X-Ray Imaging of Functional Three-Dimensional Photonic Nanostructures with 20-nm Resolution

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Three-dimensional (3D) nanostructures are drawing a fast-growing attention for their advanced functionalities in nanophotonics [1], photovoltaics, and novel 3D integrated circuits and flash memories. The functionalities of such nanostructures are fundamentally determined by their complex internal structure. Inevitably, any fabricated nanostructure differs from its initial design. Hence, the observed functionality differs from the expected one. It is thus critical to assess the structure of a 3D nanomaterial and verify how well it matches the design. Ideally such an inspection technique leaves no traces of the inspection in order to leave the nanostructure fully functional and ready for integration. Here, we introduce traceless X-ray tomography (TXT) as a new methodology in nanotechnology to non-destructively assess the functionality of nanostructures.

Traditionally, a fabricated nanostructures is inspected by scanning electron microscopy (SEM). A major limitation of SEM is that only the external surface is viewed whereas the inner structure remains hidden, see Fig. 1A. To visualize 3D nanostructures, SEM is supplemented with micro-machining or ion beam milling to cut part of the structure away. Clearly, this approach is destructive and irreversible. To achieve nanometer spatial resolution in a structure with thick (millimeter) substrates that do not need to be cut away, we pursue X-ray holographic imaging [2] as the flagship tool of TXT. Holographic tomography experiments were done at the ESRF on the nano-imaging beamline ID16A-NI. As representative example we study 3D diamond-like photonic band gap crystals made from silicon by CMOS- compatible methods, see Fig. 1A. These nanostructures are powerful tools to control the propagation and the emission of light by their broad complete 3D photonic band gap [3]. The crystal structure is defined by two perpendicular 2D rectangular arrays of pores, with pores running in the Z and X-directions that are made by CMOS-compatible deep reactive ion-etching through tailored masks [4].

Fig. 1A shows a bird's-eye view of the reconstructed sample volume of the 3D photonic crystal shown in Fig. 1[5]. The Y Z top face shows the surface of the X-directed pores, similar to the SEM surface in Fig. 2A. The alignment of the pores determines the 3D crystal structure and is a crucial step in the nanofabrication. In practice, the alignment is controlled by the etch mask for each pore array and by the directionality of the etching processes. In the XZ side face in Figure 3A, pores are running in the Z direction, whereas in the XY front face, pores are running in the X direction, matching the 3D design of the inverse woodpile structure.

Notably the fabricated structure stays fully functional after X-ray imaging as it does not undergo any preparation step.

Fig. 1. (A) SEM image of the surface of a 3D Si inverse woodpile photonic crystal from Ref. [3]
(B) Bird's-eye view of the sample volume of an inverse woodpile crystal reconstructed from X-ray tomography [5] with 20 nm resolution. The colour scale is the 3D material density $\rho(X, Y, Z)$ interpolated between air and Si, the latter set to 255.

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