Dynamics of modification of Ni/n-GaN Schottky barrier diodes irradiated at low temperature by 200 MeV Ag^{14+} ions

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Ni/GaN Schottky barrier diodes were irradiated with 200 MeV Ag ions up to fluence of 1×10^{11} ions/cm^2 at the substrate temperature of 80 K. Post-irradiation current-voltage measurements showed that the ideality factor, n increased and the reverse leakage current, I_R decreased with increase in fluence. But Schottky barrier height, ϕ_b increased only marginally with increase in ion fluence. *In situ* resistivity measurements showed orders of magnitude increase in resistivity of GaN epitaxial film with irradiation fluence. Cross-sectional transmission electron microscopy images revealed the presence of defect clusters in bulk GaN after irradiation.
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Swift heavy ion (SHI) irradiation of semiconductor devices is important for understanding their behavior under hard radiation conditions such as space and nuclear reactors. Electronic devices in satellites and detectors in nuclear reactors are prone to exposure of swift high energy ion irradiation. Studying a component of these devices, namely, Schottky barrier diodes in GaN semiconductor under irradiation conditions is very important for understanding and simulating complete device behavior. GaN has attracted an immense interest due to its electronic and optoelectronic device applications. One of its attractive but less explored property is its immunity to radiation harsh conditions.[1,2] GaN implantation has earlier been investigated in low energy regime (at keV energies) by some groups mainly for studying structural disordering and defect formation in GaN thin films.[3–7] In the previous studies, it has been assumed that lattice defects are produced as a result of nuclear (or elastic) collisions, while electronic energy loss processes (i.e., the excitation of electronic subsystem of the solid) have a negligible role in defect formation in radiation resistant materials such as in GaN under bombardment with keV ions.[6,8] But in SHI irradiation range, the electronic energy loss in GaN is at least two orders of magnitude higher than the nuclear energy loss, as calculated by the simulation program SRIM 2008.[9] For example, with increasing the energy of Ag ions from 300 keV up to 200 MeV, electronic energy loss (S_e) in GaN increases from <1 to 26 keV/nm. So the energy loss process should be dominated by electronic energy loss particularly at lower depths.[10] In SHI regime, experimental data/studies are scarcely available in GaN Schottky barrier diodes[11] as compared to Si and GaAs based Schottky barrier diodes (SBD).[12–14] Recent studies by Kumar *et al.* has shown that Ni/GaN Schottky barrier diodes parameters almost remain unchanged with increase in fluence (except some image force lowering variations), when irradiated by 200 MeV Ag ions.[15] Results were correlated with the increase in semiconductor resistivity caused by defects creation by high electronic energy loss process.[15] Apart from these studies, we could not find any other study on SHI irradiation of GaN Schottky diodes. Lack of experimental data is particularly more evident in SHI irradiation at low temperatures. In the present investigations, we report on the effect of low temperature (80 K) irradiation with 200 MeV $^{107}Ag^{14+}$ ions on the electrical and micro structural properties of GaN epitaxial layers and Ni/n-GaN Schottky barrier diodes.

GaN epitaxial layers used in this study were grown on c-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD) technique. The GaN epitaxial layers were 3.6 μm thick and un-intentionally doped ($N_D^+ \sim 3 \times 10^{16}$ cm^{-3} by Hall measurements). For low temperature irradiation studies, three set of samples were prepared. In first set, GaN epitaxial layer samples (3R1-3R4) of 1×1 cm^2 were cut from GaN/sapphire wafers for irradiation at different fluences. For second set, identical Ni/n-GaN Schottky barrier diodes were prepared on 1×1 cm^2 size of samples. Third set was a 1×1 cm^2 size epilayer sample having four ohmic contacts at corners for *in situ* resistivity measurements as described below. All samples were mounted on a ladder having arrangements for cooling down to 80 K by pouring liquid N_2 inside the hollow ladder. Ni/n-GaN Schottky diodes were prepared by depositing Au/Ni (100/40 nm) on n-type GaN epitaxial layers by electron-beam deposition system at a base pressure of 10^{-8} millibars, with Au acting as capping layer to Ni. A standard layer scheme Ti/Al/Ni/Au (20/100/20/100 nm, 730 °C RTA annealed) was used as an ohmic contact and deposited before Schottky contact metallization. The sample cleaning process and device processing methodology could be found in more detail in our earlier report.[16] The identical diodes (1 mm dia.) were irradiated by 200 MeV $^{107}Ag^{14+}$ ions at various fluences in the range of 5×10^9 to 1×10^{11} ions/cm^2 using Pelletron Accelerator facility available at Inter University Accelerator Centre (IUAC), New Delhi. Sample (ladder) temperature was maintained at 80 K during irradiation. To avoid channeling effects, the angle of incidence was kept at 7° with respect to surface normal of the sample. A Keithley sourcemeter (model 2612) was used for *in situ* resistivity measurements. Keithley semiconductor analyzer (model 4200) was used for offline electrical characterization of all the diodes. Samples for

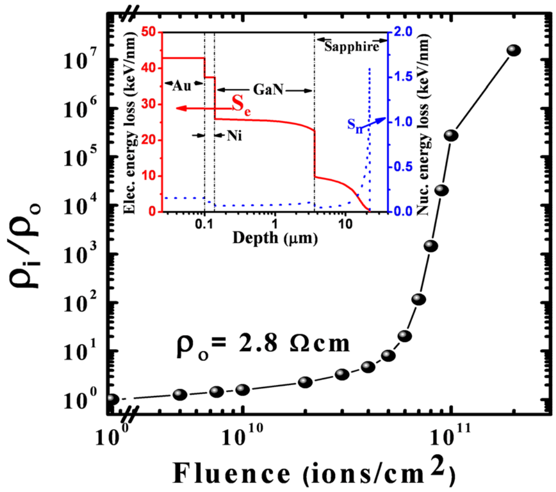

FIG. 1. *In-situ* resistance measurements of GaN epilayers irradiated at temperature 80 K by 200 MeV $^{107}Ag^{14+}$ ions at various fluences. Inset shows SRIM simulation for Ni/GaN Schottky diodes irradiated with 200 MeV $^{107}Ag^{14+}$ ions.

cross-sectional transmission electron microscopy (XTEM) analysis were prepared by FIB system and a scanning transmission electron microscope (STEM) FEI TITAN 80–300 was used for the micro-structural investigations of GaN epitaxial layers.

The Fig. 1 shows normalized resistivity data for *in situ* measurement with fluence in the range of 5×10^9 and 3×10^{11} ions/cm^2 measured at a sample temperature of 80 K. The resistivity was measured using Van der Pauw method up to maximum fluence range limited only by resistance range of instrument. Pristine (un-irradiated) sample had a resistivity of 2.8 Ω-cm (at 80 K). The resistivity increased almost exponentially after irradiation as shown in Fig. 1 and Table I (last column). Similar trend is also observed in our earlier room temperature (300 K) irradiation investigations.[15] A Monte-Carlo simulation (SRIM-2008) of 200 MeV $^{107}Ag^{14+}$ ions irradiation in Schottky diode structure of Au/Ni/n-GaN/Sapphire (100 nm/40 nm/3.5 μm/300 μm) was carried out (see inset of Figure 1). The simulations showed that at small depths in GaN electronic energy loss rate (S_e) is more than two orders higher than nuclear energy loss (S_n) for 200 MeV Ag ion beam. This high value of S_e can cause complex defect formation at M-S interface as well as in GaN layer.[10] Generally, energy levels corresponding to defects and vacancies are of acceptor nature and act as traps for charge carriers resulting in decrease in carrier density N_D^+ thereby increasing the resistivity of the samples.[14,15]

Schottky diodes of Ni/GaN were irradiated at temperature of 80 K by 200 MeV $^{107}Ag^{14+}$ ions at fluences between 5×10^9 and 1×10^{11} ions/cm^2. Electrical characterization of these diodes was performed at 300 K after irradiation. The current voltage characteristics of pristine and irradiated Schottky barrier diodes are shown in Fig. 2. It should be mentioned that the characteristics shown here demonstrate an average trend which was determined for a group of at least five diodes at each fluence value and have almost identical electrical properties. The thermionic emission equation for *I-V* characteristics is given by[17,18]

$$I = I_O \exp\left(\frac{q[V - IR_S]}{nkT}\right), \tag{1}$$

$$I_O = AA^{**}T^2 \exp\left(\frac{-q\phi_{ap}}{kT}\right), \tag{2}$$

$$n = \frac{q}{kT\left(\dfrac{dV}{d\ln I}\right)}. \tag{3}$$

Here, I_o is the reverse saturation current, R_S is series resistance, A is diode area, A** is Richardson constant (taken as 26.4 A/(cm^2 K^2), ϕ_{ap} is the measured barrier height, n is ideality factor, k is Boltzmann's constant, and other symbols have their usual meanings.[17] The Schottky barrier height (SBH) and ideality factor are calculated from the intercept and slope of forward log *I* vs. *V* characteristics from Fig. 2. Table I lists the measured barrier height, ideality factor, reverse leakage current, and series resistance calculated using Cheung and Cheung method for pristine and irradiated samples.[19] For pristine (un-irradiated) diode, similar results have been reported by other groups.[20–22] It can be seen that the Schottky barrier height increases/remains constant, while ideality factor showed clear degradation of devices. For the initial SBH calculations, we have neglected the image force lowering in Eq. (2). As we know that the measured or apparent barrier height is given by $\phi_{ap} = \phi_b - \Delta\phi_b$, where $\Delta\phi_b$ is the image force induced barrier lowering.[18] Also, since $\Delta\phi_b \propto (N_D^+)^{1/4}$, where N_D^+ is the donor concentration.[18] For image force calculations, it can be assumed that donor concentration N_D^+ in GaN is $\sim 3 \times 10^{16}\,cm^{-3}$ for pristine sample and it decreases roughly by a factor inversely proportional to increase in resistivity of films with irradiation.[15] We calculated the image force lowering $\Delta\phi_b$ for pristine as well as irradiated diodes and is shown in Table I. For pristine diode it is 0.06 eV, while 0.03 and 0.009 eV for 5×10^9 and 1×10^{11} ions/cm^2 fluence values. Therefore decreasing magnitude of image force lowering at zero bias might be responsible for observed increase or unchanged behavior of Schottky barrier height for the irradiated diodes. The

TABLE I. Calculated Schottky diode parameters.

Fluence (ion/cm^2)	Ideality factor, *n*	Barrier height, ϕ_b (eV)	Rev. leak. curr., I_R (A) at −1 V	Series resistance, Rs (Ω) of diode	Image force lowering, $\Delta\phi_b$ (eV)	Resistivity of GaN epilayer, (*in-situ* at 80 K) (Ω cm)
Pristine	1.3	0.79	2×10^{-5}	40	0.06	2.8
5×10^9	1.6	0.83	1×10^{-5}	0.65×10^3	0.03	3.6
1×10^{10}	1.6	0.82	2×10^{-6}	0.88×10^3	0.028	4.6
5×10^{10}	2.0	0.80	3×10^{-6}	9.72×10^3	0.015	19.4
1×10^{11}	2.4	0.83	4×10^{-7}	7.33×10^4	0.009	678.6

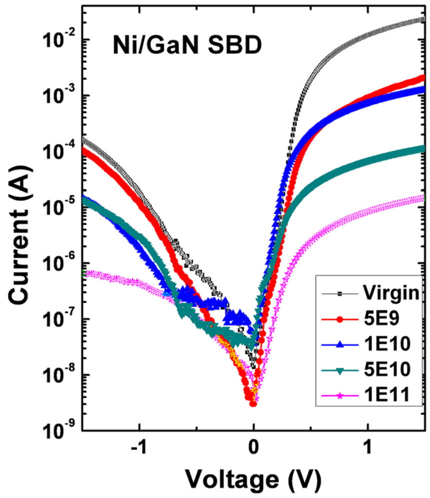

FIG. 2. I-V characteristics of Ni/GaN Schottky diodes irradiated at temperature of 80 K with 200 MeV $^{107}Ag^{14+}$ ions at fluencies between 5×10^9 and 1×10^{11} ions/cm^2.

decreased magnitude of image force may also be responsible for observed little decrease in reverse leakage current characteristics. However, the presence of defects at the interface of the metal/GaN could also assist charge transport mechanisms other than thermionic emission, which then should result in increase in the value of ideality factor of irradiated Schottky barrier diodes as compared to the pristine diode.

The epitaxial sample (3R4) irradiated at 5×10^{11} ions/cm^2 was characterized by XTEM for detailed micro-structural analysis. Fig. 3 shows XTEM bright field images for sample 3R4. There are two regions observed in the GaN epilayer, marked as thick and thin regions in graph. In the thick region part, tight thickness fringes indicate a steep wedge shape of thick sample region. TEM contrasts indicate dislocation loop in the region. For thin region, homogeneous contrast indicates a continuous shape of this sample region. In addition, in the inset of Fig. 3 regions of high density could be seen which are lined up perpendicular to the layer surface. These high-density regions demonstrate defect clusters of diameters from several nm to about 20 nm. Fig. 4(a) shows low angle annular dark-field (LAADF) TEM image of same sample which allow one to

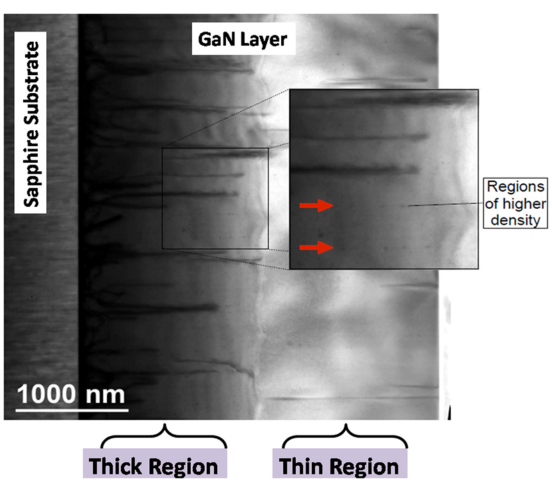

FIG. 3. TEM bright field images showing presence of aligned defects of higher density for epitaxial sample irradiated at 5×10^{11} ions/cm^2.

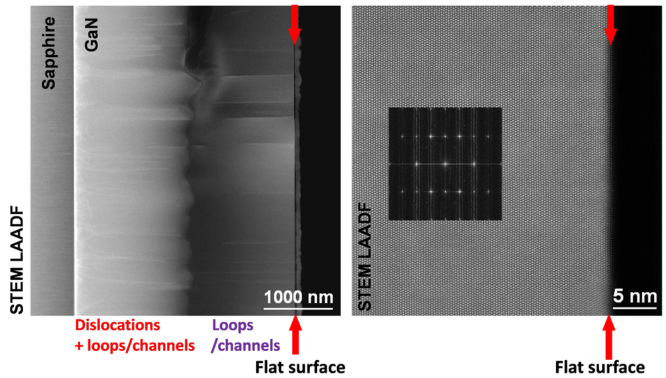

FIG. 4. STEM/LAADF contrast image (left) and High resolution LAADF (right) for epitaxial GaN sample irradiated at 5×10^{11} ions/cm^2.

view enhanced contrast from defects. Thick and thin regions from Fig. 3 are also visible in Fig. 4(a). The surfaces of the layers appear to be flat as shown in Figs. 4(a) and 4(b). We found long, straight defects in the GaN layer, which are perpendicularly oriented to the surface, and which probably correspond to dislocation loops, dipoles (vacancy loops) or channels. In the extreme case, channels were formed with diameters up to 10 nm. Fig. 4(b) shows atomic resolution image taken in LAADF STEM mode. This image shows absence of amorphization on the surface and in the bulk, which is visibly crystalline in image. Thus, at irradiation fluence of 5×10^{11} ions/cm^2, small aligned defects are produced by the incident SHI irradiation but their density is not very high, although resistance of sample has increased appreciably.

The origin of these defects at low temperatures is not cleared yet due to lack of experimental data. In GaN there are only a few experimental investigations in SHI irradiation regime and there is no study data available for SHI irradiation done at low temperatures. Kucheyev *et al.* have indicated that defect accumulation with fluence in GaN could likely be accounted for observed damage in SHI irradiation regime.[6] These defects have some minimum fluence and energy deposition criteria to be observed as clusters of defects and tracks. With Au (200 MeV, 2×10^{11} ions/cm^2 at 300 K) ions they observed clear tracks which were not amorphous.[6] However, with Ag (200 MeV, 5×10^{12} ions/cm^2 at 300 K and 5×10^{11} ions/cm^2 at 80 K), we could observe only aligned defect clusters.[10,15] Difference in S_e for Au (34 keV/nm) and Ag (26 keV/nm) could be one reason. For the present case substrate temperature might also have some role in defect evolution. So nothing conclusive can be said on the physical origin of point defects in these devices. For low temperature *in situ* resistivity measurements, the high resistivity observed could possibly be due to two reasons, one due to irradiation and second due to increased sample resistivity at low temperatures. Therefore, exact calculations of image force lowering could not be done in this case. Relatively low density of visible defects in TEM images as compared to room temperature data is probably due to low fluence value (5×10^{11} as compared to 5×10^{12} ions/cm^2 in Ref. 15).

In conclusion, it is observed that Ni/GaN Schottky diodes when irradiated in the fluence range of 5×10^9 to 5×10^{11} ions/cm^2 (at 80 K), showed an increase in ideality factor values and little or no change in Schottky barrier heights. There is also a decrease in the value of reverse leakage current observed. Schottky barrier lowering or defect assisted tunneling might be responsible for observed electrical properties. Formations of complex defects caused by defect accumulation or intense ionization were observed in XTEM images.

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