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SPUTTERED PLANAR OPTICAL WAVEGUIDES

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Some physical properties (optical attenuation, refractive index, stability) of sputtered Al_2O_3 films for use in planar optical circuits are discussed. Attention is paid to the dependance of these properties on sputtering conditions. Furthermore, the application of two etching processes (chemical etching and atom-beam milling) to the formation of optical waveguides is reported.

INTRODUCTION

Most research in the field of opto-electronics has been directed towards sources (lasers) and detectors. Integration with other components has received much less attention since conventional semiconductor lasers are unsuited for integration. The advent of Distributed Feed Back and Distributed Bragg Reflector Lasers, which do not share this disadvantage, has led to changes in this situation. Interest in both passive and active planar components is rapidly increasing.

In the authors laboratory research has been done since 1982 on passive integrated optical circuits in $SiO_2/Al_2O_3/SiO_2$ waveguide structures employing silicon substrates. Both the Al_2O_3 film and the SiO_2 cover layer are deposited by RF sputtering. The films are deposited onto a thermally oxidated silicon substrate. The optical and chemo-mechanical properties of the film-package prove to be heavily dependant on sputtering conditions and annealing treatment. With properly chosen process parameters compact and stable Al_2O_3 films can be produced with low optical losses. Lateral structures are formed by etching the Al_2O_3-layer (with atom-beam milling) or the SiO_2 cover layer (with buffered HF).

In this contribution a short treatment of the transverse and lateral structure required for optical waveguiding is followed by a description of the fabrication of the film package, emphasis being placed on the dependance of the physical properties on the production parameters. Furthermore, the etching processes employed will be discussed. All optical results reported in this paper were measured at He-Ne wavelength (0.6328 μm).

PHYSICAL REQUIREMENTS FOR OPTICAL WAVEGUIDES

For optical waveguiding we need a region of transparant material embedded in another material (or materials) which are also transparant but have a lower refractive index [1, 2, 3]. Fig. 1 shows the cross-section of

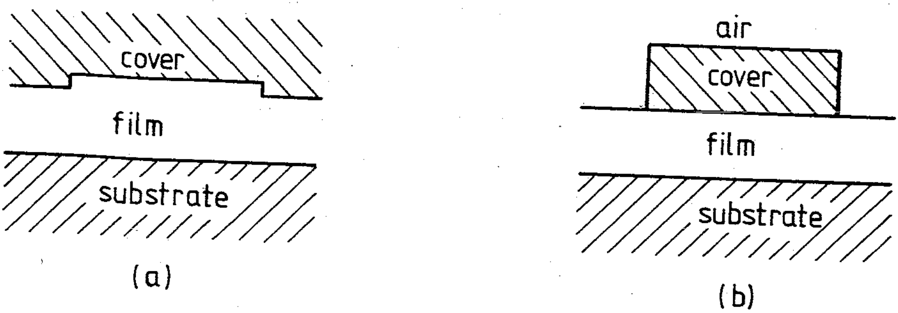


Fig. 1 Waveguide geometry for a ridge guide (Fig. 1a) and a top-loaded guide (Fig. 1b)

the structures applied at the authors laboratory. As substrate a thermally oxidated silicon wafer is used (n=1.46, oxide thickness d≈1.75 µm). The Al_2O_3 waveguiding film (n=1.69, d≈0.2 µm) and the SiO_2 cover layer (n=1.46, d≈0.6 µm) are RF-sputterdeposited. In the ridge-guide structure of Fig. 1a the light is contained in the thicker region (the ridge) and follows the guide through bends etc. In the top-loaded structure of Fig. 1b light will be contained under the SiO_2 top load in the waveguiding film. The most important properties of optical waveguides are the optical attenuation and the propagation constant, determined by the waveguide geometry and the refractive indices of guide and cladding-layers. The field profile in the guide is determined by the same parameters as the propagation constant.

Optical losses are introduced by absorption and scattering, the latter mechanism probably being the dominant one in the waveguides presently discussed. Scattering of light occurs at small inhomogeneities in the light-guiding region with a size parameter in the order of a wavelength. They may occur in the bulk of the film as well as at the interfaces of the waveguide (transverse as well as lateral). For high-quality guides it is thus important to produce homogeneous films with smooth interfaces and to etch lateral patterns with smooth edges.

For the propagation constant the production tolerances of film-thicknesses and refractive indices and of the lateral guide width are important. For many applications these requirements are not very stringent.

If the waveguide has to be laterally single-moded the lateral geometrical tolerances are severe, the required waveguide width will be in the order of 1 μm. In the transverse direction waveguides are normally single moded, the required film-thickness in the order of 0.2-0.3 μm poses no problems.

Al_2O_3 FILM-PROPERTIES

All sputtered films were deposited in a cryo-pumped Alcatel SCM-600 system with 6" targets and a water-cooled substrate table. Substrate-target distance was 6 cm. Sputtering was done in a 90% Ar-10% O_2 mixture. Most experiments were carried out at $8 * 10^{-3}$ mbar pressure. For the formation of the Al_2O_3-film the RF-diode process was selected for its deposition-rate-uniformity properties. Film thickness varied by less than 1% over 2 cm. For the formation of the SiO_2 cover layer, wich poses less stringent uniformity requirements, the RF-magnetron process was selected because of its higher sputterrate.

Attenuation

All sputtered films have high optical attenuations on leaving the sputtering chamber (> 20 dB/cm). On thermal annealing the optical attenuation reduces drastically. The refractive index and the film thickness are only slightly affected by the annealing.

Fig. 2 shows the effect of annealing on the optical attenuation. Each data point represents a 30-minute anneal. The exact shape of the anneal curve depends on the sputtering conditions; all anneal curves have qualitatively the same shape, however: a gradual reduction to a value

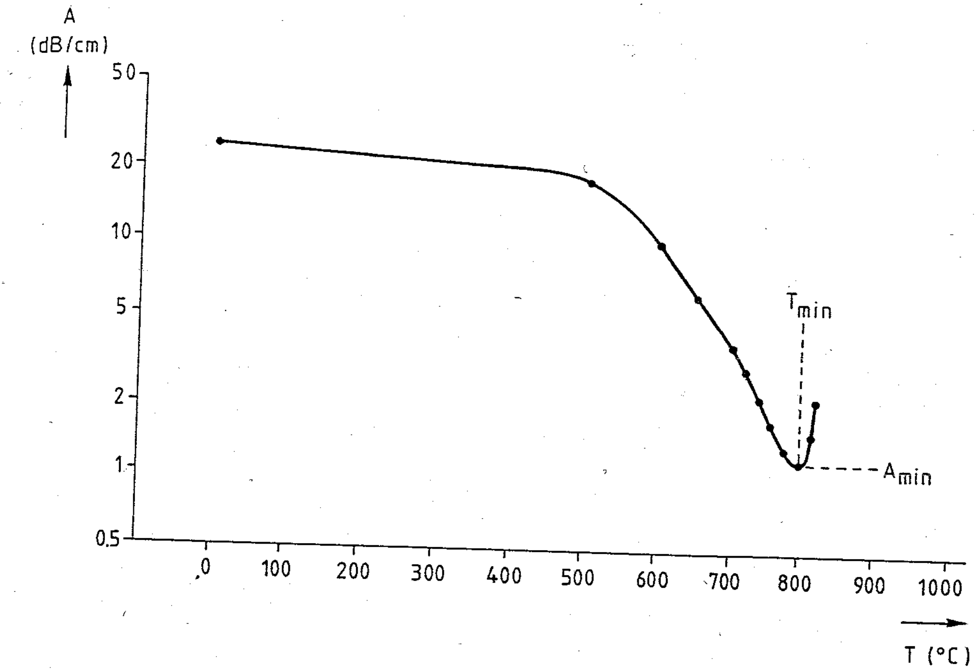


Fig. 2 Typical anneal curve of a zero-bias sputtered film (600 W RF power). Each point represents a 30 minute anneal.

A_{min} at a temperature T_{min}, and a strong increase beyond that temperature, accompanied by visually observable film damage. Fig. 3 shows the dependance of A_{min} and T_{min} on the bias voltage. Films sputtered without bias show the lowest minimum attenuation: 1 dB/cm, occuring at an anneal temperature of 800°C. The same attenuation value can also be obtained with a single 1 h anneal at 800°C, or alternately a 16 h anneal at 700°C.

Refractive index

The refractive index of our zero-bias sputtered films, 1.69-1.70, is considerably higher than reported in the literature, 1.65 being the highest value reported so far [4, 5]. The RF-power density does not affect the

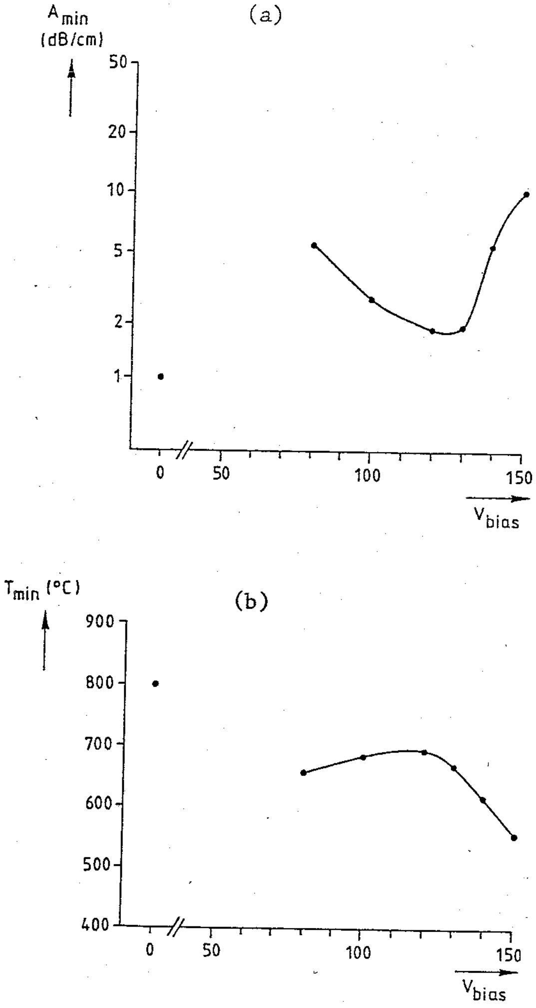


Fig. 3 Dependance of A_{min} (Fig. 3a) and T_{min} (Fig. 3b) on the bias voltage for films sputtered with 900 W RF-power

index value between values of 2.5-5 W/cm^2 (450-900 W RF power). Bias reduces the refractive-index value and introduces a strong dependence on applied RF-power. At 5W/cm^2 for bias voltages between 75 and 150 V the refractive index varies between 1.65 and 1.67. At 2.5 W/cm^2 for the same bias voltages between 1.56 and 1.58, which is considerably lower, even lower than the values obtained on layers deposited by E-gun evaporation. In conclusion: there is a great difference between films sputtered with or without bias. Films sputtered without bias have a high refractive index (≈ 1.69) independent of the target power density. Films sputtered with bias show weak dependence on bias voltage, and strong dependence on the target power density.

OTHER PHYSICAL PROPERTIES

An important property for our application is the etching resistance of the Al_2O_3 film against a buffered HF etch, which is used to etch patterns in the SiO_2 top layer. Al_2O_3 films with a low refractive index are completely destroyed during the removal of the top layer. Fig. 4 shows a SEM-photograph of a film with a low index (n=1.60) after etching. Films with

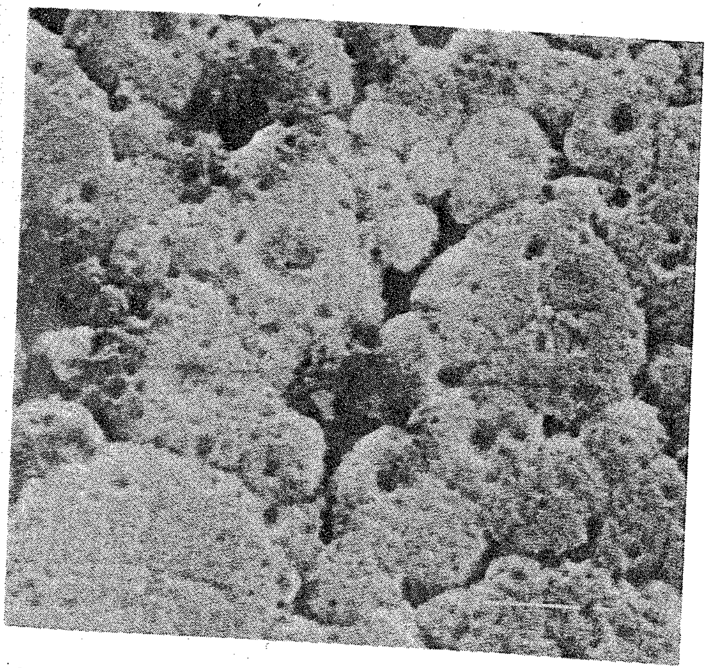
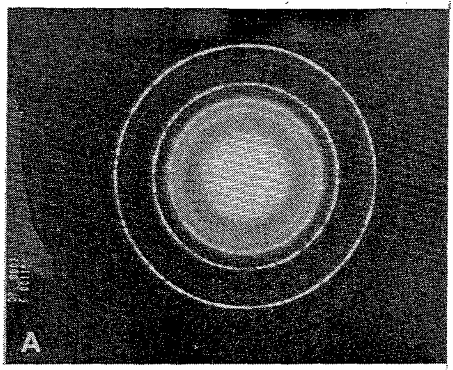


Fig. 4 SEM-photograph of a low-refractive-index Al_2O_3 film attacked by HF, showing etch resistant islands in the film. The long white bar represents a length of 1 µm

a high refractive index ($\geqslant 1.67$) are virtually inert, they are resistant against an etch time of several hours.

The refractive index seems to be related to the film compactness, as might be expected. Process conditions which produce low-index films correspond to high sputtering-rates, which is indicative of film porosity. Measurements on zero-bias films (n=1.69) with the Rutherford backscattering technique indicate a film density of 98% relative to anodic amorphous aluminium-oxide [6]. For comparison: evaporated films (n=1.65) exhibit densities in the order of 75%.

The high density is accompanied by an extremely high compressive stress in the Al_2O_3-film; we measured $2-3.10^9$ Pa. This stress disappears on annealing. Annealed films appear to be micro-crystalline. The crystallite size is small, however, the films seem to be amorphous with X-ray dif-



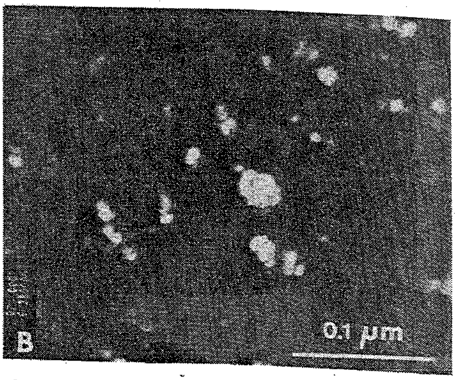


Fig. 5a Selected area electron-diffraction pattern of an annealed high-refractive-index Al_2O_3 film specimen, showing the occurence of micro-crystallites in the film.

Fig. 5b Dark field image, obtained with a Transmission Electron Microscope by selecting a few diffraction spots of the inner ring shown in Fig. 5a, revealing the size of the micro-crystallites.

fractometry. Fig. 5a shows an electron-diffractometry pattern which reveals the crystalline structure. Fig. 5b shows a dark field image obtained with a Transmission Electron Microscope by selecting a few diffraction spots of the inner ring shown in Fig. 5a. From this picture the crystallite size can be estimated to be in the order of 100 Å. More details concerning the Al_2O_3 film properties may be found in Smit et al.[7].

LITHOGRAPHY

Reticles are generated with an Electromask optical pattern generator. Resist-masks are produced according to the standard procedure (manual development) for Hunt Waycoat HPR-204 (positive) photoresist.

For top-loaded waveguides a buffered HF-etch is applied to the SiO_2 top layer. This procedure is quick and simple but has some disadvantages. If the etch-time is chosen such, that all SiO_2 besides the resist-pattern is removed, the under-etch for a 0.6 μm thick SiO_2 film varies between 0.6 and 1 μm, so that the effective waveguide width is reduced by 1.6 μm ± 0.4 μm. This inaccuracy means that our etching process is not suitable for waveguide widths less than 5 μm. A second reason which prohibits its use for narrow waveguides is the edge roughness which is probably caused by micro inhomogeneities in the sputtered film. Due to this roughness the losses resulting from edge scatter increase drastically as guide width reduces: more than 6 dB/cm for 5 μm guide-width, more that 10 dB/cm for 3 μm guide width.

Much smoother edges are produced by atom-beam milling of the Al_2O_3 film. For 3 μm waveguides we measured edge-scatter losses between 1 and 2 dB/cm (dependent on the ridge height. The patterns were defined in chrome masks, which yield much smoother edges than emulsion masks. For the atom-beam milling we applied an Ion Tech FAB-92 Flex gun. The source has a divergence of 12°. We used an incidence angle of 45° (beam centre) and a source-substrate distance of 10 cm. We found an etch rate (before annealing) for the zero-bias, $5W/cm^2$- target-power films ($n \approx 1.69$) of 0.9 nm/min; etching a ridge of 0.05 μm takes 56 minutes. The beam of the gun applied consists of a number of pencil-beams, resulting in great local etch-rate variations. By choosing a suitable substrate-movement an etch-rate uniformity of ± 1% over 35 mm has been obtained.

The atom-bombardment is not selective, the photo-resist etches about three times as fast as the Al_2O_3 film. For an etch depth of 0.1 μm or less this is no problem because the original resist thickness is 1 μm. We measured no lateral degradation of the masks (line-width reduction < 0.2 μm). The absence of under-etch makes this etch process suitable for sub-micron linewidths.

DISCUSSION AND CONCLUSIONS

Sputtered Al_2O_3-films can be made compact, stable and with desireable optical properties. With atom-beam milling optical waveguides of good quality can be produced in these films (embedded between SiO_2-cladding layers). We produced extremely short waveguide bends with low losses (R=100 μm: $A \approx 2$ dB/90°; R=250 μm: < 0.5dB/90°) and tapers from 9 μm to 3 μm guide-width over 200 μm taper length, with losses lower than 0.2 dB. $SiO_2/Al_2O_3/SiO_2$ structures seem thus to be suited to a variety of passive applications.

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