Processing of photonic crystals in InP membranes by focused ion beam milling and plasma etching

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Abstract

We present a fabrication approach for Photonic Crystals and similar nanophotonic structures in InP using focused ion beam milling and plasma etching. The high quality of ion milling lithography in a dielectric hardmask is combined with reactive ion etching to obtain simultaneously fast processing speeds and smooth and vertical sidewalls. Different hardmask materials have been investigated yielding very good results for SiO_2 and Si_xN_y. Parameters for the optimization of lithography and plasma etching are given. Finally results of a released InP membrane with a Photonic Crystal structure featuring elliptical base elements are presented.

1. Introduction

Optoelectronic and optical MEMS devices based on the Indium Phosphide (InP) offer very high material quality and the option for monolithic integration with other active or passive components operating in the near infrared spectral range. Devices like filters, detectors or lasers are widely used for telecommunication or in spectroscopic sensors [1]. A special class of optical MEMS are InP/air-gap structures making use of the high refractive index difference of released semiconductor membranes and air. Research on highly efficient and compact tunable Fabry-Pérot filter devices (Fig. 1) has been reported by using this technology approach [2-4]. Additional polarization selectivity can be added to these spectral membrane filters by introducing a periodic structure. InP/air-gap polarizers with Photonic Crystal membrane are based on the guided-mode resonance effect and exhibit polarization dependent coupling properties due to non-symmetric features, like elliptical base elements in a square lattice [5,6]. → Fig-01

Fabrication of such a device is challenging as the accuracy of the non-symmetric shape with features in the sub-100 nm range is crucial for the quality of optical properties. Moreover integration into conventional MEMS processing is required. Electron beam lithography offers very high resolution and fast beam speeds making it a preferential choice for many applications. However for structuring of MEMS devices the alignment of the Photonic Crystal pattern to a filter area and the problematic application of thin resist layers on mesa structures limit the scope of this technology. Lithography employing focused ion beam (FIB) milling is directly sputtering the sample material and can be applied without the need for a resist layer. Alignment of the samples can be conveniently accomplished in situ by an attached SEM optical system. Unfortunately, direct patterning of InP provides only insufficient quality of the nanophotonic features and sidewall profiles due to strong redeposition of sputtered material [7] and the profile of the focused ion beam as shown in Fig. 2. If deeply milled structures are desired these effects become more critical. Additionally, processing time increases drastically as the beam speed of high resolution FIB is rather slow. We developed a fabrication process using FIB milling lithography of a hard mask layer and subsequent plasma etching to overcome these limitations As proof of principle we present the successful implementation of a Photonic Crystal polarizer. → Fig-02

2. FIB Processing with Hardmasks

Since FIB milling of high resolution features with deep profiles is time consuming and delivers not the required quality in InP the use of a two step process is proposed. First the Photonic Crystal structure is milled into a thin hardmask layer by FIB processing. As the milling depth is only in the range of a few 10 nm quality of the generated pattern is very high and processing time is still reasonable. In a second step the pattern of the hard mask is transferred to the actual sample material by Reactive Ion Etching (RIE). High quality of the etch profile and high etching rates are achievable with the appropriate process parameters. The full fabrication sequence of the MEMS polarizer devices is shown in Fig. 3. A multilayer structure consisting of the InP membrane and two surrounding sacrificial GaInAs layers are grown epitaxially on an InP wafer by use of a low pressure MOVCD system. The lateral shape of the MEMS filter device is defined by optical lithography and RIE in an Oxford Plasmalab 80+ with CH_4/H_2 plasma chemistry. The hardmask layer for FIB milling is a dielectric layer with 40 nm thickness deposited in an Oxford Plasmalab 80+ PECVD at 300 °C chamber temperature. Milling of the Photonic Crystal structure into the hardmask is carried out in a Carl Zeiss NVision 40 FIB system with probe currents between 10 pA and 40 pA depending on the resolution constraints. The pattern of the dielectric layer is then transferred to the InP layer by employing again the CH_4/H_2 RIE process. Subsequently the hardmask is removed in hydrofluoric acid and the membrane is released by sacrificial wet etching of the GaInAs layers using a $FeCl_3$ solution. Removal of the liquids from the sample after the etching step has finished is accomplished by critical point drying to avoid damage due to capillary forces. → Fig-03

Similar processing flows based on the combination of FIB milling lithography of a hard mask and plasma etching have been presented previously [8,9], but with the implementation of thick dielectric layers. Although the results of these investigations are showing also very good quality of the produced structures, the thickness of the hardmask introduces some disadvantageous properties. First due to the non-conducting properties charging of the dielectric layer becomes a severe problem and an additional metal coating has to be applied. In the case of a very thin layer charging is not observed as electrons can reach the semiconductor material. Hence no extra conducting coating was applied. Secondly, dielectric materials own in general a low sputter rate due to their hardness and thus thicker layers lead to a distinct increase in processing time. Also the achievable resolution is decreasing as the profile of the focused beam may affect the sidewall profile. Another approach to improve the FIB fabrication quality in InP uses iodine gas assisted milling [10]. However the chemically aggressive properties of iodine and the limited effect for deeply milled structures restrict the possible application.

3. Experimental Investigation and Results

Different parameters of the developed fabrication process have been studied to optimize the resulting nanophotonic structures. Choice of the hardmask layer is the crucial step in defining the quality of FIB milling lithography and plasma etching. The appropriate material has to offer good FIB milling qualities as well as a high selectivity during the RIE process. Four different metal layers (Al, Ag, Cr, Ti) with thickness of 40 nm were deposited by electron beam evaporation and investigated by patterning of test fields with Photonic Crystal structures by FIB milling. A random texture in the structured areas (Fig. 4) was observed for all metal layers making them unsuitable for hard mask applications. This effect is originating in the interaction of high energy ion with the structure of the metal thin-film. This includes grain modifications, defect generation, thermal spikes and particularly ion channeling [11,12]. A second set of dielectric hard mask layers (SiO_2, Si_xN_y) also with thickness of 40 nm was deposited in a PECVD process at 300 °C chamber temperature. No texture effect was observed in the samples as show in Fig. 4 and further research was carried out with the dielectric layers. Etch selectivity in the RIE process was determined by testing the etch rate for 400 nm thick hardmask layers during process duration of up to four hours. Both materials exhibit a similar etch rate in the CH_4/H_2 RIE of 1 nm/min which results in a selectivity of better than 1:20 towards InP. For the applied thin hardmasks an even higher selectivity has been observed as with the 40 nm thick dielectric layers etching processes up to 90 min were carried out successfully. → Fig-04

With the dielectric hardmasks FIB milling lithography has been implemented with probe currents between 10 pA and 40 pA. Additionally a multi-loop exposure approach has been applied to minimize redeposition effect and increase structure quality. Stage drift, induced by thermal expansion and mechanical creep, was compensated by checking and re-adjusting the position of an alignment marker after every exposure loop. The positions of the Photonic Crystal base elements and hence the lattice constant exhibit a very high accuracy. The dimensions of the elements however are affected by deviations during ion milling and in particular by undesired lateral etching in the RIE process. Influence of these effects on the feature sizes was characterized by comparing the intended design values and the resulting structures. For the elliptical elements the two main axes were investigated as shown in Fig. 5 and adjusted dimensions implemented to the design specifications. → Fig-05

An InP membrane with Photonic Crystal structure featuring elliptical base elements was fabricated by using the newly developed process shown in Fig. 3 according to the described optimized parameters. The resulting MEMS polarizer device demonstrates the high quality of the new fabrication process as depicted in Fig. 6. Positions of the base elements defining also the lattice constant of the Photonic Crystal are matching the design values within the measurement accuracy. Process related residual deviation of the dimensions of the features is between 2-3%. The edges of the etched structures are well defined and sidewall are smooth exhibiting an angle of at least 87°. → Fig-06

4. Summary

We developed a new fabrication process for Photonic Crystals and similar nanophotonic structures in InP/air-gap MEMS devices using a two step approach. FIB milling lithography of a dielectric hardmask layer is combined with plasma etching to achieve high quality features and fast processing. The implementation of a very thin layer proves to be beneficial regarding charging effects, processing time and resolution. By a comparison of different potential hardmask materials dielectric layers deposited by PECVD were chosen, as with metal layers an undesired texture was observed. Selectivity of the hardmask was characterized and further optimizations of the process introduced. Finally, a Photonic Crystal polarizer with high quality of the fabricated structures is presented.

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Figure Captions

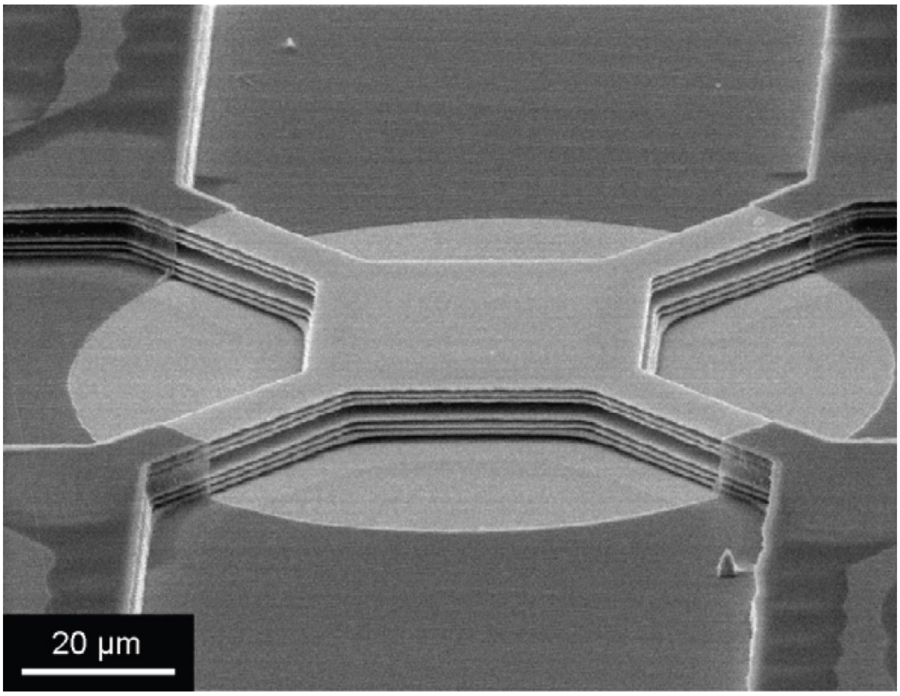

Fig 1: Optical MEMS Fabry-Pérot filter with InP/air-gap DBR mirrors and air cavity. By adding a Photonic Crystal structure to the top membrane polarization selectivity can be implemented.

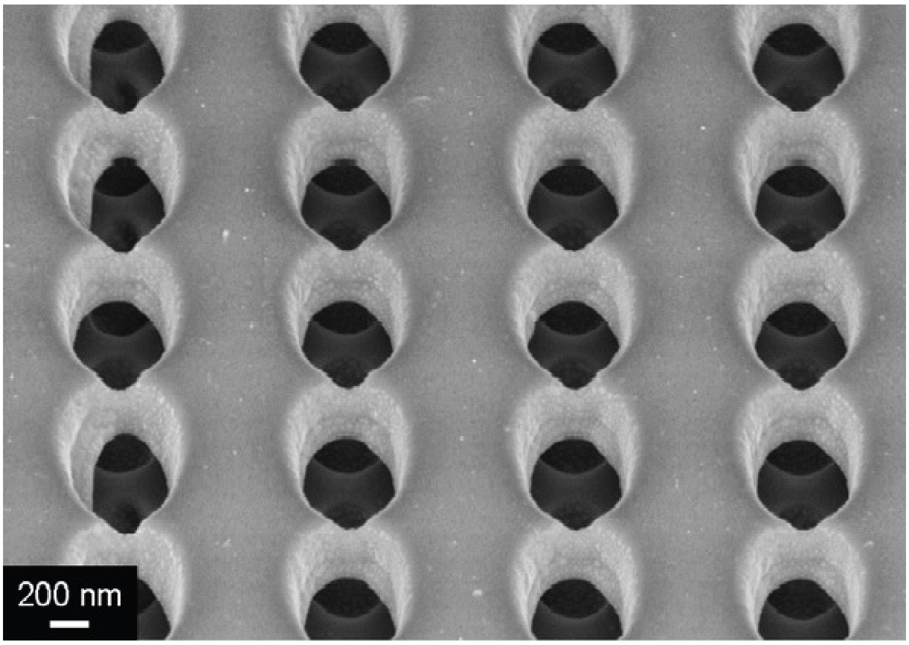

Fig 2: Photonic Crystal structure fabricated by direct FIB milling in a InP membrane. The effects of redeposition and profile of the focused ion beam are clearly visible.

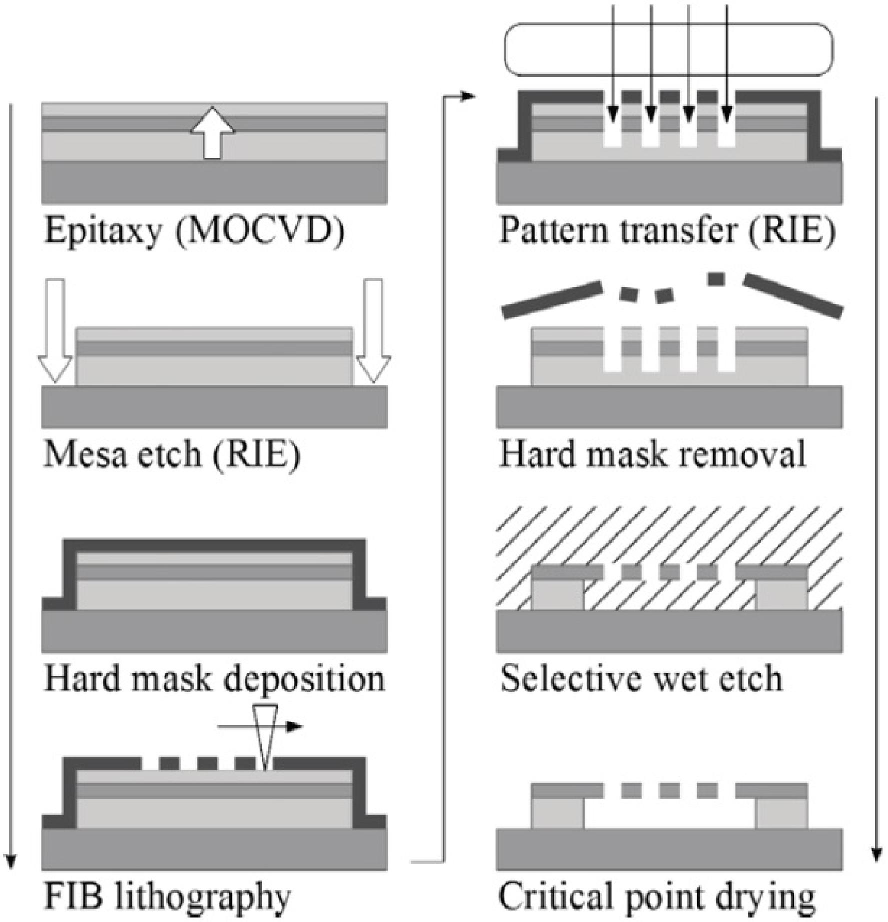

Fig 3: Overview of the new fabrication approach based on FIB milling lithography and plasma etching integrated to the conventional MEMS process.

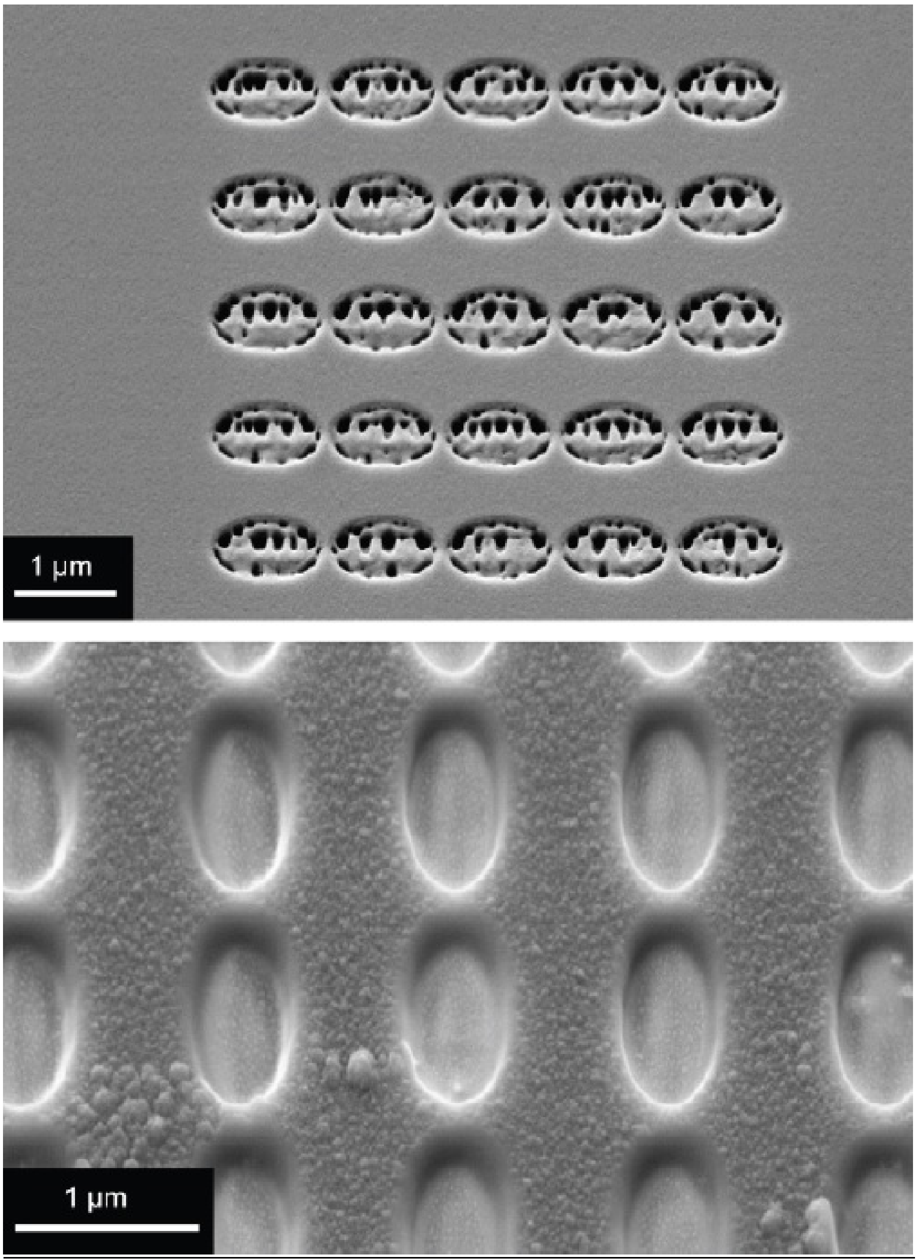

Fig 4: Texture effect observed in metal thin-films during ion milling (40 nm Cr layer, top image). The same investigation on a dielectric layer exhibits no texture and is fully usable for hardmask application (40 nm SiO_2, bottom image.

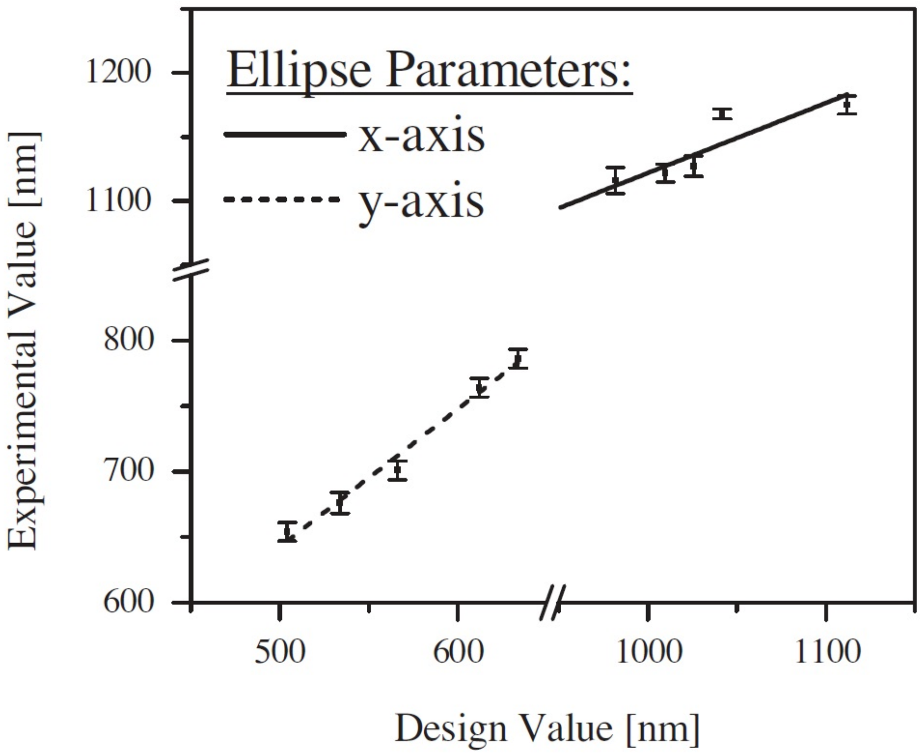

Fig 5: Characterization of the structure dimension deviations in the main axes of elliptical elements. Design and resulting values are compared showing the impact of ion milling and lateral RIE etching.

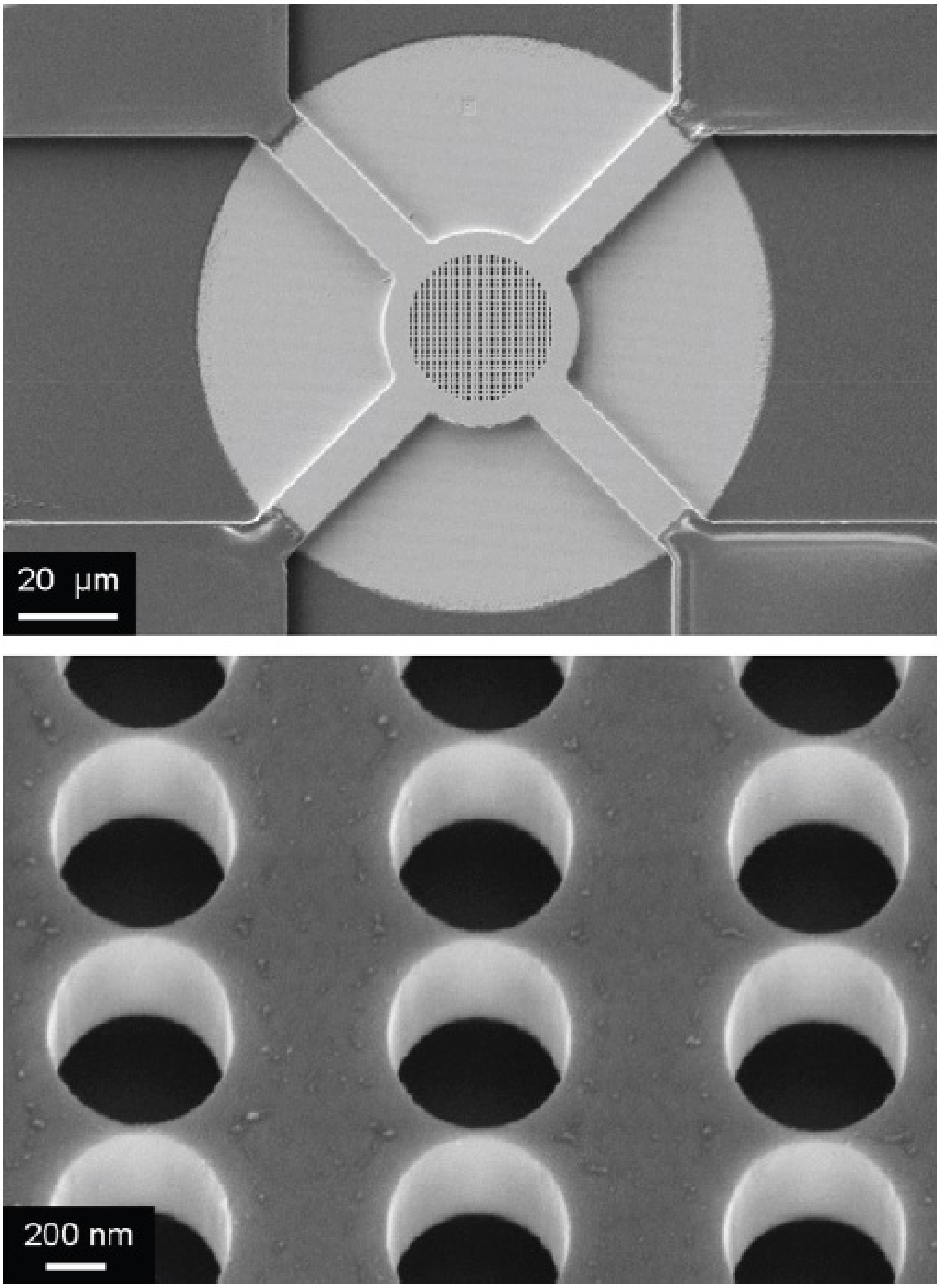

Fig 6: Overview of the Photonic Crystal polarizer with elliptical base elements fabricated by the new two step process (top image). A detailed view on the nanophotonic structure showing the high quality of structures, surfaces and sidewalls (bottom image).