Influence of 100 MeV oxygen ion irradiation on Ni/*n*-Si (100) Schottky barrier characteristics

Sandeep Kumar,[a] Y. S. Katharria, and D. Kanjilal
Inter-University Accelerator Centre, P.O. Box-10502, New Delhi, 110 067, India

(Received 20 November 2007; accepted 18 December 2007; published online 21 February 2008)

The influences of high energy ion irradiation on the Ni/*n*-Si Schottky barrier are discussed as a function of irradiation fluence. The variations in Schottky diode parameters are studied by using *in situ* current-voltage characterization in a fluence range between 1×10^{9} and 1×10^{13} ions/cm^2. The ion irradiation results in an increase of Schottky barrier height from a value of 0.59 eV for unirradiated diode to 0.68 eV after irradiation at a fluence of 1×10^{13} ions/cm^2. A decrease of the leakage current by about two orders of magnitude was observed after ion irradiation. These results are interpreted in terms of the ion irradiation induced defects inside the materials. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2885061]

INTRODUCTION

The fabrication of metal-semiconductor (MS) contacts with specific electrical characteristics has vital importance in semiconductor industry.[1] Controlling the MS interface properties is a crucial issue in device fabrication. The semiconductor surface preparation and postmetallization annealing treatments strongly affect their reproducibility.[2,3] The introduction of a very shallow dopant layer at the semiconductor surface prior to Schottky metallization is a well-known technique of tailoring the Schottky barrier height. It is well established that a thin layer of donorlike impurities will increase the barrier height on *p*-type Si (Ref. 4 and 5) and decrease it on *n*-type Si;[6,7] the change will be opposite for acceptorlike impurities.[8] Ion implantation has found universal acceptance for this process because of its ability to introduce dopants with precise concentration profiles. The practical consequence of this constraint is the necessary dopant activation after implantation, which requires a relatively high-temperature thermal annealing step. High-temperature annealing results in dopant redistribution and, hence, partial loss of Schottky barrier height control. Any attempt to reduce dopant redistribution by lowering the thermal cycling would result in incomplete activation of the dopant as well as residual damage that could manifest itself as an increase in the leakage current and noise. Therefore, new reliable processes for a better control of the properties of Ni/*n*-Si are required. The aim of present work is to examine the possibilities of using high energy swift heavy ions (when velocity of ion is comparable to Bohr velocity of electron) to tailor the characteristics of Ni/*n*-Si Schottky barrier. The important difference in swift heavy ion (SHI) irradiation phenomenon with respect to low energy ion implantation is the high electronic energy loss (S_e) due to inelastic collisions of SHI in materials, which are initially two to three orders of magnitude larger than nuclear energy loss (S_n) due to elastic collisions. S_n dominates only at the end of ion range. In case of SHI, the range of ion is a few tens of micrometer and so ion goes deep into the substrate after modifying the interface unlike the case of low implantation where ions get implanted close to the interface. Investigations by *in situ* current-voltage measurements at the irradiation chamber are performed to monitor the modification of Ni/*n*-Si Schottky barrier with ion fluence. In this paper, we report the effects of 100 MeV O^{+8} ion irradiation on Ni/*n*-Si Schottky barrier as a function of ion fluence. It is shown that irradiation by high energy oxygen ions results in an improved value of Schottky barrier height accompanied by a decrease in the value of ideality factor.

Generally, there are variations in electrical characteristics from sample to sample even for the Schottky barrier diodes fabricated on the same wafer. The effect of ion irradiation depends on the initial or pristine conditions of the diode. Therefore, to study the true effect of ion irradiation as a function of ion fluence, it is necessary that the fluence dependent study should be done *in situ* on the same sample at various fluencies without varying other physical parameters. In the present study, *I-V* characterization of SHI irradiated Ni/*n*-Si (100) Schottky barrier diode was carried out *in situ* on the single diode keeping all physical conditions such as ion flux, temperature, and vacuum environment identical.

EXPERIMENTAL DETAILS

Schottky diodes were fabricated on *n*-type Si (100) wafer with a doping of 1×10^{15} cm^{-3}. First, a silicon dioxide layer (1 μm thick) was deposited on the wafer front side. The backside of the wafer was implanted with 5×10^{15} ions cm^{-2} of phosphorus and annealed to make a highly doped layer to make low resistivity Ohmic contact. The Ohmic contact on the highly doped side was formed by sintering of a 200 nm thick Ti/Au film. The device active area (1.1×10^{-2} cm^2) was defined by standard optical lithography and oxide wet etches. The Schottky contact was formed by thermal evaporation of about 150 nm thick Ni film. Ni was chosen because diodes could be made with a reproducible barrier height (0.59 eV). The ion irradiation

[a]Author to whom correspondence should be addressed. Tel.: +91-11-26893955. FAX: +91-11-26893666. Electronic mail: sandeepiuac@gmail.com.

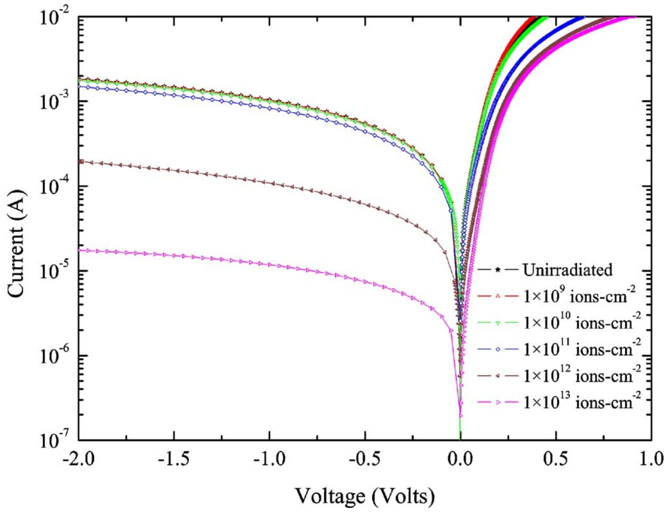

FIG. 1. (Color online) Experimental current-voltage characteristics of the Ni/n-Si(100) Schottky diode at different irradiation fluences.

was performed at room temperature by 100 MeV O^{+8} ion beam using the 15UD Pelletron accelerator[9] facility at Inter-University Accelerator Centre, New Delhi. 100 MeV O^{+8} ions have a mean projected range of 95.2 μm inside the silicon after crossing the interface with $(S_e/S_n)\sim 1800$ at the interface. The ion fluence was varied from 1×10^9 to 1×10^{13} ions cm^{-2}. During irradiation, the beam current was 1.0 nA corresponding to ion flux of 7.5×10^8 ions $cm^{-2}\ s^{-2}$. The electrical properties of the Ni/n-Si Schottky barrier were investigated by *in situ* current voltage (I-V) measurements of the diodes carried out using a Keithley 2400 source meter unit. The I-V characteristics were recorded after a particular fluence by stopping the ion beam using Faraday cup in the beam line. All measurements were carried out at various stages of irradiation in the experimental chamber maintained at a vacuum of $\sim 10^{-7}$ mbar.

RESULTS AND DISCUSSION

The experimental I-V characteristics of Ni/n-Si Schottky diode before and after ion irradiation at different ion fluencies are shown in a semilogarithmic scale in Fig. 1. The curve shows a region of linearity at low forward biases while their behavior is dominated by the series resistance at higher voltage values. From the figure, it is clear that the linear region of I-V curves shifts toward the higher voltages with increase in ion irradiation fluence, while the current decreases in the series resistance region at high bias voltages. These results are consistent with an increase of Schottky barrier height as well as series resistance of the diodes after ion irradiation.

As prepared MS contacts usually exhibit nonideal current-voltage characteristics. In case of a moderately doped semiconductor, thermionic emission is the dominant current transport mechanism across the barrier at room temperature. According to thermionic emission theory,[10] the current across the barrier is given by

TABLE I. Irradiation fluence dependence of Schottky barrier parameters of Ni/n-Si structure

Ion fluence (ions cm^{-2})	Ideality factor	Barrier height (eV)	Series resistance (Ω)	Leakage current at −2 V (mA)
0	1.36	0.59	21.5	1.83
1×10^9	1.25	0.60	22.0	1.82
1×10^{10}	1.28	0.60	24.8	1.76
1×10^{11}	1.22	0.62	39.4	1.49
1×10^{12}	1.20	0.64	52.0	0.19
5×10^{12}	1.11	0.67	57.6	0.02
1×10^{13}	1.10	0.68	62.0	0.01

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

where I_s denotes the reverse saturation current, n is the ideality factor, R_s is the diode series resistance, and other symbols have their usual meanings. The reverse saturation current is related to barrier height by the relation

$$I_S = AA^*T^2\exp\left(\frac{-q\Phi_B}{kT}\right). \tag{2}$$

Here, A is the diode area (0.011 cm^2), A^* is Richardson's constant (112 A $cm^{-2}\ K^{-2}$ for n-Si), and Φ_B is the apparent barrier height. From a fit of linear region of the forward bias I-V characteristics, the values of ideality factor and Schottky barrier height were determined. From the slope of the curve, the value of ideality factor was calculated and the intercept on y axis determines reverse saturation current (I_s). From I_s, the value of barrier height is extracted using Eq. (2). The series resistance was evaluated from the forward bias I-V data using method developed by Cheung and Cheung.[11] The values of ideality factor (n), barrier height (Φ_B), and series resistance (R_s) at various fluencies are given in Table I.

For the unirradiated diode, the barrier height is 0.59 eV, which agrees well with the values reported in the literature.[4,12] Interestingly, the SHI irradiation results in an increase of the Schottky barrier height until Φ_B reaches the value of 0.68 eV after irradiation at fluence of 1×10^{13} ions cm^{-2}. The variation of barrier height with the irradiation fluence is shown in Fig. 2. The ideality factor decreases from a value of 1.3 to 1.1 after ion irradiation. It is noteworthy that, compared to traditional implantation and heavy ion irradiation studies on n-Si, irradiation by 100 MeV O^{+8} shows reverse effects on modifying Schottky rectification characteristics. Low energy ion implantation and high energy heavy ion irradiation have been found to cause decrease in barrier height and largely increase in leakage current in n-Si.[4,6,7,13,14] However, irradiation by oxygen ions at 100 MeV has led to significant increase in barrier height and about two order of magnitude reduction in leakage current. The increase in the value of the Schottky barrier height is connected to a decrease of the leakage current with increasing irradiation fluence (Fig. 1). Change in barrier height indicates a change in electrical properties of the MS interface. An increase in series resistance was found for all irradiation fluences, indicating that the product of the mobility and car-

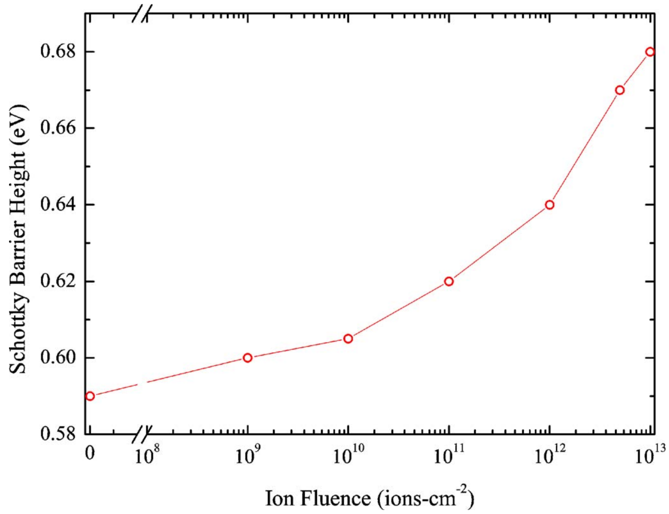

FIG. 2. (Color online) Irradiation fluence dependence of the Schottky barrier height of Ni/n-Si Schottky structure.

rier concentration has reduced. The reduction in mobility is due to the introduction of defect centers on irradiation, which act as scattering centers. This is confirmed by capacitance-voltage characteristics shown in Fig. 3. The capacitance decreases as the ion irradiation fluence increases. Decrease in capacitance implies a widening in the semiconductor depletion width. Since the charge neutrality condition at the interface should be satisfied, widening of the depletion width results from a reduction of the ionized donor concentration (N_D). One of the possible mechanisms is that ion irradiation produces defects with energy levels below the Fermi level in n-type material. These defects will capture electrons from the conduction band and reduce the equilibrium electron concentration. The carrier concentration decreases from a value of 1.9×10^{16} cm^{-3} for unirradiated diode to 6.3×10^{15} cm^{-3} after an irradiation fluence of 1×10^{13} ions cm^{-2}. These defects result in the compensation of the positive shallow donors in the depletion region so that the effective net ionized-donor

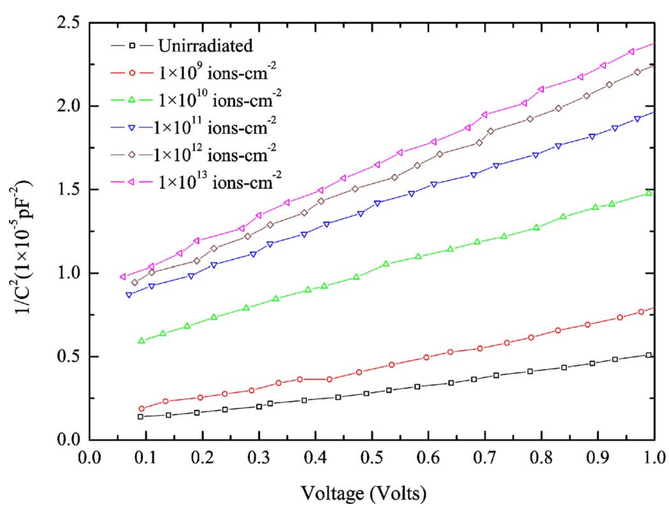

FIG. 3. (Color online) Reverse bias capacitance-voltage characteristics of Ni/n-Si(100) Schottky diode at different ion irradiation fluences.

concentration is decreased. The barrier thickness depends on N_D through the depletion width ($\propto N_D^{-1/2}$); in this case, a dopant deactivation near the MS interface determines an increase of the Schottky barrier thickness (d), which contributes to the decrease of the leakage current in reverse bias. As a consequence of the dopant deactivation after ion irradiation, a modification of the potential and electric field distribution will occur at near-interface region, which can be a reason for the increase of the barrier height. Dopant deactivation near interface region results in a decreased value of electric field at the interface as[10]

$$E_{\max} = \frac{qN_D d}{\varepsilon_s}, \tag{3}$$

where ε_s is the permittivity of semiconductor. Since the image force lowering of the barrier depends on the square root of the maximum electric field as

$$\Delta\Phi_B = \left(\frac{qE_{\max}}{4\pi\varepsilon_s}\right)^{1/2}, \tag{4}$$

therefore, a decrease of the electric field at the interface results in an increase of the Schottky barrier height.

CONCLUSION

In this work, the effect of 100 MeV O^{+8} ion irradiation on Ni/n-Si (100) Schottky barrier using *in situ* current-voltage characterization as a function of irradiation fluence has been studied. A significant increase of Schottky barrier height from a value of 0.59 eV for unirradiated diode to 0.68 eV is achieved after irradiation at a fluence of 1×10^{13} ions/cm^2. Current-voltage characteristics reveal that with an optimal choice of the irradiation parameters, these results could find useful applications in the control of the Schottky barrier height of Ni/n-Si (100) structures.

ACKNOWLEDGMENTS

Financial support in the form of fellowship to (S.K.) provided by Council of Scientific and Industrial Research (CSIR), India is gratefully acknowledged.

[1] R. Farshid and F. Rashid, Appl. Phys. Lett. **87**, 164101 (2005).
[2] A. Vilan, A. Shanzer, and D. Cahen, Nature (London) **404**, 166 (2000).
[3] R. A. McKee, F. J. Walker, M. B. Nardelli, W. A. Shelton, and G. M. Stocks, Science **300**, 1726 (2003).
[4] J. M. Shannon, Appl. Phys. Lett. **25**, 75 (1974).
[5] S. Ashok, T. P. Chow, and B. J. Baliga, Appl. Phys. Lett. **42**, 687 (1983).
[6] J. M. Shannon, Appl. Phys. Lett. **24**, 369 (1974).
[7] S. J. Fonash, S. Ashok, and R. Singh, Appl. Phys. Lett. **39**, 423 (1981).
[8] R. Singh and S. Ashok, Appl. Phys. Lett. **47**, 426 (1985).
[9] D. Kanjilal, S. Chopra, M. M. Narayanan, I. S. Iyer, V. Jha, R. Joshi, and S. K. Datta, Nucl. Instrum. Methods Phys. Res. A **328**, 97 (1993).
[10] E. H. Rhoderick and R. H. Williams, *Metal-Semiconductor Contacts*, 2nd ed. (Claredon, Oxford, 1988).
[11] S. K. Cheung and N. W. Cheung, Appl. Phys. Lett. **49**, 85 (1986).
[12] M. Y. Ali and M. Tao, J. Appl. Phys. **101**, 103708 (2007).
[13] S. Kumar, Y. S. Katharria, Y. Batra, and D. Kanjilal, J. Phys. D **40**, 6892 (2007).
[14] R. Singh, S. K. Arora, and D. Kanjilal, Mater. Sci. Semicond. Process. **4**, 425 (2001).