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Electrical and microstructural analyses of 200 MeV Ag^{14+} ion irradiated Ni/GaN Schottky barrier diode

Ashish Kumar,[1] A. Hähnel,[2] D. Kanjilal,[3] and R. Singh[1]
[1]*Department of Physics, Indian Institute of Technology Delhi, New Delhi 110016, India*
[2]*Max-Planck Institute for Microstructure Physics, Weinberg 2-06120, Halle, Germany*
[3]*Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India*

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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. The 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 increased only marginally with increase in fluence. Cross-sectional transmission electron microscopy images revealed the presence of defect clusters in bulk GaN after irradiation. However, the Ni/GaN interface did not show any intermixing or degradation after the irradiation. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4758929]

GaN has attracted much of interest in electronic and optoelectronic device applications over the past decade mainly due to many of its unique properties, such as wide band gap, high breakdown voltage, and high saturation velocity. One of these attractive but less explored properties is immunity of GaN in radiation harsh conditions.[1,2] GaN epitaxial layers and devices have been explored in low energy (keV) radiation regime.[3–5] But, there are hardly any studies available in GaN based devices, in particular, for Schottky barrier diodes (SBDs) in swift heavy ion (SHI) irradiation.[6] Kucheyev and some other groups have investigated GaN thin films for structural disordering and defect formation.[7,8] In keV energy regime, it has been found that the 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.[8,9] But, it is important to point out that in SHI irradiation range, electronic energy loss in GaN is at least two orders of magnitude higher than nuclear energy loss, as calculated by the simulation program SRIM 2008.[10] So, the interaction mechanism is dominated by electronic energy loss process particularly at low depths. In this SHI bombardment regime, intense ultrafast excitation of valence electrons occurs along ion paths. Apart from the fundamental physics point of view, GaN's applications in radiation harsh condition and in space satellite communication makes this far more technologically important to simulate the devices, current transport, and micro structural changes that may affect its electrical properties. Si and GaAs based SBDs have been studied by Singh *et al.*[11,12] and some other groups in SHI irradiation regime.[13] The investigation by Baranwal[6] has shown that ideality factor decreased with increase in fluence in Au/GaN Schottky diode irradiated by 50 MeV Ni ion. While the barrier height (Φ_b) first increases then decreases with ever increasing irradiation fluence. Results are correlated with the change in interface states density at the MS interface caused by localized heating and defects creation by high electronic energy loss process. Apart from this study, we could not find any other study on SHI irradiation of GaN Schottky diodes. Lack of experimental data makes it very difficult to understand transport mechanism in GaN Schottky barrier diodes conclusively. In this letter, we report about the effect of 200 MeV $^{107}Ag^{14+}$ ions irradiation on the electrical and micro structural properties of 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). The GaN epitaxial layers were 3.6 μm thick and un-intentionally doped ($N_D^+ \sim 3 \times 10^{16}\,cm^{-3}$ by Hall meas.). A sample cleaning process of trichloroethylene, acetone, and isopropyl alcohol solutions, respectively, in ultrasonicater bath (10 min each) was used for sample cleaning. A pre-metallization dip in HCl:H_2O (1:1) solution (1 min) followed by rinsing in DI-water were used before each metallization for oxide removal. Ni/n-GaN Schottky diodes have been prepared by depositing Au/Ni (100/40 nm) on n-type GaN epitaxial layers by e-beam deposition system at a base pressure of 10^{-8} mbar, with Au acting as capping layer to Ni. A standard layer scheme Ti/Al/Ni/Au (20/100/20/100 nm, 730 °C RTP annealed) is used as ohmic contact and deposited before Schottky metallization. The identical diodes (1 mm diam) were irradiated by 200 MeV $^{107}Ag^{14+}$ ions at various fluences in the range of 5×10^{10} and 1×10^{11} ions/cm^2 using Pelletron Accelerator facility available at Inter University Accelerator Centre, New Delhi. For *in-situ* resistivity measurements, a separate $10 \times 10\,mm^2$ sample having four ohmic contacts at corners in Van der Pauw configuration was used. A Keithley sourcemeter (model 2612) was used for *in-situ* resistivity measurements. To avoid channeling effects, the angle of incidence was kept at 7° with respect to surface normal of the sample. Keithley semiconductor analyzer (model 4200) was used for offline electrical characterization of all the diodes. Samples for cross-sectional transitional electron microscopy (XTEM) analysis were prepared by FIB system. For the microstructure investigation of the Ni/GaN Schottky diode, a scanning transmission electron microscope (STEM) FEI TITAN 80–300 was used, which was operated at 300 kV.

The current voltage characteristics of pristine and irradiated Schottky barrier diodes are shown in Figure 1. It should be mentioned here that for analysis, we have used at least

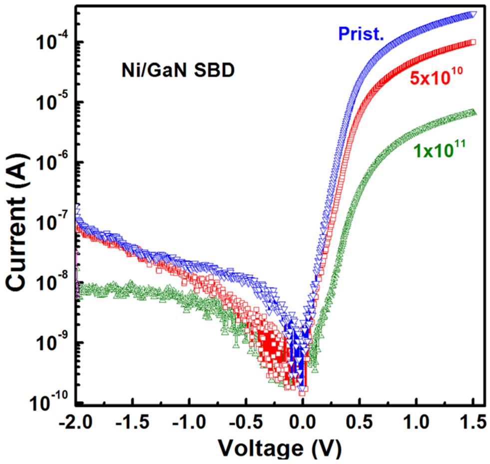

FIG. 1. Semilog forward and reverse I-V characteristics measured at room temperature for Ni/*n*-GaN Schottky barrier diode at different irradiation fluences.

five diodes at each fluence value and have almost identical electrical properties. The characteristics shown here demonstrate an average trend which was determined for a group of diodes. The I-V characteristics have been analyzed by thermionic emission equation which is given by[14,15]

$$I = I_O \exp(q[V - IR_s]/nkT), \tag{1}$$

$$I_O = AA^{**}T^2 \exp(-q[\phi_b - \Delta\phi_b]/kT), \tag{2}$$

$$n = q/kT(dV/d\ln I). \tag{3}$$

Here, I_o is the reverse saturation current, R_S the series resistance, A the diode area, A** the Richardson constant (taken as 26.4 A/(cm^2 K^2), Φ_b the barrier height, $\Delta\Phi_b$ the image force induced barrier lowering, n the ideality factor, k the Boltzmann's constant, and other symbols have their usual meanings. The barrier height and ideality factor are calculated from the intercept and slope of forward log I vs. V characteristic from Figure 1. The value of Φ_b is not very sensitive to the choice of A**, since at RT a 100% increase in A** will cause an increase of only 10 meV which is less than kT at RT.[15] For the initial calculations, we have neglected the image force in Eq. (2). Table I lists the calculated barrier height, ideality factor, reverse leakage current, and series resistance calculated using Cheung and Cheung method[16] for pristine and irradiated samples. A careful observation shows that the ideality factor increases with increase in fluence while the barrier height shows only a marginal increase with fluence. The study by Baranwal *et al.* in Au/GaN Schottky diode had shown that barrier height first increases then decreases with increase in fluence. They correlated the increase in barrier height with increasing interface state density at MS interface by nuclear energy loss process and approaching Bardeen limit for Schottky barrier. Further decrease in Schottky barrier height (SBH) and improvement in ideality barrier were attributed to localised heating as a result of the low fluence.[6] Kumar *et al.*[17] have accounted the presence of high recombination current due to irradiation caused defect concentration for the degradation in forward characteristics of 130 MeV Au^{12+} ion irradiated Au/n-Si Schottky diodes. But, this analogy cannot be used as such in Ni/GaN diode. From Eq. (2), measured or apparent barrier height is given by $\phi_{ap} = \phi_b - \Delta\phi_b$. We calculated the image force lowering $\Delta\Phi_b$ for pristine as well as irradiated diodes. For pristine diode, it is 0.06 eV while 0.03 and 0.01 eV for 5×10^{10} and 1×10^{11} ions/cm^2 fluence values. 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 and it decreases roughly by a factor inversely proportional to increase in resistivity of films with irradiation as is shown in Figure 2. The Figure 2 shows *in-situ* resistivity measurement with fluence in the range of 1×10^{10} and 1×10^{11} ions/cm^2. Also, series resistance calculations from diodes are almost equal to sheet resistance at same fluences which also validates our assumption.

For detailed microstructural investigation, we performed cross-sectional TEM of the interface of Au/Ni/GaN contacts irradiated by 5×10^{12} ions/cm^2 fluence as shown in Figure 3(a). At this fluence, electrical characterization of diodes was not possible due to very high resistance of films. It can be seen from Figure 3(a) that there is no or little inter-mixing of Ni in GaN or vice versa at such high fluence value. Even Au-Ni interface is sharp. However, we found indication of structural damage and point defects in GaN layers. That is demonstrated in the Figure 3(b), which shows traces being formed by lined up precipitates. Similar results in GaN epilayers have been reported elsewhere.[18] Defects in n-GaN layers are responsible for donor carrier density reduction which results in increased resistance of the film. For detailed analysis, high-resolution electron microscopy (HREM) was

TABLE I. The calculated Schottky diode parameters.

Fluence (ion/cm^2)	Ideality factor, n	Barrier height (eV) Φ_{ap}	Rev. Leak. Curr. I_R at -1 V (A)	Series resistance, Rs (Ω)
PRIST	1.6	0.79	2×10^{-8}	2 k
5×10^{10}	2.0	0.80	1×10^{-8}	70 k
1×10^{11}	2.3	0.84	4×10^{-9}	5.6 M

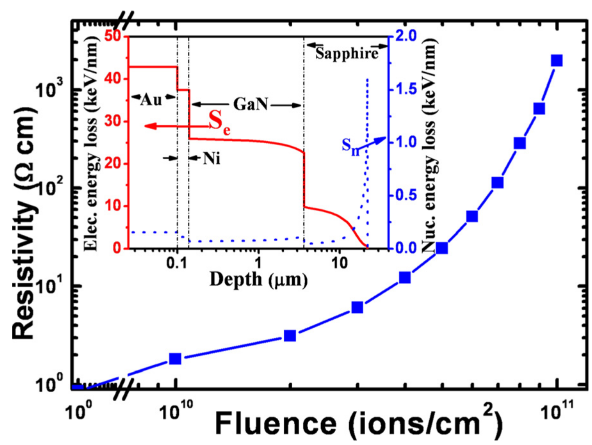

FIG. 2. *In-situ* resistivity measurement of GaN epilayers irradiated by 200 MeV Ag^{14+} ions at various fluences in the range of 1×10^{10} to 1×10^{11}ions/cm^2 using Van der Pauw technique. Inset shows the variation of S_e and S_n for Ag ions as a function of depth inside the Schottky diode (Au/Ni/n-GaN/Sapphire). The thickness stack is (100 nm/40 nm/3.6 μm/300 μm), respectively.

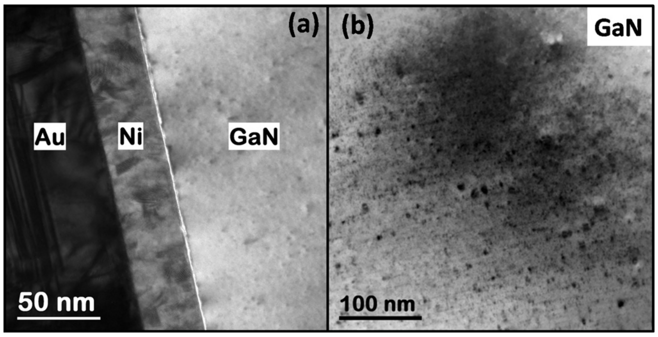

FIG. 3. TEM image of Au/Ni/n-GaN Schottky barrier diode irradiated by 200 MeV $^{107}Ag^{14+}$ ions at a fluence of 5×10^{12} ions/cm^2. Left and right panels show metal-GaN interface (a) and inside of GaN layer (b), respectively.

performed. The HREM image in Figure 4 characterizes the interface between GaN and Ni: Distinct lattice fringes of (002) GaN planes with a distance of 0.259 nm can be seen continuing to the interface which demonstrates that there is no amorphisation of films up to 5×10^{12} ions/cm^2 fluence. As detected by Energy-dispersive X-ray spectroscopy (EDX), the $\sim$2 nm thin amorphous layer in-between Ni and GaN mainly consists of oxides and carbon. This layer may thus be rather due to contamination and oxidation in device processing before metallization. EDX spectrum profiles (not shown here) across the interface also confirmed the absence of alloying or intermixing of Ni and GaN due to irradiation. This contamination layer can affect charge transport by introduction of interface states, resulting in increased ideality factor which is generally calculated by thermionic emission theory. A Monte-Carlo simulation (SRIM-2008) of 200 MeV $^{107}Ag^{14+}$ ions 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 2). The simulations showed that at Schottky barrier interface the electronic energy loss rate (S_e) is more than two orders higher than nuclear energy loss (S_n). This high value of S_e can cause complex defect formation at interface as well as in GaN layer.[18] Generally, energy level corresponding to defects and vacancies lies inside band gap of semiconductors. These energy levels are of accepter nature and act as trap for charge carriers resulting in decrease in carrier density N_D^+.[13] This may explain our assumption of decreasing magnitude of image force lowering at zero bias and hence nearly immune behavior of Schottky barrier height of irradiated samples. The 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 GaN might also induce charge transport mechanism other than thermionic emission, which then should result in increased ideality factor value of irradiated Schottky barrier diode as compared to pristine diode.

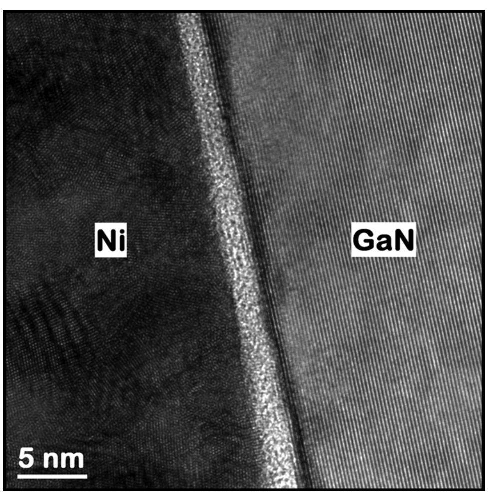

FIG. 4. High-resolution TEM image of the Ni/n-GaN Schottky diode interface irradiated by 200 MeV $^{107}Ag^{14+}$ ions at a fluence of 5×10^{12} ions/cm^2.

Current-voltage characteristics and microstructural defect creation in SHI irradiated Ni/GaN Schottky diodes have been studied by a combination of electrical and X-TEM techniques. The irradiated Schottky barrier diodes showed almost no degradation in Schottky barrier height with respect to un-irradiated diodes. The high resolution cross sectional TEM demonstrated an undamaged interface of GaN. However, TEM images of GaN layer indicated the presence of point defects by verifying precipitates. These defects decreased the carrier concentration and hence increased the series resistance in the irradiated GaN layers. In the case of SHI ions, the high magnitude of electronic energy loss rate is predominately responsible for defects formation in Ni/GaN Schottky barrier diodes. Further studies are needed to better understand the micromechanism of such a dependence of Schottky barrier diode parameters on SHI irradiation.

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