Influence of redeposition effect for focused ion beam 3D micromachining

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Around the redeposition effect, its influence on FIB 3D micromachining process is discussed. Experimental results are analyzed combining with theoretical model. It can be drawn from the analysis that recycle milling orders are very important for 3D microfabrication due to redeposition during the process. On the other hand, A groove will be formed at the root of sidewall for the sake of ion sputtering yield variation and sidewall redeposition. Finally, avoiding methods are come up with in terms of the analysis outcome.

INTRODUCTION

3D nano-scale manufacturing is one important aspect of advanced manufacturing technology. Such advanced manufacturing technology is dependent on the nanometer accuracy in manufacturing. The FIB technology is one of the most widely used in the semiconductor industry for failure analysis, device modifications and micro-component fabrication.

Using a finely focused gallium ion beam, the FIB head can precisely remove and deposit materials in nano-scale. The production of high contrast images also assist in the removal and deposition process. Even materials like insulators and conductors can be deposited on any surface with nanometer resolution. With the FIB, depositing materials in very fine lines can be realised. It is especially very useful in manufacturing semiconductors, sensors and actuators. Therefore, it's a challenging technology facing to 21 century in the area of nanometer.

Combining with experimental 3D micro manufacturing by FIB, influencing factors are analyzed for milling process. It includes ion dose, beam limiting aperture size, beam current, etc. In addition, influence of redeposition effect for focused ion beam 3D micromachining was analyzed individually.

THEORETICAL MODEL

Redeposition is a serious negative complication to milling. As material is sputtered away, some of it becomes redeposited in the volume that is being sputtered. In normal mechanical machining, buildup of machined material is avoided by the use of liquid or air streams that carry the swarf away. Redeposition is critically dependent upon how the milling is done. It has been shown that for the same total dose, scans that are repeated many times to mill a rectangular area cause less redeposition to occur than a single slow pass to mill the rectangle. For the slow scan, redeposited material is not removed, whereas for the fast repeated scans, some fraction of the primary beam is used to sputter away redeposited material, so that the sputter yield is less for the fast scans.

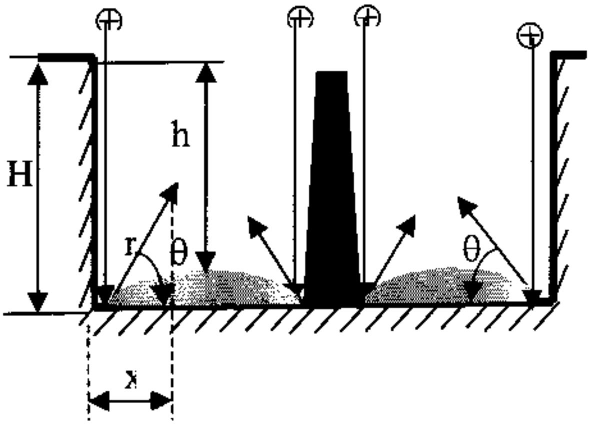

Fig.1 schematic of redeposition effect at root of sidewall

A simple geometric two-dimensional analysis of redeposition shown as Fig.1. The flux density of sputtered atoms, which escape without striking the sidewalls, is given by

$$F(x) = \frac{F_0}{2}\int_0^R \frac{\sin^2\theta dx}{r} \qquad (1)$$

F_0— total number of atoms emitted per unit length
R— outer circle diameter
R— sputtering path
θ— sputtering angle

F_0 is determined by ion dose and aperture size. The more large ion dose and aperture size, the more F_0 will be. At an aspect ratio<1, more than half of the sputtered atoms from the bottom surface redeposit. Therefore, the actual milling depth is smaller than designed value for the sake of accumulated material at the bottom.

The etch depth *z(x,y)* can be expresses as following[1]. It describes the relationship among depth and other parameters. As can be seen, etch depth is proportional to ion dose and sputtering yield. The sputtering yield is varied for different milling position of structure that will be shown by the post experimental results.

$$z(x, y) = D(x, y)\frac{Y(F, J, Ts, E, t_d, t_f)}{\rho} \qquad (2)$$

Here
$Y(F,J,_{Ts},E,t_d,t_f)$ —ion sputtering yield
$D(x,y)$ — ion dose,
F— chlorine flux,
J— ion flux,
T_s— substrate temperature,
E— beam energy,
t_d— dwell time ,
t_f— and frame time ,
ρ— atomic density.

EXPERIMENTAL RESULTS ANALYSIS

Bowl-like 3D structure milling

Experiments have been done by Micrion 9500EX FIB machine with SEM column and EDX. Fig.2 is the experimental results of milling bowl-like 3D structure with shown parameters, milling area 10μm ×10μm, Default_Mill mode. The following phenomena and rule can be drawn based on the above experiments.

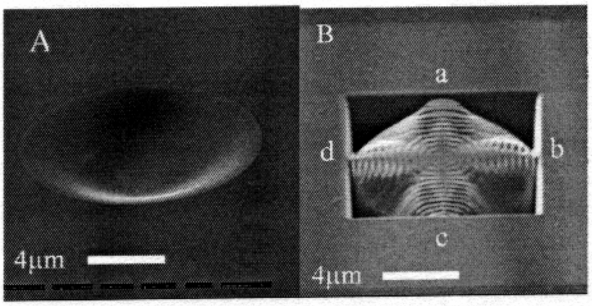

Fig.2 curve profile 3D milling

A: FIB image	B: SEM image
Program controlled milling from outside to center .	manual operated milling from center to outside.
Aperture size 250μm	aperture size 150μm

The 3D structure manufacturing can be realized only by the way of spelling many discrete 2D pattern together step by step because there is no 3D continuously moving workplate which moves along x_i, y_i, z_i, 3D points and the corresponding servo control system for the sake of design. For the case A, the bowl-like 3D structure was milled automatically by programming operation mode. Used aperture size is 250μm, it corresponds to larger spot size. The redeposition material is removed away every time by the next milling. The sidewall is smooth by virtue of overlapping each other for neighboring 2D periphery edges. But the depth is smaller than the designed value. For the case B, convex curve profile designed, the milling procedure is from center to outside edge by manual operating in a defined modifying box step by step. As can be seen, the redeposition remark is obvious along cross direction due to narrow space at the parts of *a, b, c,* and *d*. The more high aspect ratio, the more redepositing material accumulated on the convex surface. Because the near the ion beam is to the edge, the higher the sputtering yield from the sidewalls. High sputtering yield leads to milling depth increasing and produces more material removed away from root of sidewall that was accumulated along ion sputtering direction to form the shape shown as Fig.2 case B.

Annulus with tip structure milling

Milling annulus pattern structure on silicon wafer by FIB with parameters of aperture size 250μm, ion dose 15 nC/μm^2, beam current 8.66nA, Default_mill mode. A tip was formed during milling process due to the act of wing of Gaussian distribution profile. The more large aperture size selected, the more big cone angle of the tip because large aperture size corresponds to large spot size and beam current that shown as Fig.3. A phenomenon was found that a deep groove has been formed at the root of sidewall and tip for the sake of redeposition.

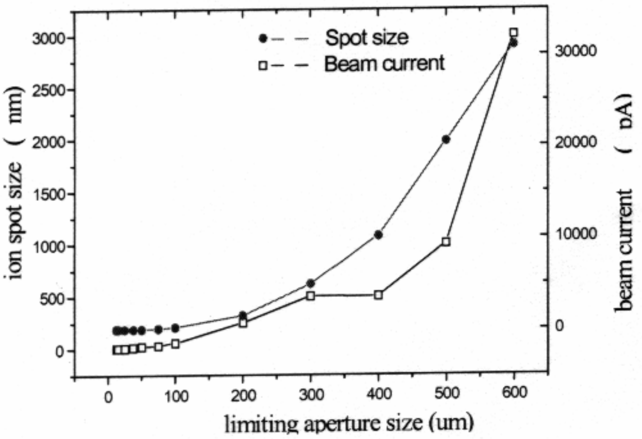

Fig.3 relationship among aperture size, beam current and spot size for 5nm ion column

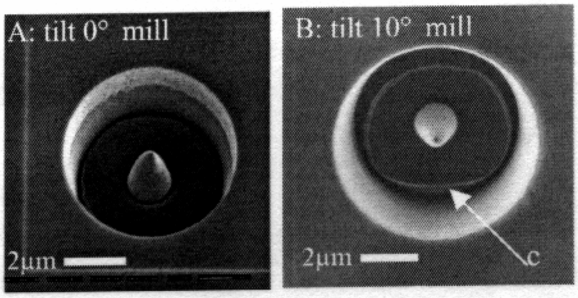

Fig.4 milled tip under different tilting angle of workpiece

When the workpiece was tilted in angle α, the down side of the redeposited groove will be milled more in the direction of ion sputtering angle θ (as shown in Fig.1). It can be seen from Fig.4 that the width of the groove is getting large. It's largest at the lowest point *c*. The more big tilt angle α, the more large width of cut groove is at the down sidewall. The thickness of redeposited material is difference in the tilt case. The upper part is thicker than the lower part. In the case of A, the thickness of redeposition is uniform.

What we wanted depth is H, but the actual depth we obtained is *h* due to the redeposition. The difference *Δ=H-h* will be increased with the increasing of ion dose and limiting aperture size. In order to look for the changing rule between the groove depth and limiting aperture size. A series of milling experiment have been done under the conditions of constant ion dose 15nC/μm^2 , X space 0.01002μm, Y space 0.01003μm, dwell time 3μs, retrace time 10μs. The milling results were measured by AFM and shown as Fig.5.

It's shown from Fig.5 that the more large aperture size, the more deep groove and large sputtering angle θ. The bottom depth *h* (shown as Fig.1) will be increased consequently. But their relationship is nonlinear. The sputtering yield near the sidewall is high. It leads to depth for the sidewall is deeper than the other area. This rule is coincide well with the theoretical relationship describes by formula (2).

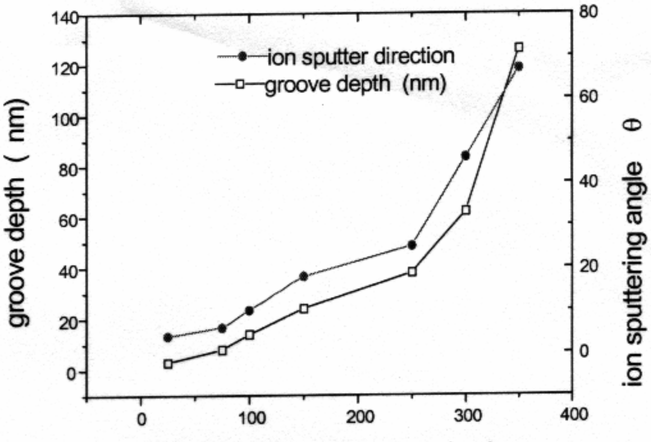

Fig.5 aperture size vs groove depth and sputtering angle θ

CONCLUSION

Combining with experimental milling and theory model, influence of redeposition effect for focused ion beam 3D micromachining has been analyzed. On the base of above analysis, the following conclusions can be drawn:

- The sidewall causes the variation of ion sputtering yield that leads to redeposition at the bottom and groove forming.
- The more large aperture size used, the more serious redeposition phenomenon is.
- The redeposited material will adhere on the sidewall for milling 3D structure with aspect ratio>1, and land on the bottom causing variation of milling depth for the structure with low aspect ratio (normally <1).
- In order to avoid redeposition for 3D milling, the recycle milling orders should be from outside edge to center. On the other hand, GAE mode can be used to refrain from redeposition. Reaction of the irradiated surface species with absorbed halogen produces volatile species which is advantageous because redeposition of surface material is essentially quenched[2].

Reference

1. A. Kalburge, A. Konkar, T. R. Ramachandran, P. Chen, and A. Madhukar. Focused ion beam assisted chemically etched mesas on GaAs(001) and the nature of subsequent molecular beam epitaxial growth. J. Appl. Phys. 82 (2), 15 July 1997, 859~864.
2. J.M. Lindquist, R.J. Young and M.C. Jaehnig. Recent advances in application of focused ion beam technology. Microelectronic Engineering 21 (1993) 179-186.
3. Craig Friedrich and Bharath Kikkeri, Rapid fabrication of molds by mechanical micromilling : process development. SPIE, Vol.2640/161.
4. . Jon Orloff edited, Handbook of Charged Particle Optics. Boca Raton, Fla. : CRC Press. 1997.
5. L. Bischoff, J. Teichert and E. Hesse, Interconnection lines following the surface topography fabricated by writing focused ion beam implantation. Microelectronic Engineering 27 (1995) 351~354.
6. Zheng Chui, Philip D Prewett, John Watson and Brain Martin, FIB repair of defects in rim and attenuated phase shift masks. Microelectronic Engineering 27 (1995) 331-334.
7. J. F. Walker, D. F. Moore and J. T. Whitney, Focused ion beam processing for microscale fabrication. Microelectronic Engineering 30 (1996) 517~522.