

InP-based Waveguides: comparison of ECR Plasma Etching and Wet-chemical Etching

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Electron Cyclotron Resonance (ECR) reactive ion etching of InP-based waveguide structures was studied using CH₄/H₂/Ar chemistry. The ECR process was first optimized on InP substrates before being used to process waveguides. Stripes of 2 μm width were patterned in silicon nitride and used as masking to etch strip-loaded waveguides. These waveguides were compared with wet-etched waveguides, in order to identify the dominant loss mechanism. Fabry-Perot loss measurements showed values as low as 1.1 dB/cm for the ECR-etched waveguides. From the comparison it appears that roughness of the sidewalls is more important than surface damage for the loss of these waveguides.

Introduction

Indium phosphide is the material of choice for monolithic integration of optical components. This material system is suitable for application in optical communication. Photonic Integrated Circuits (PICs) on InP create the possibility for mass production to fulfill the increasing demand for more complex optical functionality at ever-lower prices.

The basic building block for PICs is the optical waveguide. Usually this is a ridge etched in a layer stack on an InP-substrate. Various etching techniques have been developed over the years. Reactive Ion Etching (RIE, [1]) has emerged as the most flexible and effective technique to obtain these waveguides. One specific problem associated with RIE is surface damage caused by impact of ions and by the chemical process. Various adjustments to RIE have been proposed and developed to reduce this problem. Electron Cyclotron Resonance (ECR) is expected to result in lower impact damage, because the plasma is ignited in the ECR column away from the sample, which is placed on the lower electrode in the chamber. We have developed an ECR-process for waveguides on InP [2]. In order to examine the loss mechanism we also realized wet-chemically etched waveguides. These have no surface damage, but are more sensitive to the sidewall roughness because of their different shape.

Waveguide design

The waveguide is designed to provide monomodal propagation for both the TE and the TM polarization. This requirement limits the thickness of the waveguiding layer, the width of the ridges and the etching depth. The layer stack (see fig.1) is grown on an undoped InP-substrate and consists of two also undoped layers. The waveguiding layer, with a thickness of 600 nm, is an InGaAsP-layer with a bandgap of 0.956 eV, corresponding to a vacuum wavelength of 1.3 μm. The top layer of InP is 300 nm thick. Simulations with a vectorial waveguide solver [3] showed that waveguides as narrow as 1.5 μm would be multimodal for TM if the ridge is etched 100 nm into the quaternary layer. To avoid this the etching depth was limited to the thickness of the top layer: 300 nm. This results in a strip-loaded waveguide. The selective wet-

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chemical etch will also provide this depth, making comparison of dry- and wet-chemical etched waveguides possible.

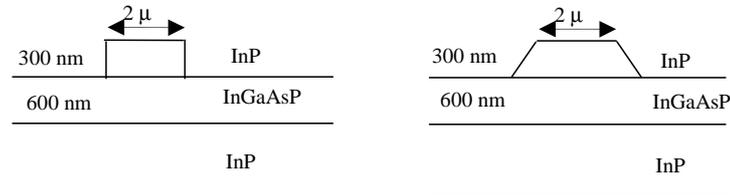


Fig.1: Waveguides designed for the loss experiments. Left: dry etched, right: wet-etched.

The width of the waveguides is chosen as small as possible. This has two reasons. First of all this makes the test for the etching technique most valuable, since narrow waveguides have higher losses due to the strong interaction of the propagating field with the etched surfaces and the sidewalls. The second reason is that one of the envisioned applications is a passive polarization converter [4], which requires narrow waveguides for efficient operation. The waveguide width is chosen to be 2 μm.

Process description

For dry etching, we use a microwave (2.45GHz) Electron Cyclotron Resonance (ECR) source and CH₄/H₂/Ar discharges with additional radio frequency (13.56MHz), resulting in a separately addressed DC bias. Smooth surface, reasonable (~20 nm/min) etch rate and vertical side-walls have been achieved. The process conditions are as follow: CH₄:H₂:Ar / 10:18:8 sccm at 150 W with a DC bias of -200V. Higher power would result in higher etch rate but rougher surface. Photoluminescence (PL) measurements on etched samples have shown a PL-intensity reduction. The reference level was recovered however after a short O₂ plasma treatment followed by a dip in 10% HCl. Schottky diodes were made on p-InP substrates after ECR etching and characterised. The barrier height and the ideality factor were fully recovered after the O₂ plasma treatment and the dip in 10% HCl. The wet-etched waveguides are realized through InP-selective wet chemical etch with a suitable etchant (C₃H₈O₃: HCl: HClO₄ ,[5]). In this way a ridge is obtained with sidewalls at angles of 35 degrees with the chip surface.

Plasma deposited SiN_x is used for masking with 2 μm stripes. The SiN_x was opened in SF₆ plasma (10 sccm SF₆ with 2 sccm Ar). After etching the waveguide width is 1.4 μm.

Measurements and results

The layer structure is grown in an MOVPE reactor using trimethyl-indium and gallium sources for the metals and phosphine source for P. Layer thicknesses are 10% below the design values.

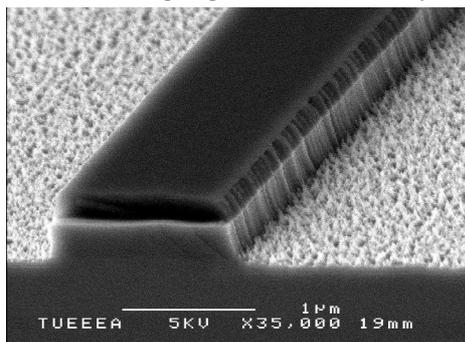


Fig. 2: A SEM viewgraph of the dry etched waveguide. The rough surface next to the ridge is due to the HCL-dip, which removes In-rich material.

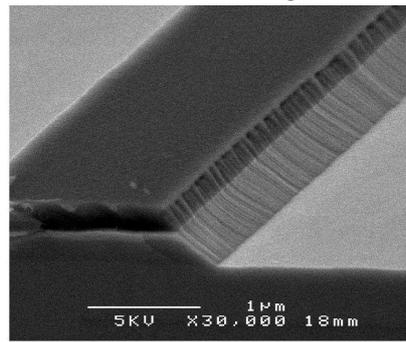


Fig. 3: A SEM viewgraph of the wet etched waveguide.

Prior to ECR etching, the protective top quaternary layer of 5 nm was removed using a selective wet etching. Subsequently etching of the waveguides was performed using the ECR dry etching process and the wet-chemical process described above. Cleaving the sample into bars with various lengths formed the mirrors necessary for the Fabry-Perot loss measurements of the waveguides. Figures 2 and 3 show SEM photographs of dry etched and a wet etched waveguides. The SiNx masking pattern is still visible on top of the waveguides.

The waveguide losses are determined for the TE-polarization with the well-known Fabry-Perot measurement technique. In this technique the reflection from the end facets of the waveguide are used to create a cavity, in which resonances can be observed. The strength of these resonances depends on the reflectivity and the waveguide loss. To determine the FP-resonances the wavelength is scanned (by adjusting the laser temperature). In this way the minimum and maximum of the transmitted signal can be determined. From these the product of the total propagation loss α and the reflection coefficient R is found:

$$\alpha R = \frac{\sqrt{\max/\min} - 1}{\sqrt{\max/\min} + 1}$$

The reflection coefficient is calculated for the TE polarized mode, and found to be 0.3707.

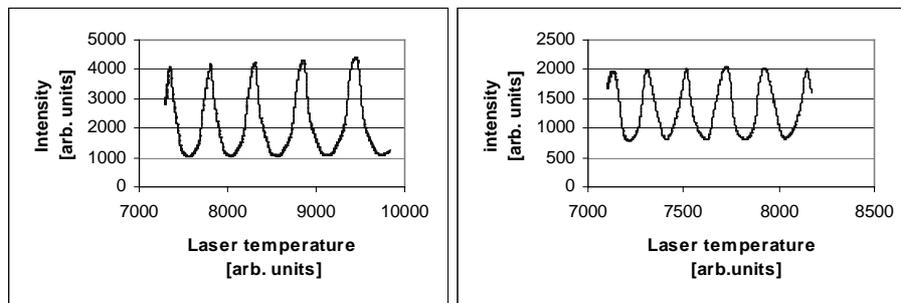


Fig.4: Fabry-Perot resonances for the best dry-etched (left) and wet etched (right) waveguides.

The best results are obtained for waveguides from the defect-free center of the wafer. Clear FP-resonances are observed (see fig.4), from which a lowest waveguide loss of 1.1 dB/cm is found for a 3.5 mm long sample. There appears to be a uniformity problem, since the waveguide losses increase toward the edge of the sample to values of 2 to 10 dB/cm (see fig.5). The cause of this is as yet unknown.

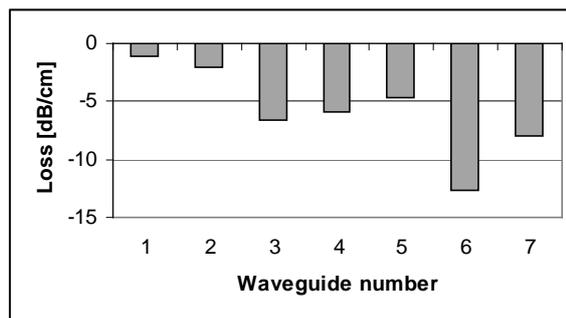


Fig.5: Waveguide losses for dry-etching. The waveguide numbers follow the position on the sample.

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A second sample was made from an area of the wafer with growth defects. This immediately shows up in the results: waveguide losses increased to more than 10 dB/cm, indicating the importance of the growth quality.

The wet-etched waveguides show more damped FP-resonances (fig. 4, right), and thus higher losses than the best dry etched waveguides. Losses range from 3.3 dB/cm to 5.3 dB/cm (with one spurious result of 10 dB/cm, probably from a defected waveguide), measured on a 6.5-mm long sample. This result provides a clear indication about the cause of the losses.

Discussion and conclusion

The best value for propagation loss obtained for the dry etched waveguides compares favorably with results for other waveguides of the same width [1]. This shows that the ECR-RIE process is indeed capable of producing low-loss waveguides.

The loss in these waveguides has a number of contributions. It can result from:

1. Interaction of the propagating fields with defects and roughness at the etched surface.
2. Scattering from sidewall roughness, caused by the photolithography.
3. Scattering from growth defects.
4. Scattering from layer interfaces.

The ECR-etched and the wet-chemically etched waveguides are made from the same wafer, and therefore causes 3 and 4 do not lead to differences between them. This does not hold for the first two causes mentioned. A dry-etching process will involve some physical sputtering, because of the ions colliding with the surface. Furthermore, a phosphorus-depleted layer can easily occur, since the gaseous P-containing reaction products of the etching process are the most volatile. Removal of this layer with an HCL-dip results in extra roughness of the etched surfaces (see fig.2). For wet-chemical etching this type of damage does not occur, since there is no ion impact and there are no volatile reaction products. On the other hand, the influence of the sidewall roughness is much larger for the wet-etched ridges. Because of the different shape (angled sides) of the etched ridges the sidewall area is larger than for the dry-etched samples, so that the scattering for the guided modes due to the sidewall roughness is stronger.

From our results it is seen that the scattering from the sidewall roughness is dominant over the etching defects, since the losses from the wet-etched waveguides are appreciably higher. This in turn implies that the ECR-process used here results in a relatively defect-free etched surface. Further improvement of waveguide losses should therefore concentrate on improving the photolithography, in order to reduce the roughness of the sidewalls.

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