ACOUSTOOPTIC INTERACTION OF ACOUSTIC SURFACE WAVES WITH GUIDED OPTICAL WAVES IN PLANAR TANTALUM-PENTIOXIDE WAVEGUIDES

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Summary

We have investigated acoustic and acoustooptic properties of planar thin-film Ta_2O_5 waveguides with ZnO surface acoustic wave /SAW/ transducer. We have measured velocity and attenuation of SAW and acoustooptic interaction efficiency as a function of Ta_2O_5 waveguide thickness. Measured SAW velocity in Ta_2O_5 has equaled 2250 m/s. Maximum diffraction efficiency per unit acoustic power and unit transducer aperture has equaled 0.61 %/mW·mm.

Introduction

Acoustooptic modulator is a basic element of integrated-optic devices such as spectrum analyser, correlator, switcher etc. Fig. 1. shows a diagram of one of possible solution of integrated-optic acoustooptic modulator. Optical wave has been guided in Ta_2O_5 planar waveguide. SAW has been generated with a interdigital transducer in ZnO film. An oxidized silicon plate has bee used as the substrate. Both the films, i.e. the waveguide and the transducer, have been deposited on the same substrate. Acoustic wave, being propagated in the substrate, forms a periodic strain field which due to elastooptic effect produces periodical changes in refractive index of the medium. Light diffraction can occur on the phase diffraction grating produced in such a way. From a viewpoint of applications in integrated-optic processors the most interesting phenomenon seems to be the Bragg diffraction.

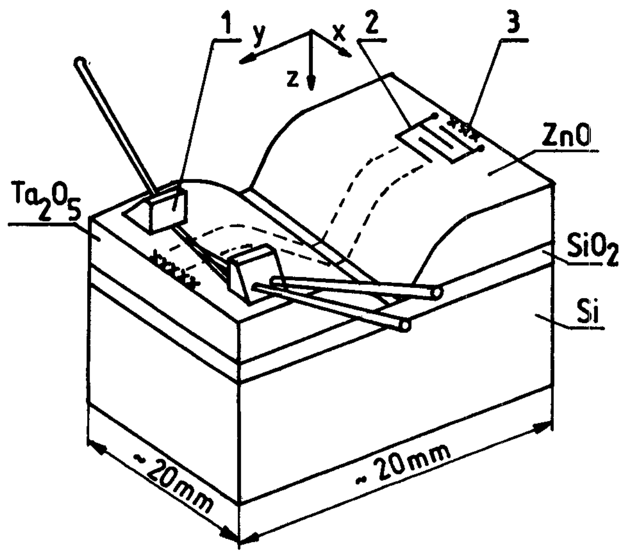

Fig. 1. Schematic diagram of integrated acoustooptic modulator made of Ta_2O_5 waveguide. Both Ta_2O_5 waveguide and ZnO piezoelectric layer have been deposited on oxidized silicon substrate with 1.2 µm-thick SiO_2 film. 1-prism coupler, 2-interdigital transducer, 3-attenuating layer of epoxy resin.

Technology

Acoustooptic modulator has been prepared on silicon substrates covered with SiO_2

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film of 1.2 μm thickness. Silicon oxide has been obtained with thermal oxidation method. Two films of Ta_2O_5 and ZnO have been deposited side by side with a reactive ion sputtering technique. Ta_2O_5 film has constituted both the waveguide and elastooptic-interaction medium. Aluminium electrodes of the interdigital transducer have been evaporated onto zinc oxide film. The interdigital transducer has 20 pairs of fingers with thickness of 200 nm, the aperture being 3 mm. In the ZnO film, the transducer has generated a wave with frequency ranging from 180 to 230 MHz, depending upon the ZnO film thickness, the wavelength being 20 μm. ZnO- and Ta_2O_5-film edges at their common boundary have been smooth and slightly sloping. This shape has been obtained due to mechanical masking of the substrate during the deposition process. Outer film edges have been covered with epoxy attenuating SAW.

Experiment

Film thickness dependence of both surface-wave velocity and acoustooptic interaction efficiency have been determined for the obtained modulator species. SAW velocity has been measured with laser probe method (1). In the layered structure, Rayleigh wave velocity is determined by the ratio H/Λ , where H denotes the film thickness, and Λ is the SAW wavelength (1). Dependence of the SAW velocity in the structure of Ta_2O_5-SiO_2-Si is shown in Fig. 2. Solid line illustrates the course approximated with the following polynominal:

$$V = \sum_{i=1}^{3} (H/\Lambda)^i \; a_i$$

where: $a_o = 4615$, $a_1 = -16972$
$a_2 = 43502$ $a_3 = -36970$

Since a frequency of the generated acoustic wave depends upon ZnO piezoelectric-film thickness, there is a

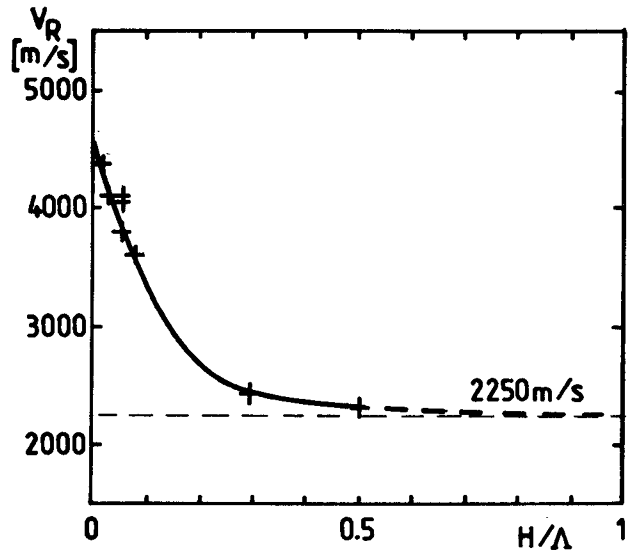

Fig. 2. SAW velocity in Ta_2O_5 film versus H/Λ ratio. H-film thickness, Λ - SAW wavelength.

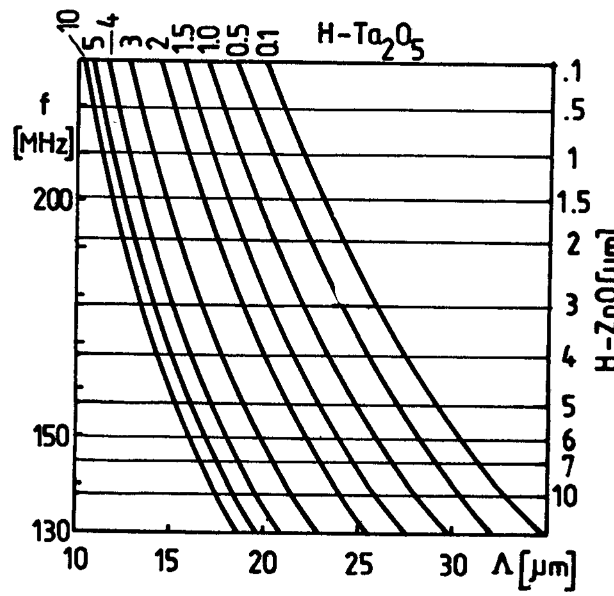

Fig. 3. Dependence of SAW wavelength and frequency upon ZnO and Ta_2O_5 film thicknesses. It can be seen from the diagram that by proper choice of the film thickness one can independently select SAW frequency and wavelength in the interaction region.

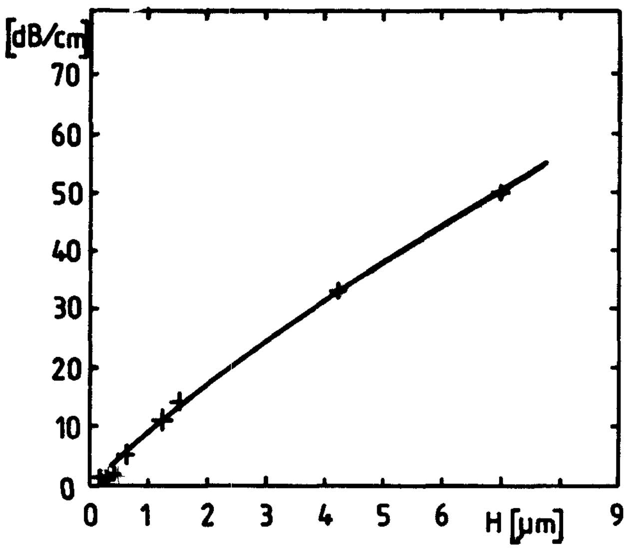

Fig. 4. SAW attenuation versus Ta_2O_5 film thickness /200 MHz/.

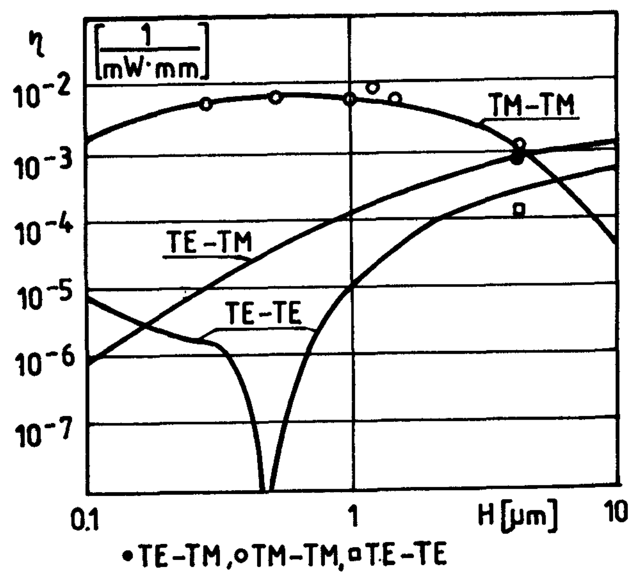

Fig. 5. Dependence of acoustooptic interaction efficiency in Ta_2O_5-film waveguide upon film thickness. The efficiency is calculated for unit acoustic power and unit SAW aperture.

possibility of an independent selection of acoustic-wave frequency and wavelength in the interaction region of the modulator shown shematicaly in Fig. 1. It can be learnt from Fig. 3. how ZnO transducer film- and Ta_2O_5-waveguide thicknesses should be chosen such that in the acoustooptic-interaction region, given values of SAW frequency and wavelength be attained. This figure shows also that having the interdigital transducer with fingers of 5 μm thickness,which generates the acoustic wave of 20 um wavelength in ZnO, an acoustic wave of wavelength twice shorter, i.e. Bragg angle twice greater, can be obtained in Ta_2O_5 planar waveguide. This effect allow us to improwe twice a resolution of the integrated-optic spectrum analyser buit in the described structure. Moreover, this effect has no equivalence in $LiNbO_3$ acoustooptic modulators widely used nowdays.

Theoretical analysis

The aim of the analysis has been to give: 1. the way efficiency of acoustooptic interaction depends upon tantalum pentioxide film thickness,

2. the reason the diffraction efficiency for TM modes is much higher than that for TE modes,
3. the values of Ta_2O_5 elastooptic constants.

Acoustooptic interaction with SAW in thin-film waveguide is described by the relation (2):

$$\frac{\eta}{P\,W} = \left| \int_0^\infty E_{Bi}(z)\varepsilon_{ik}\, p_{klab} S_{ab}(z)\varepsilon_{lj} E_{Ij}(z)\,dz \right|^2 \qquad (2)$$

where:

$E_{Bi}(z)$ - electric field of diffracted and
$E_{Ii}(z)$ incident waves
ε_{ik} - element of dielectric tensor
p_{klab} - element of photoelastic tensor
$S_{ab}(z)$ - strain
P - acoustic power
W - aperture of SAW transducer

The equation is valid for small Bragg--diffraction efficiency and for small diffraction angles. A notation of summation with respects to repeated index has been assumed. Coordinate system is defined in Fig. 1. For amorphic waveguides equation (2) can be transformed to the form (3):

$$\frac{\eta}{P\,W} = N_B^3 \cdot N_I^3 \cdot p_{12}^2 \cdot \Gamma^2 \qquad (3)$$

where:

$$\Gamma = \begin{cases} \int \sin^2(\pi z/H)(qS_2+S_3)\,dz & \text{for } TE_o - TE_o \\ \int \sin^2(\pi z/H)(qS_3+S_2)\,dz & \text{for } TM_o - TM_o \\ \int \sin^2(\pi z/H)(q/2-1)\,dz & \text{for } TE_o - TM_o \end{cases}$$

interaction

$q = p_{11}/p_{12}$

N_B, N_I - effective refractive indices for diffracted and incident beams respectively.

Formula (3) can be used for calculating qualitative dependence of diffraction efficiency upon the waveguide thickness.

In order to calculate strain distribution S_{ab} z one must know elastic constants for Ta_2O_5. They have not been measured yet. We have evaluated experimental values of elastic constants for Ta_2O_5 by extrapolating the dependence of some elastic constants of glasses upon density. Since for all practicaly used substrate materials strain distribution of SAW near the surface are similar, a layered structure of the investigated system has been neglected when calculating this distribution for given elastic constants, which made it possible to estimate the efficiency of acousto-optic interaction Eq. 3 . Such procedure is justified at this juncture for we are interested in qualitative data only.

Different values of q Eq. 3 yield different curve shapes, but one value only (q=0.39) provides that calculated Bragg diffraction efficiency for TM mode exceeds that for TE mode by two orders of magnitude. The latter has been experimentaly proved for waveguides of thickness below 2 μm. Qantitative dependence presented in Fig. 4. has been determined by comparing a qualitative diagram calculated for TM-TM diffraction with the experimental results obtained for the waveguides of thicknesses ranging from 0.3 to 1.5 μm. From this figure can be seen that diffraction efficiency for TM-TM interaction decreases for greater waveguide thicknesses, whereas the efficiencies increases both for TE - TE and TE - TM interactions.Taking advantage of this all the three efficiencies have bean measured for the prepared waveguide with 4.3 μm-thickness. The respective experimental results have agreed very well with the theoretical predictions for TM - TM and TE - TM interactions. For TE - TE interaction the agreement, though worse, is still satisfactory. The performed analysis has yield the following Ta_2O_5 photoelastic constants: p_{11}=0.024, p_{12}=0.062, p_{44}=-0.038.

References

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