# Characterization of focused-ion-beam-induced damage in *n*-type silicon using Schottky contact

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The effects of focused-ion-beam-induced damage on electrical properties of *n*-type Si are investigated by Schottky contacts. Crystalline Si is exposed to 10–30 keV focused ion beam (FIB), followed by Pt deposition under vacuum of $4\times10^{-4}$ Pa. From current-voltage-temperature measurements, barrier heights of the Schottky contacts are found to increase almost linearly as the FIB energy increases, with the maximum increment of 0.29 eV. The increase is suggested to be related to the arising of acceptorlike defects and an amorphous layer due to FIB damages. A theoretical model is set up to quantitatively describe the barrier height changes. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2195109]

Focused ion beam (FIB) technology has been massively used in modern silicon-based integrated circuit (IC) failure analysis and modification and, recently, also finds applications for high-precision machining in micro/nanoelectromechanical systems (MEMS/NEMS).[1,2] The technology offers the functions of high-energy ion beam (typically 30 keV $Ga^+$) sputtering and ion assisted chemical vapor deposition in the size of nanometer scale, and thus allows localized and controlled material removal and deposition. Since the milled Si is subsequently used for device fabrication, it is important to investigate the impact of FIB process upon Si.

A surface damage layer of 10–100 nm is always brought about in Si by FIB milling.[3–7] As electronic and electromechanical devices scaling down to sub-100 nm scale, it can be expected that the surface damage may take a non-neglectable portion in device structures and would thus lead to changes in their electrical and mechanical properties.[8–10] Therefore, a better understanding on FIB-induced surface damages in Si is required very much for the increasing applications of FIB technology in IC and MEMS/NEMS.

FIB-induced damage in Si was characterized by transmission electron microscope (TEM) in recent researches,[3–7] focusing on parameters affecting the damage layer thicknesses and physical processes of the damage formation. For a certain ion species and target material, the damage layer thickness is found mainly affected by the ion energy and incident angle. TEM and energy-dispersive x-ray spectrometer studies illuminate that the damage layers are amorphous and associated with direct amorphization by the $Ga^+$ beam.[7] Despite little work on electrical characterization, these physical processes might change the electrical properties of the Si surface layer in the forms including (1) ion-induced creation of surface defects and (2) unintentional passivation of dopants by lattice damaging due to amorphization.

In the present study, we report an electrical characterization on the FIB-induced damage in *n*-type Si using Schottky contact. Schottky contact has been recognized as a simple and effective tool in obtaining information about dry-etching-induced damage in semiconductors.[11–15] In particular, the junction current offers an extremely sensitive measure of surface damage due to the exponential dependence of current on the surface barrier height $\phi_B$. This method is simple and fast compared with previous TEM characterization, because it does not need any TEM sample preparation, in the process of which additional FIB damage might be introduced.[3–7] Current-voltage (*I-V*) characteristics of Schottky contacts on FIB-milled Si surfaces are investigated. The Schottky barrier heights $\phi_B$ on Si surface milled under different ion beam conditions are evaluated through current-voltage-temperature (*I-V-T*) measurements. From these, the mechanism on how the damage layer affects electrical properties of the contact is suggested. A simple model is set up to quantitatively describe the relationship between changes of $\phi_B$ and characteristics of FIB-induced damage layer.

In the experiments, 300-nm-thick $SiO_2$ was grown by thermal oxidation on a $3\times10^{15}$ cm$^{-3}$ P-doped, 5-$\mu$m-thick epitaxial Si layer upon a $10^{21}$ cm$^{-3}$ As-doped substrate. $150\times150$ $\mu$m$^2$ rectangular Si surface areas with round angles were formed by lithography and buffered HF etching. An FEI Strata DB235 FIB/SEM (scanning electron microscope) dual beam system with gallium ion source was used for damage formation. We employed the SEM to observe and position the specimen so that Si was not exposed to ion beam during experimental setup. Pristine single crystal Si surface was then milled by FIB in a raster scanning fashion at room temperature with the beam incident direction perpendicular to the surface. The milling depth was set to 0.5 $\mu$m, and single time "filled-box" mills were used, so that redeposited layers caused by complex sequences of mills were avoided.[7] Ion beam energies were varied over a range of 10–30 keV. Pt of 500 nm thickness was then sputtered on the surface areas in vacuum ($4\times10^{-4}$ Pa) to form the Schottky contacts. Undamaged single crystal areas were included in metal-semiconductor contact formations for reference. *I-V* characteristics of the diodes were recorded by an HP4156B parameter analyzer.

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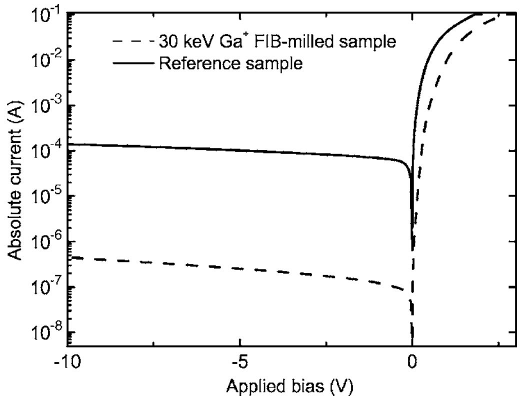



FIG. 1. *I-V* characteristics of Pt Schottky contacts fabricated on both the reference and FIB-milled *n*-Si surfaces.

The *I-V* relation for a Schottky barrier under forward bias ($V > 3kT/q$) is well known to be

$$I = I_{\mathrm{sat}}(e^{q(V-IR)/nkT} - 1), \tag{1}$$

where $I_{\mathrm{sat}}$ is the saturation current, $V$ the applied voltage, $R$ the series resistance, and $n$ the ideality factor. In the reference Pt/$c$-Si Schottky contact, the saturation current is given by thermionic theory

$$I_{\mathrm{sat}} = A_e A^{**} T^2 e^{-\phi_B/kT}, \tag{2}$$

where $A_e$ is the effective contact area and $A^{**}$ the effective Richardson coefficient. In the case of FIB-damaged Schottky contact, considering the fact that the Schottky barrier is actually formed between Pt and amorphous Si, the diffusion theory of metal-semiconductor rectification rather than thermionic emission model should be applicable because of the short electron mean free paths in amorphous materials.[16] Thus, the saturation current can be described by the following equation:

$$I_{\mathrm{sat}} = A_e q \mu N_c E_s e^{-\phi_B/kT}, \tag{3}$$

where $\mu$ is the electron mobility, $N_c$ the effective density of states in the conduction band, and $E_s$ the surface electric field in the semiconductor. Figure 1 shows the room-temperature *I-V* characteristics of the Pt/Si Schottky diodes for the reference sample and 30 keV FIB-milled sample. Both the forward and reverse currents are reduced in the damaged sample, and particularly the reverse current $I_R$ decreases by more than two orders of magnitude. It can be deduced that FIB milling creates an increase of $\phi_B$ on *n*-type Si surface.

To determine the values of $\phi_B$, the active energy plot method[17,18] involving *I-V-T* measurements was utilized. The forward-bias *I-V* characteristics at different temperatures of the Pt/Si Schottky contact were measured. The active energy plot involves plotting $I/\exp(qV/\mathrm{nkT})$ vs $I$ for each temperature. A linear curve fit yields the saturation current $I_{\mathrm{sat}}$ as the $y$ intercept. For the reference sample, $\phi_B$ can be extracted from the slope of $\log(I_{\mathrm{sat}}/T^2)$ as a function of $1/T$ in Eq. (2), whereas for the FIB-milled sample, $\phi_B$ can be extracted from the slope of $\log I_{\mathrm{sat}}$ as a function of $1/T$ in Eq. (3), as shown in Fig. 2. One thing to note is that the information of the effective contact area $A_e$ is contained in the $y$ intercept of the plots, so that the impact of $A_e$ uncertainty on barrier height extraction is excluded. This could be extremely advantageous since the surface roughness might be increased by dry etching[15] and thus $A_e$ become far different from the apparent area. $\phi_B$ of reference Pt/Si Schottky contact is 0.82 eV which agrees well with the values reported in the literature. In 30 keV Ga$^+$ FIB-milled sample, $\phi_B$ is found to increase to 1.11 eV.

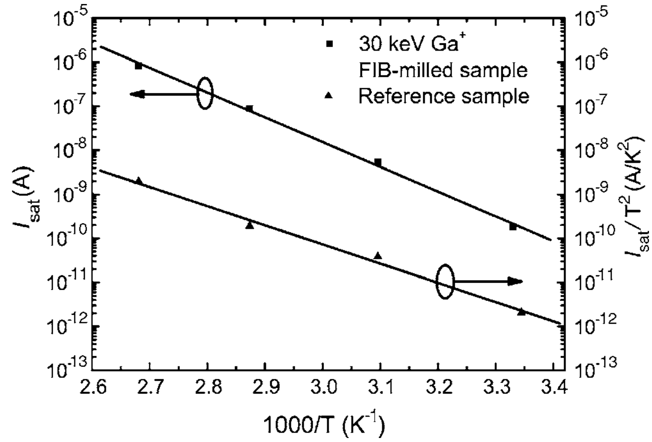



FIG. 2. Activation energy plot using the saturation current as a function of temperature from the forward-bias *I-V* characteristics.

It is noteworthy that, compared with traditional dry-etching-induced damages in semiconductors, FIB-induced damage shows reverse effects on modifying Schottky rectification characteristics. Reactive ion etching (RIE) damage has been massively reported to decrease $\phi_B$ and largely increase $I_R$ in *n*-type Si. Inductively coupled plasma (ICP) etching was also found to cause the similar severe degradation in electrical properties, perhaps due to generations of trapping centers and enhanced polymerization on the etched surface.[14,15,19] However, significant increases of $\phi_B$ and more than two orders of magnitude reduction of $I_R$ are found in FIB-milled Schottky contact.

The reverse effect should relate to the specific physical processes during FIB milling. In particular, the increase of $\phi_B$, as revealed in Fig. 1, could be explained by the energy band diagram of the contact, with a thin (10–100 nm) surface amorphous layer and negative charges at the Pt/$a$-Si interface due to acceptorlike defects created by the Ga$^+$ damage. Considering that the space charge in the high resistance amorphous layer can be omitted due to the passivation of dopants, the interface charge modifies the band bending at the surface of the Si as shown in Fig. 3. Using Poisson's equation, the increment of the effective barrier height will be approximately

$$\Delta \phi_B = q D_A a / \varepsilon_s \varepsilon_0, \tag{4}$$

where $D_A$ is the defect dosage and $a$ the thickness of the amorphous layer. The defect dosage $D_A$ is expected to be

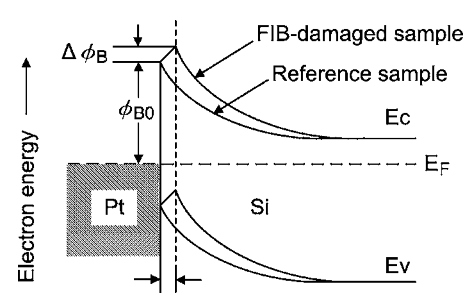
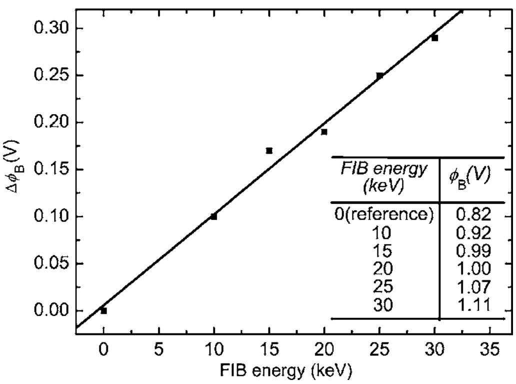



FIG. 3. Schematic diagram of the energy band in a Schottky barrier on *n*-type Si surface with and without a shallow FIB-damaged layer.




| FIB energy (keV) | $\phi_B$(V) |
|---|---|
| 0(reference) | 0.82 |
| 10 | 0.92 |
| 15 | 0.99 |
| 20 | 1.00 |
| 25 | 1.07 |
| 30 | 1.11 |

FIG. 4. Variation of barrier height increment in $Ga^+$ FIB-milled Si planar diodes as a function of FIB energy.

nearly constant since the surface dosage of $Ga^+$ causing damage maintains at the level of critical sputtering dose ($10^{17}$ cm$^{-2}$) (Ref. 6) independent on the ion beam energy. Therefore, in this model, $\Delta\phi_B$ and $a$ should exhibit nearly linear relationship. The thickness of the damage layer, which shows linear dependence on incident ion energy up to 50 keV,[3,5] is varied by changing the FIB energy. The exposure time for each sample was ~40 min, and the calculated total ion dose was $\sim 1.33\times 10^{18}$ cm$^{-2}$. Figure 4 shows $\Delta\phi_B$ extracted from *I-V-T* measurements of the Schottky contacts with damage layers of different thicknesses. The extracted values of $\phi_B$ are summarized in the inset table in Fig. 4. A linear fitting of experimental data is also shown in Fig. 4, and the data show a quite good linear relationship. By using this simple model, the unique relation between the damage layer thickness and the Schottky barrier height increase can be explained, although a more rigorous analysis should be developed to further understand the exact nature of the interface defects.

In summary, we have found that $Ga^+$ FIB-induced damage in $n$-type Si leads to an increase of the Pt/Si Schottky barrier height $\phi_B$, reverse to the effects of RIE and ICP induced damages. From *I-V-T* measurements, $\phi_B$ increases almost linearly as the ion energy increases over the range of 10–30 keV. The increase of $\phi_B$ can be explained by the modification of surface band diagram of Si due to the arising of acceptorlike defects at the Pt/Si interface and a thin amorphous layer caused by $Ga^+$ implantation. Considering the nearly constant defect dosage, it can be expected that the increase of the thickness of the damage layer, $a$, plays a dominant role in the linear increase of Schottky barrier height. The strong dependence of the damage characteristics on the Schottky barrier height can be advantageously used for determining the degree of FIB-induced damage.

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