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RAPID COMMUNICATION

Low-loss ridge waveguides on lithium niobate fabricated by local diffusion doping with titanium

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Abstract The development of a novel self-aligned photolithographic process is reported enabling selective Ti-deposition on the surface of wet etched ridges on lithium niobate. Thus local diffusion doping of the ridges becomes possible to fabricate optical waveguides. They have surprisingly low propagation losses down to 0.05 dB/cm for TE-polarization (at ∼1.55 µm wavelength). The fabrication procedure of locally doped ridge guides in LN and their optical properties are presented in detail.

1 Introduction

Ridge waveguides in lithium niobate ($LiNbO_3$, LN) are important basic structures of integrated optics [1]. They enable a further miniaturization of waveguide devices, allow smaller bending radii and lead in this way to a higher integration density [2]. In particular nonlinear devices profit from the small mode fields in ridge guides resulting in enhanced efficiencies [3]. Also ridge guide modulators of improved electro-optic interaction can be developed resulting in low drive voltages [4].

The performance of integrated optical devices, especially of resonant structures, strongly depends on the waveguide attenuation. Therefore, reliable fabrication methods for low-loss ridge structures are required. Several approaches have been investigated recently to fabricate ridge guides in LN. Plasma etching or wet etching is used to form ridges confining light in the horizontal direction, while vertical confinement of light is achieved by proton exchange or Ti-indiffusion [5–8].

We report the development of a novel self-aligned photolithographic process to allow selective coating the surface of micrometer-wide ridges only. Using Ti-deposition, local diffusion doping of the ridges becomes possible to fabricate optical waveguides. In comparison with our previous work [8], the results show that the sequence of fabrication steps has a strong influence on the waveguide losses. The local Ti-indiffusion after ridge fabrication is preferable over the inverse sequence. The high-temperature process of indiffusion smoothes the walls of the ridge leading to single-mode (at ∼1.55 µm wavelength) waveguides of surprisingly low propagation losses down to 0.05 dB/cm for TE-polarization in a ridge of 9 µm width and 6.5 µm height.

In the following, the fabrication procedure of locally doped ridge guides in LN and their optical properties are presented.

2 Fabrication

The LN ridge waveguides were fabricated in three steps. Contrary to the procedure described in [8] and similar to the procedure described in [7], the ridge was fabricated first by wet chemical etching followed by local Ti-diffusion doping enabled by a novel self-aligned photolithographic Ti-stripe definition.

2.1 Ridge fabrication by wet chemical etching

At first, a homogeneous 80 nm thick Cr film was deposited on the $-Z$ face of the LN substrate by sputtering. Using optical contact lithography with an e-beam written mask, 4 to

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12 μm-wide Cr stripes along the X-direction of the crystal were defined by wet etching with cerium sulphate solution [9]. The distance between the Cr stripes was 100 μm. They served as etch masks for the subsequent wet etching process to define the ridge structures in LN. Before etching, the sample was annealed at 300°C for 3 hours to improve the adhesion of the Cr stripes. Without annealing, serious underetching was observed [8]. Etching was done in a mixture of 20 ml HF (40% concentration), 13 ml HNO_3 (100% concentration) and 5 ml ethanol for 8 hours. Before etching, ethanol was added to the mixture of HF and HNO_3 drop by drop in a cooled container to reduce the formation of hillocks on the surface [8]. Such hillocks are formed when micrometer-size bubbles (of hydrogen?) generated during etching are adsorbed on the surface and impede further chemical etching. To get a constant etch rate of 0.8 μm/h, the mixture was continuously stirred and its temperature was controlled at 24°C. Finally, the Cr stripes were removed by cerium sulphate solution. Figure 2 shows on the left a micrograph of a typical ridge of 6.5 μm height on LN, taken with a scanning electron microscope (SEM). The two walls (Y-faces) are asymmetric due to different etching rates of $+Y$- and $-Y$-surfaces [10].

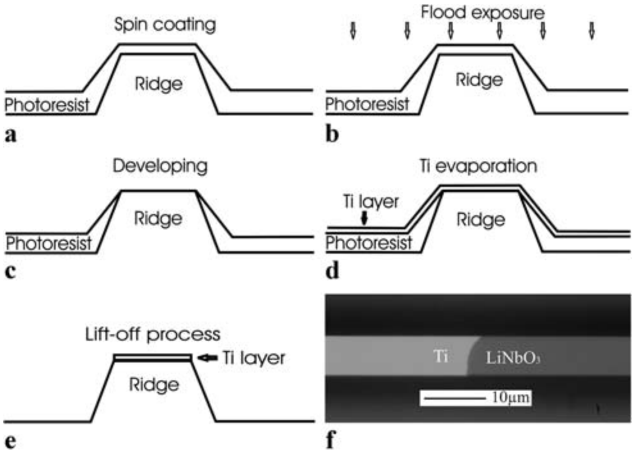

Fig. 1 (**a**) Photoresist thickness distribution after spin coating; (**b**) flood exposure of 5 s; (**c**) developing; (**d**) 94-nm Ti-deposition; (**e**) lift-off process; (**f**) top view of a ridge with partially removed Ti on the *right*

2.2 Self-aligned photolithographic Ti-stripe definition

After ridge fabrication the sample was spin-coated by a photoresist (OIR 907-17) with 5000 rpm for 5 seconds. It had a thickness distribution as schematically sketched in Fig. 1a. On top of the ridge the photoresist is considerably thinner than on the bottom LN surface. The thickness ratio depends on the viscosity of the photoresist and on the parameters chosen for spin coating. This inhomogeneity of the thickness of the photoresist was exploited by the following short-time flood exposure (5 s) of the sample in a commercial photolithography machine leading to full exposure on top of the ridge only (Fig. 1b). On the other hand, 30 s are required for full exposure of the thicker photoresist on the bottom. Therefore, by the subsequent developing process, only the resist on top of the ridge was completely removed, while a thin layer remained on both sides of the ridge and on the ridge walls (Fig. 1c). Subsequently, a 94 nm thick Ti layer was vacuum deposited on the surface of the whole sample (Fig. 1d). By the following lift-off process (in acetone) the Ti film on the photoresist was removed while only a Ti stripe on top of the ridge was remaining (Fig. 1e). Figure 1f shows a top view of a ridge surface taken with an optical microscope. It was completely covered by Ti. No misalignment was observed as seen on the right, where the metal was peeled away to show the ridge underneath. It is evident that the Ti stripe and the ridge have the same width.

2.3 Local Ti-indiffusion

The Ti stripe was diffused into the body of the ridge at 1060°C during 8.5 hours in argon (7.5 hour) and in oxygen (1 hour) atmosphere, respectively. Finally, the waveguide end faces were carefully polished perpendicular to the ridge axis to enable coupling of light into the channel.

Figure 2 shows SEM micrographs of ridges before and after Ti-indiffusion, respectively. It is evident that this high-temperature process considerably smoothed the walls of the ridge [11], which would reduce the scattering losses of the optical waveguides (see below).

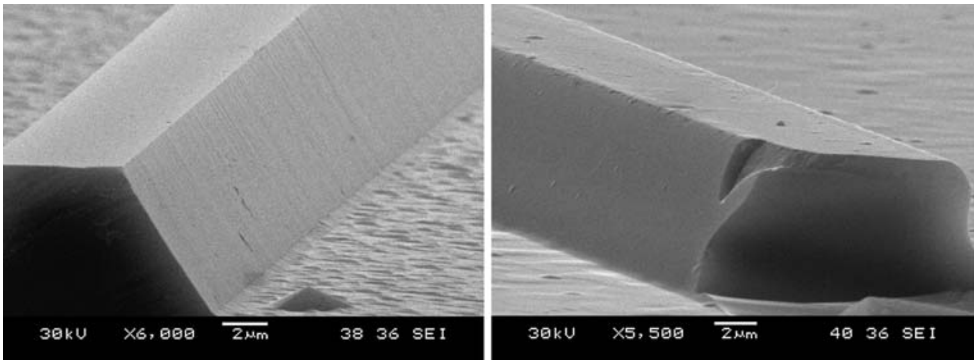

Fig. 2 SEM micrographs of ridges of 6.5 μm height on LN fabricated by wet etching before (*left*) and after (*right*) Ti-indiffusion. By the high-temperature process (1060°C), the walls of the ridge are considerably smoothed, resulting in low propagation losses

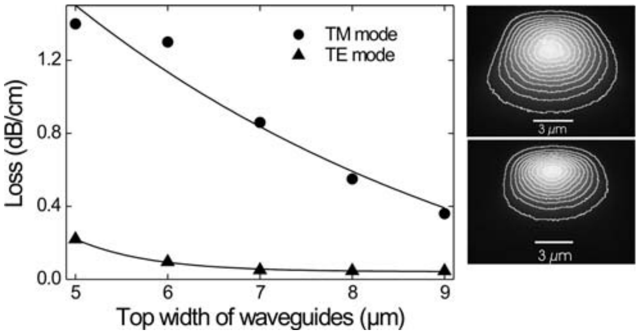

Fig. 3 *Left*: Propagation loss of the fundamental TE- and TM-modes versus the top width of wet etched Ti-indiffused ridge waveguides in LN with a height of 6.5 μm. *Right*: Measured mode distribution for TE- (*top*) and TM- (*bottom*) polarization, respectively, in a ridge guide of 7 μm top width

3 Optical waveguide properties

All waveguides of 6.5 μm height and of a top width between 5 and 9 μm were single mode at 1.55 μm wavelength (for both polarizations). The mode propagation losses in the ridge waveguides were measured at 1.55 μm wavelength using the Fabry–Pérot resonance method [12]. Their dependence on the (top) width of the ridge guides is shown in Fig. 3 (left) for both polarizations; they decrease strongly with increasing width. It is remarkable, that the losses of the TE-modes are nearly one order of magnitude smaller than those of the TM-modes. To be specific, the TE- (TM-) loss for 5 μm top width is 0.22 (1.4) dB/cm. The TE-loss drops to 0.05 dB/cm for a top width ≥ 7 μm, whereas the TM-loss decreases more weakly to 0.4 dB/cm for a top width of 9 μm. This strong polarization dependence is surprising, as the cross-section of the fundamental TM-mode in conventional Ti: LN channel guides of high Ti-concentration is usually significantly smaller than that of the TE-mode [13]. Such a relation was also found for the ridge guides described here using a standard setup magnifying the near field at the waveguide end face by a microscope objective. Figure 3 (right) shows the measured mode distribution for TE- (TM-) polarization, respectively, in a ridge guide of 7 μm top width; the corresponding mode size is about 24.6 μm^2 (13.6 μm^2). Due to this stronger localized guiding of a TM-mode in the core of the waveguide, a residual surface roughness of the walls of the ridge should have a smaller influence on the propagation loss of the TM-mode. On the other hand, the Ti-indiffusion is accompanied by a Li_2O-outdiffusion through the three walls of the ridge, modifying the deficiency volume within the ridge stronger than within the diffused channel of a conventional waveguide with in-/out-diffusion through the surface of the substrate alone. Assuming an inhomogeneous Li_2O-outdiffusion through the ridge walls, inhomogeneities of the extraordinary index along the channel would be the consequence. As only the extraordinary index (n_e) is modified by a Li_2O-outdiffusion, while the ordinary refractive index (n_o) is only weakly affected [14], a large polarization dependent loss-as observed-may result.

4 Conclusions

In conclusion, a novel self-aligned photolithographic process has been developed to open a photoresist layer on the surface of micrometer-wide ridges only. Therefore, this process allows coating the surface of LN ridges with Ti to fabricate low-loss optical waveguides by local diffusion doping. The results show that the sequence of fabrication steps has a strong influence on the waveguide losses. Ti in-diffusion after ridge fabrication is preferable compared to the inverse sequence. The high-temperature diffusion smoothes the walls of the ridge leading to waveguides of surprisingly low propagation losses down to 0.05 dB/cm for TE-polarization in a ridge of 9 μm width and 6.5 μm height. On the other hand, a strong polarization dependent loss is observed with TM-losses of 0.36 dB/cm in the same waveguide. This property is not fully understood, though it might be explained by an inhomogeneous outdiffusion of Li_2O along the ridge. There is a wide range of potential applications for low-loss LN ridge guides. They reach from modulators of low drive voltage [15] to nonlinear devices of high efficiency [16].

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