Optical propagation loss reduction in ZnO thin films under CO_2 laser treatment

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The reduction of propagation losses in ZnO thin film waveguides for integrated optics after CO_2 laser treatment is studied. RHEED patterns show that the measured decrease of optical losses is accompanied by an increase of ordering after the laser treatment. The reordering depends on the initial film state and the laser irradiation conditions.

I. INTRODUCTION

A few years ago it was shown that annealing with a CO_2 laser resulted in a large decrease of propagation losses in a number of thin film optical waveguides deposited on different substrates.[1,2] In particular, in the case of ZnO waveguides, Bertolotti *et al.*[3] confirmed these results showing that for both ZnO films deposited on Corning glass or silicon oxide substrates a large decrease in propagation loss was obtained which was larger for lower order modes.

No clear explanation of the operating mechanism was given, although Dutta[2] ascribed it to a reduction of interface scattering.

To look closer at the explanation of the observed effect, the experiment was repeated using optical waveguides made of ZnO films deposited on Corning glass or sapphire substrates. Laser treatment was performed with a cw scanning CO_2 laser, and the influence of scanning velocity was also examined. Reflection high energy electron diffraction (RHEED) of the treated surface was also performed.

The results show that an optimum scanning velocity exists for loss reduction, and that in this case a marked reordering of the material occurs.

II. MATERIAL AND EXPERIMENTAL SETUP

ZnO films were prepared using a rf diode sputtering system using Corning glass 7059 or c-axis oriented sapphire substrates.

A commercially available sintered ZnO target (diameter 100 mm) of 5 N purity was used. The deposition conditions were substrate temperature: 300 °C; sputtering gas pressure: 2.5×10^{-3} mbar; gas mixture composition: 28% O–72% Ar; rf power: 100 W; target substrate distance about 60 mm; deposition rate about 0.5 Å/s.

The surface morphology and RHEED patterns were observed with an AEI EMG6 electron microscope at 60 kV. The analysis yields information about the structure of the samples within a depth of a few tens of nanometers.

The ZnO was deposited as a thin film in general with a polycrystalline columnar structure with a preferred orientation of the crystallites, such that the c-axis is perpendicular to the plane of the substrate.[4]

The waveguiding properties were studied with a one-prism coupling technique, using a rutile prism. The analysis was performed by observing the m-lines distribution, and the waveguide attenuation was obtained by the in-plane light scattering. The setup for this measurement is shown in Fig. 1, in which a He–Ne polarized laser beam (λ = 6328 Å), after passing through a

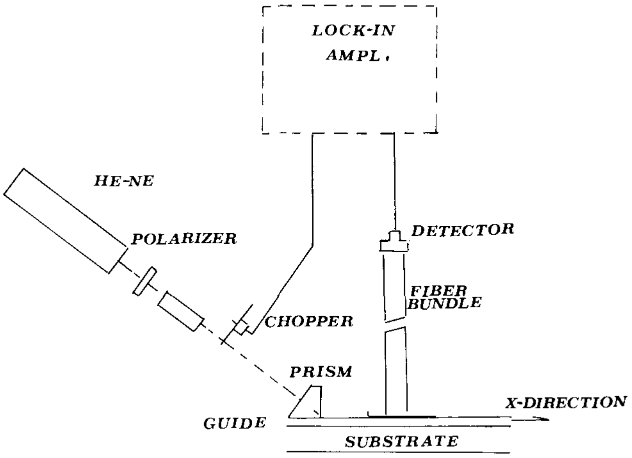


FIG. 1. Setup for the measurement of mode propagation losses.

chopper, was coupled via a rutile prism into the ZnO film along the x-direction. In order to make the measurement system inexpensive and easy to align and operate, instead of using a reference branch as is frequently done, a coherent optical fiber bundle 0.15 mm in diameter and 2 m long was used. One termination was placed in close proximity to the planar waveguide to form an image of the scattered light at a remote detector plane at the other termination where a diode with a lock-in amplifier was used to detect the scattered light. The best value of the attenuation coefficient was obtained considering the light $I(x)$ scattered at many different points x with the usual least square fitting.

III. LASER ANNEALING

Laser annealing has been performed by using a cw CO_2 laser (λ = 10.6 μm) of about 4.4 W power focused on the ZnO film with a germanium lens over a 200 μm diameter spot. Samples during the laser treatment were taken by means of an external heater at a temperature

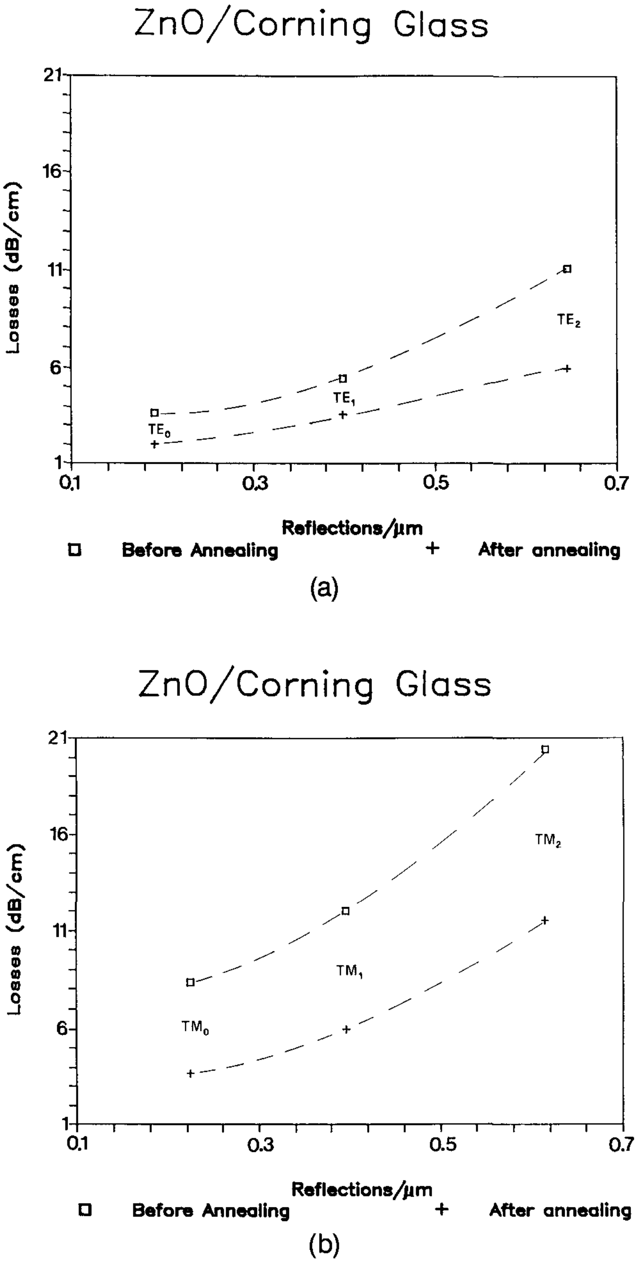


FIG. 2. Propagation losses at λ = 6328 Å as a function of the number of reflections suffered by the mode per μm of length of the guide, before and after CO_2 laser annealing for a ZnO/Corning glass waveguide for (a) TE modes and (b) TM modes.

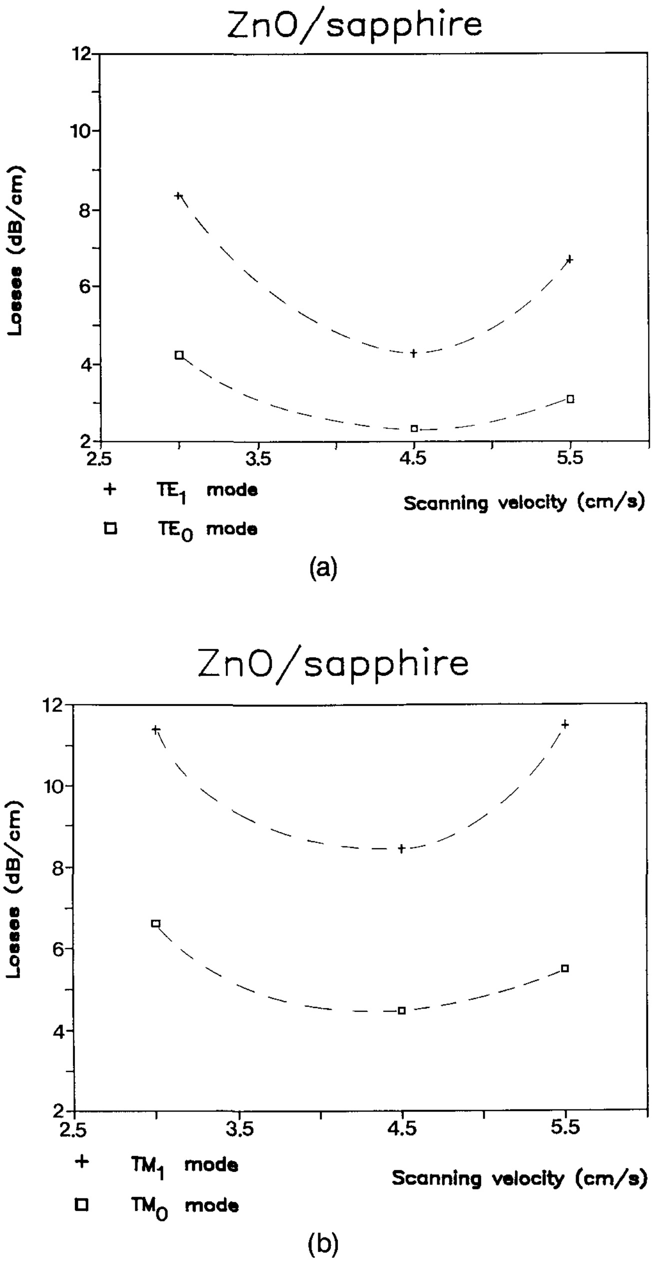


FIG. 3. Propagation losses at λ = 6328 Å as a function of CO_2 laser scanning velocity, in a ZnO/sapphire waveguide for (a) two TE modes and (b) two TM modes.

of about 140 °C to prevent any damage to the substrate due to thermal stresses.

Figures 2 and 3 show results obtained on ZnO on Corning glass and on sapphire substrates, respectively. In Fig. 2 losses for three different modes are given before and after the laser treatment performed at a scanning velocity 5.5 cm/s as a function of the number of reflections suffered by the mode per μm of length of the guide. At lower velocities the sample fractured.

A decrease of losses, greater for the higher order modes, occurs after the laser treatment.

Figure 3 shows, instead, the influence of scanning velocity on a sample of ZnO on sapphire. The sample allowed only two TE and two TM modes with initial

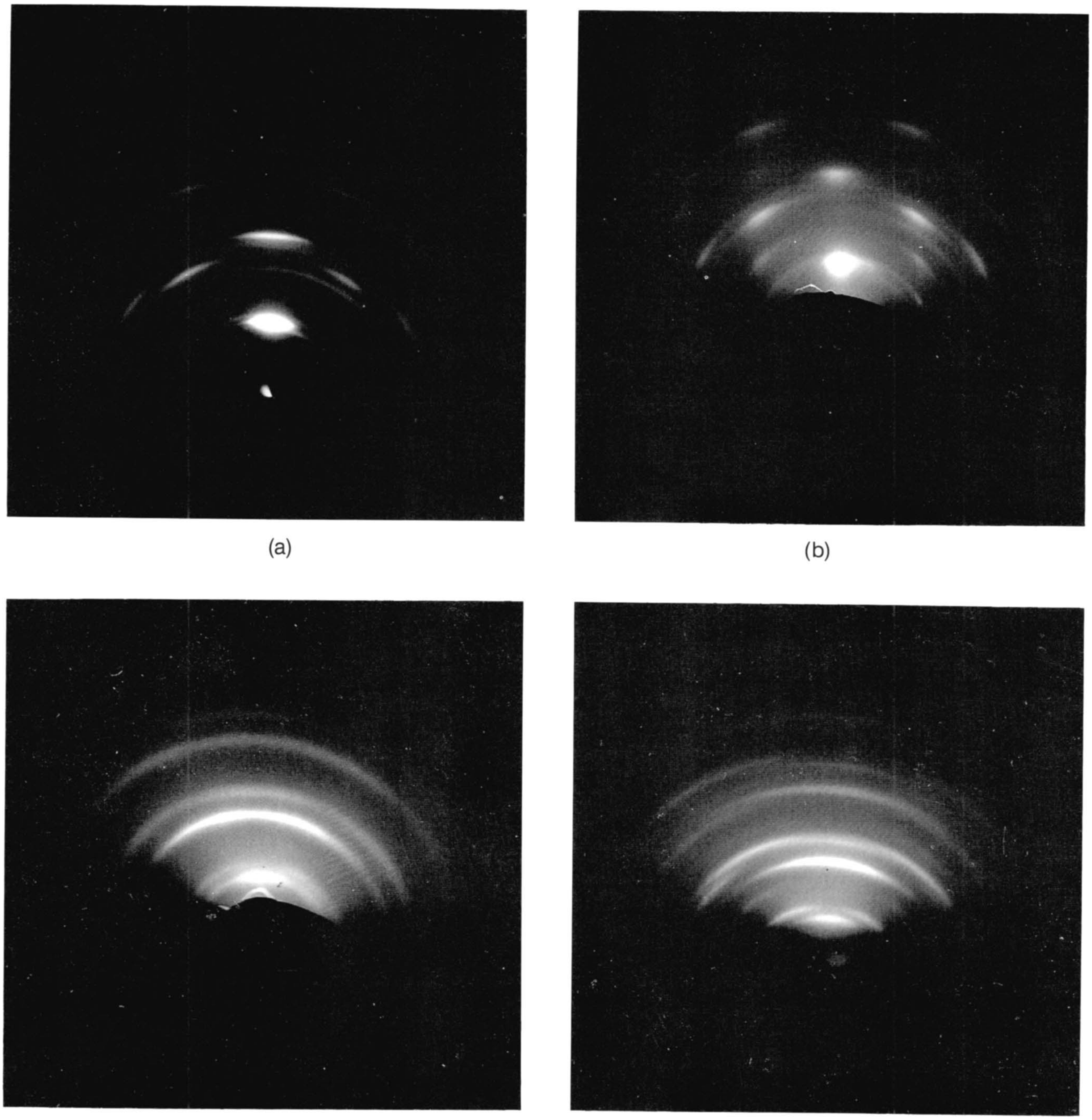
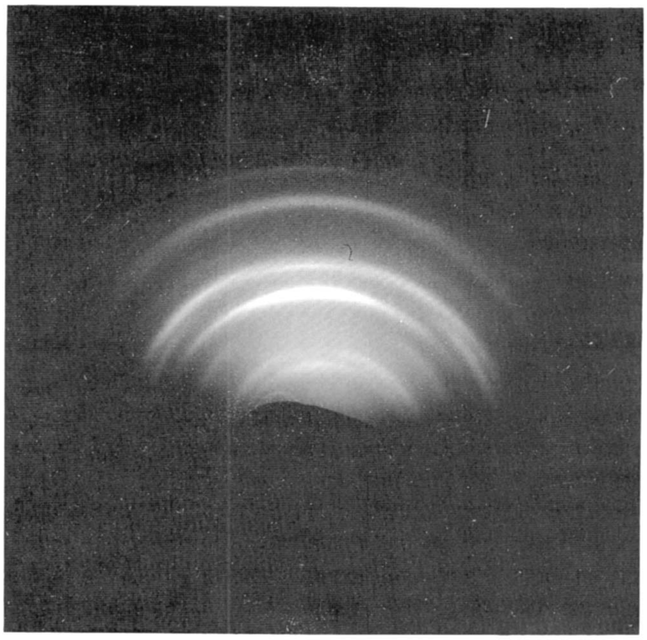

(a) (b) (c) (d)

FIG. 4. RHEED patterns for (a) ZnO/Corning glass as grown, (b) *idem* after laser annealing, (c) ZnO/sapphire as grown, (d) *idem* after laser annealing at a scanning velocity $v = 4.5$ cm/s, and (e) *idem* after laser annealing at $v = 5.5$ cm/s.



(e)

FIG. 4. (continued)

losses of 7.70 and 10.59 dB/cm, for TE_0 and TE_1 modes, respectively, and 11.10 and 17.01 dB/cm for the TM_0 and TM_1 modes, respectively, and was scanned at three different velocities between 3 and 5.5 cm/s. Simple inspection shows that losses have a marked minimum for all modes at a scanning velocity $v = 4.5$ cm/s.

Observation with RHEED showed a marked reordering of the structure, as can be seen in Fig. 4. Figure 4(a) shows the Corning glass film, as grown, which shows a fiber texture structure characterized by the arcs visible in correspondence with the spots which would have been obtained in an ideal fiber texture. Its RHEED pattern shows a preferential c-axis orientation along the perpendicular direction to the substrate surface.[4,5] After laser annealing [Fig. 4(b)], an increasing of the orientation is obvious by comparing the width of the corresponding arcs on the patterns. The narrowing of the arcs is indicative of an increase of order.

The sample on sapphire before annealing [Fig. 4(c)] gave a nearly uniform ring structure without any appreciable preferential orientation. Annealing causes the appearance of a preferred orientation [Fig. 4(d)] that was almost completely absent before annealing. This behavior is very evident when the laser scanning velocity is 4.5 cm/s [Fig. 4(d)]; it is less marked, but still present at 5.5 cm/s [Fig. 4(e)].

The indications given by the RHEED analysis are in good agreement with the change in propagation losses, and allow us to make a correlation between the propagation optical losses and the degree of orientation of the film. The better the film is oriented, the lower the optical losses are.

IV. DISCUSSION AND CONCLUSIONS

The presented results show that the measured decrease of optical propagation losses is accompanied by an increase of ordering of the film structure upon laser annealing. This reordering depends on the laser irradiation conditions. For example, in the case of the sapphire substrate there is an optimum velocity at which losses have a minimum, and although we have not performed similar analyses on the Corning glass substrates, we expect similar behavior for them.

In all cases losses seem to be lower for samples where the film is better aligned.

In the results discussed in Ref. 3 the high initial losses compared with the initial losses of the films investigated here (e.g., TE_0 mode in as grown ZnO/Corning had losses of 23 dB/cm as compared with the 3.5 dB/cm of the film studied here) suggest that poor quality films were studied in that case.

Our results indicate that laser annealing is effective in producing a larger degree of order in "bad" films which initially have a poor orientation. In "good" films that already have a strong preferred orientation no improvement should be expected by the laser treatment.

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