Optical interference method for the approximate determination of refractive index and thickness of a transparent layer

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Optical interference fringe measurements of the thickness of transparent layers can be rapid, accurate, and nondestructive. If the refractive index n of the layer being measured is known, it may be combined directly with interference fringe information to yield the layer thickness t. If, however, n is unknown, the measurement procedure necessarily becomes more complicated. In this paper, a new and simpler optical interference method is presented for the approximate determination of both n and t of a transparent layer on a transparent substrate. The required experimental information is obtained from a single spectrophotometric recording of either the reflectance or transmittance of the layer and its substrate. The theory of the method is presented, and an application of the method to measurements of layers of SIPOS (Semi-Insulating POlycrystalline Silicon) is described. The method requires that the layer being measured must be uniformly deposited on a flat substrate, and it must neither absorb nor scatter the light passing through it. The major approximation inherent in the method is that both the layer and the substrate are assumed to be nondispersive over the wavelength region of interest.

I. Introduction

Optical interference fringe measurements of the thickness of transparent layers can be rapid, accurate, and nondestructive.[1,2] The experimentally measured quantity is usually the optical reflectance or transmittance of the layer and its substrate as a function of either (1) the angle of incidence at fixed (monochromatic) wavelength[3,4] or (2) the wavelength at a fixed angle of incidence.[5–24] Technique (1) is known by the acronym VAMFO (Variable Angle Monochromatic Fringe Observation).[4] Technique (2) is often referred to as CARIS (Constant Angle Reflection Interference Spectroscopy) when the measured quantity is reflected light. A logical extension of this acronym is to use the term CATIS (Constant Angle Transmission Interference Spectroscopy) when the measured quantity is transmitted light.

In the most common mode of usage, the interference fringe information (maxima and/or minima) obtained from CARIS, CATIS, or VAMFO is combined with a prior knowledge or a previous measurement of the refractive index of the layer in question to determine its thickness.[3,5,6,8,10,11,13–15,17,22,23]

If, however, the refractive index of the layer material is unknown, the required measurement procedure becomes more complicated. For example, both the index and the thickness may be determined from CARIS or CATIS at two angles of incidence[6,7,11,12,18,20,21,24] or from VAMFO at two or more wavelengths.[6,18,20,24] A variety of other combinations of measurement techniques is also possible, and a discussion of these is given in Ref. 2.

In the present work, the object was to develop an extremely simple technique for determining both the refractive index and the thickness of a transparent layer on a transparent substrate in a production environment. The various combinations of techniques for determining both index and thickness were considered but were discarded in favor of a simpler, albeit approximate, technique in which both index and thickness can be determined from a single spectrophotometric recording of either the reflectance or transmittance of the layer and its substrate. In Sec. II, the theory of this technique is presented for both experimental arrangements: measurement of reflectance in Sec. II. A and measurement of transmittance in Sec. II. B. The results of experiments using both arrangements are presented in Sec. III and compared with independent measurements. A summary is presented in Sec. IV.

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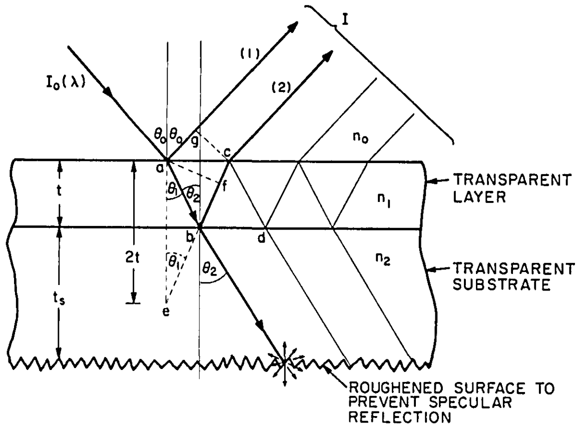

Fig. 1. Sample arrangement for reflectance measurement.

II. Theory

A. Reflectance Measurement

Consider the experimental arrangement shown in Fig. 1. The layer to be characterized is flat and of uniform thickness t and refractive index n. The substrate thickness t_s is much greater than t, and the substrate refractive index n_2 may be either greater or less than n_1. Both the layer and the substrate are assumed transparent. The incoming beam is incident upon the sample at an angle θ_0; Fig. 1 illustrates the behavior of a single ray of this beam whose intensity (power per unit area) is I_0 and whose wavelength is λ. At point a the incident ray is partly reflected (1) at angle θ_0 and partly transmitted at an angle θ_1. The transmitted portion upon arrival at b is again partly reflected (toward c) and partly transmitted (at an angle θ_2). This latter transmitted portion is diffusely scattered at the roughened back surface of the substrate and need no longer be considered in the analysis. The angles θ_0, θ_1, and θ_2 are related by Snell's law: $n_0 \sin\theta_0 = n_1 \sin\theta_1 = n_2 \sin\theta_2$. The reflected portion reaches c and is again partly reflected (toward d) and partly transmitted (2) in the same direction as the original reflected ray (1). However, the optical pathlength of ray (2) is longer than that of ray (1) by[25]

$$\Delta = n_1(\overline{abc}) - n_0(\overline{ag}) = n_1(\overline{abf}),$$
$$\Delta = 2n_1 t \cos\theta_1. \tag{1}$$

If this analysis process is continued, and all the components of the reflected beam I are considered, it can be shown that the reflectance R is given by[1]

$$R = \frac{I}{I_0} = \frac{r_1^2 + 2r_1r_2\cos 2\delta + r_2^2}{1 + 2r_1r_2\cos 2\delta + r_1^2r_2^2}, \tag{2}$$

where

$$\delta = (\Delta/\lambda)\pi = (2n_1 t\pi \cos\theta_1)/\lambda, \tag{3}$$

and the r's are Fresnel coefficients which depend upon the polarization of the incident light. If the polarization is in the plane of incidence,

$$r_1 = r_{1p} = \frac{\tan(\theta_1 - \theta_0)}{\tan(\theta_1 + \theta_0)}, \tag{4}$$

$$r_2 = r_{2p} = \frac{\tan(\theta_2 - \theta_1)}{\tan(\theta_2 + \theta_1)}. \tag{5}$$

If the polarization is normal to the plane of incidence,

$$r_1 = r_{1s} = \frac{\sin(\theta_1 - \theta_0)}{\sin(\theta_1 + \theta_0)} \tag{6}$$

$$r_2 = r_{2s} = \frac{\sin(\theta_2 - \theta_1)}{\sin(\theta_2 + \theta_1)}. \tag{7}$$

If I_0 contains both polarizations, it must be resolved into its s (normal) and p (in-plane) components which we may designate I_{0s} and I_{0p}, respectively. Similarly I will consist of two components I_s and I_p. The component reflectances are

$$R_s = I_s/I_{0s} = R\Big|_{\substack{r_1=r_{1s}\\ r_2=r_{2s}}}, \tag{8}$$

$$R_p = I_p/I_{0p} = R\Big|_{\substack{r_1=r_{1p}\\ r_2=r_{2p}}}. \tag{9}$$

It is recognized that as λ is varied, δ will vary [Eq. (3)] causing cyclic variations in R [Eq. (2)] due to constructive and destructive interference of the rays that are superimposed to form the reflected beam. Examination of Eqs. (2) and (3) for the conditions under which maxima and minima occur produces the following results, which are equally applicable to either polarization.

(1) Negative r_1 and r_2, i.e., $n_0 < n_1 < n_2$. In this case, each ray undergoes a phase change of π upon reflection at each interface. It follows that maxima in R occur when

$$M\lambda = 2n_1 t \cos\theta_1 = 2t(n_1^2 - \sin^2\theta_0)^{1/2}, \tag{10}$$

where M is an integer, and the maximum value of R is

$$R^{\mathrm{MAX}} = \frac{r_1^2 + 2r_1r_2 + r_2^2}{1 + 2r_1r_2 + r_1^2r_2^2} = \frac{(r_1 + r_2)^2}{(1 + r_1r_2)^2}. \tag{11}$$

Minima in R occur when

$$(M + 1/2)\lambda = 2n_1 t \cos\theta_1 = 2t(n_1^2 - \sin^2\theta_0)^{1/2}, \tag{12}$$

and the minimum value of R is

$$R^{\mathrm{MIN}} = \frac{r_1^2 - 2r_1r_2 + r_2^2}{1 - 2r_1r_2 + r_1^2r_2^2} = \frac{(r_1 - r_2)^2}{(1 - r_1r_2)^2}. \tag{13}$$

(2) Negative r_1 and positive r_2, i.e., $n_0 < n_1$ and $n_2 < n_1$. In this case each ray undergoes a phase change of π only upon reflection at the $n_0 - n_1$ interface. Minima in R occur for the condition defined by Eq. (10), and maxima occur for the condition defined by Eq. (12). The values of R^{MAX} and R^{MIN} are given by Eqs. (11) and (13).

In the general case R^{MAX} and R^{MIN} are functions of wavelength because of the variation with wavelength of n_1 and n_2. If n_2 is known, n_1 may be determined from an absolute measurement of either R^{MAX} or R^{MIN}. Accurate absolute reflectance measurements require considerable experimental finesse. Relative reflectance measurements, however, are quite straightforward. We note that the ratio of R^{MAX} to R^{MIN} can be written as

$$\rho_R = \left[\frac{(r_1 \pm r_2)^2}{(1 \pm r_1 r_2)^2}\right]_{\lambda=\lambda^{MAX}} \times \left[\frac{(1 \mp r_1 r_2)^2}{(r_1 \mp r_2)^2}\right]_{\lambda=\lambda^{MIN}}, \quad (14)$$

where the upper algebraic sign is appropriate when $n_0 < n_1 < n_2$, and the lower algebraic sign is appropriate when $n_0 < n_1$, $n_2 < n_1$. If the variations of n_1 and n_2 are sufficiently small in the wavelength region of interest, r_1 and r_2 may be assumed independent of wavelength; this gives the approximation

$$\rho_R \cong \frac{(r_1 \pm r_2)^2(1 \mp r_1 r_2)^2}{(r_1 \mp r_2)^2(1 \pm r_1 r_2)^2}. \quad (15)$$

The value of n_1 can then be determined from a measurement of ρ_R by solving Eqs. (15) and (4)–(7) either graphically or by an iterative approximation method. Examples of graphical solution are presented in Sec. III.

The film thickness may then be determined from the position of an extremum and Eq. (10) or Eq. (12). It is usually more convenient to use two extrema and the Eqs. (10) and (12) in the form

$$t = \frac{M_{ab}\lambda_a\lambda_b}{2(\lambda_a - \lambda_b)(n_1^2 - \sin^2\theta_0)^{1/2}}, \quad (16)$$

where λ_a and λ_b are the wavelengths of two extrema (minima or maxima) and M_{ab} the number of fringes separating these extrema. For example, if two adjacent maxima (or two adjacent minima) are chosen, $M_{ab} = 1$. If one minimum and an adjacent maximum are chosen, $M_{ab} = 1/2$. If λ_a and λ_b correspond to a maximum and a minimum separated by an intervening maximum and minimum, $M_{ab} = 3/2$.

B. Transmittance Measurements

Consider the experimental arrangement shown in Fig. 2(a). The layer to be characterized is flat and of refractive index n_1. The monochromatic incoming beam with intensity $I_0(\lambda)$ impinges upon the sample surface at normal incidence. Both the layer and the substrate are transparent in the wavelength region of interest. It is assumed that:

(1) The thickness of the layer to be characterized t_1 is sufficiently small and uniform that phase coherence is maintained by the multiply reflected and multiply transmitted light elements transversing the layer and that this results in constructive and destructive interference depending upon the wavelength of the incident light.

(2) The substrate thickness t_2 is sufficiently large and/or nonuniform that light transversing it loses phase coherence and may be treated in the limit of geometrical optics.

In order to determine the optical transmittance of the sample, it is convenient to treat the problem as if it were composed of two interfaces: (1) a fictitious interface (first interface) equivalent to the air–layer–substrate sandwich having transmittance T_1 which must be determined using physical optics and (2) the substrate-air interface (second interface) which has a transmittance T_2. The over-all transmittance T can then be obtained from T_1 and T_2. This equivalent structure is shown in Fig. 2(b).

The transmittance T_1 is [from Eq. 4(55) of Ref. 1]

$$T_1 = \frac{8n_0 n_1^2 n_2}{(n_0^2 + n_1^2)(n_1^2 + n_2^2) + 4n_0 n_1^2 n_2 + (n_0^2 - n_1^2)(n_1^2 - n_2^2)\cos\left(\frac{2\pi n_1 t_1}{\lambda}\right)}. \quad (17)$$

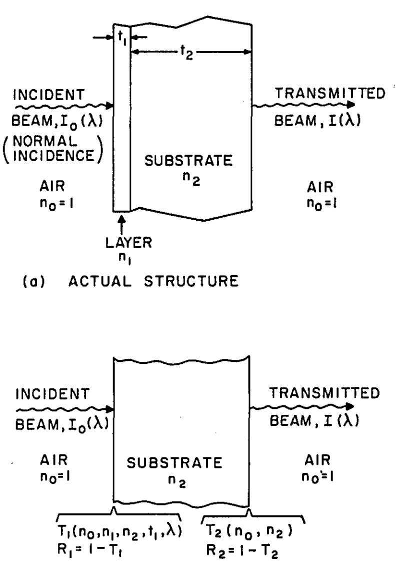

Fig. 2. Sample arrangement for transmittance measurement: (a) actual structure; (b) equivalent structure.

The transmittance T_2 is [from Eq. 4(28) of Ref. 1]

$$T_2 = \frac{4n_0 n_2}{(n_0 + n_2)^2}. \quad (18)$$

The corresponding reflectances at these interfaces are $R_1 = 1 - T_1$ and $R_2 = 1 - T_2$.

At the first interface, part of I_0 is transmitted (I_0T_1), and part is reflected. The transmitted portion continues to propagate to the second interface where part ($I_0T_1T_2$) is transmitted, and part ($I_0T_1R_2$) is reflected. When it reaches the first interface, part ($I_0T_1R_2R_1$) is reflected, and part is transmitted. If this process is continued, it will be seen that the transmitted light intensity I can be written as

$$I = I_0[T_1T_2 + T_1T_2R_1R_2 + T_1T_2(R_1R_2)^2 + \ldots]. \quad (19)$$

The series may be factored and summed to give

$$I = I_0[(T_1T_2)/(1 - R_1R_2)]. \quad (20)$$

It follows that

$$T = I/I_0 = T_1T_2[1/(T_1 + T_2 - T_1T_2)] \quad (21)$$

It can be seen from Eq. (17) that T_1 and therefore T

will exhibit periodic maxima and minima as a function of the wavelength λ. Examination of Eqs. (17), (18), and (21) for the conditions under which maxima and minima in T occur produces the following results:

(1) When $n_0 < n_1 < n_2$,

$$T^{MAX} = \frac{4n_0 n_1^2 n_2}{(n_0^2 + n_1^2)(n_1^2 + n_2^2)}, \tag{22}$$

$$T^{MIN} = \frac{2n_0 n_2}{n_0^2 + n_2^2}, \tag{23}$$

and the ratio of T^{MAX} to T^{MIN} can be written as

$$\rho_{T1} = \frac{T^{MAX}}{T^{MIN}} = \left[\frac{4n_0 n_1^2 n_2}{(n_1^2 + n_0^2)(n_1^2 + n_2^2)}\right]_{\lambda=\lambda^{MAX}} \times \left(\frac{n_0^2 + n_2^2}{2n_0 n_2}\right)_{\lambda=\lambda^{MIN}}. \tag{24}$$

If the variation of n_1 and n_2 is sufficiently small in the wavelength region of interest that they may be considered constant, ρ_{T1} takes the approximate form

$$\rho_{T1} \cong \left[\frac{2n_1^2(n_0^2 + n_2^2)}{(n_1^2 + n_0^2)(n_1^2 + n_2^2)}\right], \tag{25}$$

Eq. (25) may be solved explicitly for n_1; this gives

$$n_1 = \left\{\frac{-(n_0^2 + n_2^2)\left(1 - \frac{2}{\rho_{T1}}\right) + \left[(n_0^2 + n_2^2)^2\left(1 - \frac{2}{\rho_{T1}}\right)^2 - 4n_0^2 n_2^2\right]^{1/2}}{2}\right\}^{1/2}. \tag{26}$$

Evidently, for our previous assumptions to be valid $1 < \rho_T < 2$. The value of n_1 can then be determined from a measurement of ρ_{T1} by using Eq. (26) or a graphical solution of Eq. (25).

(2) When $n_0 < n_1$ and $n_2 < n_1$, the expressions for T^{MAX} and T^{MIN} [Eqs. (22) and (23)] must be interchanged, and the ratio of T^{MAX} to T^{MIN} is

$$\rho_{T2} = \frac{T^{MAX}}{T^{MIN}} = \left(\frac{2n_0 n_2}{n_0^2 + n_2^2}\right)_{\lambda=\lambda^{MAX}} \times \left[\frac{(n_1^2 + n_0^2)(n_1^2 + n_2^2)}{4n_0 n_1{}^2 n_2}\right]_{\lambda=\lambda^{MIN}},$$

and the approximate form in the case of negligible dispersion is

$$\rho_{T2} \cong \left[\frac{(n_1^2 + n_0^2)(n_1^2 + n_2^2)}{2n_1^2(n_0^2 + n_2^2)}\right]. \tag{28}$$

Equation (28) may be solved explictly for n_1 with the result

$$n_1 = \left\{\frac{-(n_0^2 + n_2^2)(1 - 2\rho_{T2}) + [(n_0^2 + n_2^2)^2(1 - 2\rho_{T2})^2 - 4n_0^2 n_2^2]^{1/2}}{2}\right\}^{1/2}. \tag{29}$$

Here, ρ_{T2} may have any positive value greater than 1. The value of n_1 can then be determined from a measurement of ρ_{T2} by using Eq. (29) or a graphical solution of Eq. (28).

The film thickness may then be determined from the position of an extremum and either Eq. (10) or (12) bearing in mind that a transmission maximum corresponds to a reflectance minimum and vice versa It is usually more convenient, however, to use two extrema and Eq. (16) as described previously for the reflectance measurements.

III. Application and Experimental Results

A. Experimental Details

The method, for which the theory has been described in Sec. II, was used to characterize layers of oxygen-doped polycrystalline Si. This material commonly known by the acronym SIPOS (Semi-Insulating POlycrystalline Silicon)[26–28] was prepared by chemical vapor deposition (CVD) in both atmospheric pressure (AP) and low pressure (LP) reactors. The CVD was carried out at ~665°C using SiH_4 and N_2O as the reactants (in a carrier gas of N_2 for the AP depositions). The oxygen content of the deposited layer is known to be a function of γ, the volumetric ratio of N_2O to SiH_4 in the gas stream.[27] Three types of substrate material were used for the layers intended for optical measurements: (1) clear sapphire; (2) Si; and (3) SiO_2 (clear fused quartz). The Si was, for the most part, oxygen-free floating-zone-refined material with resistivity greater than 50 Ω-cm, and the wafer thickness was greater than 635 μm. Some of the silicon substrates used for reflectance measurements were of heavily doped material ($\rho \sim 10^{-3}$ Ω-cm); the effect of this will be discussed. For transmittance measurements, the substrates were optically polished on both sides; for reflectance measurements, the layer side was polished, and the opposite side was rough. The sapphire rough side was a lapped finish, while the rough sides of the Si and SiO_2 substrates were produced by sandblasting.

The measurements were carried out using a Cary model 14 spectrophotometer in the 1–2.5-μm spectral range. Transmittance measurements were made at normal incidence while reflectance measurements were

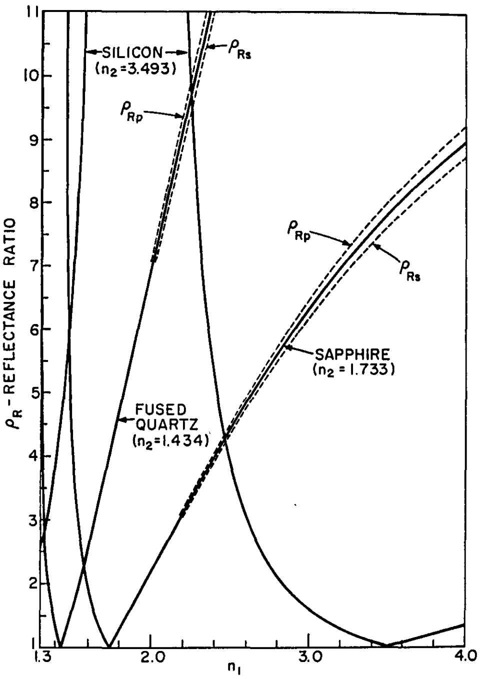

Fig. 3. Reflectance ratio ρ_R vs transparent layer refractive index n_1 for three substrates assuming an angle of incidence of 10° (see text for further explanation).

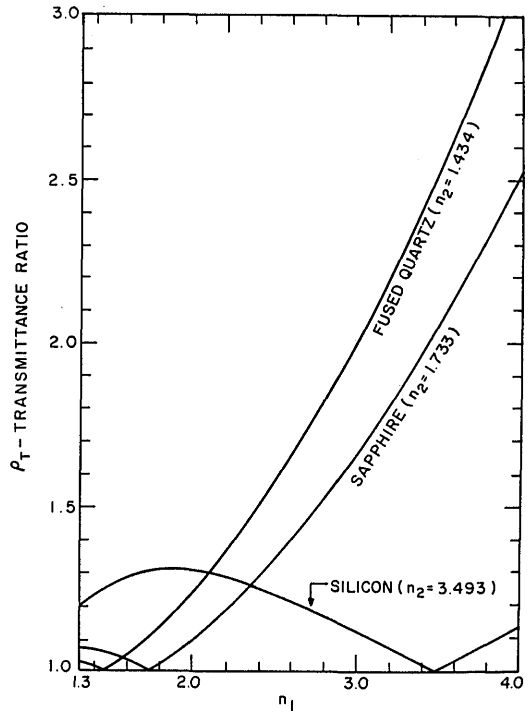

Fig. 4. Transmittance ratio ρ_T vs transparent layer refractive index n_1 for three substrates.

made at a 10° angle of incidence. In order to determine n_1 from the experimental data, graphs of ρ_R and ρ_T were constructed for each of the three substrate materials using a median value of the refractive index in the 1.1–3.0-μm spectral range. These values and their maximum "error" limits in this spectral range are n_2(sapphire) = 1.733 ± 0.021[29], n_2(Si) = 3.493 ± 0.061,[30,31] $n_2(SiO_2)$ = 1.434 ± 0.015.[32] The term "error," of course, means an approximation error due to the assumption that the substrate is nondispersive.

In order to obviate the difficulties associated with two polarizations in the reflectance measurements, we used the approximation

$$\rho_R = (R_p^{MAX} + R_s^{MAX})/(R_p^{MIN} + R_s^{MIN}).$$

This is equivalent to assuming that the light used for the measurements is unpolarized. These plots of ρ_R as a function of n_1 are shown as the solid lines in Fig. 3. It is known, however, that the Cary model 14 spectrophotometer does have polarization characteristics and that they vary with wavelength and from one instrument to another.[33] An upper bound on the error introduced by this instrumental polarization was obtained by calculating ρ_R for each polarization individually (ρ_{R_p} and ρ_{R_s}) and comparing those values with the values corresponding to the solid lines in Fig. 3. For the most part the maximum error in the determination of n_1 would be equal to or less than ~0.01. Under certain conditions, however, the maximum error could be greater; these regions are indicated by the dashed-line plots of ρ_{R_p} and ρ_{R_s} in Fig. 3.

A graph of ρ_T vs n_1 for normal incidence is shown in Fig. 4 for each of the three substrate materials. The use of normal incidence for transmittance measurements, of course, eliminates difficulties due to instrumental polarization.

The graphs of Figs. 3 and 4 were used to determine n_1 from the extrema of the experimental data, and the thickness values were then obtained using Eq. (16). It is true, of course, that a measurement of ρ_T or ρ_R for a completely unknown layer on a single substrate may not uniquely determine n_1, e.g., if ρ_T = 1.20 for an unknown layer on a Si substrate, the value of n_1 could be 1.31 or 2.66. If a layer of the same material were also deposited on another substrate (e.g., sapphire or SiO_2), the ρ_T from a measurement of that layer would resolve the ambiguity. In many cases the ambiguity can be resolved more simply by a knowledge of the approximate range of the unknown index. For example, a layer composed of oxygen-doped Si is unlikely to have an index less than that of SiO_2; thus n_1 would have to be 2.66 rather than 1.31 in the example of ambiguity posed above (Fig. 4).

B. Results

Two fairly typical examples of experimental data are shown in Fig. 5 (reflectance) and Fig. 6 (transmittance). The structural features evident in these data near 1.27 μm, 1.37 μm, 1.85 μm, and 2.2 μm are artifacts of the measurement arising from peculiarities of the spectrophotometer used for the measurement[34]; they are not related to the sample.

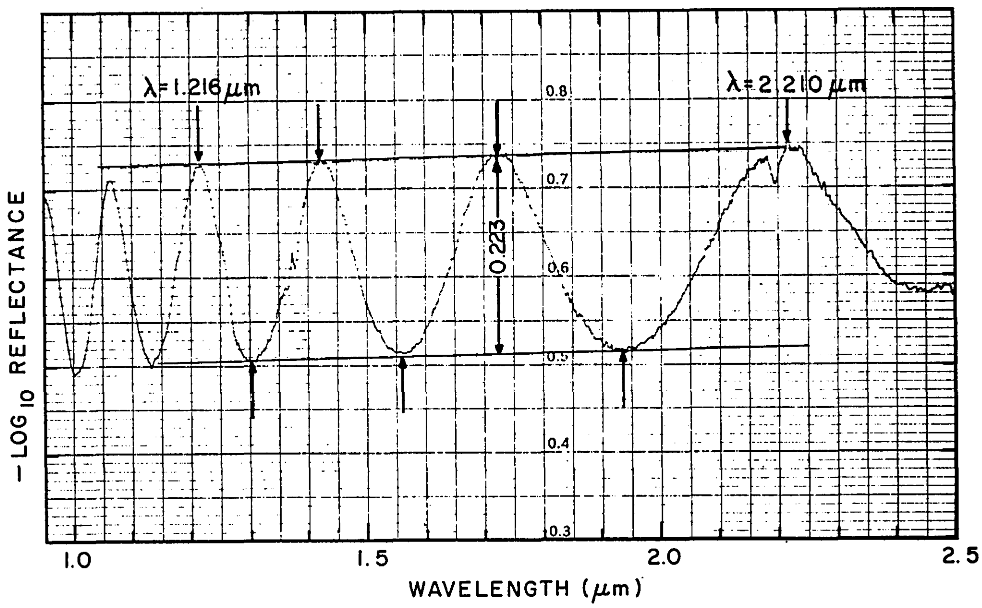

Fig. 5. Variation of $\log_{10}$ reflectance with wavelength of a SIPOS layer on an N^{+}–Si substrate.

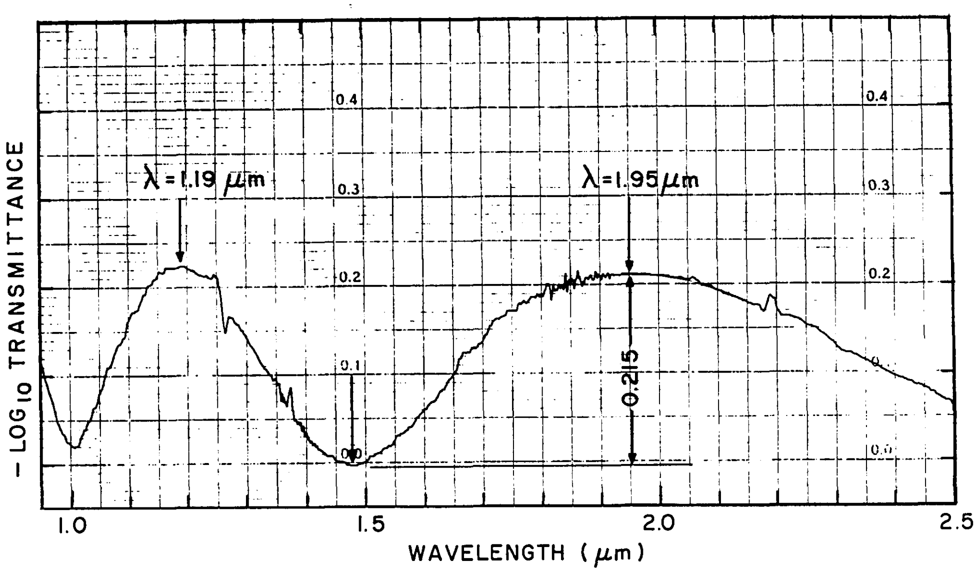

Fig 6. Variation of $\log_{10}$ transmittance with wavelength of a SIPOS layer on a sapphire substrate

In order to determine how well the method worked with a material of known index and a thickness that could be accurately determined, the relative transmittance of an undoped single crystal silicon-on-sapphire (SOS) layer was measured (in the 1.1–2.5-μm spectral range) and used to determine the refractive index and the thickness. The values determined were $n_t = 3.43$ and $t_t = 0.628\ \mu$m. A step was chemically etched in the SOS layer in order to measure its height with a Talysurf surface profile analyzer; this result was $t_T = 0.622$. The agreement between n_t and the known value for single crystal silicon (3.493 ± 0.061) is excellent. The agreement of t_t and t_T is also excellent, better, in fact, than the maximum uncertainty of the Talysurf calibration. An attempt was then made to roughen the back side of the sapphire by sandblasting so that it would be suitable for a reflectance measurement. This resulted in a somewhat but not completely matte surface. A reflectance measurement on this sample gave the results $n_r = 3.14$ and $t_r = 0.712\ \mu$m. The rather significant error here is due to the failure of the roughened back surface of the sapphire to completely scatter the light as was assumed in the analysis. An attempt to absorb the light at the roughened back surface by coating it with a velvet black paint did not result in any significant improvement. An attempt to further roughen the back surface using an abrasive wheel introduced strains which caused cracking of the SOS.

Sandblasted back surfaces for Si substrates gave excellent results as shown in another experiment carried out to ascertain the extent to which the method gives self-consistent results. Here, twelve SIPOS depositions having a wide range of γ were used to produce sets of layers on two types of substrate. From each deposition,

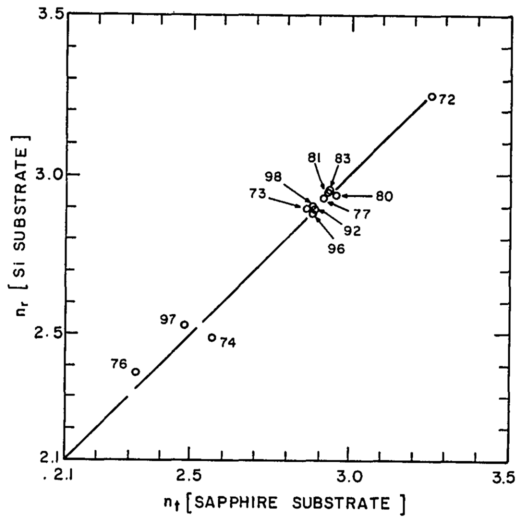

Fig. 7. Refractive index n_r of SIPOS layers on Si substrates determined from reflectance measurements vs refractive index n_t determined from transmittance measurements of similar layers on sapphire.

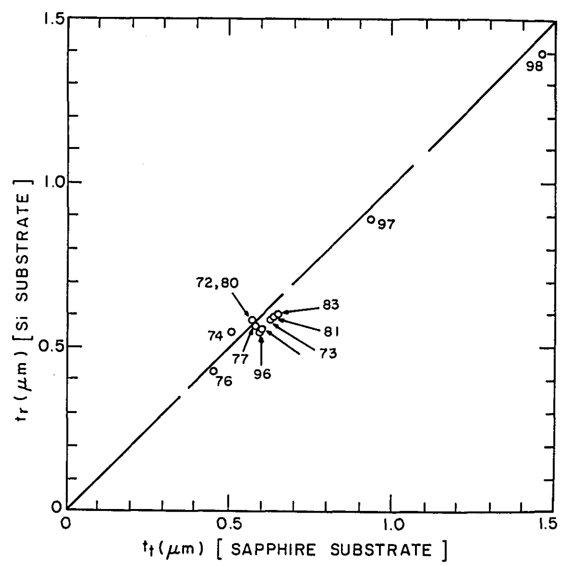

Fig. 8. Thickness t_r of SIPOS layers on Si substrates determined from reflectance measurements vs thickness t_t determined from transmittance measurements of similar layers on sapphire.

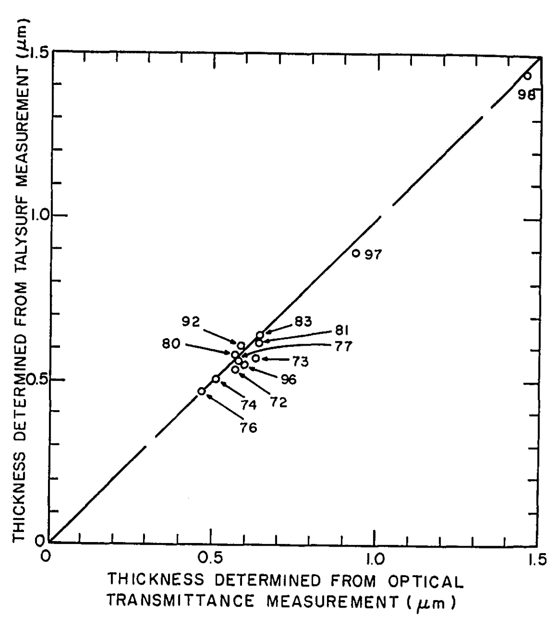

Fig. 9. Comparison of thickness values of SIPOS layers on sapphire substrates determined from transmittance measurements with Talysurf measurements of the same layers.

one SIPOS on silicon sample was used for a reflectance measurement, and one SIPOS on sapphire sample was used for a transmittance measurement. One feature of the LP CVD reactor used to carry out the deposition is that the layers deposited on different substrates during a particular run should be uniform in both composition and thickness (±5%). A comparison of the index and thickness values obtained from reflectance and transmittance measurements of each layer is shown in Figs. 7 and 8. The maximum disagreement in index is less than 3%, and the maximum disagreement in thickness is about 8%. Some thickness disagreement is undobutedly due to real variations in layer thickness within an individual run. Step-height-measurement average values of the layer thickness t_T on the same samples (sapphire substrates) are plotted against t_t in Fig. 9; here, the maximum disagreement is about 9% while the rms deviation is less than 5%.

In all the optical measurements described thus far, a relatively small area was sampled by the light beam (0.046 cm^2 for transmittance measurements and 0.044 cm^2 for reflectance measurements). It was anticipated that some layers might not be uniform in thickness across the substrate and that this nonuniformity might affect the measurement accuracy. To test this hypothesis, transmittance measurements were carried out on some layers using two different test area sizes: (1) small area = 0.046 cm^2, defined by a light-limiting aperture adjacent to the sample and (2) large area ≈ 0.5 cm^2, defined by the slit image in the sample compartment of the spectrophotometer. The SIPOS layers used for this test were deposited in two different AP CVD reactors which are known to produce less uniform layers than LP CVD reactors. It was reasoned that any nonuniformity would tend to wash out the interference fringes and result in an apparent value of the refractive index that would be lower than the real one and an apparent value of the thickness that would be larger than the real one. If such an effect were present, it should be more noticeable when a larger area of the layer being tested is being sampled by the light beam.

The results are shown in Table I. That the expected effect is present is strongly suggested by a comparison of the refractive index and thickness values obtained by using the large and small areas. Also, a plot of the layer thickness determined from a step-height measurement

Table I Comparison of Measurement Results on SIPOS Layers Produced by Atmospheric Pressure Chemical Vapor Deposition

		Optical transmittance measurement				
		Small area[a]		Large area[b]		Talysurf
Sample	Area	n	$t(\mu m)$	n	$t(\mu m)$	$t(\mu m)$
2G	1	3.09	0.691	3.01	0.694	0.655
2G	2	3.12	0.626	Broken wafer		0.672
4G	1	3.08	0.571	3.01	0.595	0.568
4G	2	3.08	0.567	2.97	0.599	0.572
6G	1	3.13	0.671	3.07	0.677	0.664
6G	2	3.13	0.636	3.04	0.654	0.640
4S	1	3.01	0.531	2.93	0.549	0.512
4S	3	3.01	0.517	2.93	0.556	0.536
4S	5	3.02	0.537	2.93	0.556	0.516

[a] Area sampled by light beam = 0.046 cm^2.
[b] Area sampled by light beam ~0.5 cm^2.

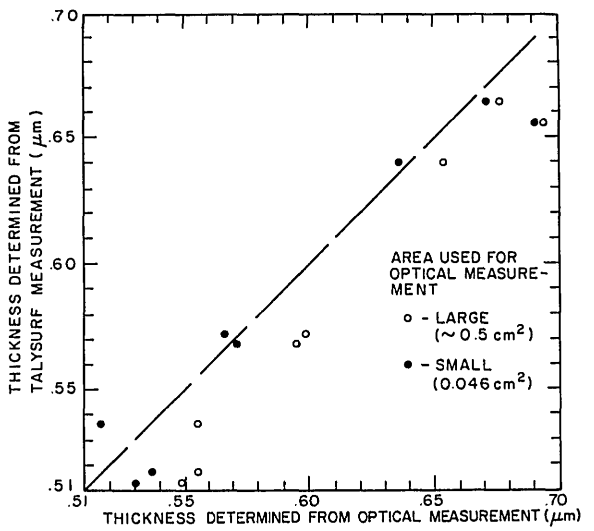

Fig. 10. Comparison of the thickness values of SIPOS layers determined from transmittance measurements using two different sampling areas with Talysurf measurements of the same layers.

vs the thickness determined from the optical measurements (see Fig. 10) clearly shows that better agreement is obtained using the small area measurement results for thickness. The large area measurement results for thickness are skewed toward higher values as one might expect if the film were nonuniform. The effect, although clearly present, is not large for layers in this thickness range. The errors due to nonuniformities would become much more significant in the case of thicker layers.

The principal effect of heavy doping in the Si used as a substrate in reflectance mode measurements is to diminish the reflectance maxima and minima at the long wavelength end of the spectrum due to free-carrier absorption. An example of this effect is the reduced reflectance maximum near 2.5 μm in Fig. 5. Since the film is, in this case, thick enough to provide a choice of extrema in the data, the use of an N$^+$–Si wafer presents no problems. If, however, the layer were so thin that only one minimum and one maximum were present, the use of N$^+$– Si as a substrate material could lead to large errors.

Another source of error is the obfuscation of extrema locations due to baseline anomalies in the spectrophotometer used for the measurement. Here also the problem is more troublesome with the measurement of thinner layers where fewer extrema are present, and it is not possible to select clean data.

IV. Summary

A simple optical interference method has been described for the approximate determination of both the refractive index and the thickness of a transparent layer on a transparent substrate. It is appropriate to summarize the features—both advantages and limitations—of the method.

(1) The method requires that the layer being measured must be uniformly deposited on a flat substrate, and it must neither absorb nor scatter the light passing through it. That is, the layer must be clear (transparent) rather than cloudy. Cloudiness will show up as an anomalously low value of n_1 and a correspondingly high value of thickness. Since a cloudy deposited layer can be produced by a leak in the deposition system or some other source of contamination, the method could be used as a diagnostic tool for this type of problem.

(2) There is a minimum layer thickness $t_{\min}$ that may be determined since at least one minimum and one maximum in the experimental data are required. For example, in the case of SIPOS layers which absorb when $\lambda \lesssim 1.2\ \mu m$, $t_{\min} \approx 1.2/n\ \mu m$. For typical layers in which $\gamma \approx 0.2$, $n_1 \approx 3$, and $t_{\min} \approx 0.4\ \mu m$.

(3) In the implementation of the method only a single spectrophotometric sweep is required; this is simpler than any other optical method used to obtain the same information.

(4) The method may be used in either a transmittance or reflectance measurement mode.

(5) The method is rapid and can be implemented in a way that requires only trivial data reduction on the part of the user.

(6) The major approximation inherent in the method is that both the layer and the substrate are assumed to be nondispersive over the wavelength region of interest.

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