Three-dimensional (3D) alignment with 10-nm order accuracy in electron-beam lithography on rotated sample for 3D nanofabrication

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Three-dimensional (3D) nanofabrication with a high degree of freedom is desired for various nanotechnology applications such as nanoelectromechanical systems. We have already devised a 3D nanofabrication technique[1,2] using electron-beam (EB) lithography on rotated samples, which has much higher fabrication speed than charged-particle-beam-induced deposition and shows application potential to various materials when used in association with 3D resist coating[3] and etching. However, alignment in 3D space and its improvement have not been well investigated, which is essential for creating various 3D nanostructures with a high degree of freedom. We have achieved 3D alignment accuracy as high as 10-nm order in 3D EB writing, which is carried out on resist blocks from directions along three Cartesian axes.

Detecting the projected shape of a block, as a locating mark, using transmission electron signal allowed us to obtain a mark location accuracy of 10-20 nm and an overlay accuracy of several-ten nanometers (Table I). Another key is precise rotation control to less than 1 mrad for micron-order resist blocks on a small substrate in the EB writing apparatus. This precise rotation control makes possible EB writing on the blocks from just the side-face directions, which means that the EB almost touches the substrate surface. Figure 1 shows a 3D structure made of hydrogen silsesquioxane (HSQ) on a 1-mm Si cube, demonstrating a high 3D alignment accuracy. We adopted two-step process for the negative resist: 2D EB writing and weaker development to make a block, and then EB writing from the side-face directions and stronger development. EB writings of dot-array patterns from Z, $\pm X$, and $\pm Y$ directions met in the resist block and resulted in knots. Figure 2 shows another 3D nanostructure made of positive poly(methyl methacrylate) (PMMA) resist, which demonstrates the high degree of freedom of our technique with the high alignment accuracy.

This highly accurate 3D alignment largely expands the applicability of 3D EB lithography, allowing us to fabricate various 3D nanostructures for novel nanotechnology applications.

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[1] K. Yamazaki T. Yamaguchi, and H. Namatsu, Jpn. J. Appl. Phys. **43**, L1111 (2004).
[2] K. Yamazaki and H. Namatsu, Microelectron. Eng. **73-74**, 85 (2004).
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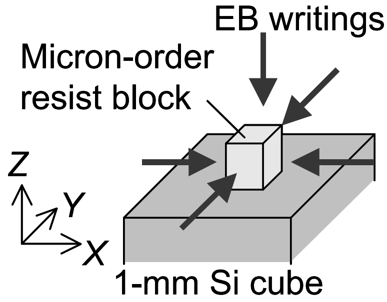
Table I. Accuracy (standard deviation) [nm]

	X or *Y*	*Z*
Mark locating	21	16
Positioning of mark	18	25
Overlay (vernier writing)	36	51



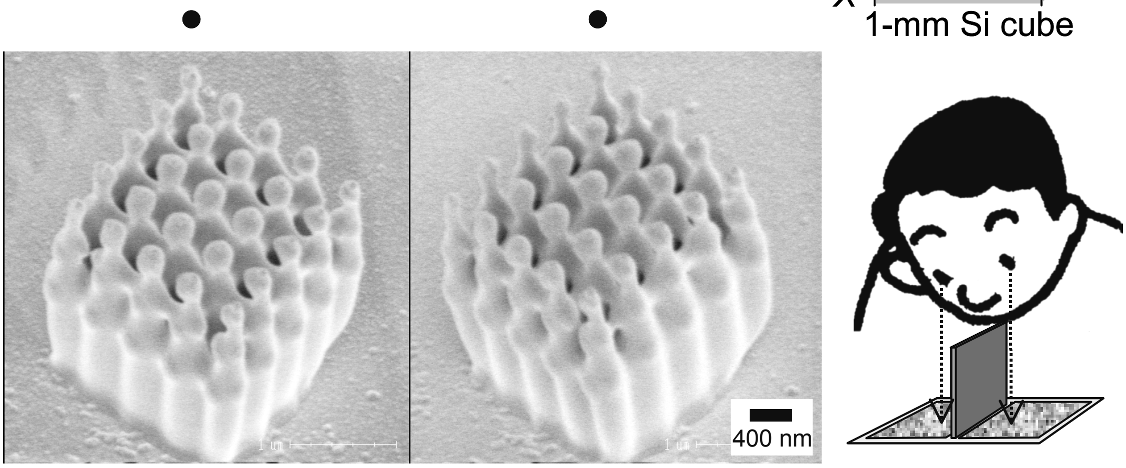


Fig 1. 3D HSQ nanostructure made by writing dot arrays from ±*X*, ±*Y*, and *Z* directions to demonstrate high 3D alignment accuracy. The two images constitute a stereogram (parallel viewing).

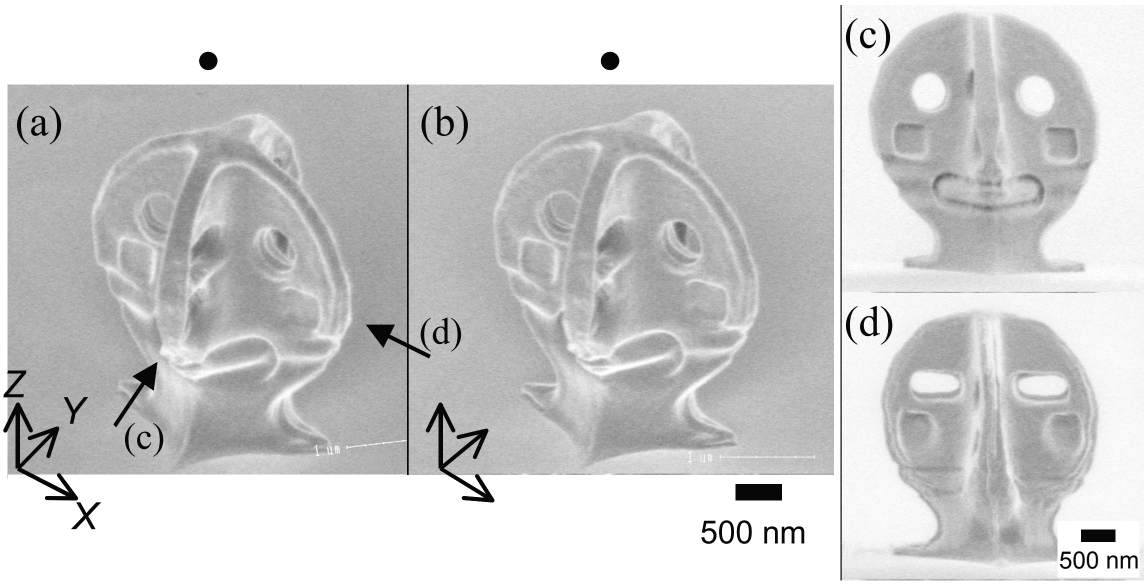


Fig 2. 3D PMMA nanostructure made by writing from ±*X*, ±*Y*, and *Z* directions to demonstrate the high degree of freedom in creating 3D structures. Images (a) and (b) constitute a stereogram (parallel viewing).