titania in a well controlled way is yet to be established. However, it is obvious that pores should be made in several consequential drilling steps.

To facilitate a repeated drilling of pores, toggling of sample is required. Markers at the top- and tilted-view are used to optimize sample positioning (Fig. 7). Such markers allow to toggle and set sample with precision ± 10 nm. The size of a structure required for the optical characterization is 60×60 holes (or $\sim 15 \times 15$ μm^2) area drilled to a ~ 2 μm depth. The time required for a single pore milling is few seconds, hence, time required for a large area sample for optical characterization would take several hours. For the larger pore diameters the aspect ratio is expected to increase (see, Fig. 4) even without chemical enhancement. It is noteworthy, that high-vacuum conditions of $\sim 10^{-7}$ bar were essential to obtain deep pores without apparent material redeposition.

Metal or anti-charging coating must be used to fabricate large areas with tens-of-μm in cross section for optical characterization. No changes of a pattern geometry were observed during ion fabrication over a 10-nm-platinum coated substrate as illustrated on a smaller area in Fig. 7.

The achieved aspect ratio of ~ 10 is already enough for the proof-of-the-principle demonstration and improves upon earlier demonstration of Si milling by FIB [14]. Moreover, the SP_3 structure used in previous experiments [14] is more complex to fabricate and has narrower bandgap as compared with the SP_2 structure demonstrated here by a two-step milling approach.

5. Conclusions

Ion beam direct writing is proposed as a tool to form PhC structures with the feature sizes required for functionality at the visible spectral range. The maskless direct write approach using IBL enters a promising parameter space of 100 nm feature size required for precise control of functionality of PhC structures at visible wavelengths. Numerical modeling of the fabrication tolerances in terms of pore radius and structure thickness demonstrates potential of high-resolution 3D-IBL in the field of photonic applications. Implementing anti-charging coating and fabricating pores with increasing diameter in several runs is expected to deliver required quality of the 3D PhC needed for demonstration of full PBG at the visible wavelengths. PhCs have important practical applications in confining light on an optical micro-chip for all-optical information processing, in trapping and absorbing light in thin films for efficient solar energy harvesting, and novel light emitters, to mention a few [25–27].

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