Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp218-219

Behavior of Focused Ga^+ Beam Spot Milling and its Superimposition Propetry

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Abstract

Surface morphology evolution of Si(001) milled with a single Ga^+ beam spot of different dwell time was investigated. The depth at each radial distance of the milled Si pit was found to vary linearly with dwell time in the range of 1.5-84 ms. The slopes of the depth-dwell time graph can be described by a Gaussian function of radial distance. Additionally, because initial ion doses inherently contribute to surface swelling, the time required from swelling to milling is defined as incubation time, which can be described by an exponential function of radial distance. By combining these two functions, the surface profiles of the single-spot-milled pits can be accurately estimated. Based on these results, one-dimensional line structures were also examined to further understand the superimposition behavior of the ion beam spot milling process.

1. Introduction

Focused ion beam (FIB) technique enables micro/nanomachining of materials directly and site-specifically. During a FIB machining process, the final material surface topography results from consecutive milling of adjacent ion beam spots. Thus, it is essential to study the process of ion spot milling for the fabrication of high-resolution structures. In this report, we investigate the topography evolution of a series of Si pits milled with a single ion spot of different dwell time. Based on this result, we also examined one-dimensional line structures composed of overlapped pits to further understand the superimposition behavior of the ion beam spot milling process.

2. Experimental procedures

The process of single spot milling was performed on Si(001) substrates with a Ga^+ ion beam of 30kV and 48pA. The focus and stigma were carefully adjusted so that each milled pit exhibits a circular shape and minimum diameter. The investigated dwell time ranges from 88μs to 84ms. For the samples of line structures, a line array of ion spots is arranged so that each milled pit overlaps each other. The finished samples were examined by atomic force microscopy (AFM) to obtain their surface topography.

3. Results and discussion

Typical AFM images of single-spot-milled Si(001) surfaces are shown in Fig. 1. For the samples of short dwell time, the surface shows a protruding topography which comes from the amorphization of Si after a low dose of ion bombardment (swelling effect) [1]. Fig. 2 shows the surface profiles measured through the center of the pits at different dwell time. As the dwell time exceeds 1 ms, the milling process begins to dominate and the depth of the pit increases toward the center. The depth at each radial distance varies almost linearly with dwell time as shown in Fig. 3. The slopes of the depth-dwell time graph can then be described by a Gaussian function of radial distance (Fig. 4)

$$-\frac{\partial D}{\partial t} = a e^{-\left(\frac{r}{c}\right)^2}, \qquad (1)$$

where D is the depth, t is the dwell time, and r is the radial distance. The parameters a and c are 1.2 nm/ms and 42.3 nm respectively in this case (30kV&48pA). During the milling process, some initial ion doses actually contribute to surface swelling but not milling as mentioned above. Here we define the time required from swelling to milling at each radial distance as incubation time $t_{incu}(r)$, which increases outward from the center of the pit. The incubation time can also be described by an exponential function of radial distance as shown in Fig.5. Combining this function with (1) we can get

$$D(r,t) = \frac{\partial D}{\partial t}(r) \times \left(t - t_{incu}(r)\right) = -a e^{-\left(\frac{r}{c}\right)^2} \times \left(t - t_{incu}(r)\right). \qquad (2)$$

In the region of $t \leqq t_{incu}(r)$, the swelling effect dominates and the depth is assumed to be zero. Fig. 6 shows the calculated profiles by (2) as well as the AFM data. The difference between measured and calculated values is within only 3 nm.

Figs. 7(a) & 7(b) show the 3D AFM images of line structures composed of overlapped pits with 90 nm and 87 nm pitch respectively. Their surface topographies are also shown in Figs. 7(c) & 7(d). The red dashed lines depict calculated profiles based on the superposition of pit depth by (2). Obviously the depth is underestimated, especially for the line structure with a pitch of 87 nm. A reasonable explanation is that the sputtering yield increases with the angle of incidence of the ion beam [2]; since the substrate surface is no longer flat after the milling of first pit, the angular dependence of sputtering rate should be taken into consideration in the subsequent milling process. The effect of incident angle or even the curvature of material surface on the superimposition behavior of ion beam milling is still under investigation. Nevertheless, the proposed approach provides a basis for further studies in complex FIB machining process.

Acknowledgments

This work was supported by the Ministry of Science and

Technology of the Republic of China under contract no. MOST 102-2221-E-002-151-MY3.

References

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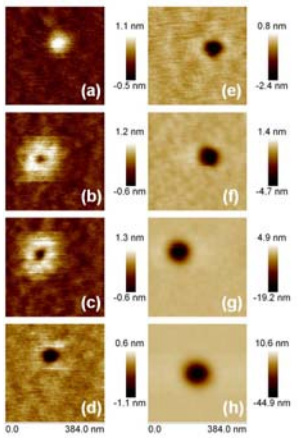

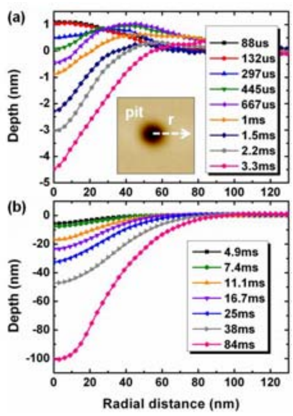

(Left) Fig. 1: AFM images of Si(001) after the process of single spot milling with a dwell time of (a) 88 μs, (b) 445 μs, (c) 667 μs, (d) 1.5 ms, (e) 3.3 ms, (f) 7.4 ms, (g) 16.7 ms, and (h) 38 ms.
(Right) Fig. 2: Surface profiles measured through the center of the milled pits. The milling process begins to dominate as the dwell time exceeds 1 ms.

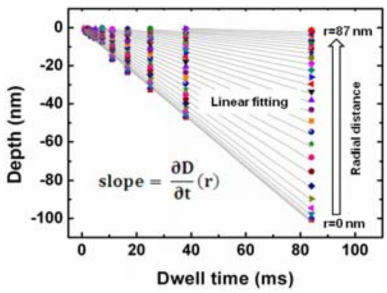

Fig. 3: Change of depth with dwell time at each radial distance of the pit. The slopes decrease outward from the center.

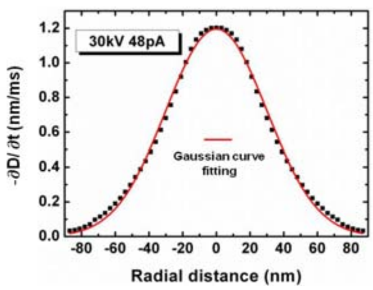

Fig. 4: Change of the slope of depth-dwell time graph (Fig. 3) with radial distance. The red solid line represents a Gaussian fitting curve.

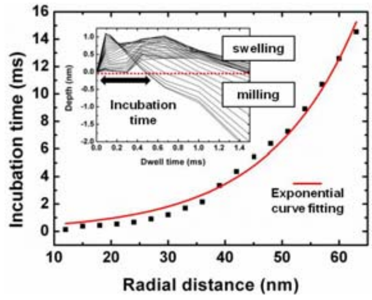

Fig. 5: Increasing of incubation time with radial distance. The red solid line represents an exponential fitting curve. The inset shows that initial ion doses contribute to surface swelling but not milling.

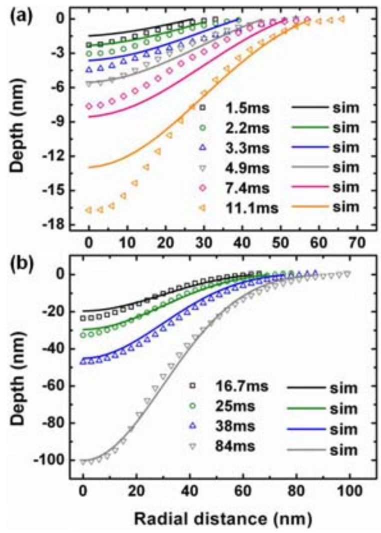

Fig. 6: Calculated depth profiles (solid lines) as well as the AFM data (hollow dots). The difference between measured and calculated values is within 3 nm.

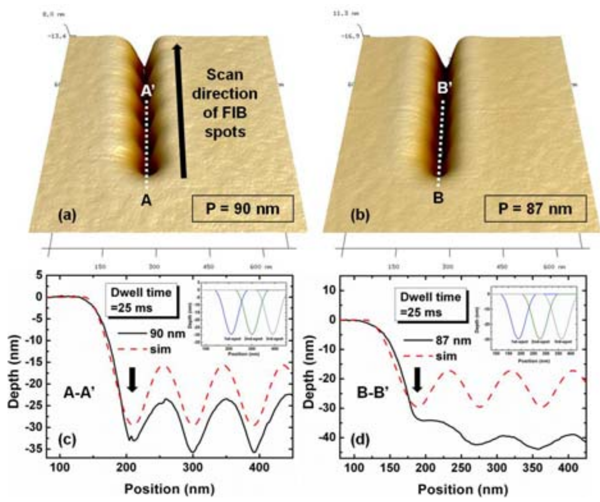

Fig. 7: 3D AFM images of line structures composed of overlapped pits with a pitch of (a) 90 nm and (b) 87 nm. Their corresponding surface topographies are shown in (c) and (d) respectively. The red dashed lines represent calculated profiles based on the superposition of depth of each single pit (as shown in the insets). The black arrows indicate the position of first pit.