Shape Transition of Nanostructures created on Si(100) surfaces after MeV Implantation

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Abstract

We have studied the modification in the Surface morphology of the Si(100) surfaces after 1.5 MeV Sb implantation. Scanning Probe Microscopy has been utilized to investigate the ion implanted surfaces. We observe the formation of nano-sized defect features on the Si surfaces for the fluences of $1 \times 10^{13} \text{ions/cm}^2$ and higher. These nanostructures are elliptical in shape and inflate in size for higher fluences. Furthermore, these nanostructures undergo a shape transition from an elliptical shape to a circular-like at a high fluence. We will also discuss the modification in surface roughness as a function of Sb fluence.

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1 Introduction

In Si based semiconductor technology Sb is considered an important dopant for its role in the development of field effect transistors and infrared detectors [1]. Ion implantation is a useful technique for fabricating such devices as it produces buried layers with well defined interfaces, expanding possibility of designing novel structures. The increased density in VLSI circuits also makes the technological applications of the ion implantation, especially in MeV energy range, increasingly important. MeV implantation however can also produce severe modifications in the material depending on the nature and the energy of the impinging ion, and the implantation dose [2].

Extensive usage of ion implantation in device fabrication and the continued miniaturization of device structures has brought the issue of surface modifications, via ion implantations, to the forefront. However, the factors responsible for such modifications and the surface morphology after ion implantation, have received little attention [3].

Atomic force microscope (AFM) is a very effective tool for examining surface modifications and surface structures. However, there are very few studies in literature that have investigated the morphological changes of the ion implanted surfaces by AFM. Furthermore, most of these surface studies are performed after keV implantations [4, 5, 6], or at low fluences for individual cascade studies [7]. Surface modifications after high energy, 100 MeV, ion irradiation have also been investigated [8]. However, the role of MeV ion implantation on the surface topography remains poorly understood. In the present study we have made detailed investigation on Si(100) surfaces after 1.5 MeV Sb implantation. The technique of AFM has been applied to understand the modification in roughness and morphology of silicon surfaces upon ion implantation. We also investigate here the formation of nano-sized defects zones on Si(100) surfaces after MeV implantations. The results of shape transition in these
nanostructures, from being elliptical at low fluences to becoming deformed circular at high fluences, will also be discussed here. Experimental procedure are mentioned in section 2 and the results will be discussed in section 3. Conclusion are presented in section 4.

2 Experimental

A mirror polished (100)-oriented Si single crystal (p-type) wafer was used in the present study. The samples were implanted at room temperature with a scanned beam of 1.5 MeV Sb$^{2+}$ ions at various fluences ranging from $1\times10^{11}$ to $5\times10^{14} ions/cm^2$. The implantations were performed with the samples oriented 7$^\circ$ off-normal to the incident beam to avoid channeling effects.

AFM Nanoscope E and Nanoscope III from Veeco were used to image the implanted silicon sample surfaces. Images have been acquired in contact and tapping modes. Images ranging from 0.2 to 10 $\mu m$ square were obtained.

3 Results and Discussion

Figure 1 shows the $1 \times 1\mu m^2$ and $200 \times 200nm^2$ 3D-images of the virgin silicon surface. It is observed that the virgin Si surface is smooth. 1.5 MeV implantation was carried out at various fluences and several $1 \times 1\mu m^2$ and $200 \times 200nm^2$ images were taken at all the fluences. The $1 \times 1\mu m^2$ images were utilized for measuring the rms surface roughness of Si(100) surfaces after implantation. The average roughness at each fluence is plotted in Figure 2. The rms roughness for a virgin Si(100) surface, measured to be 0.234 nm, is also marked. It can be clearly seen from Fig. 2 that the rms surface roughness exhibits three prominent behaviors as a function of fluence. For low fluences, up to $1 \times 10^{13} ions/cm^2$, the roughness is small and does not increase.
much compared to the virgin surface roughness. Beyond this fluence an enhanced
surface roughness, increasing at a much steeper rate is observed. This trend continues
up to the fluence of $1 \times 10^{14}$ ions/cm$^2$ where a high roughness of 0.296 nm is measured.
A saturation in surface roughness with a slight decrease in the roughness is observed
beyond this fluence. The decrease in surface roughness, at $5 \times 10^{14}$ ions/cm$^2$, seems
reasonable in view of high level of amorphicity at this dose [9], as beyond a certain
high amorphicity, further higher levels of amorphization should tend to make the
surface more homogeneous. A similar decrease in surface roughness with increasing
fluence, beyond a critical fluence, has been observed for keV implantations of P and
As in amorphous films [10].

Our earlier RBS/C and Raman scattering results [9, 11] show that Si lattice dis-
order also displays 3 similar behaviours as a function of ion fluence. Initially a low
lattice damage, due to simple defects, is seen upto the fluence of $1 \times 10^{13}$ ions/cm$^2$.
The disorder becomes larger with the onset of crystalline/amorphous (c/a) transition
in Si-bulk at $1 \times 10^{13}$ ions/cm$^2$. Finally the disorder saturates with the Si-lattice as
well as Si-surface becoming amorphised at $5 \times 10^{15}$ ions/cm$^2$. The roughness on the
Si surface will be determined by several roughening and smoothening process that
undergo on an ion implanted surface. Nuclear Energy loss effects are also crucial.
In addition lattice disorder and the associated stress will also be important in the
evolution of the ion implanted surface.

High resolution 200 $\times$ 200 nm$^2$ images of the Si-surfaces were acquired for all the
fluences and are shown in Figure 3 for two representative Sb fluences of $1 \times 10^{13}$ and
$5 \times 10^{14}$ ions/cm$^2$. The images of Si surface acquired upto the fluence of $1 \times 10^{12}$ ions/cm$^2$
(not shown) are similar to the virgin surface (of Fig. 1b) and their surface roughness
is also similar (Fig. 2). However, after a fluence of $1 \times 10^{13}$ ions/cm$^2$, several nano-
structures can be seen on the Si-surface (see Fig. 3a). Fig. 4a is same as Fig. 3a and
shows the approximate outlines of some of the nanostructures. The nanostructures represent the damage due to ion implantation and are roughly of elliptical shape. For a quantitative analysis of these nanostructures, the two axial lengths were measured and the mean lengths of the minor and the major axes are found to be 11.6 and 23.0 nm respectively. The mean lengths of the two axes and the mean areas of the surface features are tabulated in Table 1 for various incident ion fluences.

For a Sb fluence of $5 \times 10^{13} \text{ions/cm}^2$, although the silicon surface is again found to be decorated with the elliptical nanostructures, the features have expanded along both the axial directions (with the mean lengths of axes being 14.5 and 26.1 nm respectively). The average area of the nanostructures at this stage is calculated to be 297 $\text{nm}^2$, which is about 41% higher than that at $1 \times 10^{13} \text{ions/cm}^2$. For a fluence of $1 \times 10^{14} \text{ions/cm}^2$, the area of these nanostructures further inflates to $325 \pm 31 \text{ nm}^2$.

Although the length of the minor axis has not changed much at this fluence compared to that at $5 \times 10^{13} \text{ions/cm}^2$, the major axis is elongated and has an average value of 31.6 nm. Upto this stage the eccentricity of the elliptical structures, for all fluences is found to be $\sim 0.85 \pm 0.4$. The eccentricity of the elliptical structures, at each fluence is listed in Table 1. Interestingly, after a fluence $5 \times 10^{14} \text{ions/cm}^2$, the surface structures undergo a shape transition with the nanostructures having axial lengths of $30.1 \pm 4.4 \text{ nm}$ and $30.7 \pm 2.4 \text{ nm}$, respectively (see Fig. 3b). Fig. 4b is same as Fig. 3b and shows the approximate outlines of some of the nanostructures. The nanostructures have become much bigger in size and appear somewhat of circular shape. The nanostructures are not fully circular and have eccentricity $\sim 0.19 \pm 0.05$ (the eccentricity for circle=0). However, the eccentricity of these nanostructures is much reduced compared to those at lower fluences (where eccentricity $\sim 0.85 \pm 0.4$). Hence, we refer to these nanostructures as approximately circular. An explosion in size ($\sim 120\%$) of these features compared to that at $1 \times 10^{14} \text{ions/cm}^2$ suggests a tremendous
modification in surface morphology at this stage. Our results are in contrast to the keV implantation study of Sb in Si where, for doses lower than $1 \times 10^{14}$ ions/cm$^2$, no change in the surface topography was observed [4].

The random arrival of ions on the surface constitute the stochastic surface roughening. Surface diffusion, viscous flow, and surface sputtering etc. contribute towards the smoothening of the surface [12]. The mechanism for the formation of surface damage is also postulated as a results of cascade collision due to nuclear energy loss ($S_n$). In the present study also, $S_n$ seems to be the dominating factor in the creation of the nanostructures after Sb implantation. In addition several factor like c/a transition in Si lattice, the strain in the surface and in bulk, defect and disorder in the medium etc. may also responsible for the structure formation at the surface. For Sb implantation in Si we observe the formation of nanostructure at Si(100) surface only after the fluence of $1 \times 10^{13}$ ions/cm$^2$. These nanostructures inflate in size with increasing fluence. The size inflation may also be related to the increased disorder [9, 11] in the Si lattice. The shape transition of nanostructures, from being elliptical at lower fluence to deformed circular at $5 \times 10^{14}$ ions/cm$^2$, may be caused by the increase in the density of the electronic excitations. Our earlier studies [9, 11] show that the amorphization of Si-surface at this stage also leads to stress relaxations on the ion implanted surface.

4 Summary and conclusions

In the present study we have investigated the modifications in the morphology of the Si(100) surfaces after 1.5 MeV Sb implantation. We observe the presence of nano-sized defect zones on the Si surfaces for the Sb fluences of $1 \times 10^{13}$ ions/cm$^2$ and higher. These nanostructures are elliptical in shape and their size increase with fluence. We observe an abrupt increase in size of nanostructures accompanied by a
shape transition after the fluence of $5 \times 10^{14} \text{ions/cm}^2$. The nanostructures become approximately circular at this stage. We have also investigated the modifications in the surface roughness of the ion implanted Si surfaces and find that surface roughness demonstrates 3 different stages as a function of fluence.

5 Acknowledgments

This work is partly supported by ONR grant no. N00014-97-1-0991. We would like to thank A.M. Srivastava for very useful comments and suggestions. We would also like to thank Puhup Manas for his help with the figures.
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Figures

Fig. 1: 3-D AFM images of the virgin Si(100) surfaces. Image areas are (a) $1 \times 1 \mu m^2$ and (b) $200 \times 200 \ nm^2$.

Fig. 2: The rms roughness of the Sb implanted Si(100) surfaces, measured using AFM, is plotted as a function of Sb ion fluence. Symbol sizes denote the error in the measurement. Data for the virgin sample is also shown.

Fig. 3: Surface structures on silicon surface: AFM images of silicon surfaces after implantation with 1.5 MeV Sb ions at the fluences of (a) $1 \times 10^{13} \text{ions/cm}^2$, and (b) $5 \times 10^{14} \text{ions/cm}^2$. Area of each image is $200 \times 200 \ nm^2$.

Fig. 4: (a) Same as Fig. 3a with approximate outlines of some of the nanostructures drawn and (b) same as Fig. 3b with approximate outlines of some of the nanostructures drawn.

Table

Table 1: Lengths of minor axis, major axis, area and the eccentricity of the nanostructures as a function of Sb ion fluence.
| Fluence  \((ions/cm^2)\) | Minor Axis (nm) | Major Axis (nm) | Area \((nm^2)\) | Eccentricity |
|-------------------------|-----------------|-----------------|-----------------|--------------|
| \(1 \times 10^{13}\)   | 11.6±2.2        | 23.0±3.7        | 210±23          | 0.86±0.04    |
| \(5 \times 10^{13}\)   | 14.5±1.8        | 26.1±2.9        | 297±22          | 0.83±0.04    |
| \(1 \times 10^{14}\)   | 13.1±2.3        | 31.6±4.2        | 325±31          | 0.87±0.05    |
| \(5 \times 10^{14}\)   | 30.1±4.4        | 30.7±2.4        | 726±52          | 0.19±0.05    |
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