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Angular effects in focused ion beam milling of silicon

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Introduction

Effects of angled ion beam milling and halo implantation on sputtering for Nanofabrication still remain largely unexplored. In this study the effect of incident angle during FIB milling of Silicon was investigated.

Substantial variations can be observed as the incident angle of the ion beam is varied. Generally, increasing the incident angle would increase the sputter yield due to increasing the density of energy deposition near the surface plane [1]. However in angled milling other effects such as redeposition play a significant role on the final geometry of milled features as it reduces the milling rate and the aspect ratio of milled structures. [2]

Theory

The characteristic behavior of the sputter yield as a function of the incident angle θ can be approximated by Yamamura's semi-empirical formula [1]:

$$Y(\theta) = C_1.(cos\theta)^{-C_2}.\exp(C_3.(1-(cos\theta)^{-1}))$$

Where the C_1, C_2 and C_3 are the fitting factors for the sputtering yield of 2.5 (atoms/ion) are 2.5, 1.87, 0.26 respectively.

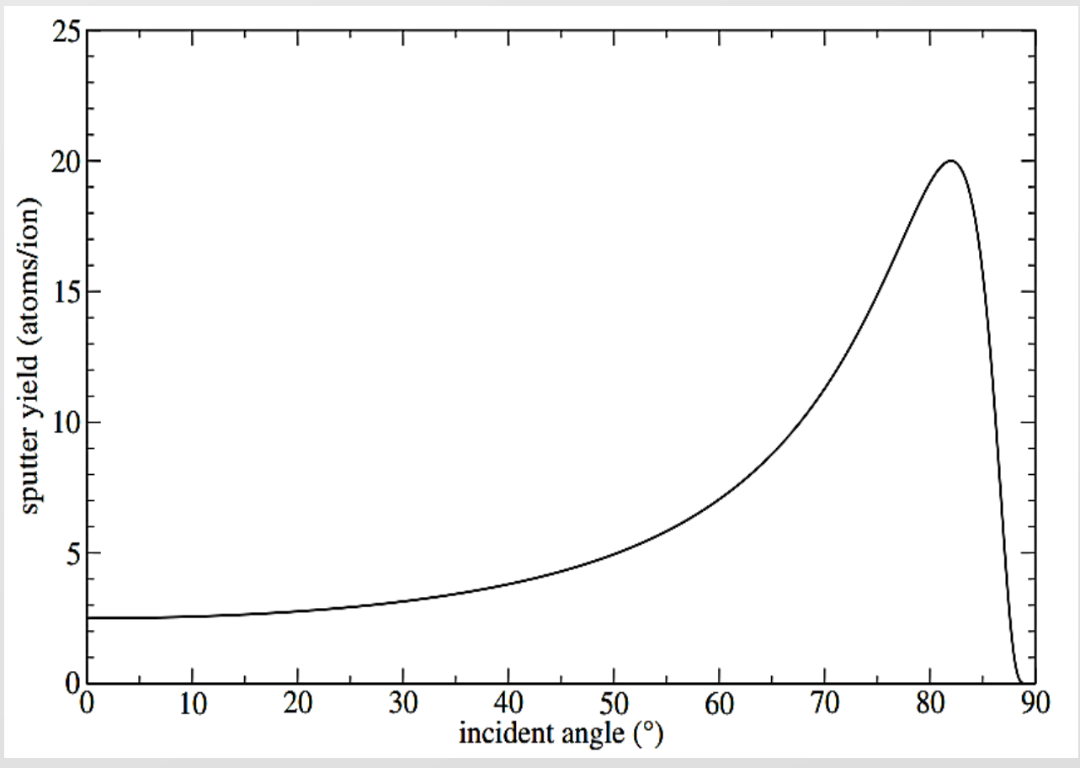
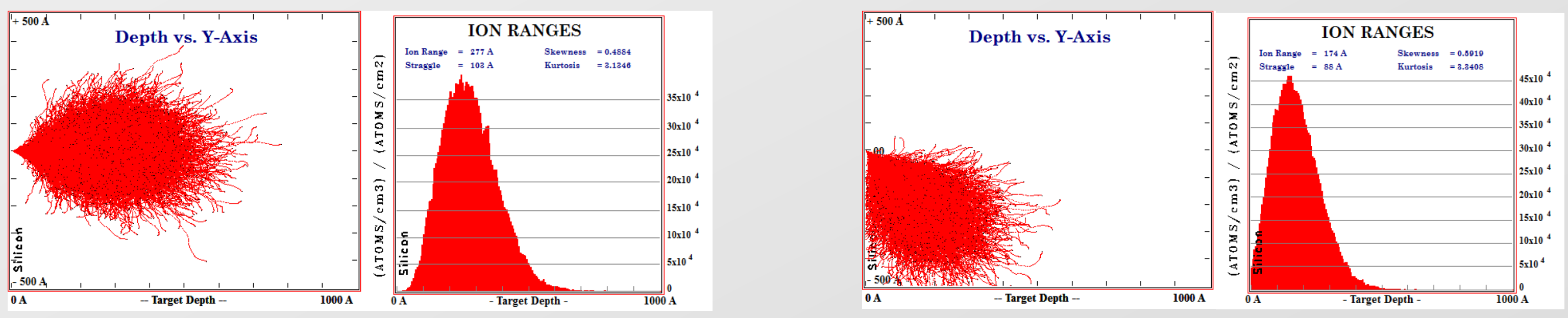


Figure 1. Sputter yield vs. incident angle

Simulation

Ion implantations simulations were performed for normal incident and 52 degree using SRIM Monte-Carlo simulations for Ga at 30 keV in Si.[3] (Figure 2)



(a) (b)

Figure 2. SRIM ion implantation simulation (a) at normal incident (b) at 52 degree

Experiment

The experiment involved FIB milling of 21 5μm×5μm squares at 30keV on (100) silicon at doses from 6.75×1017 ions/cm2 to 2×1018 ions/cm2 and milling angles varying from 0 degree to 52 degree with a current of 500pA. In particular, the depth of milling and bottom surface width that results from sputtering and redeposition were examined using an atomic force microscope (AFM). Also the substrate damage at different angles was studied through Raman measurements. Figure 3(a) shows the schematic view of angular milling and the effect of redeposition. A 3-D AFM measurement for milled structure at 50 degrees for dose of 6.25×10^{17} ions/cm^2 is shown in figure 3(b).

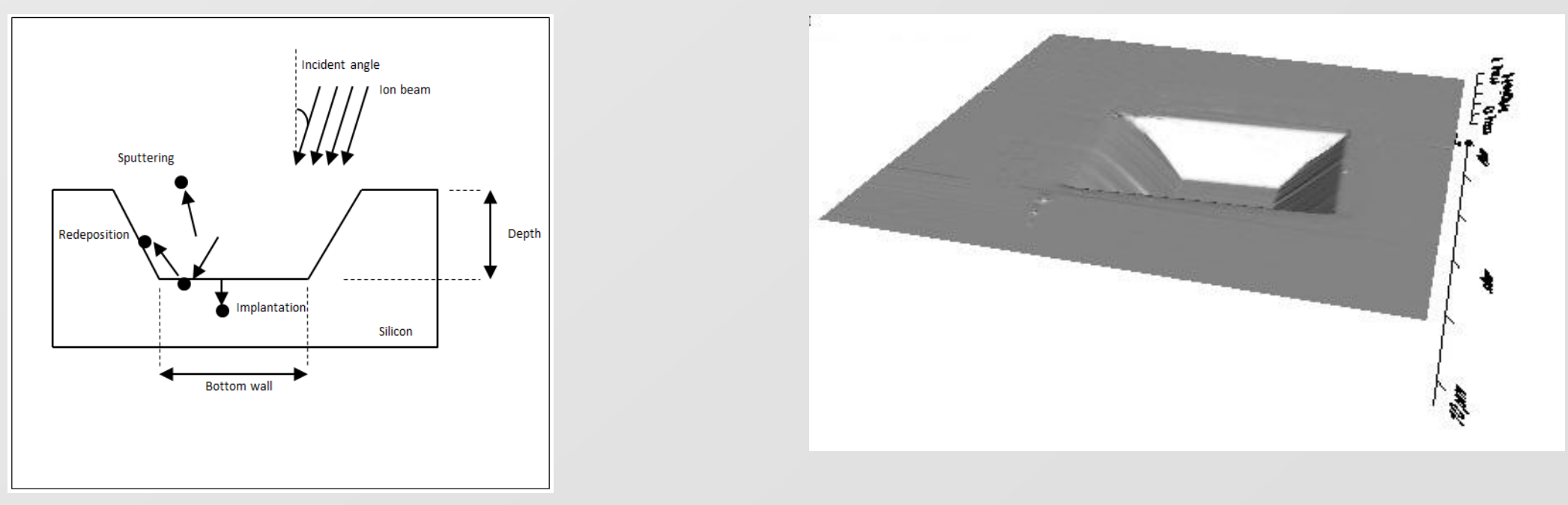


Figure 3(a). Schematic view of FIB angular milling of Silicon. (b) 3d image of milled silicon from AFM measurements

Results and discussions

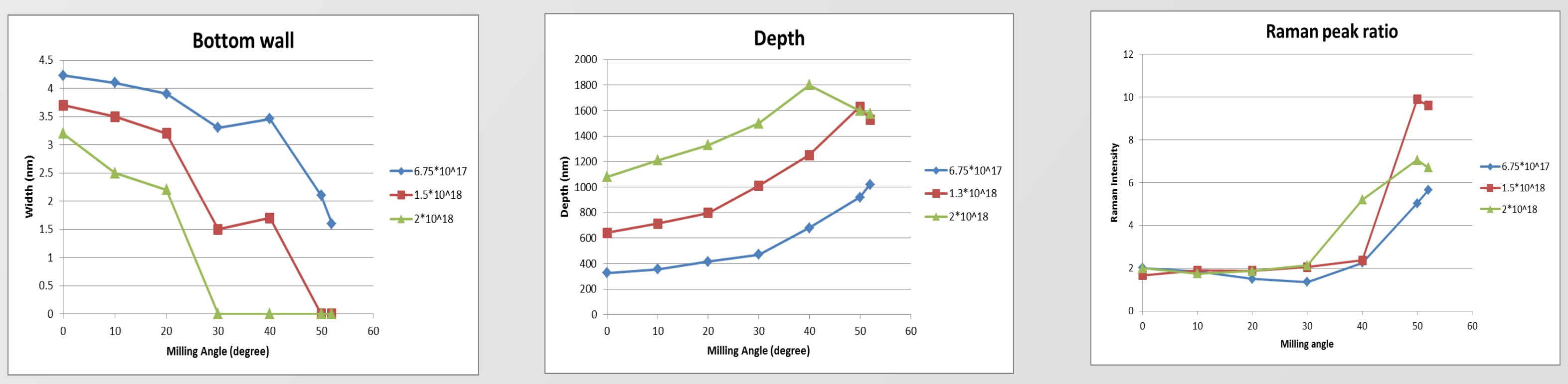
Figure 4(a) shows the depth of the trench at different milling angles. It has been observed that, by increasing the angle, the depth increases up to the point where the bottom surface has disappeared and the trench becomes essentially a V-shape. Further increases in milling angle, gradually decreases the depth.

It has been also observed that bottom wall width is decreased as angle of milling increased.

By increasing the dose the flat bottom surface disappears at smaller angles. (Figure 4(b))

The above mentioned effects are mainly due to redeposition as, by increasing the incident ion impact angle and the dose, the redeposition effect is increased and becomes more significant [4].

For investigation of the silicon damage, Raman measurements were performed. Figure 4(c) shows the intensity ratios of crystal silicon peak to amorphous silicon peak. It was observed that by increasing the angle of milling, damage of the milled squares is reduced. The reason is as follows: as the angle is increased, the ion trajectories have lower stopping mean range, which produces a thinner layer of implanted Gallium and break fewer silicon-silicon bonds.



(a) (b) (c)

Figure 4. (a) Milling depth for three different doses at chosen angles(b) Bottom surface width vs milling angles at different doses (c)Raman peak ratio at different angles for three milling doses at the centre of the milled structure

Conclusion

Angled milling can be used as an effective method for fabrication of 3-D Nano scale inclined walls for applications such as Nano Imprint Lithography.

In this study angular milling of Silicon was investigated. The surface topographies and effective milling depth were measured by means of AFM. The Raman measurements revealed the damage caused by ion milling on silicon at different angles.

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