s and J_s are considered as the variable input parameters. The initial values of these parameters were determined from the forward $ln\ J$ versus V method where the slope of linear part gives ideality factor (η) and its intercept gives J_s and Φ_B [7], [8]. The series resistance R_s was determined from the Cheung's model [8]. The final values of Φ_B, ηR_s and J_s were obtained after a finite number of iterations of the experimental data based on equation (1). A detailed description of the iteration method is given elsewhere [9].

B. Capacitance–Voltage Characteristics

The variation in capacitance (C) of SB diode under gamma irradiation is shown in Fig. 3; which is a plot of C^{-2} versus V. The capacitance of the DUT varies with gamma irradiation due to accumulated charges at the interface. The C^{-2} versus V plot shows that initially the capacitance of the SB diode decreases with increase in gamma dose and further there is no significant change in capacitance of the device. The C^{-2} versus V characteristics were fitted using ideal C–V relationship [7] of the SB diode given by equation (3). The donor concentration and SBH are extracted from the slope and intercept of the C–V curve respectively

$$\frac{1}{C^2} = \left(\frac{2}{qA^2 \varepsilon_s N_D} \right) \left[V + V_i - \frac{k_B T}{q} \right] \tag{3}$$

(V is taken +ve here).

IV. DISCUSSIONS

The interaction of gamma radiation with material is purely inelastic. Out of three principal modes of gamma interaction with material, the Compton scattering is the dominant mode of interaction in silicon for 1.25 MeV gamma photons. The gamma radiation interacts with the electrons of the target atoms via electronic energy loss mechanism. The recoiled Compton electrons displace a primary knock-on atom (PKA) out of Si lattice site and create Frenkel pairs (pairs of a Si interstitial and a vacancy). The threshold of this process is ~25 eV/pair. On the other hand, the scattered gamma photons lose their energy via photoelectric effect, thereby ionizing the target atoms and creating electron hole pairs. For Si, the energy required to generate an electron hole (e-h) pair is 3.6 eV; therefore 1 rad (Si) gamma radiation generates about 4×10^{13} (e-h) pairs cm^{-3} in Si [10]. These electrons are called secondary electrons and if these secondary electrons have sufficient energy, they create further displacement damages in the target material. The radiation damage caused by gamma photons is, therefore, exclusively due to point defects (interstitials and vacancies) because the formation of complex defect clusters is not possible in this case [3], [10], [11].

The electrical parameters of the device from I–V and C–V measurements are tabulated in the Table I. The high value of ideality factor 2.36 for pristine sample indicates that the current transport is not purely thermionic emission. The current transport is also assisted by other mechanisms like generation–recombination (G–R) currents and trap or defect-assisted tunneling through the barrier [12]–[14]. It may be attributed to initial high density of interface states at M–S junction caused during wafer processing (wafer cleaning and oxide etching) and during metal deposition by thermal evaporation. The ideality factor keeps decreasing up to a dose of 17 Mrad (Si) of gamma radiation, showing that the contribution of current transport mechanisms other than the thermionic emission is decreasing. The marginal improvement in the ideality factor is attributed to annealing of the interfacial trap centers due to the secondary electrons produced during gamma irradiation.

After a dose of 17 Mrad (Si), the electrical parameters of SB diode start deteriorating. It is evident from Table I that the ideality factor and series resistance increases after 51 Mrad (Si) of gamma dose. The increase in η and R_s is due to radiation induced charge build-up at SB interface after gamma irradiation. The charge build up takes place at the interface due to the slow moving trapped holes which are left in the valance band (VB) after the electrons have moved to conduction band (CB). The space-charge build-up at the interface leads to reverse current enhancement and excess forward current [15]–[18] of the SBD. Further, at highest dose of 340 Mrad (Si), the recovery in the electrical characteristics has been observed. The ideality factor and series resistance values have improved and the forward I–V characteristics recover towards the pre-irradiated I–V characteristics. The proposed mechanism of the recovery in electrical characteristics is annealing effects of electronic energy loss (S_e) by gamma radiation. After 170.37 Mrad (Si) gamma dose, a dynamical equilibrium between two competitive processes i.e., creation and annihilation of defects starts. As mentioned earlier gamma irradiation creates e-h pairs at the SB interface. The progressive irradiation to higher levels of absorbed gamma dose causes space charge build-up and thus, an increase in the surface recombination velocity. After a threshold total dose the generation and recombination rates of these e-h pairs reaches equilibrium and hence the partial recovery in the electrical characteristics is observed. Similar results have been observed after swift heavy ion irradiation [5]. The threshold fluence in case of 100 MeV Ni ions irradiation on Pt/n-Si interface occurred near 4×10^{12} ions cm^{-2} [5]. The recovery in gamma irradiated SB interface also starts around 340 Mrad (Si) which is equivalent to $\sim 2 \times 10^{12}$ ions cm^{-2} fluence of 100 MeV Ni ion beam. The second mechanism that may anneal the defects is the rise in temperature of the DUT. Several reports mention that the electrical characteristics of gamma irradiated semiconductor devices, particularly Schottky diodes recover to its pre-rad characteristics after a low temperature annealing [16], [17]. The displaced atoms in irradiated material diffuse to re-occupy their normal lattice sites due to sufficient thermal energy obtained during low temperature annealing. The continuous exposure to gamma radiation up to very high doses can increase the temperature of DUT. However it was observed that the temperature of the irradiation chamber went up to 40 °C even after 340 Mrad dose. The displacement related defects have been reported to be stable up to 150 °C and they don't anneal below this temperature [19]. Therefore annealing of point defects at high doses of gamma radiation is only due to electronic energy loss mechanism.

The SBH and the donor concentration (N_D) remain almost constant after irradiation with first dose of 0.85 Mrad (Si). Further from equation (2) it is obvious that variation in saturation current corresponds to variation in SBH. Therefore, saturation current also remains almost fixed. The constant SBH during irradiation reveals that Fermi level is strongly pinned at the interface. Further, the position of Fermi level is affected by effective concentration of ionized dopants (N_D) at the interface. Since there is no major change in donor concentration with gamma irradiation, Fermi level and hence SBH does not change much with gamma irradiation.

V. Conclusion

The electrical characterizations (I–V and C–V) of the gold (Au) Schottky barrier contact on n-Si (100) under the controlled and incremental doses of the gamma irradiation have been studied systematically. Though there is no significant effect of gamma irradiation on SBH and donor concentration (N_D) for dose as high as 340 Mrad (Si) but a marginal improvement in ideality factor of the Schottky interface was observed for initial small gamma doses. The electrical characteristics have been observed to recover back to their pre-irradiation characteristics at the final gamma irradiation dose (340 Mrad (Si)). The recovery of electrical characteristics of Schottky barrier interface is correlated with annealing effects of the electronic energy loss due to swift heavy ion irradiation. It is understood that the recovery effects in the device parameters is due to annealing of the defects by electronic energy loss. The recovery is observed at high doses of gamma irradiation where a dynamic equilibrium in defect creation and annealing starts.

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