Focused ion beam milling of three dimensional nanostructures with high precision

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Abstract

The fabrication of an extended three-dimensional nanostructure with dimensions much larger than the feature size using a focused ion beam is described. By milling two identical patterns of pores with a designed diameter of 460 nm in orthogonal directions, a photonic crystal with an inverse woodpile structure was made in a gallium phosphide single crystal. The patterns are aligned with an unprecedented accuracy of 30 nm with respect to each other. The influence of GaP redeposition on the depth, shape, and size of the pores is described. The work is published in J. Vac. Sci. Technol. B [1].

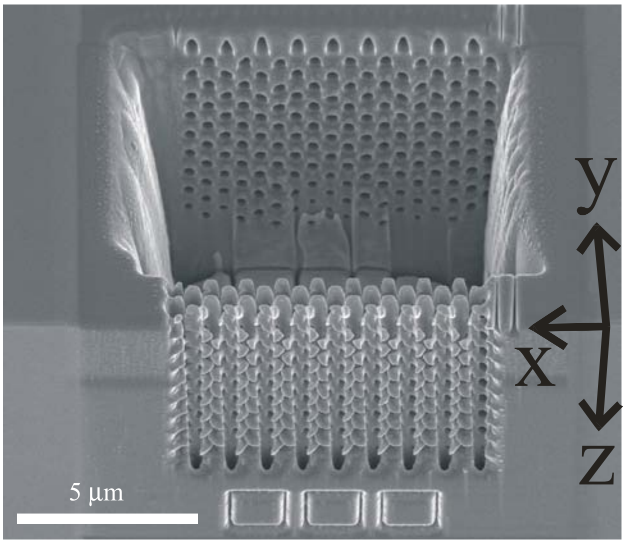

Figure 1: Three dimensional inverse woodpile nanostructure made by focused ion beam milling. The x, y, and z axes are indicated.

An inverse woodpiles tructure was milled in GaP. We chose GaP because of its high index of refraction and large electronic gap, with a view to eventually making photonic crystals for the visible range. There are few alternative methods to focused ion beam milling in GaP, in contrast to Si, for which many different processing techniques have been developed [2,3]. This makes the study of the milling of GaP with a focused ion beam relevant.

The parameters of the inverted woodpile structure that was milled were chosen such that a photonic band gap would, in principle, be centered at wavelengths around 2000 nm. Therefore the diameter D of the pores was 460 nm, and the lattice parameters were a = 958 nm, and c = 677 nm. The thickness of the GaP walls between the pores is only 253 nm.

When three-dimensional structures with dimensions that are large compared to their smallest features have to be fabricated, the mutual alignment of the various parts poses a challenge. The orthogonal components are aligned with an accuracy better than 30 nm by using simple

alignment marks. This is the first time a nanostructure was made by milling with FIB in two orthogonal directions and aligning the two patters with respect to each other with very high precision using alignment marks. We will call the pores that traverse the slab in the y-direction the y-pores, and the pores that traverse the slab in the z- direction the z-pores.
To investigate the influence of porosity on milling, we performed experiments both on bulk wafers and in slabs with a thickness below 2 µm. The diameter of the pores in bulk GaP was designed to be 483 nm. Since the best results were obtained with slabs, we now describe their fabrication.
In the first step of the fabrication process a slab was made by milling a large rectangular hole at a distance of about 2 µm from the cleaved edge of the sample. The slab had two faces: the front face, (the cleaved surface of the sample), and the back face, (one of the walls of the rectangular hole). The back face of the slab was smoothened with the "polish mill" option of the focused ion beam apparatus. In this way a slab with the desired thickness of 1.6 to 1.9 µm could be made. After the slab was formed the sample was rotated and the first hole pattern of the structure was milled in the y-direction. Automatic drift correction was applied during milling, using specially milled square markers. In this way a two-dimensional crystal structure of 9 by 9 unit cells with parameters D = 460 nm, a = 958 nm, and c = 677 nm was formed in the slab. In the next step, alignment marks, consisting of two narrow lines with a width of approximately 50 nm and a spacing of 340 nm, were milled in the side of the sample. The sample was again rotated to be able to mill on the top of the slab. Using a cross-shaped alignment mark we aligned the second pattern of pores with respect to the first pattern, and milled it parallel to the front face of the slab, perpendicular to the previously drilled pores, and in the desired places.
The diameter of the pores made in bulk material decreased rapidly with depth at the top of the pore, close to the surface of the sample, and more slowly at distances further from the surface (fig. 2, circles). In the slab, however, the diameter of the second set of pores was nearly constant over their whole length. Fig. 2 shows that the average diameter of the z- pores is approximately 300 nm, independant of the distance from the top of the slab. The walls between the pores are 413 nm thick. We observe that the pore diameter is significantly smaller than the designed value of 460 nm. This result is remarkable because the diameter of pores milled in this way is usually slightly larger than the designed diameter, due to beam- and stage drift. Here, stage drift is negligible, and the reduction in the diameter is caused by redeposition during milling.

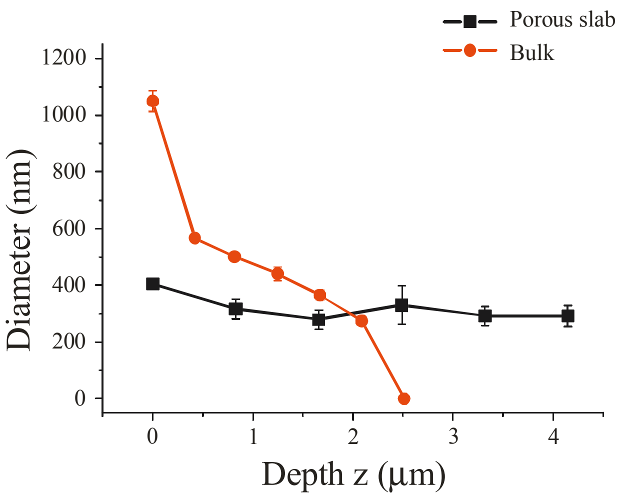

Figure 2: The average diameter of all z- pores in the slab as a function of the depth z inside the pore (connected squares). The average diameter of 5 pores made in bulk material as a function of the depth is shown as connected circles. The tapering of the pores in the slab is much less than that of the pores in bulk material.

Fig. 3 shows the final diameter of the y- pores, measured after the z- pores were milled, as a function of the distance z from the top of the wall. The thickness of the redeposited layer inside the pores was calculated on the basis of the initial diameter of the pores (460 nm). The figure clearly shows that the pores located near the top of the wall have the smallest diameter (approximately 30 nm). With increasing depth, the pore diameter increases to approximately 140 nm, which is much smaller than the initial diameter of 460 nm. Fig. 2 shows that the thickness of the redeposited layer in the pores decreases with depth from 220 nm to 160 nm. This result can be explained as follows: when the second set of pores is milled, the y-pores closest to the top of the slab are penetrated first. These y- pores suffer the most from redeposition because they are more exposed to sputtered material during milling. Redeposition of sputtered material during focused ion beam milling of GaP tends to deteriorate the quality of the final structures.

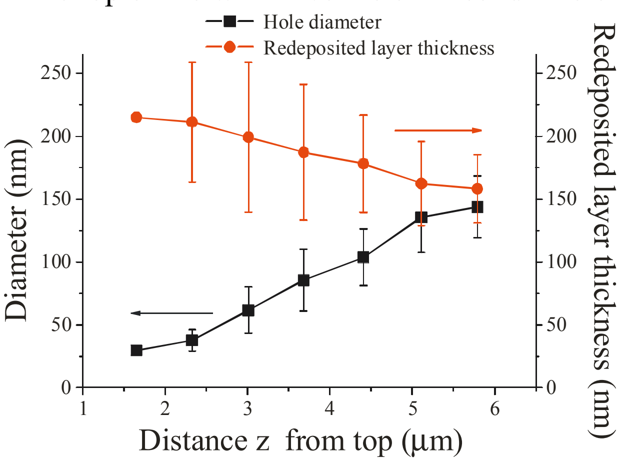

Figure 3: Average diameter of the y- pores as a function of their distance z to the top of the porous wall (black squares). The average thickness of the redeposited layers inside the pores is also indicated (red circles).

Three-dimensional nanostructures were created in single-crystal GaP wafers using focused ion beam milling in two orthogonal directions. A special holder was designed for the process. The two orthogonal patterns of pores were aligned with an accuracy of approximately 30 nm. The highest aspect ratio of pores obtained in bulk GaP was 2.8 ± 0.15, which limits the maximum size of the three dimensional structures. The maximum obtainable aspect ratio in porous material is much larger than 13.

References

[1] R.W. Tjerkstra, F.B. Segerink, J.J. Kelly en W.L Vos, J. Vac. Sci. Technol. B. **26**, 973-977 (2008)

[2] J. Schilling and A. Scherer, Photonics and Nanostructures - Fundamentals and applications 3, 90 (2005)

[3] L.A. Woldering, R.W. Tjerkstra, H.V. Jansen, I.D. Setija, and W.L. Vos, Nanotechnology **19**, 145304: 1-11 (2008)