High Resolution Patterning on Non-Planar Substrates with Large Height Variation Using Electron-Beam Lithography

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Emerging applications in the field of optics, flexible electronics, sensors, and biotechnology require the fabrication of nano-scale devices on non-planar substrates. For non-planar systems with substantial height variation, the nano-patterning technology is still in its infancy. Imprint lithography can cope with certain curved surfaces but it is restricted to substrates that have a constant magnitude of curvature.[1] Electron-beam lithography has been used to pattern on substrates with high topography by manually focusing on the different planes.[2]

We employ a non-contact, high precision, automatic measurement of surface topography with a laser probe microscope, the Mitaka NH-3N, to get accurate height values across the substrate to be patterned. This data is integrated with the electron-beam lithography system, the JEOL JBX-6300FS. The system allows the plane of focus of the electron beam to be adjusted based on the height mapping data obtained from the laser microscope, thereby maintaining correct focus along the substrate with varying topography. Figures 1(a) and (b) show the height maps for a 25 mm diameter plano-convex lens with a radius of curvature of 30.9 mm and a titled 150 mm Si wafer with a depth variation of 6.5 mm, respectively.

We quantify our nano-patterning results by analyzing the field stitching accuracy, field positioning accuracy (based on a reference mark on the substrate holder), and the uniformity of the high resolution patterns. Figures 2(a) and (b) are representative images of field stitching and field positioning accuracy, respectively, patterned on various locations on the convex side of the plano-convex lens. A field stitching accuracy of <±45 nm and a positioning accuracy of <±100 nm (based on the substrate holder reference mark) were obtained. Our resolution tests were done on a 75 mm diameter Si wafer that was tilted to provide a depth variation of 1.5 mm. The wafer was mapped and patterned with 50 nm lines and a 100 nm pitch at various height locations. Figure 3(a) shows a representative image of the patterns. Analysis of the patterns at various height locations indicated that the variation of the critical dimension is <5 nm. This is shown in Fig. 3(b). Note that since the patterns were written as single pass lines, the line edge roughness contributes between 12 and 20 nm to the final dimension of the lines patterned at a given height location. Similar nano-patterns have been obtained on a 75 mm diameter Si wafer that was tilted to provide a depth variation of 2.5 mm, and also on different substrates each of which was patterned at a height location of 250 μm below the top plane of the substrates as shown in Figs. 4 (a), (b), and (c).

The excellent nano-patterning results combined with the fact that it is directly applicable to practically any kind of substrate with large depth variation opens up a new avenue for patterning of non-planar substrates.

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[1] J. Casey, “Curvature of Curves,” in *Exploring Curvature.* Braunschweig, Germany: Vieweg, 1996.

[2] J. Linden, Ch. Thanner, B. Schaaf, S. Wolff, B. Lägel, and E. Oesterschulze, Microelectron. Eng. **88**, 2030 (2011).

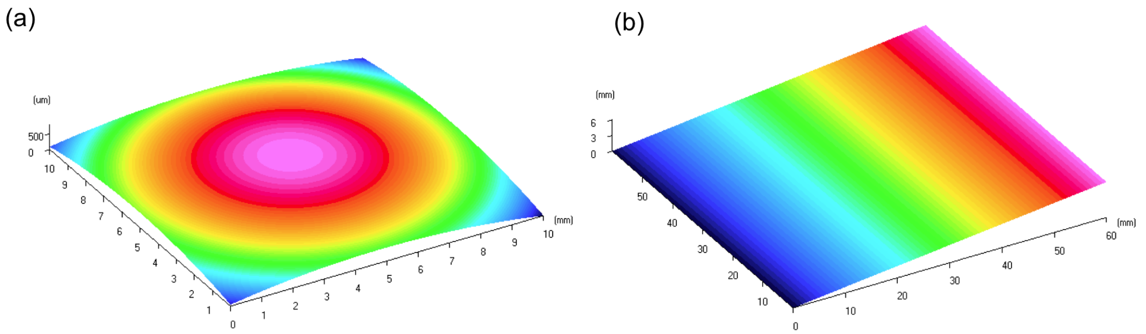

Fig. 1. High precision measurement of surface topography with laser probe microscope. (a) Height map for a 25 mm diameter plano-convex lens having a radius of curvature of 30.9 mm. (b) Height map for a 150 mm Si wafer tilted to provide a depth variation of 6.5 mm.

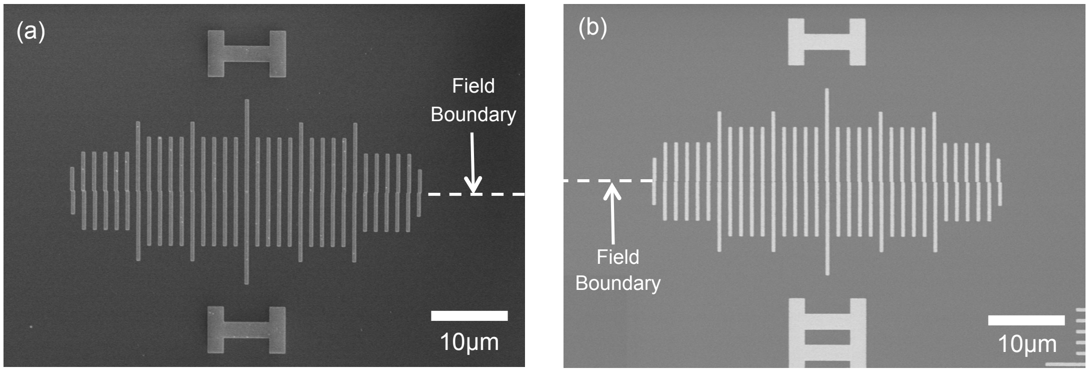

Fig. 2. Field stitching and field positioning accuracy results for patterning on plano-convex lenses. (a) Field stitching accuracy better than ±45 nm. (b) Field positioning accuracy (based on a reference mark on the substrate holder) better than ±100 nm.

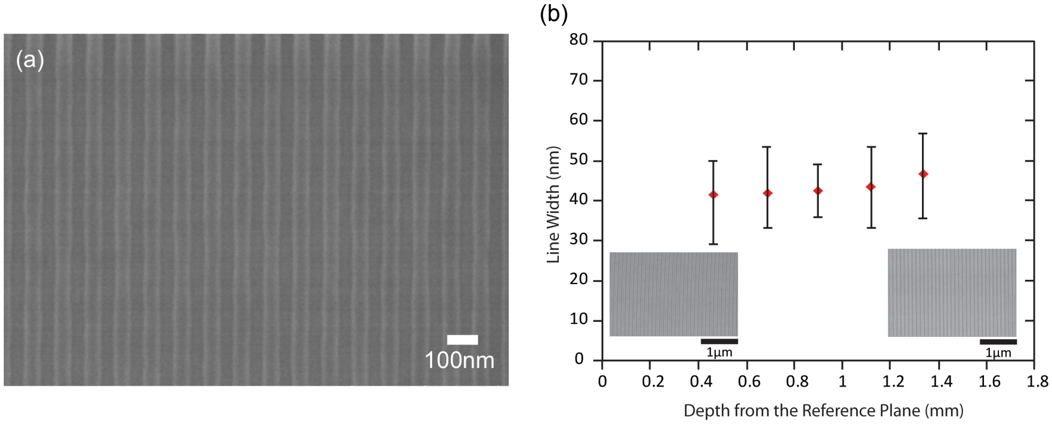

Fig. 3. (a) 50 nm lines with 100 nm pitch patterned on a 75 mm diameter Si wafer at a depth of 0.82 mm below the top plane of the substrate. (b) Variation of the critical dimension as a function of the depth below the top plane of the substrate.

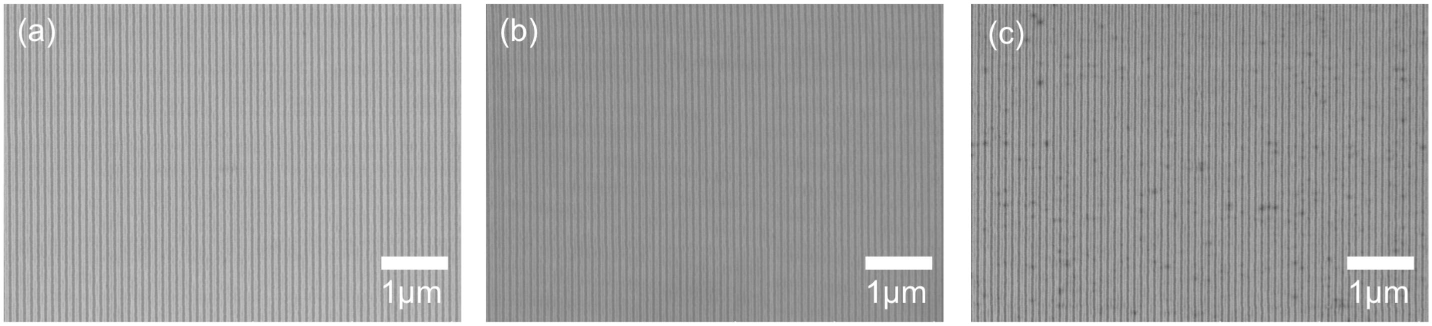

Fig. 4. 50 nm lines patterned at a height location of 250 µm below the top plane of the substrates. (a) 25 mm diameter plano-convex lens, (b) 75 mm diameter Si wafer, and (c) etched surface of a 75 mm diameter Si wafer.