New Technique of Three-Dimensional Nanofabrication in Semiconductors by Using Electron Beam Lithography

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Creating three-dimensional (3D) nanostructures in semiconductors would be very useful in various nanotechnology fields such as nanomechanics and nano-robotics. Reported techniques, however, seem to have at least one of the following drawbacks: low resolution along the height direction, a time-consuming process, or poor structural flexibility regarding what can be created. On the other hand, we have already developed a 3D nanofabrication technique for resist materials,[1,2] which does not have such drawbacks. We here report the first demonstration of 3D semiconductor nanofabrication through a combination of resist coating on vertical side faces,[3,4] EB writing from multiple directions, and etching parallel to substrate surface. This technique has allowed us to perform fast 3D fabrication in Si with a high resolution and great structural flexibility.

Figure 1 illustrates the fabrication process we use for creating 3D nano-structures in Si. In this case, each EB pattern written from three directions (+/–*X*, *Z*) can be freely designed. To coat resist on vertical side faces of a micrometer-order Si block [Fig. 1(c)], we use spin coating and our original resist solution with low viscosity, which results in uniform thickness on the vertical side faces.[3,4] Reactive ion etching from the sides [Figs. 1(h), 1(i)] is performed with an angle very close to a right angle (88°), which is enabled by using small sample (1-2 mm) and dummy substrates surrounding it. Figure 2 shows micrographs of the first demonstration of 3D nanostructures we created using this process. The close-up [Fig. 2(b)] shows that our technique has a resolution better than 50 nm. The total writing time to create the structure was less than 5 sec, although the beam current was very small (50 pA).

As an application of our technique, we have also designed a 3D nano-mechanical resonator in crystal Si (Fig. 3). The resonator consists of two thin/narrow nanobeams and a microcantilever whose thickness continuously changes along the length direction. This kind of real 3D nanostructure cannot be created by conventional 2D techniques. Our calculations of the mechanical characteristics of this resonator revealed that it provides much higher quality factors than conventional prismatic cantilevers. This is because major parts of energy dissipation occur around the small nanobeams, while the microcantilever vibrates with large kinetic energy.

Our new 3D nanofabrication technique is a promising step towards the development of useful nanodevices such as high-performance nanomechanical devices.

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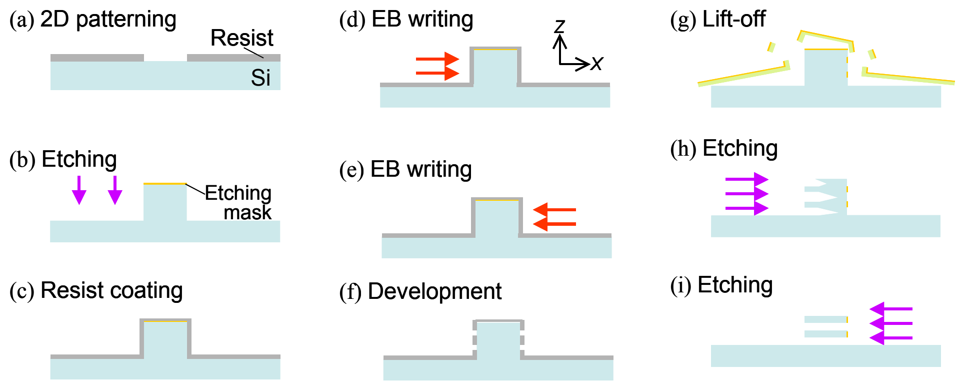

Figure 1: Fabrication process for creating 3D nanostructures in Si. (a), (b) 2D fabrication of Si blocks, (c) resist coating on vertical side faces, (d)-(g) EB writing/patterning, and (h), (i) etching from the sides.

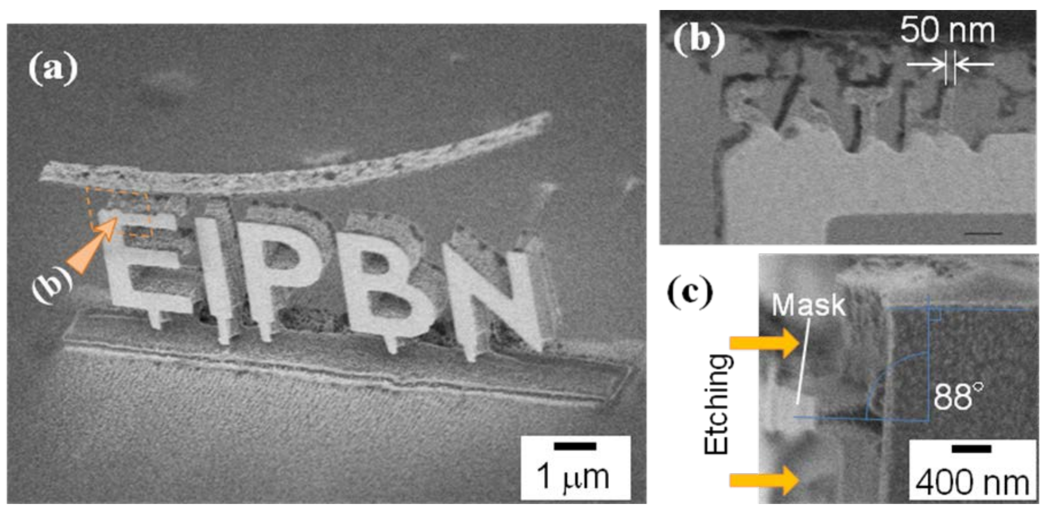

Figure 2: Micrographs of 3D Si nanostructures created by using the process shown in Fig. 1. The minimum feature size is about 50 nm as the first attempt. (c) Cross-sectional micrograph taken after partial side-etching. The measured angle of etching from the sides is about 88 °.

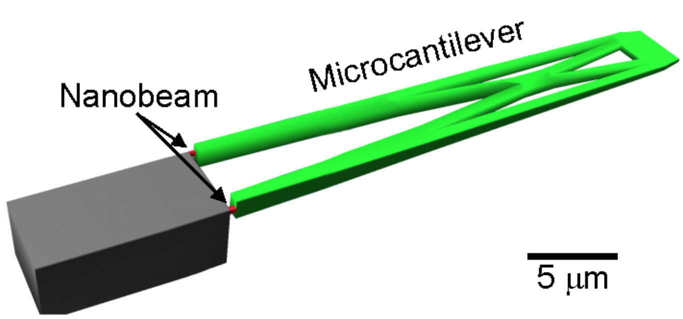

Figure 3: Designed micromechanical resonator in Si, consisting of a micro-cantilever and two nanobeams. Calculated energy dissipation due to thermoelastic damping relative to the total kinetic energy is about 30% of that for a prismatic microcantilever with the same resonant frequency (260 kHz) and total length (40 µm)/width (5 µm).