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MODES OF PROPAGATING LIGHT WAVES IN THIN DEPOSITED SEMICONDUCTOR FILMS

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We report theory and experiment on modes of propagating light waves in deposited semiconductor films. The modes are excited by a novel prism-film coupler which is also used for the measurement of their phase velocities. Up to 50% of the incident laser energy has been fed into a single mode of propagation. The positions and linewidths of the modes, the wave intensity inside the film, and a dramatic view of the mode spectrum displayed by the scattered light are discussed in detail.

Guidance of light waves in semiconductor films may lead to numerous new applications in the laser and electro-optical field. In particular, one might explore nonlinear optics of guided waves which offer new possibilities of phase-matching at high concentrations of light energy. In many of these applications a distance of propagation of the order of 1 cm would be sufficient. Such a length does not require materials of excessively high optical quality, and standard techniques of film deposition can be employed. In our experiments, we used sputtered films of ZnO and films of ZnS evaporated by electron bombardment. The films used range from 800 to 30 000 Å thick. We report here: (1) the use of a novel prism-film coupler for exciting in those films any selected mode of propagating light wave, (2) a method of probing the modes by measuring their phase velocities, (3) a dramatic view of the mode spectrum of a multimode film as a series of bright lines displayed by the scattered light.

In earlier experiments,[1-4] light guidance was studied in *pn* junctions when the light was focussed onto the edge of the junction. These experiments were usually handicapped by simultaneous excitation of many modes and by excessive scattering at the edge of the junction. We have avoided these difficulties by the use of the prism-film coupler shown in Fig. 1. A laser beam enters a prism of sufficiently high refractive index n_3. It reaches the base of the prism at an angle of incidence θ_3 and is totally reflected. The film is placed at a close distance S parallel to the prism base. Normally, the incident power is totally reflected. Under certain conditions, however, the light energy can be transferred into the film by "optical tunneling." This coupling is effected by the evanescent fields that are excited in the gap S by the total reflection. The

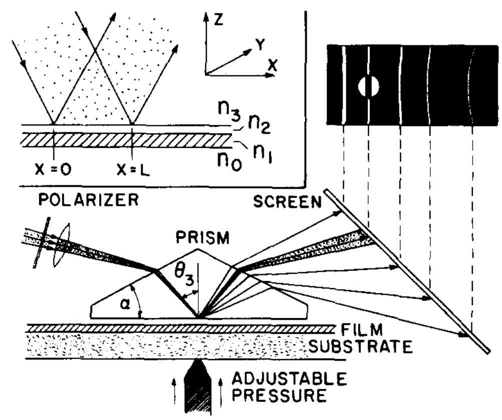

Fig. 1. Experimental arrangement for observation of coupling and intermode scattering. This setup was also used for the determination of the propagation constants β.

conditions for coupling are (1) the incident beam must have the proper angle of incidence so that the evanescent fields in the gap S travel with the same phase velocity as the mode to be excited in the film. This direction θ_3 will be called a synchronous direction. (2) As the modes of the film have a distinct polarization (TM or TE) the incident beam must have the same polarization as the mode to be excited. (3) The film must be placed close enough to the prism base. Typically, S is in the order of half a wavelength.

In order to state the condition (1) more precisely, let the propagation constant of the mode under consideration be β. For the incident beam the component of the propagation vector parallel to the film is $kn_3 \sin \theta_3$, where $k = \omega/c$, and ω and c are, respectively, the angular frequency and the velocity of light in vacuum. Then a direction θ_3 is a synchronous one if $\beta = kn_3 \sin\theta_3$. Since different modes in the film generally have different β's, we can thus selectively excite any one of them by adjusting θ_3. Alternatively, the propagation constant β or the phase velocity ω/β of a mode can be determined by measuring the synchronous direction of θ_3 of that mode.

Theory. For simplicity, we will neglect losses in the various media, restrict ourselves to a one-dimensional analysis in which all quantities are independent of y, and assume an arrangement infinitely extended in x and y directions. For TM modes the nonvanishing field components are E_x, E_z, H_y. The film thickness is W. Let us use the subscripts 0, 1, 2, 3 to denote quantities in the substrate, film, gap and prism, respectively. In order to support propagating modes, the film refractive index n_1 must be $n_1 > n_0$ and $n_1 > n_2$. For the prism $n_3 > \beta/k$ is required. We have one set of waves in each of the four media. The waves in the prism and in the film are ordinary plane waves. Let the incident and reflected waves in the prism have amplitudes A_3 and B_3. They vary as $\exp(-ib_3z)$ and $\exp(ib_3z)$, respectively, and their wave vectors form the angles $\pi - \theta_3$ and θ_3 with the z axis. Similarly, the waves A_1, B_1 in the film vary as $\exp(\pm ib_1z)$ and travel at angles $\pi - \theta_1$ and θ_1. In the coupling gap S and in the substrate, the fields are evanescent waves. These vary as $\exp(\pm p_2z)$ and $\exp(p_0z)$, respectively. Here all b's and p's are real positive quantities. We do not lose the generality of the problem, if we let all waves vary as $\exp(i\beta x - i\omega t)$ and allow the amplitudes to be complex functions of x. As the waves described must satisfy the wave equations we have for $i = 1$ or 3 and $j = 0$ or 2

$$\beta^2 = (kn_i)^2 - b_i^2 = (kn_j)^2 + p_j^2 \quad , \quad \beta = kn_1 \sin\theta_i \ . \tag{1}$$

To facilitate our later discussion, we introduce the following angles ψ_{ij} (half the reflection phase at the interface between the media i and j) and the quantities ψ_{12}' and t_1^2:

$$\tan\psi_{ij} = (n_i/n_j)^2 p_j/b_i \quad \text{for TM modes} \ , \tag{2a}$$

$$\tan\psi_{ij} = p_j/b_i \quad \text{for TE modes} \ , \tag{2b}$$

$$\psi_{12}' = \psi_{12} + \sin 2\psi_{12} \cos 2\psi_{32} \exp(-2p_2S) \ , \tag{3}$$

$$t_1^2 = 4 \sin 2\psi_{12} \sin 2\psi_{32} \exp(-2p_2S) \ . \tag{4}$$

By matching the wave amplitudes at the boundaries between the media, the intensity of the waves inside the film is obtained. This intensity exhibits sharp maxima at a finite number of discrete values of β's. These maxima represent the modes of propagation of light in the film when the prism is present. The propagation constants β of the modes are the solutions of

$$2b_1(\beta)W - 2\psi_{12}'(\beta) - 2\psi_{10}(\beta) = 2m\pi \ , \tag{5}$$

where the ψ_{ij} satisfies (2) and $0 \le \psi_{ij} \le \pi/2$. The integer $m = 0, 1, 2, 3, \ldots$ is called the order of the mode. For weak coupling ($p_2S > 1$), ψ_{12}' is given by (3). From (3) and (5), the positions of the modes in β are seen to vary slightly with the coupling. For a given thickness W there exists a finite number of discrete β's, their number increasing with W. From the symmetry of the problem it follows that to each mode or order m there exists an infinite number of degenerate modes, whose propagation vectors all lie in the xy plane. To evaluate the linewidths of the modes, we replace $2m\pi$ in (5) by δ. We find the half intensity points at $\delta = 2m\pi \pm t_1^2$, and the linewidth $2t_1^2$. The finesse[5] is then π/t_1^2 in the δ scale. As $S \to \infty$, $\psi_{12}' \to \psi_{12}$ and (5) is reduced to the usual equation of modes for the film alone.[4] The linewidths in this case vanish since losses have been neglected.

Next we show how the light intensity in the film builds up in the direction of propagation due to its coupling to the input laser beam. Let this beam be incident in a synchronous direction and illuminate the prism base uniformly between the limits $x = 0$ and $x = L$ (Fig. 1). The amplitudes of the various waves are normalized so that $|A|^2$ is the power flow through a unit area parallel to the xy plane. We now ask for the x dependence of the intensities of the A_1 and B_1 waves constituting the field in the film. For $0 < x < L$ we find

$$|A_1(x)|^2 = |B_1(x)|^2 = 4t_1^{-2}|A_3|^2\{1 - \exp[-xt_1^2/(4W\tan\theta_1)]\}^2 \tag{6}$$

and for $x > L$

$$|A_1(x)|^2 = |B_1(x)|^2 = |A_1(L)|^2 \exp[-(x-L)t_1^2/(2W\tan\theta_1)] \ , \tag{7}$$

where for weak coupling, t_1^2 is given by (4). The power density (6) inside the film builds up gradually from $x = 0$ and then approaches an asymptotic value $4t_1^{-2}|A_3|^2$. A typical value of t_1 being 0.1, the power density inside the film can theoretically be several orders of magnitude higher than that of the incident beam, a feature important to nonlinear optics. The total power carried by the film is $2W|A_1(x)|^2 \tan\theta_1$. Thus it follows from (6) that by proper choice of S or L a maximum of about 81% of the incident power can be transferred into a film under the prescribed uniform illumination. For $x > L$, the light intensity (7) in the film decreases exponentially since here the prism serves as an output coupler. In order to retain the power $|A_1(L)|^2$ inside the film beyond $x = L$, it is therefore necessary to decouple film and prism in the region $x > L$. This can be done by increasing there the gap S or by cutting away the prism beyond $x = L$, as will be discussed later in the experiment.

Experiment. Both ZnO and ZnS films, deposited on glass, have been used for the experiments. The

ZnO films were sputtered in an argon–oxygen atmosphere from sintered ZnO powder. The c axes of the crystallites in the film are oriented within a cone of 5° from the film normal. These films were polished after growth to reduce their surface roughness. The ZnS films, evaporated by electron bombardment, are not oriented. The coupling prism was of rutile, $\alpha = 26°$, optical axis parallel to the y axis of Fig. 1. Thus, light coupling to TM modes of the film propagates as ordinary ray in the prism, and that coupling to TE modes as extradordinary ray. The film is pressed with adjustable pressure against the prism base (Fig. 1). Residual dust particles, serving as spacers, and the elasticity of the substrate permit adjustment of S by variation of the pressure. The linear polarized laser beam is directed on the coupling spot at the prism base. As shown in Fig. 1, the reflected light is observed on a screen. The whole prism-film assembly, including the screen but not the laser, is mounted on a turntable so that the direction θ_3 can be varied at will.

In the experiment, a bright spot produced by the reflected wave B_3 is always observed on the screen. When the film is turned into any one of the synchronous directions, three phenomena can be observed: first, a reduction in the intensity of the bright spot. This dip, occasionally down to 50%, means that part of the incident light has been fed into the film and was then lost by absorption or scattering before it could be coupled back into the prism again. Thus, the dip indicates that a mode was launched into the film. Second, a small area of the film near the coupling spot appears very bright. Third, we observe one or more (depending on the film thickness) bright lines on the screen (Fig. 1). One of these lines always intersects the bright B_3 spot. These lines will be called m lines because they display the modes of different orders m, as will be explained later. With increasing coupling the lines become brighter first, and then become broader and shift. All these phenomena disappear if any of the three coupling conditions mentioned in the beginning is violated. These observations are explained as follows: The laser beam, incident in the xy plane at a synchronous angle, excites in the film a mode of order m. This mode propagates in the positive x direction. By scattering, one part of its light is directed into the substrate and causes the observed bright appearance of the film in the coupling area. Another part of the light of the main mode is scattered into other modes that can propagate in the film. Two cases are to be distinguished here. First, scattering into those modes that are azimuthally degenerate with the main mode of excitation. The light of these modes, being coupled out of the film by the very same prism, produces the m line that intersects the bright B_3 spot. Second, intermode scattering into modes of order numbers m different from that of the main mode, including their degenerates. When coupled out on the screen, the light of these modes produces the other m lines. The m lines are therefore a direct display of the spectrum of the film modes.

Table I. Comparison between observed and theoretically expected propagation constants of a ZnO film. Film thickness $W = 15\ 881 \pm 60$ Å, refractive index of glass substrate $n_0 = 1.5127$ at 6328 Å and $n_0 = 1.5206$ at 4880 Å.

λ	Polaris	n_1	m	β/k Observed	β/k Theory	β/k Diff.
6328 Å	TE	1.9732	0	a	1.9647	a
			1	1.9383	1.9389	−0.0006
			2	1.8961	1.8954	0.0007
			3	1.8329	1.8332	−0.0003
			4	1.7518	1.7510	0.0008
			5	1.6469	1.6473	−0.0004
			6	1.5248	1.5249	−0.0001
	TM	1.9779	0	a	1.9686	a
			1	a	1.9404	a
			2	1.8933	1.8929	0.0004
			3	1.8251	1.8249	0.0002
			4	1.7353	1.7355	−0.0002
			5	1.6242	1.6246	−0.0004
4880 Å	TE	2.0428	0	2.0360	2.0377	−0.0017
			1	2.0215	2.0223	−0.0008
			2	1.9973	1.9964	0.0009
			3	1.9603	1.9596	0.0007
			4	1.9117	1.9115	0.0002
			5	1.8511	1.8513	−0.0002
			6	1.7786	1.7781	0.0005
			7	1.6907	1.6910	−0.0003
			8	1.5898	1.5892	0.0006
	TM	2.0485	0	a	2.0430	a
			1	a	2.0265	a
			2	a	1.9987	a
			3	1.9598	1.9593	0.0005
			4	1.9089	1.9078	0.0011
			5	1.8432	1.8433	−0.0001
			6	1.7649	1.7652	−0.0003
			7	1.6727	1.6729	−0.0002
			8	1.5677	1.5687	−0.0010

[a]These modes could not be observed with the 26° rutile prism.

An interesting detail of Fig. 1 is the dark line visible in the bright B_3 spot. The diameter of this spot corresponds to the aperture of the incident beam which is about 1° (inside the prism) in this case. At the chosen coupling, however, the linewidth of the mode is so narrow, that only a small fraction of this θ_3 range is acceptable to the film. The ratio of the separation between adjacent m lines to the width of the dark line is roughly equal to the finesse F discussed in the theory. In one case, we have approximately $F = 50$, indicating $t_1^2 = 0.06$.

At weak coupling the synchronous directions become very sharply defined. Then the synchronous angles θ_3 and thus the β's can be determined quite accurately from a measurement of these directions. The refraction of the incident beam at the first prism face must be taken into account. Table I shows the results of such measurements on a ZnO film. Also given are the theoretical β's computed from (5), the lineshifts caused by the difference

Fig. 2. The path of a light wave propagating in a ZnS film is visible as a bright streak. Film thickness 1500 Å, wavelength 6328 Å, height of the prism 0.5 cm, viewed through the substrate.

between ψ_{12}' and ψ_{12} being neglected. In arriving at these theoretical β's both the film thickness W and its refractive index n_1 were treated as free parameters. They were adjusted for best agreement between the observed and computed β's of the 6 lowest TE modes at 6328 Å. The thickness thus determined, $W = 15881 \pm 60$ Å was subsequently used for the computation of all theoretical β's, while the refractive index n_1 was fitted separately for each group. It is seen that good agreement is obtained between the theoretical and measured β's. Because of the crystalline orientation of the ZnO film the TE modes propagate as ordinary ray in the ZnO. The value $n_1 = 1.973 \pm 0.001$ at 6328 Å determined by the present experiment is only slightly less than the value of 1.988 interpolated from Bond's measurement[6] of bulk ZnO. The agreement is equally good for the other groups of Table I. This supports electrical and x-ray measurements in indicating the good crystalline perfection of our ZnO films.

In another experiment we show that a mode, once it is launched into the film, will propagate freely provided that coupling back into the prism is prevented. For this purpose we cut the prism of Fig. 1 along its plane of symmetry and removed the right half-prism. The laser beam is adjusted so that the 90° corner plays the role of the point $x = L$ discussed in the theory. Figure 2 is a photograph of the arrangement. The film (ZnS, 1500 Å thick) is pressed against the prism base by a pointed tool. The laser beam, not visible in this photograph, enters the prism through the hypotenuse face from the upper left. It is set to the synchronous direction of this single-mode film and a bright streak of light is seen extending from the coupling spot toward the lower right. The streak is about 1 cm long and consists of light scattered from the propagating mode, much like a laser beam is visible in dusty air. When the continuity of the film is interrupted by scratching across the streak with a fine point, the streak ends sharply at the scratch and the scratch itself radiates brightly. We have also used two such 90° prisms, one as an input coupler and the other for output, 3 mm apart. In addition to the desired bright spot of directly transmitted light, again an m line is observed on the output screen. Details of the theory and experiments will be described elsewhere.

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