

Cl₂-based inductively coupled plasma etching of photonic crystals in InP

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We have investigated Cl₂-based inductively coupled plasma etching for fabrication of two-dimensional photonic crystals in the InP-based material system. The influence of temperature, ion current density and ion energy on etch rate and hole profile was studied. Nitrogen was added to the Cl₂-chemistry for sidewall passivation to obtain vertical hole profile.

Introduction

InP based two-dimensional (2D) photonic crystals are likely to be present in many of the future optical devices involving the telecommunication wavelength of 1550 nm. Implementation of these devices in standard InP/InGaAsP photonic integrated circuits requires deep etching of the photonic crystal holes. To fulfill the requirements of operation around 1550 nm and low optical loss, the etched holes should be on a triangular lattice with lattice constant a of ~ 400 nm, have a diameter d of ~ 250 nm and a depth of ~ 2.5 μm with smooth and vertical sidewalls [1]. Excellent results have been achieved with chemically assisted ion beam etching (CAIBE) using Ar/Cl-chemistry [2]. A more versatile technique for large-scale fabrication is inductively coupled plasma (ICP) etching. Excellent results have been obtained with ICP-etching using SiCl₄-chemistry [3]. In the present work ICP-etching based on Cl₂-chemistry is reported.

Experimental

All experiments were performed on (100) n-type Sn-doped InP substrates with a size of approximately 8x8 mm². The photonic crystal pattern is defined into a layer of ZEP520A (positive e-beam resist) with e-beam lithography. This pattern is then transferred into a 400 nm thick, PECVD deposited SiN-masking layer with a CHF₃-based reactive ion etching process. After the final ICP etch step, samples were cleaved through the structures and the cross-section was inspected with a scanning electron microscope (SEM). The ICP etch experiments were carried out in a load-locked Alcatel MET system and a load-locked Oxford Plasmalab 100 system. As the main etch-product, InCl₃, is not enough volatile at room temperature [4], etching was performed at elevated temperature in the range 120-250 °C. Substrate temperature control in ICP etching can be difficult due to significant heating by the ion bombardment [5]. To keep the sample temperature as close to the preset value as possible the following measures were taken. In both ICP-systems, samples were glued with heat conducting paste onto a 4 in. carrier wafer, which was made either of stainless steel (MET) or silicon (Plasmalab). In the MET a He-backflow provided thermal contact between the wafer

and the substrate holder. The table temperature was regulated by resistive heating in combination with either constant liquid nitrogen cooling (MET) or short sequenced processing (Plasmalab). The temperature was measured with a Luxtron fluoroptic probe (MET) or a thermocouple (Plasmalab). As the etching process is assisted by the ion bombardment, important parameters are ion current density and ion energy. In our experiments the ion current density was varied with the inductively coupled source power. However, as the ion current density also depends on reactor design and is not directly measured, this parameter cannot be compared for the two ICP-systems that were used for the experiments. The ion energy was determined by the DC-bias voltage, which is induced by capacitive coupling of additional power to the plasma.

Etching with pure Cl₂-chemistry

Etch experiments with pure Cl₂-chemistry were performed in the Plasmalab system with a Cl₂-flow of 7 sccm. Several combinations of current density and ion energy were evaluated for a measured substrate temperature of 180 °C and a pressure of 0.26 Pa. For the lowest ion energy process the pressure was 0.13 Pa, since the etching was inhibited at higher pressure and the temperature was 150 °C, because severe sidewall etching was already observed at this temperature. The experiments consisted of two etching runs of 30 seconds, with 10 minutes intermediate pumping of the chamber to allow the sample to cool down to the substrate temperature. This sequence was repeated for the lowest ion energy process, because of the relatively low etch rate in this case. In figure 1 the SEM-results for three different combinations of current density and ion energy are shown. The respective values for bias voltage and source power are denoted in the pictures. High current density and low ion energy (left picture in figure 1) resulted in low selectivity to the SiN-mask and significant undercut. Broadening of the top part of the hole, which will be referred to as the ‘neck’ in the following, and conical hole shape were observed at moderate current density and - ion energy (center picture of figure 1). The hole profile was improved for low current density and high ion energy (right picture of figure 1), but the neck and the conical shape of the holes could not be completely eliminated. However, a sufficient hole depth of 2.3 μm was obtained with only 250 nm SiN consumed during etching. Conclusions on sidewall roughness cannot be drawn from the SEM-results in figure 1.

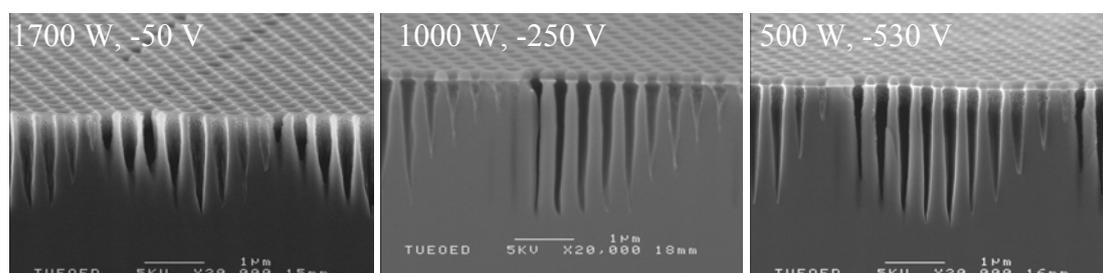


Figure 1: SEM-pictures of a photonic crystal structure with $a = 400$ nm and $d = 200$ nm as etched in InP with the pure Cl₂ ICP-process for different combinations of current density and ion energy. *Left:* high current density and low ion energy. *Center:* moderate current density and – ion energy. *Right:* low current density and high ion energy. The respective values for the source power and bias voltage are denoted in the pictures.

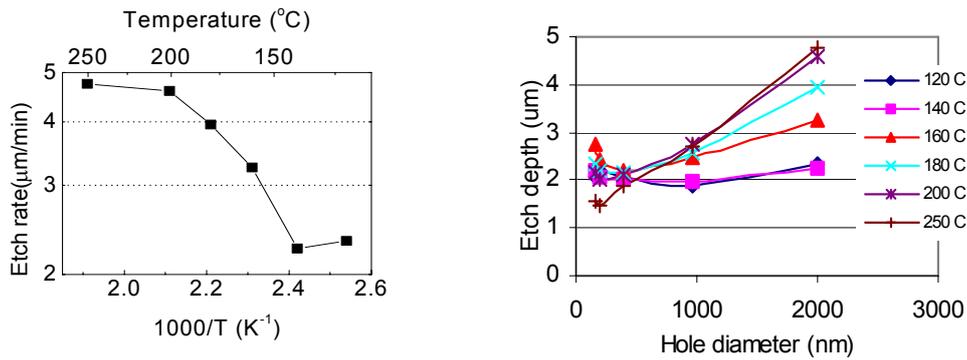


Figure 2: Temperature dependence of the large area etch rate (left) and the feature size dependent etch depth (right) of the pure chlorine process. Note the logarithmic vertical scale in the figure on the left.

The temperature dependence of the optimized process (low current density and high ion energy) was also investigated. On the left side of figure 2 an Arrhenius plot of the large area etch rate is displayed. Three regions are visible in this graph. For a measured substrate temperature between 140°C and 200°C the etch rate increases exponentially with temperature. For higher temperatures the etch rate saturates and is most likely limited by the supply of chlorine. For lower temperatures the etch rate stabilizes, which indicates that the etching is fully ion driven at these temperatures and any spontaneous desorption of InCl_3 is negligible. The right side of figure 2 displays the dependence of etch depth on aspect ratio, often denoted as “RIE lag”, and the impact of temperature. In the overview of Gottscho *et. al.* [6] four possible causes of the RIE lag are considered: Knudsen transport of neutrals, ion shadowing, neutral shadowing and differential charging. The temperature dependence of the lag suggests neutral shadowing or depletion of neutrals as the primary cause of the RIE-lag in our process. The process remains to be fine-tuned with respect to pressure. While such work is ongoing we do not expect the neck shape to be completely eliminated. Therefore, for further improvement of the hole profile sidewall passivation is crucial.

Sidewall passivation by N_2

We previously demonstrated, using the MET system, that nitrogen is capable of InP sidewall passivation during etching in a Cl_2 -plasma [7]. With an ICP power of 1000 W and a pressure of 0.5 Pa, good sidewall passivation can be obtained at 190°C with a Cl_2/N_2 -ratio of 1/3. Unfortunately, the InP etch rate also decreases by a factor of ~ 3 , presumably due to nitrogen passivation of the bottom surface. This causes a significant decrease in etch selectivity.

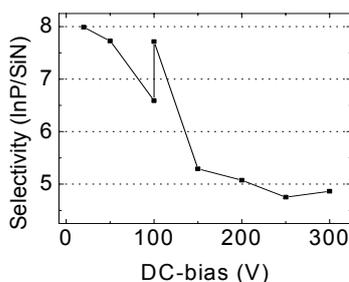


Figure 3: InP/SiN etch selectivity as a function of bias voltage.

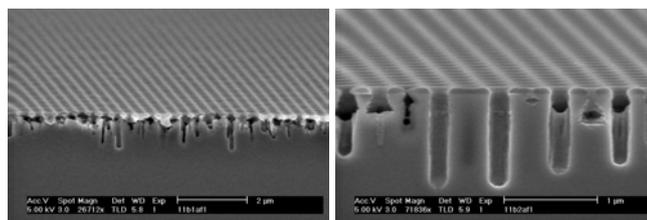


Figure 4: SEM-pictures of a photonic crystal structure with $a = 400$ nm and $d = 200$ nm as etched in the Cl_2/N_2 -process with a bias voltage of -20 V (left) and -50 V (right).

The impact of bias voltage on the InP/SiN selectivity is depicted in figure 3 and suggests low bias for deep etching. Shown in figure 4 are two low bias processes: -20 V (left) and -50 V (right). While the lowest bias voltage results in significant undercut, most likely caused by the broadening of the ion angular distribution, the slightly higher bias (-50 V) seems more profitable in terms of shape without losing much in selectivity. This optimal low bias is in contrast to the high bias with the pure Cl₂ process. There the high bias was necessary to obtain anisotropy without the nitrogen sidewall passivation. With the Cl₂/N₂-process at -50 V bias voltage a hole depth of 1 μm is obtained with 300 nm SiN consumed during etching. This depth is insufficient and a thicker or more selective etch mask is needed. An alternative route to larger etch depth may be a multi-step Cl₂/N₂-process where the Cl₂/N₂-ratio is progressively varied as to passivate the top part of the hole where the neck appears, retain the sidewall verticality and increase the selectivity.

Conclusion

Two-dimensional photonic crystals were fabricated with a Cl₂-based ICP-process. Sufficient hole depth of 2.3 μm was obtained with pure chlorine chemistry at low current density and high ion energy. The conical hole shape and neck formation at these optimal conditions could not be completely eliminated without the use of sidewall passivation. Vertical hole profile was obtained by addition of nitrogen to the etching chemistry. Further optimization of this process is required to achieve sufficient hole depth, which will be discussed in a forthcoming paper.

Acknowledgements

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