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Properties of Ta_2O_5 and $Ta_2O_5N_x$ thin films waveguides

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1. Introduction

Recently, Ta_2O_5 and $Ta_2O_5N_x$ waveguide structures deposited on oxidized silicon or glass substrates have been widely investigated. The waveguide enables the preparation of both passive and active elements for integrated optics, e.g., strip waveguides, direction couplers, Luneburg lenses and acoustooptic modulators. Ta_2O_5 and $Ta_2O_5N_x$ are of the particular interest for the following reasons:

- high refractive index (1.93–2.15),
- elastooptic properties,
- well developed deposition techniques.

Tantalum pentoxide has been produced by using the following methods:

- thermal oxidation of Ta film [1],
- thermal oxidation of N_2 doped Ta films [2],
- reactive DC sputtering of Ta target in $Ar + O_2$ atmosphere [3],
- reactive RF sputtering of Ta target in $Ar + O_2$ atmosphere [4].

$Ta_2O_5N_x$ waveguides have been prepared with DC reactive sputtering of Ta target in N_2+O_2 atmosphere as well as with reactive RF sputtering of the target in N_2+O_2 atmosphere. The paper presents the properties of planar Ta_2O_5 and $Ta_2O_5N_x$ waveguides deposited with reactive RF sputtering of Ta target in $Ar+O_2$ and $Ar+O_2+N_2$ atmospheres, respectively.

The influence of deposition process parameters, the waveguide attenuation, refractive index value and its anisotropy have been studied.

2. Experiment

Light guiding films were deposited in diode RF sputtering system. Tantalum target with diameter of 124 mm was sputtered. Prior to deposition, the system was evacuated by means of rotary and diffusion pumping system equipped with vapour freezer. The final pressure was $2\cdot10^{-6}$ Torr. System atmosphere composition, partial pressures of the gases used were maintained with needle valves. Diffusion pump inlet was partly shut during the process. Waveguides were deposited on 1.5 inches diam. silicon substrates which, prior to the deposition, had been oxidized to the depth of 0.8 μm in presence of water. Total pressure during the process was changed within the range of $3\cdot10^{-2}$–10^{-3} Torr. Desposition rate was equal to 3–5 nm/min. The maximal thickness of deposited films was 1.6 μm. During deposition the substrates were cooled down to 20°C. All the deposited films were transparent. He-Ne laser light beam was coupled to the films with a rutile prism. Refractive index value was determined by measuring the angles at which TE and TM mode coupling took place. Synchronic angles were measured with respect to the normal to the light introducing prism-plane with 20″ accuracy. In order to determine the refractive index and film thickness numerical calculations were made. The optical quality of deposited films was evaluated by measuring the amount of scattered light from the waveguide with a fibre coupled with the photomultiplier.

3. Determination of refractive index and film thickness

Refractive index and film thickness were calculated by solving the characteristic equation for the structure shown in Fig. 1 [5]. The wave equation was solved assuming that the films were anisotropic and lossless. Refractive index tensor is given by

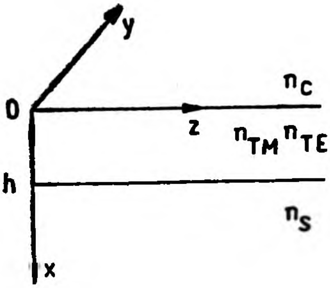

Fig. 1. Waveguide geometry

$$[n] = \begin{bmatrix} n_{\mathrm{TM}} & & 0 \\ & n_{\mathrm{TE}} & \\ 0 & & n_{\mathrm{TE}} \end{bmatrix}.$$

For TE modes characteristic equation has the following form

$$h = \frac{1}{k\sqrt{n_{\mathrm{TE}}^2 - N_m^2}}\left(m\pi + \tan^{-1}A'_m + \tan^{-1}B'_m\right) \tag{1}$$

where

$$A'_m = \sqrt{\frac{N_m^2 - n_c^2}{n_{\mathrm{TE}}^2 - N_m^2}}, \quad B'_m = \sqrt{\frac{N_m^2 - n_c^2}{n_{\mathrm{TE}}^2 - N_m^2}}.$$

For TM modes characteristic equation is the following:

$$h = \frac{1}{k\sqrt{n_{\mathrm{TM}}^2 - N_m^2}\,\dfrac{n_{\mathrm{TE}}}{n_{\mathrm{TM}}}}\left(m\pi + \tan^{-1}A''_m + \tan^{-1}B''_m\right), \tag{2}$$

$$A_m = \left(\frac{n_{TE}}{n_c}\right)^2 \sqrt{\frac{N_m^2 - n_c^2}{n_{TM}^2 - N_m^2}} \left(\frac{n_{TM}}{n_{TE}}\right),$$

$$B''_m = \left(\frac{n_{TE}}{n_s}\right)^2 \sqrt{\frac{N_m^2 - n_s^2}{n_{TM}^2 - N_m^2}} \left(\frac{n_{TM}}{n_{TE}}\right)$$

where: h – film thickness,

n_c – ambient-medium refractive index,

n_{TE} and n_{TM} – waveguide refractive index for TE and TM modes,

n_s – refractive index of substrate.

N_m–m-order – mode effective refractive index.

n_{TE} and h can be determined by equating two expressions (1) for modes with different propagation constants. Since m modes can be guided in the film, there are $1/2\ m(m-1)$ different modes combinations. Deviation from the calculated values of n_{TE} and h determined measurement accuracy. The value of n_{TE} calculated in such a way was inserted into Eq. (2) and the procedure was repeated to determine n_{TM}. In order to improve the accuracy of n_{TE}, n_{TM} and h determinations in multimode waveguides an iterative procedure was employed. Exemplary measurements and results of calculation are presented in Table.

Comparison between observed and theoretically expected propagation constants of a Ta_2O_5 film, $\lambda = 0.6328$ μm

n	m	Observed	Theory	Difference
TE 2.1443	0	2.12974	2.12997	−0.00024
	1	2.08660	2.08641	0.00020
	2	2.01202	2.01217	−0.00015
	3	1.90427	1.90456	−0.00028
TM 2.1385	0	2.12197	2.12230	−0.00034
	1	2.07341	2.07315	0.00026
	2	1.98900	1.98922	−0.00022
	3	1.86700	1.86745	−0.00045

Film thicknnes $h = 1.159$ μm∓ 5 nm, refractive index of SiO_2 substrate $n_s = 1.4572$.

4. Results

Thin-film planar waveguides were deposited in two different mixtures of gases, namely $Ar+O_2$ and $Ar+O_2+N_2$. Relation: waveguide attenuation–oxygen concentration was studied. It has been found that for the total pressure of $2\cdot 10^{-2}$ Torr and oxygen concentration of $10^0/_0$, waveguides exhibited the least losses equal to 3 dB/cm, when the substrates were cooled down to 20°C. When, however, the substrates were heated up to 90°C the attenuation was three times higher. Ta_2O_5 film deposited in $Ar+O_2$ atmosphere exhibited a small positive anisotropy $\Delta n = n_{TE} - n_{TM}$ equal to 0.007. This value was determined from the measurement of ten waveguides deposited under the same conditions. Average values of refractive indices for TE and TM were equal to 2.118 and 2.111, respectively. The dependence of the refractive indices and anisotropy upon N_2 concentration in the mixture was studied in $Ta_2O_5N_x$ for constant oxygen concentration of $10^0/_0$. The results are illustrated in Fig. 2. The highest anisotropy was obtained for sputtering in O_2+N_2 atmosphere. The values of indices were the following: $n_{TE} = 1.950$, $n_{TM} = 1.973$, $\Delta n = -0.023$. Mode-transforming device was produced on the basis of this waveguide [6]. X-ray diffraction studies have shown that the film is amorphous.

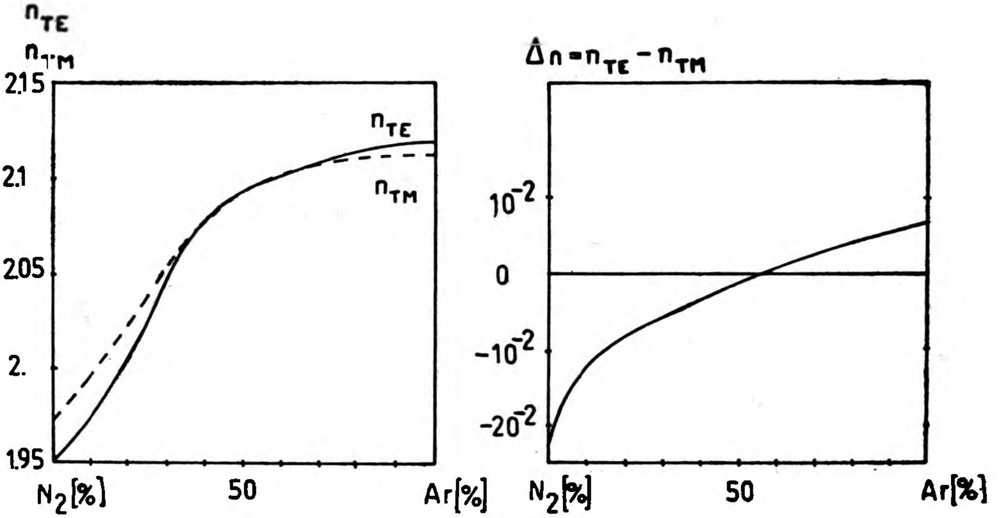

Fig. 2. Dependence of the refractive indices and anisotropy upon N_2 concentration in the mixture at constant oxygen concentration of $10^0/_0$ for $Ta_2O_5N_x$ waveguide

5. Conclusions

The paper presents basic properties of Ta_2O_5 and $Ta_2O_5N_x$ films deposited with reactive RF sputtering which is of a great significance for construction of integrated optics devices. Insignificant anisotropy occurring in the waveguides obtained can be due to mechanical stresses. Birefringence found in the amorphic $Ta_2O_5N_x$ waveguide is caused by presence of nitrogen in the film. The question about the reason of such a high anisotropy is difficult to be definitely answered due to certain measuremental barriers. As one can see in Fig. 2, anisotropy increased with the increasing N_2 concentration in process gases, whereas refractive index decreased, this being associated with the decrease of density.

Anisotropy may be due to near-range ordering in electric field throughout the deposition [4].

Reactive sputtering enables a deposition of films with refractive indices ranging from 1.95 to 2.15. High optical properties of Ta_2O_5 and $Ta_2O_5N_x$ waveguides and possibility of changing both the refractive indices and amount of anisotropy make these films preferable in integrated optics.

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