KrF EXCIMER LASER DIRECT WRITING OF TITANIUM LINES: MODELING AND APPLICATION TO THE FABRICATION OF Ti:$LiNbO_3$ WAVEGUIDES

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ABSTRACT

The deposition of titanium lines by KrF excimer laser direct writing on lithium niobate ($LiNbO_3$) has been investigated. A detailled study of the line profile has been performed since this is critical in the fabrication of Ti:$LiNbO_3$ optical waveguides. We show that at a low power density E, the maximum thickness t is proportional to E, while increasing E leads to the diffusion of Ti into $LiNbO_3$ resulting in a saturation and even a decrease in thickness. Preliminary results on Ti:$LiNbO_3$ optical waveguides show that their characteristics are similar to those made by conventional methods.

INTRODUCTION

We have recently [1,2] reported the development of a laser direct writing system for the production of titanium lines from titanium tetrachloride ($TiCl_4$). Here, we use a KrF excimer laser on the 248nm line whereas previous work by Tsao et al. [3] used a frequency doubled Ar^+ laser. Laser direct writing of Ti on lithium niobate ($LiNbO_3$) is interesting for the production of new and more efficient Ti in-diffused $LiNbO_3$ optical waveguides. Compared to the conventional evaporation technique, this system has the advantage of avoiding the critical photolithography steps as well as giving the possibility of varying the Ti thickness and width along the line leading to better quality integrated optical devices [4].

In Ti:$LiNbO_3$ optical waveguide fabrication, the line profile is critical in determining and controlling the propagating optical modes. In this paper, we present a detailed study of the line profile as a function of the most important process parameters with an emphasis on process modeling. We propose that at low fluences, Ti thickness is proportional to the laser power whereas Ti diffuses into the $LiNbO_3$ when the energy is increased. Preliminary results on optical waveguide characteristics are also presented.

$TiCl_4$ ADSORPTION AND LARGE AREA PROCESSING

The $TiCl_4$ adsorption phenomenon was studied by measuring both the pressure change and the quartz crystal microbalance variations in an isolated reaction chamber previously heated to 80°C during 30 minutes and then exposed to $TiCl_4$[5,6]. Our

measurements show that several monolayers (from 16 up to 50) could be chemisorbed and physisorbed on the substrate. Pumping to 0.02 Torr on a chamber exposed to few Torr of $TiCl_4$ leaves an adsorbed $TiCl_4$ layer on all internal surfaces including the windows. We verified that micrometer thick film is deposited on fused silica windows by exposing an unfocussed beam into such a chamber. Since the growth occurs only where the laser hits the window, we conclude that the growth occurs through the photochemical decomposition of the $TiCl_4$ adsorbed layer and that the gas phase is not involved in the process. Between pulses, $TiCl_4$ diffuses to the reaction zone leading to a fresh adsorbed layer which is ready to be transformed into solid titanium at the next pulse.

EXCIMER LASER DIRECT WRITING OF Ti ON $LiNbO_3$

The excimer laser direct writing system of Ti on $LiNbO_3$ has been described previously [1,2]. Very briefly, a KrF excimer laser is focused with a reflective objective (15X, NA=0.25) onto a $LiNbO_3$ substrate placed in a chamber whose position is controlled by a XY electronic positioner with a 0.1 µm resolution. To avoid damages to the brittle $LiNbO_3$, the laser energy has to be kept below the damage threshold of 17 nJ/pulse. This corresponds to a power density $E = 4.4$ MW/cm^2 when a pulse length of 10 ns and a beam spot of 7 µm diameter is used [5]. All experiments were performed in a chamber using a flow rate of 0.5 sccm while maintaining the $TiCl_4$ pressure, P, below 0.5 Torr in order to prevent any powder formation and deposition on the window.

The composition of the Ti lines has been determined by Auger electron spectroscopy (AES). In addition to Ti, samples contain oxygen throughout. This is probably because they were exposed to air before performing AES. Within the limits of the system, no chlorine was detected thus suggesting that $[Cl]<2at\%$. Note that the presence of oxygen in the film does not affect the Ti in-diffused $LiNbO_3$ waveguide properties since, during the fabrication, the Ti will be oxidized in a wet O_2 atmosphere at 1025°C during the Ti diffusion.

Ti LINE PROFILE

Figure 1 shows a scanning electron micrograph of four ~1 mm long lines written on $LiNbO_3$ at 5 µm/s with a laser power density of E = 1.4, 2.0, 2.5, and 3.1 MW/cm^2 respectively. The Dektak profile is also shown for each line and it will be discussed in detail. Along a 1mm long line, thickness and line cross section vary by less than 10%, approaching 3% in certain cases. This is acceptable for waveguide fabrication.

Figure 2 shows the maximum thickness t (nm) as a function of power density E for lines made at 0.5 Torr and 0.3 Torr of $TiCl_4$ and at a speed of 2 µm/s. For

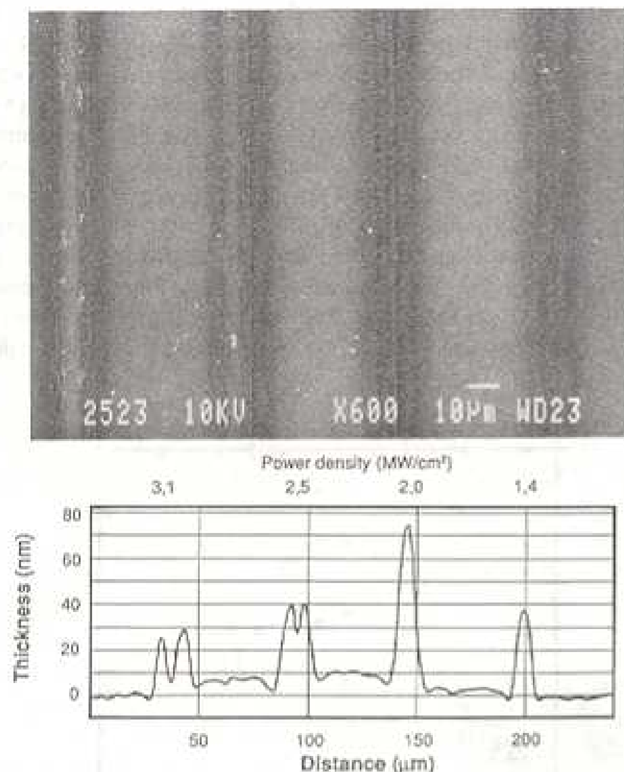

Figure 1 SEM Micrograph and Dektak profile of four long lines. Writing speed is 5 µm/s.

E<2MW/cm² at P = 0.5 Torr and for E < 1MW/cm² at P = 0.3 Torr, t is proportional to E. The growth occurs through the photochemistry of the adsorbed layer [5] following the overall reaction :

$$TiCl_4(\text{adsorbed}) \xrightarrow{h\nu} Ti(s) + 2Cl_2(g). \qquad (1)$$

When the number of adsorbed $TiCl_4$ molecules is sufficient, the growth should be proportional to the number of photons arriving on the adsorbed layer. This is indeed observed at low energy where t is proportional to E. However, when E > 2MW/cm² for P = 0.5 Torr and when E > 1 MW/cm² for P = 0.3 Torr, saturation in thickness is observed. The pressure dependence of this phenomenon suggests that it is not related to a photoablation of the Ti deposit. Using reaction (1), we expect saturation to occur due to the limited thickness of the $TiCl_4$ adsorbed layer that can be transformed to Ti by the laser beam. As mentionned in reference [5,6], the $TiCl_4$ adsorbed layer thickness increases with the $TiCl_4$ pressure. This is observed in figure 2: t saturation occurs at a lower E for P = 0.3 Torr than for P = 0.5 Torr as expected.

Pursuing the increase in E, a decrease in t is observed. By looking at the Dektak profile of figure 1, we notice a sharp decrease in the middle of the line for E≥2.5 MW/cm². This suggests that, in addition to transforming $TiCl_4$ adsorbed layers into Ti(s), the laser energy arriving on the surface is absorbed by the substrate leading to a local increase in temperature. The resulting substrate heating might lead to a combination of $TiCl_4$ desorption as well as Ti diffusion into the $LiNbO_3$. In a previous publication [1], the decrease in thickness was primarily explained by desorption or ablation of the deposited film. We now propose that diffusion is probably the main explanation. Al-Chalabi et al. [8] reported that they were able to diffuse electron beam evaporated Ti thin film in $LiNbO_3$ by KrF excimer laser with power density comparable to the one used here. Moreover, as explained in the next section, there are indications that Ti is possibly diffused into the $LiNbO_3$ by the laser before performing the diffusion in the furnace.

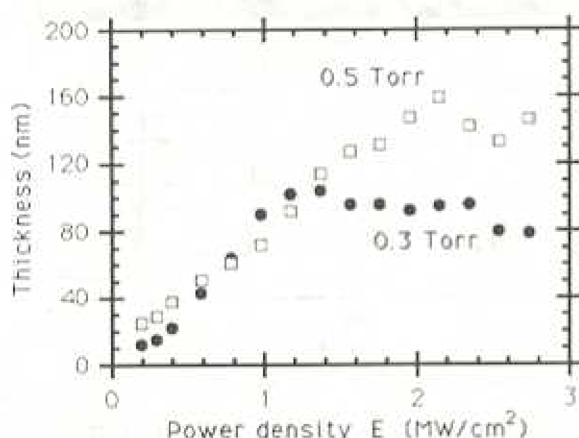

Figure 2 Maximum thickness t (nm) as a function of power density E (MW/cm²). Writing speed is 2 μm/s.

Figure 3 shows the line width W_{20} at t = 20nm as a function of E when P is 0.3 and 0.5 Torr. W_{20} was chosen because it corresponds to the line width measured with an optical microscope. As mentionned previously [1,2], W_{20} is essentially independent of pressure, indicating again that the deposition occurs through the photochemistry of adsorbed layers. This curve depends on the beam profile for which the FWHM has been determined as 7 μm [5,7]. Using this value and the distance of 0.1μm between pulses, we calculated [5] that 74 pulses arrive at any specific point along the line. Since the line thickness varies typically from 10 to 185 nm, the growth rate ranges from 0.13 to 2.5 nm/pulse. This corresponds to 0.5 up to 8 Ti layers formed/pulse and is in the same order of magnitude as the one for large area excimer laser induced deposition of Ti [5,6].

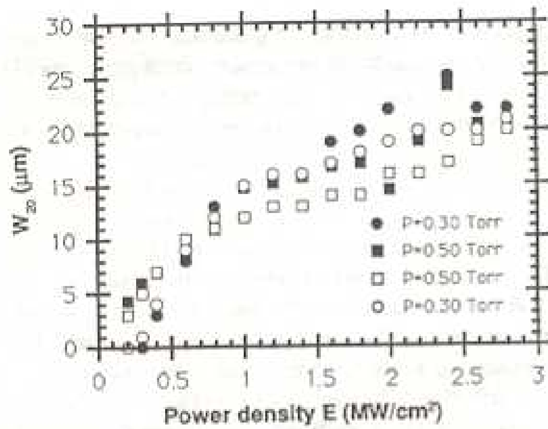

Figure 3 Line width at t=20nm, W_{20}, as a function of E for various $TiCl_4$ pressures.

Ti:$LiNbO_3$ WAVEGUIDE FABRICATION AND CHARACTERIZATION

Deposited Ti lines are diffused during 6 hours in wet O_2 (2 liters/min) at 1025°C [9]. For optical characterization, light from a HeNe laser is coupled into the waveguide and the transmitted light is directed on a video camera. Figure 4 shows

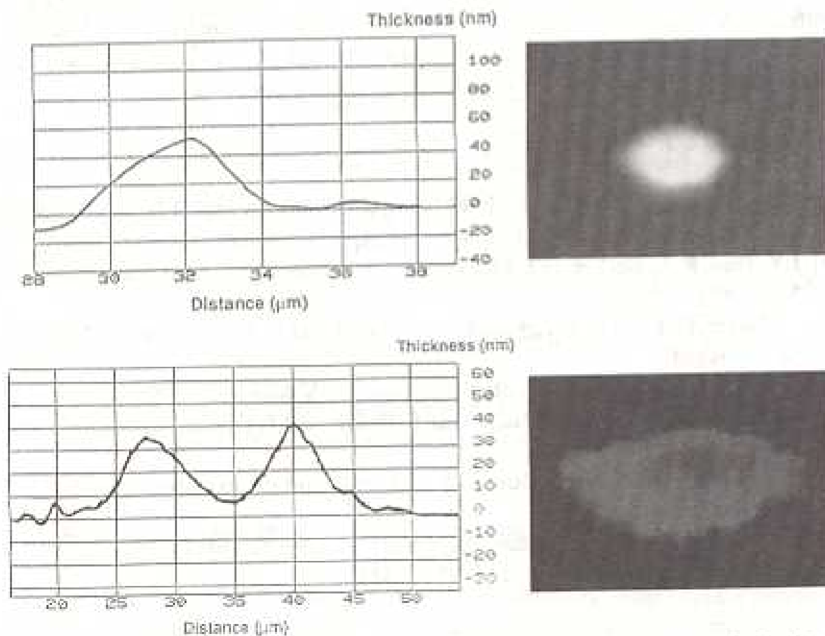

Figure 4 Photographs of the modes and Dektak profiles of laser fabricated waveguides. λ=633nm

pictures of the mode profiles of two of the fabricated waveguides. These waveguides have qualities similar to those produced by conventionnal processes [4].The dip in the Ti profile may be due to diffusion of Ti during deposition process. This results in a deeper waveguide after diffusion and consequently a larger mode profile.

CONCLUSION

Titanium lines are deposited by excimer laser on $LiNbO_3$ through the photochemistry of the $TiCl_4$ adsorbed layers. At low power density, the Ti line profile follows the beam profile and the maximum thickness t is proportional to the number of photons or the power density E. Increasing E leads to a sharp decrease in the middle of the line resulting in a saturation and even a decrease in maximum t. This is probably due to the diffusion of Ti into $LiNbO_3$ as suggested by the optical characterization of a waveguide made in these conditions. Preliminary results on $Ti:LiNbO_3$ optical waveguides show that their characteristics are similar to the ones made by conventional methods.

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