Journal of Alloys and Compounds 480 (2009) 962–965

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Effect of ion irradiation on current–voltage characteristics of Au/n-GaN Schottky diodes

V. Baranwal[a,b,*], S. Kumar[c], A.C. Pandey[b], D. Kanjilal[c]

[a] Laboratorio Nazionale, TASC-INFM, Area Science Park, Trieste 34012, Italy
[b] Department of Physics, Allahabad University, Allahabad-211 002, India
[c] Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi-110 067, India

ARTICLE INFO

Article history:
Received 31 December 2008
Received in revised form 18 February 2009
Accepted 21 February 2009
Available online 5 March 2009

PACS:
61.72.uj
61.80.Jh
73.30.+y
73.40.−c

Keywords:
Schottky diode
Gallium nitride
Ion irradiation
I–V characteristics

ABSTRACT

The effect of 50 MeV Ni ion irradiation on Au/n-GaN Schottky diode has been studied by in situ current voltage characterization. The variation of Schottky parameters with ion irradiation is discussed by varying the irradiation fluence from 5×10^9 to 5×10^{11} ions cm^{-2}. These results are interpreted on the basis of energy loss mechanisms of swift heavy ion (SHI) irradiation at the metal–semiconductor interface.

1. Introduction

The study of Schottky contacts on GaN has been a subject of extensive research due to its importance in technological applications e.g. optoelectronic devices acting in the full range of visible spectrum, as well as high temperature, high power and high frequency devices. It is extremely important to understand the ion irradiation effects on the electrical characteristics of Schottky behavior in the development of particle detectors and in the areas such as testing of radiation hardness for space applications. Several reports are available in literature on the study of irradiation effects of low energy ions, lasers and neutrons on Schottky diodes [1–3]. To the best of authors' knowledge there are no such reports available on the influence of swift heavy ion (SHI) irradiation on Schottky contacts relating to GaN films. Nevertheless, there exist few reports on the effect of SHI irradiation on Si and GaAs Schottky diodes [4–8]. Recently Kim et al. have observed the reduction in the Schottky barrier height of GaN_xAs_{1-x} alloy after increasing the nitrogen content in the alloy by ion implantation [9].

In particular, ions loose its energy via inelastic and elastic collisions with the solid in case of SHI irradiation. At higher energies the electronic energy loss due to inelastic collisions is the dominant mechanism over the elastic collisions i.e. due to nuclear energy loss. Electronic energy loss can cause interface mixing and dynamic annealing of the defects at interface [10].

In this work, we report in situ current–voltage (*I–V*) characteristics of Au/n-GaN Schottky barrier diode by varying the irradiation fluence from 5×10^9 to 5×10^{11} ions cm^{-2} of 50 MeV Ni ion beam.

2. Experimental details

The samples used to fabricate the Schottky diodes were grown by metal-organic chemical vapor deposition on (0 0 0 1) sapphire substrates of 3.5 μm thick Si doped GaN epitaxial layer. The samples were chemically cleaned in tetrachloroethylene, acetone and methanol for 10 min each followed by rinsing in de-ionized water for 5 min. To make ohmic contacts, Pd thin films of 200 nm were deposited using thermal evaporation technique in a high vacuum chamber followed by annealing in the Ar gas environment at 525 °C for 25 min. The samples were subjected to *I–V* measurements and the contacts showed the Ohmic behavior in forward and reverse bias both. For the Schottky diode fabrication Au was deposited by thermal resistive technique in an ultra high vacuum chamber on the samples with Ohmic contacts. Prior to the deposition of Au, the samples were again cleaned chemically. An Au layer of 20 nm was deposited through a stainless steel mask of 2 mm

* Corresponding author at: Laboratorio Nazionale, TASC-INFM, Area Science Park, Trieste 34012, Italy. Tel.: +39 0403756439; fax: +39 040226767.
E-mail address: baranwal@tasc.infm.it (V. Baranwal).

0925-8388/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jallcom.2009.02.094

diameter, at a base pressure of 10^{-8} mbar. The quartz crystal thickness monitor was used for monitoring the thickness of the film. The samples were irradiated with 50 MeV Ni ion beam using the 15 UD Pelletron accelerator facility at Inter University Accelerator Centre, New Delhi [11]. The fluence was varied from 5×10^9 to 5×10^{11} ions cm^{-2}. Programmable Keithley 2400 source meter was used for I–V measurements.

3. Results and discussion

Fig. 1 shows the forward I–V characteristics of the Au/n-GaN Schottky diode for the pristine as well as irradiated samples with the varying fluences from 5×10^9 ions cm^{-2} to 5×10^{11} ions cm^{-2}. The experimental data are fitted with the thermionic emission equation, which is given by [12]

$$I = I_S \left[\exp\left(\frac{q(V - IR_s)}{nk_BT} \right) - 1 \right]$$

where I_s is the saturation current and n is the ideality factor, V is the voltage drop across the rectifying barrier and R_s is series resistance.

The saturation current I_s is expressed by

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

and

$$\phi_B = \frac{k_BT}{q} \ln\left(\frac{AA^*T^2}{I_S} \right)$$

where q is the electron charge, T is measurement temperature, A^* is the effective Richardson constant, ϕ_B is the barrier height, and A is the effective area of the contact.

From the slope of the curve of Fig. 1, ideality factor n is calculated. I_s is calculated from the intercept at the y-axis of ln(I) vs V curve. The value of Schottky barrier height (SBH) is calculated by using the above equation.

The variation of the ideality factor and the barrier height with irradiation fluence is shown in Fig. 2. For pristine diode the value of ideality factor n was found to be 4.01. This high value of ideality factor shows that the current transport is not due to the thermionic emission, but may be due to other transport mechanisms like tunnelling and field emission. After irradiation with the fluence of 5×10^9 ions cm^{-2}, the value of ideality factor decreases initially to a value of 2.2 and further decreases to a value of 1.7 as the fluence increases to 5×10^{11} ions cm^{-2}. The decrease in value of ideality factor indicates that contribution due to the tunnelling and field emission for the current transport is minimised with the increase in ion irradiation fluence and the current transport mechanism tends towards the thermionic emission.

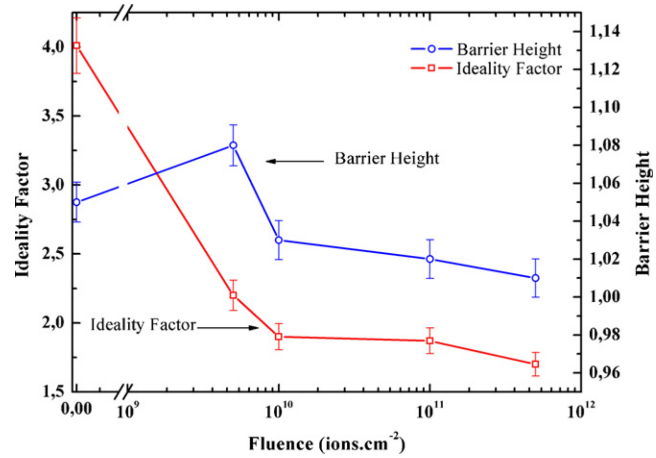

Fig. 2. The variation of the barrier height and the ideality factor with the irradiation fluence.

The other important parameter of interest is the barrier height ϕ_B of Schottky diode, which depends on the electric field across the metal-semiconductor contact and consequently on the applied bias voltage. The SBH for the unirradiated diode is (1.05 ± 0.01) eV which increases to a value (1.08 ± 0.01) eV after irradiation with the fluence 5×10^9 ions cm^{-2}. After a further increase in the fluence the value of SBH starts decreasing and goes up to (1.01 ± 0.01) eV corresponding to the fluence 5×10^{11} ions cm^{-2}. Indeed, there is not much variation in SBH with the increase in the irradiation fluence, which is clearly evident from the Fig. 2. The series resistance calculated by using Cheung and Cheung method [13] for unirradiated diode was 15.6 kΩ which increased to 17.9 kΩ after irradiation at the fluence 5×10^{11} ions cm^{-2}.

It is known that when the SHI passes through the material, it loses energy via two mechanisms: (i) nuclear energy loss (S_n), which is responsible for the displacements of the target atoms from the regular lattice sites (ii) electronic energy loss (S_e), which results from the ionization/excitation of the electrons inside the material, which dominates at the higher energies. At the metal semiconductor (MS) interface region S_e is the dominant energy loss mechanism whereas S_n dominates at the end of the ion range which is shown in Fig. 3. The ion reaches deep inside the substrate far away from the MS interface. Now at the MS interface the S_n value is 0.10 keV nm^{-1}

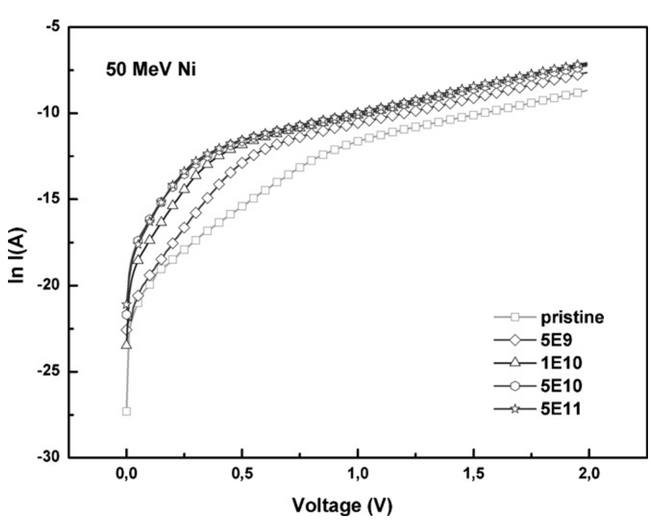

Fig. 1. Forward I–V characteristics of the pristine and the irradiated Schottky diodes.

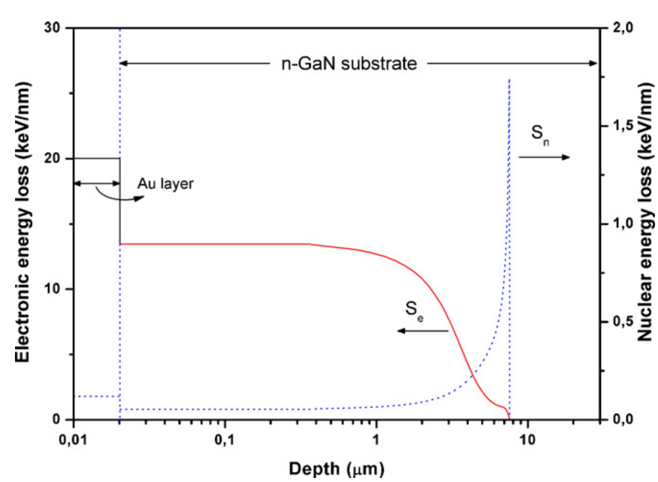

Fig. 3. The electronic and nuclear energy losses of 50 MeV Ni ions as a function of depth inside an Au/n-GaN Schottky diode.

while S_e is 20.4 keV nm^{-1} (in the GaN substrate). It is well established that S_n causes creation of defects such as vacancies and interstitials at the interfaces [12] which leads to an increase in the interface state density D_s. SHI irradiation results in the introduction of interface states at MS interface which influence the SBH [14–15]. Au layer of Schottky barrier diode is not affected by electronic excitation due to the strong screening of charge carriers in metals. According to Fermi level pinning model of Bardeen [16], when the interface density D_s is very high, the SBH of SBD on n-type semiconductor in the Bardeen limit is given by

$$\phi_{bB} = E_g - \phi_0 - \Delta\phi$$

Here, E_g is the band gap of the semiconductor, ϕ_0 is the energy level coincidence with the Fermi level before the metal–semiconductor contact was formed and $\Delta\phi$ is the lowering of the Schottky barrier due to the image force. On the other hand, when D_s is zero, then the SBH of a SBD on n-type semiconductor in Schottky limit is given by

$$\phi_{bS} = \phi_M - \chi - \Delta\phi$$

where ϕ_M is the work function of the metal and χ is the electron affinity of the semiconductor. According to S_{ze} [17] $\phi_0 = 2.27 \pm 0.01$ eV, $\Delta\phi = 0.04$ eV and $E_g = 3.39$ eV for GaN at 300 K and $\phi_M = 5.1$ eV for Au, $\chi = 4.1$ eV. Using these values the estimated values of ϕ_{bB} and ϕ_{bS} are 1.08 ± 0.01 eV and 0.96 eV respectively. This means that when interface state density D_s increases from the Schottky limit to the Bardeen limit, the SBH should increase from 0.96 eV to 1.08 ± 0.01 eV. From the *I–V* characteristics for pristine diode, the calculated value of the SBH is 1.05 eV, which means that there is a finite density of interface states D_s existing at the Au/n-GaN interface for unirradiated sample. When SBD is irradiated with a fluence of 5×10^9 ions cm^{-2}, SBH increases to 1.08 eV that shows an increase in the interface state density. For the fluence of 5×10^{10} ions cm^{-2}, the SBH is found to be 1.03 eV. There is further decrease in SBH to 1.02 eV at the fluence 1×10^{11} ions cm^{-2} which remains nearly constant to the value of 1.01 eV at the fluence 5×10^{11} ions cm^{-2} indicating that there is a decrease in the interface state density D_s. The variations of the barrier height and ideality factor are shown in the Table 1.

The observed increase in the barrier heights of Au/n-GaN after the irradiation can easily be correlated with the increase in the density of interface states at the MS interface and the consequent tendency of shift of the Schottky barrier towards the Bardeen limit. These results exhibit that with the increase in fluence, the interface state density decreases at the MS interface as compared to that of state of lowest fluence and that is the underlying effect of slower decrease of SBH with increasing fluence. As the SHI passes through the SBD, it produces strong ionization of the target atoms near the MS interface due to heavy electronic energy losses at this interface. During their relaxation, the electronic excitation can also produce phase transition as well as several specific structural defects. The defects caused thus shall have deep energy levels in band gap and if these defects have their level below the Fermi level in the band gap, they will capture the electrons, which will in turn result in a decrease in carrier concentration. During the forward bias, the Fermi level will be above the defect level and these defects will capture the electrons, decreasing the majority carrier concentration and shall result in the compensation of the positive shallow donors in the depletion region so that the effective net ionized-donor concentration is decreased. Since the barrier thickness depends on N_D through the depletion width ($\propto N_D^{-1/2}$), it will increase the contribution of tunnelling on one hand and decrease in field emission current on the other, resulting in a decrease in the value of ideality factor. As the fluence increases, the defect concentration increases whereas ideality factor decreases with increasing ion fluence.

Table 1
The variation of the barrier height and ideality factor of unirradiated as well as irradiated Au/n-GaN Schottky diode.

Fluence (ions cm^{-2})	Barrier height (φ_B)	Ideality factor (n)
Pristine	1.05	4.01
5×10^9	1.08	2.2
1×10^{10}	1.03	1.9
5×10^{10}	1.02	1.87
5×10^{11}	1.01	1.7

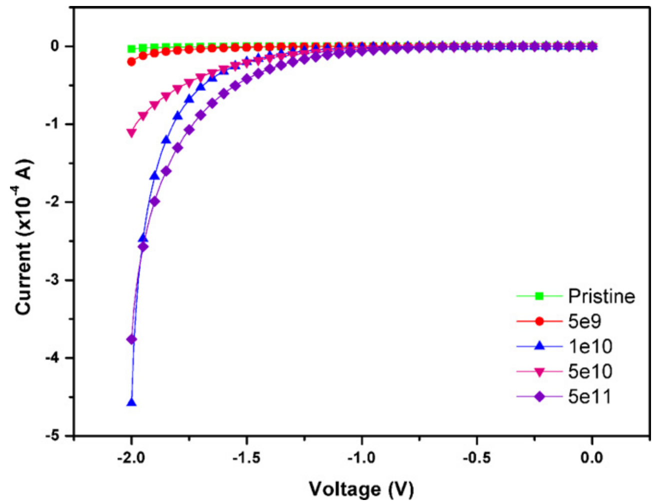

Fig. 4. Current–voltage characteristics of Au/n-GaN Schottky barrier diodes unirradiated as well as irradiated with 50 MeV Ni ions under the reverse bias.

Under the reverse bias, the Fermi level will be below the defect level and defect will emit electron to the conduction band ensuing defect assisted tunnelling current. So the leakage current will increase with increasing ion fluence. Fig. 4 shows a linear plot of current–voltage characteristics of the same Schottky diode under the reverse bias. The reverse bias leakage current was very small and of the order of 10^{-9} A at a reverse voltage of (−)0.1 V.

Fig. 5 shows the variation of leakage current with different fluences for irradiation. As is evident from the Fig. 5, the leakage current increases with the irradiation fluence up to the fluence of 5×10^{10} ions cm^{-2} and then decreases for the fluence of 5×10^{11} ions cm^{-2}.

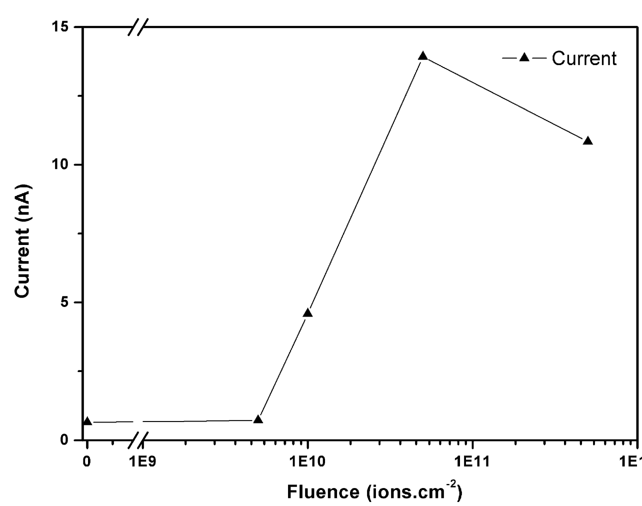

Fig. 5. The leakage current variation of the pristine as well as irradiated Au/n-GaN Schottky diode.

4. Conclusions

In this work in situ *I–V* characterization of Au/n-GaN Schottky diodes is carried out during irradiation by stopping beam after varying the fluence. It is found that ideality factor decreases after SHI irradiation while the barrier height shows an increase and decrease with ever-increasing irradiation fluence. The fidelity of ideality factor shows that current transport mechanism is thermionic emission. The improvement in the current transport, with the improvement in ideality factor is attributed to localized heating as a result of the low fluence SHI irradiation and in this way one can also control the SBH with the swift heavy ion irradiation.

Acknowledgements

One of the authors (V. B.) is grateful to UGC for financial assistance through UFUP for carrying out this work. We are thankful to the Pelletron group of Inter University Accelerator Centre, New Delhi for providing a stable beam during the in situ measurements.

References

[1] J.S. Kim, H.H. Choi, S.H. Son, S.Y. Choi, Appl. Phys. Lett. 79 (2001) 860.
[2] H.W. Jang, J.K. Kim, J.-L. Lee, J. Schroeder, T. Sands, Appl. Phys. Lett. 82 (2003) 580.
[3] C.-W. Wang, Appl. Phys. Lett. 80 (2002) 1568.
[4] S. Kumar, D. Kanjilal, Nucl. Instr. Meth. B 248 (2006) 109.
[5] R. Singh, S.K. Arora, J.P. Singh, D. Kanjilal, Rad. Eff. Def. Sol. 157 (2002) 367.
[6] R. Singh, S.K. Arora, J.P. Singh, R. Tyagi, S.K. Agarwal, D. Kanjilal, Mater. Sci. Eng. B 86 (2001) 228.
[7] S. Kumar, Y.S. Katharria, V. Baranwal, Y. Batra, D. Kanjilal, Appl. Surf. Sci. 254 (2008) 3277.
[8] S. Kumar, Y.S. Katharria, Y. Batra, D. Kanjilal, J. Phys. D: Appl. Phys. 40 (2007) 6892.
[9] T. Kim, K. Alberi, O.D. Dubon, M.J. Aziz, V. Narayanamurti, J. Appl. Phys. 104 (2008) 113722.
[10] S.O. Kucheyev, J.S. Williams, C. Jagdish, J. Zou, G. Li, Phys. Rev. B 62 (2000) 7510.
[11] D. Kanjilal, S. Chopra, M.M. Narayanan, I.S. Iyer, V. Jha, R. Joshi, S.K. Datta, Nucl. Instr. Meth. A 328 (1993) 97.
[12] M. Levalois, P. Bogdanski, M. Toulemonde, Nucl. Instr. Meth. B 63 (1992) 14.
[13] S.K. Cheung, N.W. Cheung, Appl. Phys. Lett. 49 (1986) 85.
[14] W.E. Spicer, I. Lindau, P. Skeath, C.Y. Su, J. Vac. Sci. Technol. 17 (1980) 1019.
[15] M.O. Aboelfotoh, Phys. Rev. B 39 (1989) 5070.
[16] J. Bardeen, Phys. Rev. 71 (1947) 717.
[17] J.S.M. Sze, Physics of Semiconductor Devices, 2nd ed., Wiley, New York, 1981, p. 258 (Chapter 5).