Buried InAlGaAs–InP Waveguides: Etching, Overgrowth, and Characterization

St. Kollakowski, Ch. Lemm, A. Strittmatter, E. H. Böttcher, and D. Bimberg

***Abstract*—We report on the fabrication and characterization of InP-buried InAlGaAs rectangular core waveguides. LP-MOCVD is used for growth of the InAlGaAs–InP material system and the regrowth of InP. Reactive ion-etching is employed for achieving smooth and precise etch profiles. An efficient procedure for preparing the surface is described that results in homogeneous epitaxial InP overgrowth by preventing re-oxidation of the air-exposed etched surface. The loss characteristics of waveguides with a core layer thickness of 450 nm and widths ranging from 3.5 to 6 μm are investigated at 1.3-μm wavelength. The propagation loss is found to increase from 3 to 10 dB/cm with decreasing core width. Scattering loss caused by residual sidewall roughness is found to be the dominant loss mechanism.**

***Index Terms*— Electrochemical processes, etching, InP, InAlGaAs, semiconductor waveguides.**

I. INTRODUCTION

THE quaternary material system InAlGaAs is gaining importance for the fabrication of long-wavelength semiconductor waveguide devices. Lattice-matched to InP, InAlGaAs is attractive for replacing InGaAsP in various applications due to its refractive index ratio between waveguide and cladding which is higher than that of InGaAsP–InP with identical bandgap. InAlGaAs offers an additional advantage due to the ease by which its bandgap can be varied while retaining lattice-matching to InP during epitaxial growth. InAlGaAs has been employed as core layer for low-loss waveguides [1] and related waveguide devices such as electrooptic modulators [2] and photodetectors [3], [4]. Because of the relatively high-mode confinement that can be obtained through the application of InAlGaAs the propagation constant of the mode increases. This is beneficial for enhancing the coupling efficiency from waveguide to absorber in vertical waveguide photodetectors [4].

Previous reports on InAlGaAs–InP waveguide devices refer almost exclusively to uncladded rib waveguides. For various applications, it is highly desirable to use a waveguide geometry where the InAlGaAs rectangular core layer is fully embedded in the InP cladding in order to obtain a symmetrical mode profile. Such structures are important for optical spot-size converters which are applied for low-loss fiber-to-chip coupling. As a consequence of the high degree of symmetry, there is no cutoff height of the core. This feature enables one to realize very thin stripes with improved coupling in vertical absorbing arrangements. The major practical problem in fabricating such structures is related to the epitaxial overgrowth of Al containing III–V semiconductors. The difficulty arises from the formation of stable Al-oxides [5], [6] due to the often inevitable air-exposure of the InAlGaAs core layer during device processing. This may be the cause why little has been published about buried InAlGaAs waveguide structures thus far [4].

Here, we report on a complete fabrication process of rectangular InP-buried InAlGaAs waveguides on an InP substrate using LP-MOCVD for growth and regrowth. Furthermore, the propagation loss of the waveguides is determined. We investigated thin waveguides with a height of only 450 nm and widths ranging from 3.5 to 6 μm.

II. ETCHING AND OVERGROWTH

The $In_{0.53}Al_{0.31}Ga_{0.16}As$:Fe–InP:Fe ($\lambda_{g,\mathrm{InAlGaAs}} = 1180$ nm) samples are grown by MOCVD in a vertical rotating-disk reactor operating at low pressure. The epitaxial layer sequence consists of a 200-nm-thick InP:Fe buffer layer, 450-nm InAlGaAs:Fe, and 30-nm InP:Fe cap layer. Prior to etching, stripes are defined by a silicon nitride mask deposited with nonreactive RF magnetron sputtering and patterning by a standard lithography process. The stripes are oriented along [011]. The structures are etched using a reactive-ion-etching (RIE) process with a Technics Plasma 4000. Optimal results in terms of etch rate, profile, and smoothness of the etched surface are obtained at 6 sccm CH_4/40 sccm H_2/5 sccm Ar, 1 Pa, and a power density of 0.33 W/cm^2. The power density corresponds to a total power of 250 W. The corresponding etch rates of InP and InAlGaAs are 35 nm/min and 7 nm/min, respectively. The polymer deposition rate is <3 nm/min. After every 30 min of the CH_4–H_2–Ar RIE, we incorporate a O_2-plasma-etching step in the same etch-chamber for about 3 minutes. This procedure has been shown to be beneficial for polymer removal on the mask and profile control of the stripes [7], [8]. After etching, the silicon nitride mask is removed by a CHF_3–O_2 RIE process using 45 sccm CHF_3/4.4 sccm O_2 at 1.2 Pa and a total power of 50 W. The etch rate is about 12 nm/min. As shown in Fig. 1(a), we achieve a smooth and precise etch profile. More details about the etching process and its optimization as well as the dependence of the shape on the etching conditions can be found elsewhere [7].

Before overgrowth, the samples are etched in $C_6H_8O_7$–H_2O_2–H_2O for about 5 s. This step removes about 7 nm of InAlGaAs and <2 nm of InP. Afterwards, a 1-min H_2SO_4 cleaning step is employed. The effect of

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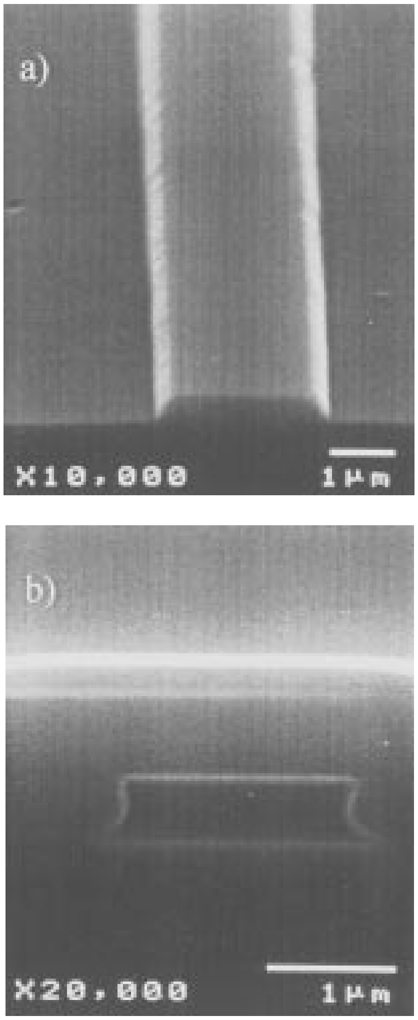

Fig. 1. (a) SEM picture of an as etched waveguide stripe. (b) SEM picture of an InP buried waveguide stripe. Contrast enhancement was achieved by etching the cleaved facet.

three alternative surface preparations on the quality of the regrown InP is studied: 1) HF, 2) HF and 2-Propanol, and 3) $(NH_4)_2S_x$. After the surface treatment, the samples are loaded in the LP-MOCVD reactor to carry out the InP overgrowth in a standard process. The pre-heating is performed in a PH_3 atmosphere. The InP overgrowth is performed at 660 °C and 20 hPa with a growth-cycle of 30-s growth and 15 s interruption. The growth rate is about 1.5 μm/h. The regrown InP is about 1 μm thick.

We observe that the yield of homogeneously overgrown samples is fairly low with the first and second preparation. Mostly, the regrown InP shows island-type growth behavior. However, very smooth and regular overgrowth is observed after each growth-run when the samples are subjected to the third preparation procedure. The details of the sulfur based surface treatment have been published previously [9] and will be only briefly summarized here. The first step is immersion of the sample in a solution of 3.2 ml $(NH_4)_2S_x$/45 ml H_2O at 50 °C under illumination of a halogen lamp for about ten minutes. After this the sample is rinsed in water for about 20 min to remove excess sulfur from the surface. Due to the sulfur passivation re-oxidation of the surface is prevented. During the pre-heating of the sample before overgrowth the sulfur evaporates leaving behind a clean surface. In Fig. 1(b), a typical result of the waveguide structure after InP overgrowth of the sulfur-passivated surface is shown. To enhance the contrast of the SEM picture we etched the cleaved facet of the waveguide. One can see a very homogeneous overgrowth without any visible growth interface besides the stripe. Please note that two different interfaces are involved in the InP overgrowth (InP–InP and InP–InAlGaAs).

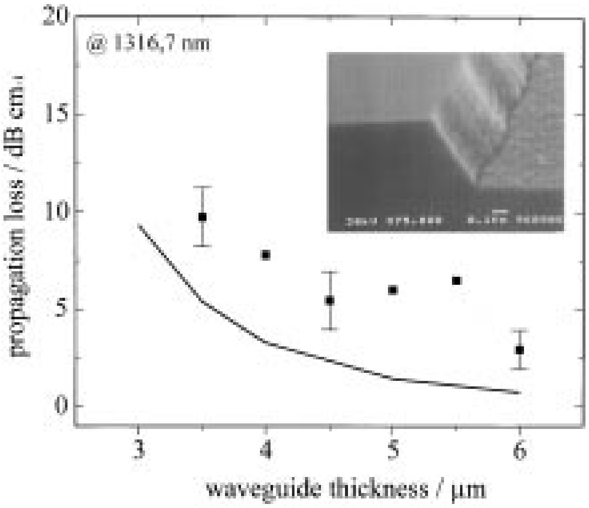

Fig. 2. Propagations loss as a function of waveguide width. The lower curve represents calculated loss due to sidewall roughness.

III. Waveguide Characterization

Waveguide-loss measurements are performed at 1.3-μm wavelength using the so-called cutback method. As shown in Fig. 2, the propagation loss drastically decreases with increasing waveguide width. It ranges between 10 dB/cm for a 3.5-μm-wide waveguide and 3 dB/cm for a 6-μm-wide device. The relatively high measurement uncertainties are inherent to the cutback method [10]. Furthermore, Fig. 2 includes a curve indicating the radiation-losses that are caused by side-wall roughness. They are calculated using an approximation given by Tien [11]. This approximation has been originally developed for planar guides with roughness at the top and bottom interfaces. By means of an effective index calculation, the approximation is applicable for our case with roughness on both sidewalls of the stripe. The formula for the attenuation α in units of dB can be written as

$$\alpha = \frac{40 \log e\sigma^2}{w + 2/p} \frac{h^3}{\beta}$$

where σ is the interface roughness, w the width of the waveguide core, and p a term for width correction. The propagation constant and transverse propagation constant are β and h, respectively. The sidewall roughness is inferred from SEM measurements as shown in the inset of Fig. 2. We extract an interface roughness of $\sigma \approx 60$ nm. The calculation suggests that the observed increase of the loss with decreasing waveguide width can be attributed to scattering loss. Thus, a further considerable reduction of the sidewall roughness appears to be necessary for obtaining values of about 2 dB/cm with waveguides of a few micrometers width. In view of process technology, two measures can be taken to achieve this goal. The first is an improvement of the etching masks used for the patterning process. The second is the introduction of a further smoothening process step. As has been reported recently [12], striations of the resist sidewalls after lithography can be reduced by an O_2 treatment in a microwave discharge.

IV. CONCLUSION

We have reported a complete fabrication process of InP buried InAlGaAs waveguides which is based on LP-MOCVD growth. The optimized parameters of a CH_4–H_2–Ar RIE procedure used for patterning the InAlGaAs stripes are described. In conjunction with a re-oxidation preventing sulfur passivation high-quality InP overgrowth of the waveguide structures is demonstrated. Propagation loss of fabricated thin core waveguides of 450-nm height is characterized at 1.3-μm wavelength. With increasing waveguide width from 3.5 to 6 μm the propagation loss is found to decrease from 3 to 10 dB/cm. The analysis of the loss dependence upon width indicates that the residual sidewall roughness of the waveguide stripes of about 60 nm yields a significant contribution to the total loss. Improved processing steps for reduced sidewall striations that should result in about 2.0 to 4.0 dB/cm loss are discussed.

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