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Cathodoluminescence study of inductively coupled plasma (ICP) etched InP waveguide structures: Influence of the ridge dimension and dielectric capping

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Abstract

This work is focused on the characterization of different defects introduced on InP material during the fabrication of classical photonic structures (ridge waveguides,. . .). These defects can arise from either the plasma etching procedure (reactive ion etching, RIE or inductively coupled plasma, ICP) or the reactive gases used in the etching procedure. The nature of the mask used for etching can also play a determinant role in the defect creation. The characterization of defects, which are susceptible to harm the devices performance, is essential in order to fabricate devices with improved performance and reliability. Due to the reduced dimensions of the studied features, the characterization techniques must combine a high spatial resolution with a spectral information that would permit an identification of the defects at a reduced spatial scale. The cathodoluminescence (CL) technique fulfils these requirements. We present herein a CL study of micrometric size waveguide structures made by ICP in InP substrates.

Keywords: Cathodoluminescence; InP; ICP etching; Defects

1. Introduction

Ion etching techniques are commonly used for the fabrication of heterostructure devices based on III–V semiconductor, with micro- and submicrometer characteristic dimensions [1]. Buried ridge lasers (BRL), vertical cavity surface emitting lasers (VCSEL) or waveguide passive structures such as photonic crystals (PC) used for integrated optics are some of the examples of devices fabricated by this kind of etching procedure [2].

For this kind of components, it is essential to control the verticality of the engraved walls, as well as to achieve walls with low residual roughness. Rough walls would induce scattering of photons and propagation optical losses that should lead to a limitation of the device performance. On the other hand, roughness can enhance the surface recombination velocity (SRV), which can contribute to device degradation. The studies carried out for the optimisation of the etching procedures have been mainly focused on the morphological analysis, e.g. the verticality of the engraved walls, and the residual roughness [3,4]. These studies are currently carried out by morphology inspection techniques, as scanning electron microscopy (SEM) and atomic force microscopy (AFM).

Due to the high energy of the ions involved in the ion etching procedures, defects are induced at the surroundings of the etched surface. Some research was focused on the characterization of these defects, but they were concerned about simple etched surfaces [5]; the characterization of the defects created by dry etching on specific photonic structures is still lacking. Therefore, taking into account that etched surfaces play a relevant role on the structures of reduced dimension structures, and that the active zone of the devices can be affected by the presence of the defects induced at the surface surroundings, the characterization of those defects appears very necessary.

Indirect studies of this problem have been carried out by the study of intermixing in quantum well structures, using annealing treatments as the driven force for the defect migration [6,7].

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However, this is just an indirect evidence of the presence of the etching induced defects as a catalyst of the observed interdiffusion processes. Nowadays, it seems essential to know precisely where the defects are formed during the etching stages leading to the fabrication of photonic devices. CL is a powerful technique allowing the spectroscopic characterization along with a submicronic spatial resolution. The results presented herein evidence the necessity for this kind of study if one aims to understand the defects induced by plasma etching techniques in low dimension photonic structures.

2. Experimental

CL measurements were carried out in a Gatan XiCLone system attached to a SEM. The detector was a CCD camera that allows the acquisition of a complete spectrum at each point probed by the electron beam. Measurements were carried out at both liquid nitrogen (~80 K) and room temperatures. The engraved micro- and nanostructures were studied on both the top surface and the cleaved one.

The studied samples are structures etched on (1 0 0) oriented bulk InP wafers, sulphur doped with a concentration of $1.5 \times 10^{18}\,cm^{-3}$. A 400 nm-thick SiN_x mask was deposited by plasma enhanced chemical vapour deposition (PECVD) at 250 °C. The structures to etch are defined on a resin layer by contact optical photolithography or electronic lithography in the case of the ICP structures. The trenches on the SiN_x are transferred by RIE etching with a mix of $SF_6/CHF_3/O_2$. After removing the resin and polymers in microwave O_2 plasma, the structures are transferred to the InP by plasma etching either in a RIE reactor or ICP one.

An Adixen 601E with $SiCl_4$ as reactive gas is used for performing the ICP etching. The plasma is excited to 13.56 MHz. For ICP etching, a second source of RF polarization (also at 13.56 MHz), allowing the application of power to the sample separately to the one that excites the plasma, was used. This is a specific characteristic of the ICP etching reactors: the average ion energy can be controlled by a second RF source separately from the plasma density. For the etching herein presented, the surface autopolarization bias is fixed to around 60 V and the current density to $8\,mA/cm^2$. The ICP etching speed at these conditions is about 500 nm/min.

Different etching masks were used, SiN_x, where x was not specifically controlled, and SiO_2. The complete etching procedures of etched ridges on InP are described in ref. [8].

3. Results and discussion

This study concerns ridges for passive waveguides working at 1.55 μm. Guides of different widths (ranging from 1 to 5 μm) and depths were studied. The etching depth was varied by means of the etching time. Fig. 1 shows a panchromatic CL image (integrating all wavelengths emitted) measured on a ridge structure etched by ICP with non-stoichiometric SiN_x mask. A strong contrast between the signals measured on the ridge and on the etched surface (etched floor), at both sides of the ridge can be appreciated in this figure. The CL contrast was dark on the ridge and bright on the etched floor, contrarily to what was expected, because etching induces an enhancement of the SRV the luminescence emission is expected to be lower in the etched floor. The surface of an etched material is admitted to increase the probability of non-radiative electron–hole recombination (as it can be explained by the increase of the SRV). This is due to the damage induced on the surface by the etching together with the point defects created at the surface neighbourhood by the ion bombardment [3]. The lower CL intensity on the ridge can arise from the strong increasing of the SRV at the side walls; the carriers generated inside the ridges have a non-negligible probability of reaching the sidewalls and to recombine therein non-radiatively; this probability should depend on the ridge width, the narrower the ridge the higher the probability of minority carriers to reach the ridge sidewalls recombining non-radiatively. Another possibility concerns the generation of point defect inside the ridge, which would act as non-radiative recombination centres.

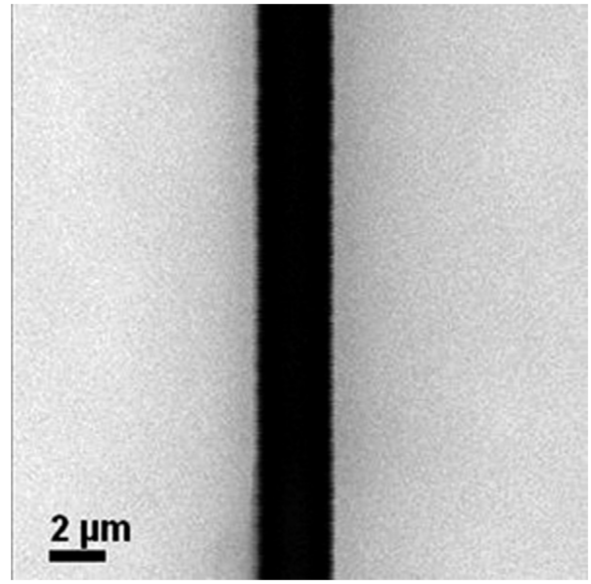

Fig. 1. Panchromatic top view image ($T = 80$ K) of an ICP etched waveguide.

Spectroscopic measurements were carried out focusing the electron beam on the ridge and on an area close to it for finer analysis. The spectrum measured at an etched region is the typical luminescence of an InP material doped with sulphur in the $10^{18}\,cm^{-3}$ range. It shows a transition centred at an energy close to the InP gap. It consists of two contributions, one around 1.43 eV corresponding to a conduction band to valence band transition, and the second one peaking around 1.395 eV which is generally associated with a free to bound transition, related to S donors. The spectra on the etched floor were not dependent on the etching procedure, only the intensity of the band changed. A sample etched by reactive ion etching (RIE) was also studied for comparison. The spectra measured in the etched floor were almost identical to the one measured on an unetched control bare InP substrate. The only difference with the control sample concerns the intensity, which accounts for the enhanced SRV of the etched samples, Fig. 2.

The CL spectrum measured at the ICP ridge, exhibits and additional luminescence band peaking around 1.27 eV. The pres-