PROPAGATION MODE OF COLD EVAPORATED ZINC SULFIDE PLANAR WAVEGUIDES

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ABSTRACT. *This paper discusses the propagation mode of ZnS waveguides fabricated by thermal evaporation technique at cold substrate temperature. A substrate holder that was fitted with a thermoelectric cooler was used to cool the substrate. The substrate temperature of the deposition is controlled at 50°C. The substrates used were silica (glass) slides and oxidized silicon wafers. The propagation modes of the waveguides were studied with a Prism Coupler which was fitted with a 633 nm laser source. There was only one TE mode observed for the 150 nm thick waveguide and five TE modes for the 800 nm thick waveguide for both types of substrates. From the modal analysis, the refractive index of the ZnS thin films is 2.346.*

KEYWORDS. ZnS thin film, cold evaporation, propagation mode, planar waveguide

INTRODUCTION

Zinc Sulfide (ZnS) has been extensively used as an evaporant in the past as a component in dielectric coatings, as a high index layer in conjunction with magnesium fluoride and as low index layer with lead fluoride. Its optical properties make it useful for planar waveguides, filters, reflectors, and potentially integrated optical components. Undoped ZnS is an II-VI compound semiconductor with a wide direct energy band gap (E_g = 3.7 eV). It exits in two modifications. Depending on the conditions of preparation, it crystallises in the cubic structure of zinc blende (β-ZnS) or in the hexagonal structure of wurtzite (α-ZnS). Bulk ZnS has a high index of refraction of 2.35 and is transparent over a very broad range (0.4-13 μm).

In thermally evaporated ZnS waveguides, the substrate temperature is found to have marked influence on the losses. The lack of crystallinity and absence of well-defined columnar structures in films prepared with cold substrates reduces the scattering losses. Ruffner *et al.* (1989) reported that the loss is minimum (~ 2 dB/cm) when deposited at the substrate temperature of 50°C. Below this temperature, propagation losses increased as a result of pinhole formation and eventually tensile stress failure with decreasing deposition temperature. For higher deposition temperatures, the enhanced crystallinity of the film may induced scattering centres and resulted in higher losses (Al-Douri, 1986).

In this study, we investigated experimentally the optical propagation in ZnS thin films waveguides. In order to produce the ZnS films that will exhibits waveguide characteristics, the deposition were operated at the substrate temperature of 50°C.

THE WAVEGUIDE THEORY

The propagation modes of the waveguides are examined by ray optics theory taking into account the total internal reflection at the interfaces and accompanied by the related phase shift (Palik and Addamiano, 1985). The modes are generally characterised by propagation constant, although they are classified by their incident angle θ in ray optics. The plane wave propagation constant in the wave-normal direction is defined as $k_o n_f$, where $k_o = 2\pi/\lambda$ and λ is the wavelength in free space. The relationship between the incident angle and the propagation constant along the x and z directions are:

$$k_x = k_o n_f \cos\theta \qquad \{1\}$$

$$k_z = k_o n_f \sin\theta = \beta \qquad \{2\}$$

Particularly, $k_z = \beta$ for lossless waveguides in which is equivalent to the plane wave propagation constant in an infinite medium with an index of $n_f \sin\theta$. Therefore, effective indices, N of the modes can be defined as:

$$\beta = k_o N, \text{ or } N = n_f \sin\theta \qquad \{3\}$$

The guided mode propagating along the z direction actually sees the index N. Because of the guided modes can be supported in the range of $\theta_s < \theta < 90°$. The corresponding range of N is $n_s < N < n_f$. Similarly, the radiation modes exist in the range of $N < n_s$. If n_c is larger than n_f, however, the waveguide supports leaky modes whose energy leaks to the cover.

The related Maxwell's equations in isotropic, lossless dielectric medium are (Lee, 1986):

$$\nabla X \mathbf{E} = -\mu_o.\delta\mathbf{H}/\delta t \qquad \{4\}$$

$$\nabla X \mathbf{H} = -\varepsilon_o n^2.\delta\mathbf{E}/\delta t \qquad \{5\}$$

where μ_o and ε_o are the magnetic permealibility and dielectric permittivity of free space, respectively and n is the refractive index. In the orthogonal coordinate (x, y, z), suppose that the plane wave propagates along the z direction with the propagation constant, . The electromagnetic fields vary as:

$$\mathbf{E} = \mathbf{E}(x, y).\exp j(\omega t - \beta z) \qquad \{6\}$$

and

$$\mathbf{H} = \mathbf{H}(x, y).\exp j(\omega t - \beta z) \qquad \{7\}$$

where the angular frequency, $\omega = 2\pi c/\lambda$, and c is the light velocity in free space.

In the step-index planar waveguide, the electromagnetic fields are independent of y. Accordingly, since $\delta/\delta t = j\omega$, $\delta/\delta z = -j\beta$ and $\delta/\delta y = 0$, Equations 6 and 7 yield two different physical modes with mutually orthogonal polarisation states. One is the Transverse Electric (TE) mode, which is consists of the field components E_y, H_x, and H_z. The other is the Transverse Magnetic (TM) mode, which has H_y, E_x and E_z.

Wave equations for the TE and TM modes are,

$$\frac{\partial^2 E_y}{\partial x^2} + (k_0 n^2 - \beta^2) E_y = 0 \qquad \frac{\partial^2 H_y}{\partial x^2} + (k_0 n^2 - \beta^2) H_y = 0$$

$$H_x = -\frac{\beta}{\varpi \mu_0} E_y \qquad E_x = \frac{\beta}{\varpi \varepsilon_0 n^2} H_y$$

$$H_z = -\frac{1}{j\varpi \mu_0} \frac{\partial E_y}{\partial x} \qquad E_z = \frac{1}{j\varpi \varepsilon_0 n^2} \frac{\partial H_y}{\partial x}$$

The field solutions and the boundary conditions at the interfaces x = - T and x = 0 lead to eigenvalue equations that determine the propagation characteristics of the TE and TM modes.

EXPERIMENTAL DETAILS

Thin Film Deposition

Thin films of ZnS were prepared by Edwards (Auto 306) thermal evaporation system with a metal chamber. The system utilizes an 8 inch turbomolecular pump backed with a rotary pump. The turbomolecular pump and the vacuum chamber are separated by a chevron baffled liquid nitrogen cold trap that was filled prior to all depositions. This tends to reduce carbon and oxygen contamination of the films. System pressure was monitored with both Penning gauge and Pirani gauge while the foreline pressure was monitored with a Pirani gauge. The system was regularly pumped to down to a base pressure of less than 5×10^{-7} mbar.

The thermal source for material deposition was an alumina crucible heated with a tungsten crucible heater. The source material was pure ZnS (pieces, 3 12 mm) purchased from Aldrich that was approximately 99.99%. Approximate deposition rate and thickness are recorded with a quartz crystal oscillator. The distance between the vaporising source and the substrate is kept large (at about 30 cm) for better uniformity of thickness. The current through the crucible heater is gently increased to allow deposition rates of between 0.2 to 2.5 nm/s. During deposition, the pressure was slightly increased to between 10^{-5} and 10^{-6} mbar. After deposition, the films were allowed to warm slowly to ambient temperature while still under vacuum. Substrate temperatures are monitored with a chromel/alumel thermocouple that is soldered directly to the substrate.

The substrate materials used in this research were silica (glass) slides and silicon wafers wit 1.8 μm oxide layer. The film properties and adhesion partly depend on the substrate surfac cleanliness. Acetone and propanol were used in the cleaning process. To enhance the cleanlines the substrates were then cleaned with acid mixture (sulphuric acid and hydrogen peroxide) an rinsed thoroughly with de-ionised water. All steps above were done in a heated bath (50 55°C equipped with an ultrasonic vibration. The substrates were dried with a cleaned nitrogen gas flo and were baked overnight in an oven at 120°C. Finally, the substrates were examined unde reflections from the room lights. The whole cleaning process will be repeated whenever significa scatter from dust particles was spotted.

A specially design substrate holder which was fitted with a thermoelectric cooler (TEC) wa used to cool the substrates during the deposition process (Saafie Salleh *et. al.*, 2003). The coo side of the TEC was soldered with a copper plate for the substrates attachment. The hot side of th TEC was soldered with a liquid cooler in order for flowing chilled water (constantly at 5°C) t remove the excess heat. Prior to the depositions, preheating was done by blowing hot air (150 t 200°C) onto the substrate for about 10 minutes with the TEC cooling, preventing high temperatu damage. By applying this procedure, the ZnS thin films were found to adhere on the substrate bette and were very stable. The depositions were only carried out when the substrate temperature wa constant at 50°C.

Characterisation Technique

The excitation of guided wave can be done by several methods such as prism coupling, en coupling and grating coupling. In our experiment, we used prism coupling for the excitation.

The prism coupling method utilises a high index prism to excite a guided wave throug phase matching between the incident wave and a guided mode. A commercial Prism Couple (Model 2010) supplied by Metricon Corporation was used for this analysis. The prism for th apparatus was a rutile prism with refractive index of 2.872 for TE mode excitation. A He-Ne las was attached to the coupler for the light source. The film to be measured was brought into conta with the prism base by a coupling head. Laser beam strikes the prism base and reflected onto photodetector. The angle of incidence, Θ, of the laser beam can be varied by means of a rotary tab upon which the prism, film, coupling head and photodetector are mounted.

At certain values of Θ, called mode angles, photons violate the total internal reflectio criterion and tunnel from the prism base into the film and enter into optical propagation mode causing a sharp drop in the intensity of light striking the photodetector. For a given substrate typ the angular location of the modes depends only on the film thickness and refractive index. Thus, soon as two mode angles are measured, the film thickness and index can be calculated by a appropriate computer algorithm. If one mode is found, only one parameter (thickness or index) ca be calculated and the other parameter must be provided (Nishihara *et. al.*, 1989).

RESULTS AND DISCUSSION

In order to study the propagation modes of ZnS thin films for different thicknesses, ZnS films were deposited for two different nominal thicknesses, 150 nm and 800 nm. The nominal thicknesses were actually the thicknesses that were recorded by the quartz oscillator. For each nominal thickness, both silicon wafer and glass slide substrates were placed side by side on the holder. This simultaneous deposition was important to make sure the same deposition conditions applied for both substrates and direct comparison could be done.

The samples were then measured with the Prism Coupler for modal analysis. All measurements were carried out using He-Ne laser with the emission of 633 nm wavelength. For the purpose of this study, only TE mode was taken into considerations. Figure 1 shows the results of the TE modes of 150 nm thick ZnS planar waveguides on silica and Si wafer. Figure 2 shows the results of the TE modes of 800 nm thick ZnS planar waveguides.

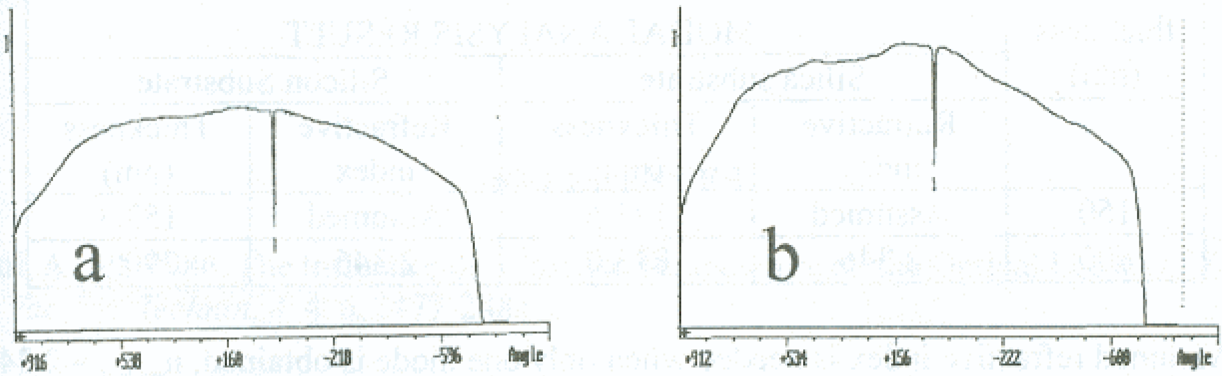

Figure 1. TE mode for 150 nm ZnS films. (a) on silica slide (b) on Si wafer.

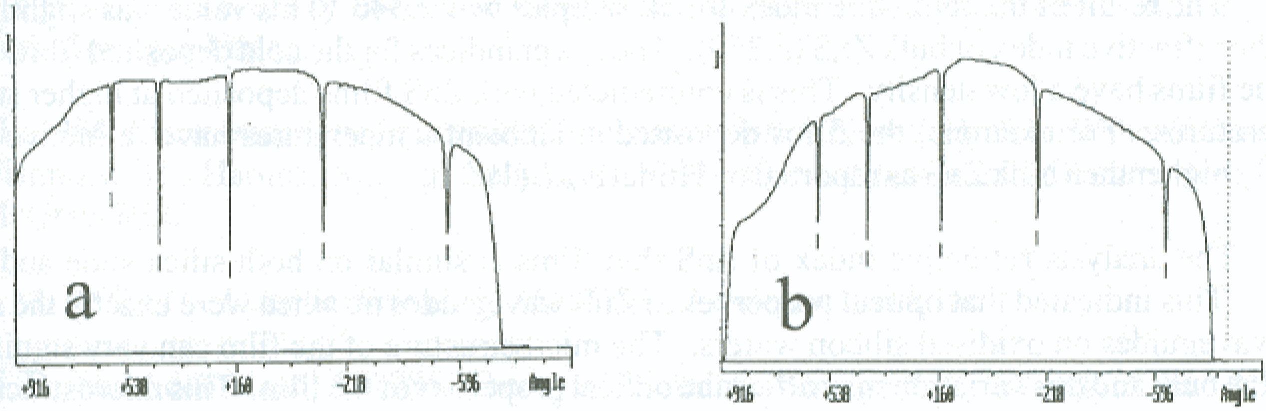

Figure 2. TE modes for 800 nm ZnS films. (a) on silica slide (b) on Si wafer.

Only one propagation mode was observed for the 150 nm thick ZnS films on both silica glas and Si wafers, whereas five modes were observed for the 800 nm thick films for both substrate The numbers of propagation modes were consistent for both types of substrates. It was ver obvious that the thicker waveguide could support more modes compared to the thinner waveguide For a given film refractive index, the number of guided modes the waveguide will support i dependent upon the film thickness. (Kogelnik, 1979).

In order to understand more about the physical aspects of the waveguides, the modal analysi was done. Modal analysis was actually the computerised calculation of the thicknesses and th refractive index from the results of propagation mode measurement (Hall, 1987). The results of th modal analysis are tabulated in Table 1.

Table 1. The modal analysis results.

Nominal thickness (nm)	MODAL ANALYSIS RESULT			
	Silica substrate		Silicon Substrate	
	Refractive index	Thickness (nm)	Refractive index	Thickness (nm)
150	Assumed	141.6	Assumed	153.3
800	2.346	813.0	2.346	790.9

*Assumed refractive index is needed when only one mode is obtained, $n_{assumed} = 2.346$

The analysis thicknesses are varied from the nominal thicknesses in average is about 5 % This small difference is may be due to the non-uniformity of the films. Therefore, the depositior system is capable of producing ZnS thin films with a good control of thickness.

The result of the refractive index for all samples was 2.346. This value was slightly lowe then the refractive index of bulk ZnS (2.350). The lower indices for the cold deposited films sugges that the films have a low density. This is contradicted with ZnS films deposited at higher substrate temperatures. For example, the films deposited at ambient temperatures have refractive indice slightly higher then bulk ZnS as reported by Himel *et al.* (1988).

The analysis refractive index of ZnS thin films is similar on both silica slide and silicon wafer. This indicated that optical properties of ZnS waveguides on silica were exactly the same as ZnS waveguides on oxidised silicon wafers. The microstructure of the film can vary significantly from the bulk and this variation may affect the optical properties of the film. This microstructure can be directly related to the deposition conditions especially the substrate temperature (Zhao-Hong, *et al.*, 1998).

CONCLUSION

ZnS waveguides on silica glass slides and oxidised silicon substrates were fabricated with cold evaporation. The substrate temperature of 50°C was attained by thermoelectric cooler accompanied with the chilled (5°C) water flow. We have shown that cold evaporation using TEC is possible in producing ZnS waveguides. For the propagation mode, only one mode is observed for 150 nm thick waveguide and five modes for the 800 nm thick waveguide. The refractive index of cold evaporated ZnS waveguides was slightly lower than bulk ZnS.

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