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Contrast enhancement in the detection of defects in transparent layered structures: The use of optothermal interference technique in solar cell investigation

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This article shows the enhanced sensitivity of the optothermal interference technique in the detection of local differences (nonhomogeneity in thickness and optothermal parameters), compared to the conventional optical interference, when investigating layered transparent structures. The measured signal is sensitive to the reflectance variation at the distinct interfaces, function of temperature, as well as to the optical phase lag between the reflected beams. Measurements made on solar cells show contrast of the order of 100% in the optothermal interference, while the conventional optical interference presents a contrast of only 15%. A model based on the reflectance variation at each interface describes the signal behavior as a function of modulation frequency. Theoretical calculation based on this model evidences the influence of the optothermal parameters in the signal contrast. © 2000 American Institute of Physics. [S0021-8979(00)04821-0]

I. INTRODUCTION

The optical detection of the photothermal phenomena has been successfully used in many cases. From the applications of the technique, one can identify two main advantages over other detection schemes: high sensitivity and high spatial resolution. The former has been vastly explored in thermal lens spectrometry¹ and mirage effect.² The second advantage is explored in photothermal microscopy investigations through reflectance measurements.^{3–12} Despite the high spatial resolution achieved by this technique, its sensitivity is usually ordinary and strongly dependent on the material optical properties and probe wavelength, as discussed in Ref. 9. Conjugate high resolution with high sensitivity, in this case, is a valuable challenge.

Photothermal reflectance microscopy has been extensively used in the characterization of local thermal and electronic properties of materials and structures^{3–5} as well as in the investigation of heat source distribution in operating microelectronics devices.^{6–9} The main thermal parameter obtained with these measurements is the thermal diffusivity. Recently, particular attention has been devoted to the characterization of the thermal properties of thin films.¹⁰ One must observe, however, that most parts of the studies in this field deal with optically opaque films, so the signal source is directly connected to the reflectance variation caused by temperature oscillations in the sample surface. The investigation

of transparent films is sometimes limited because of the low optical absorption/reflection of the sample. Adding a thin metallic film on the sample surface usually solves this problem.¹¹ In this case, the heating beam absorption is enhanced, as well as the probe beam reflection.

When the substrate is highly absorbing (and reflecting), and the film is transparent, one can still get a high photothermal reflectance signal. The heat generation in this case is located on the substrate/film interface. The probe beam is mainly reflected at the same interface, but a non-negligible reflectance may occur at the film/air interface, and optical interference of both reflected beams can take place. This effect was observed before¹² in a context where the film thickness was under analysis.

In this article, we show the enhanced sensitivity of the optothermal interference technique in the detection of local differences (nonhomogeneity in thickness and optothermal parameters), compared to the conventional optical interference, when investigating layered transparent structures. The measured signal is sensitive to the reflectance variation at the distinct interfaces, function of temperature, as well as to the optical phase lag between the reflected beams. The temperatures at the interfaces may present significant phase lag, depending upon layer (film) thickness, its thermal diffusivity, and the modulation frequency. Parameters such as substrate and film refraction indexes and their temperature coefficients, and film thermal expansion coefficient, are all involved in the optothermal signal amplitude and phase. Measurements made on solar cells show amplitude contrast of the order of 100% in the optothermal interference, while the

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FIG. 1. Vertical structure of the solar cell (nonscaled), with the four main regions: the silicon cell itself ($200\ \mu\text{m}$), the antireflecting coating, the adhesive layer ($20\ \mu\text{m}$ nominal thickness), and the cover glass ($120\ \mu\text{m}$). The TiPdAg grid used for the front electrical contact, as well as the rear Al-Ag contact layer are also depicted. The distance between two grid wires is $800\ \mu\text{m}$. The incident probe beam and its reflections are also illustrated.

conventional optical interference presents a contrast of about only 15%. A model based on the reflectance variation at each interface describes quite well the signal behavior as a function of modulation frequency, both in amplitude and in phase. Theoretical calculation based on this model evidences the influence of the optothermal parameters in the signal contrast.

II. EXPERIMENTAL SETUP

The experimental setup used in this work is described in details in Ref. 4. A laser diode operating at $670\ \text{nm}$ is used as probe beam, while an Ar^+ laser ($514.5\ \text{nm}$) is used as excitation. Both laser beams were focused at the same point on the sample with powers of about $0.1\ \text{mW}$ (probe) and a few milliwatts (excitation). Modulation frequencies from $100\ \text{Hz}$ to $1.0\ \text{MHz}$ were employed. The reflected probe beam was deviated to a Si photodiode, whose output was analyzed by a lock-in amplifier. The sample was scanned in a given direction, in steps of $1.0\ \mu\text{m}$, and the signal amplitude and phase were measured as function of position: when crossing non-uniform regions a signal variation was expected.

The samples used in this work were solar cells for space applications.¹³ Figure 1 depicts the vertical structure of the cell, with the four main regions: the silicon cell itself ($200\ \mu\text{m}$), the antireflecting coating, the adhesive layer ($20\ \mu\text{m}$ nominal thickness), and the cover glass ($120\ \mu\text{m}$). The adhesive (silicone, Dow Corning DC 93500) is used to bond the cover glass on the silicon cell. The role of the cover glass is to protect the cell against the intense damaging ionizing extra-terrestrial environment. In Fig. 1, the TiPdAg grid used for front electrical contact, as well as the rear Al-Ag contact layer are depicted. The cell with the metallic grid was covered with a Ta_2O_5 antireflecting coating before placing the adhesive and the cover glass. The p - n junction is located about $0.2\ \mu\text{m}$ below the silicon surface. Experiments were performed with the solar cells in an open circuit configura-

FIG. 2. Experimental result (symbols) and theoretical calculation (solid line) for a scan along the line depicted in Fig. 1 using a modulation frequency of $100\ \text{Hz}$. (a) ac signal amplitude (circles) and dc signal component (crosses); (b) ac signal phase.

tion. Since the cover glass and the adhesive are transparent to visible light, the absorption of the excitation beam occurs in the silicon cell, with a depth of penetration smaller than one micron. In the same way, the probe beam is reflected mainly at the silicon cell/adhesive interface. Therefore, both laser beams were focused on this interface with diameters of about 2.5 (excitation) and $3.3\ \mu\text{m}$ (probe).

III. EXPERIMENTAL RESULTS

Figure 2 presents the experimental results (symbols) for a scan along the line depicted in Fig. 1 using a modulation frequency of $100\ \text{Hz}$. In Fig. 2(a) one can see that the signal amplitude (circles) has a periodic behavior, oscillating between minima and maxima. The minima present roughly a single value around 1×10^{-4} in $\Delta R/R$, the relative change in the reflectance of the whole structure. One must observe that ΔR is proportional to the ac signal component at the modulation frequency, while R is proportional to the dc component. Therefore, by measuring both components the ratio $\Delta R/R$ is obtained. The maxima, on the other hand, present two distinct and alternate values: 14.5×10^{-4} and 9.5×10^{-4} . At this point one must say that, for a naked solar cell (a cell without cover glass and adhesive), a similar measurement results in uniform signal amplitude (not shown), as one would expect from a homogeneous medium. The same

behavior was observed for the phase and for the dc signal component. The value of the phase in this case is around 180 deg. For silicon, one would expect the phase to be around zero, but the addition of the coating inverts the ac reflectance signal, as confirmed by theoretical calculation (not shown). The observed oscillations in the measurements of Fig. 2 are caused, therefore, by the addition of the adhesive and cover glass on the cell.

Figure 2(b) shows the signal phase as a function of the position. It is observed that the phase also presents a periodic behavior, oscillating between values around 180 and 360 deg (or zero). Moreover, its shape is squared, and the transitions from 180 and 360 deg and vice-versa occur when the amplitude is a minimum. Finally, the highest maxima occur with phases at 180 deg, while the lowest ones have phases of 360 deg. In other words, the set of peaks of the lowest amplitude is 180 deg delayed with respect to the set of peaks of highest amplitude. Now, observing the dc component of the signal [crosses in Fig. 2(a)], which is proportional to the reflectance of the sample, one sees a small sinusoidal oscillation ($\sim 15\%$ of variation). The period of the dc component is the same of the amplitude and phase. Furthermore, the maxima and minima of the dc signal occur in the same position of minimum amplitude, i.e., at the transitions of the phase from 180 to 360 deg and vice-versa. The highest maxima in the amplitude (with phase of 180 deg) belong to the increasing part of the dc curve, and the lowest maxima (with phase of 360 deg) are located at the decreasing regions of the dc component. Since the dc signal is a purely optical one, its oscillation seems to be related to the partially destructive and constructive interference of the reflected beams at the silicon/coating, coating/adhesive, and adhesive/glass interfaces. In this case, the oscillation would be originated in the nonuniformity of the adhesive layer thickness, revealing a wedge shape for the adhesive.

In order to confirm such hypothesis the dc reflectance signal was measured using several wavelengths, λ_p , for the probe beam: 457.9, 488, 514.5 nm, besides 670 nm as shown in Fig. 2(a). The period observed in the dc reflectance signal changed from 106 μm for $\lambda_p=670$ nm to 69 μm for $\lambda_p=457.9$ nm, thus confirming the existence of a varying thickness l_a in the adhesive layer. The slope obtained from the optical measurements for the scanned line indicated in Fig. 1 (near the left border of the cell) was $(dl_a/dz)=2.2$ nm/ μm . It was also observed that the period of both the purely optical and the optothermal interference signal varies from place to place in the cell, e.g., left border, center, right border etc. From the analysis of such slope distribution it was possible to detect problems with the tool used to bond the cover glass on the cell. Further investigation may be useful in the correction of this problem.

Still concerning the experimental data of Fig. 2, one must note the significant enhancement of the contrast (defined as the signal variation divided by the maximum signal) obtained with the optothermal interference method, which is of about 100%, when compared to that of the purely optical signal which is of only 15%. This feature makes the method especially suitable for detecting local nonuniformity in transparent layered structures.

FIG. 3. Same as Fig. 2 using a modulation frequency of 100 kHz: ac signal amplitude (circles) and phase (triangles).

The measurement presented in Fig. 2 was performed with a modulation frequency $f=100$ Hz. At this frequency the thermal diffusion length in the adhesive ($\mu_a=(\alpha_a/\pi f)^{1/2}$, α_a being the thermal diffusivity⁴) is $\mu_a=20$ μm , equal to the layer thickness. In this situation, the thermal wave generated mainly at the silicon/coating interface is not strongly attenuated at the adhesive/glass interface. Now, increasing the modulation frequency up to 100 kHz, the thermal diffusion length in the adhesive becomes smaller than 1 μm . At this frequency the thermal wave is strongly attenuated at the adhesive/glass interface, and does not modulate the reflectance at this interface anymore. The result of a measurement at such a frequency is shown in Fig. 3 (symbols). From the amplitude data (circles) one can observe that only the higher maxima remained. Indeed, the lowest maxima diminished with respect to the highest ones as the modulation frequency increased from 100 Hz until 100 kHz, thus disappearing at all. It is also observed that the contrast decreased from 100% at 100 Hz to roughly 66%. The phase (triangles) has a much smaller variation along a period than it had at 100 Hz, oscillating from 145 to 210 deg. It is noticeable that the phase oscillates around the value of 180 deg that was found in the naked cell measurement.

IV. THEORY

In order to better understand the signal evolution with modulation frequency, as well as its dependence on the optothermal and geometrical parameters of the sample, a model was developed based upon the interference of the reflected beams at the silicon/coating, coating/adhesive, and adhesive/glass interfaces. The reflectance (refraction indexes) coefficients were considered temperature dependent as well as the adhesive thickness. The temperature distribution was obtained by solving the three-dimensional (3D) heat diffusion equation⁴ for the three media: Si substrate, adhesive, and glass. The $p-n$ junction and the coating were disregarded in the calculation of the temperature; for the optical reflection, however, the coating was taken into account.

Let us first consider the reflections at different interfaces, and the optical interference between the reflected beams. In Fig. 1 the four media are depicted, namely: Si cell (c), anti-

TABLE I. Geometrical and optothermal parameters^a of the cover glass, adhesive, coating, and Si cell.

Layer	Cover glass	Adhesive	Coating	Si cell
Thickness (μm)	120	20	0.072	200
Refraction index @670 nm	1.484	1.412	2.200	3.825
$\partial n/\partial T(\text{K}^{-1})$ @670 nm	1×10^{-6}	1×10^{-5}	1×10^{-5}	2×10^{-5}
Thermal conductivity (W/cm K)	1.51×10^{-2}	1.46×10^{-3}	...	1.50
Thermal diffusivity (cm^2/s)	8.0×10^{-3}	1.3×10^{-3}	...	0.79
Thermal expansion coefficient (K^{-1})	...	2.4×10^{-5}	2.0×10^{-5}	...

^aSee Refs. 13–18.

reflection coating (film–f), adhesive (a), and cover glass (g). The incident probe beam and its reflections are also illustrated in Fig. 1. The incidence is considered normal to the interfaces (in Fig. 1 the beams are drawn obliquely for explicitness purposes). The incident beam has intensity I_0 ; I_1 is the intensity of the reflected beam from the glass–adhesive interface; I_2 and I_3 are the intensities of the beams reflected at the adhesive–film and at the film–cell interfaces, respectively. The reflection on the top of the cover glass was disregarded since the probe beam is focused on the Si cell surface, and the glass layer is thick enough to uncouple this beam from the others. The three other beams interfere and the resulting intensity is given by

$$I = I_1 + I_2 + I_3 + 2\sqrt{I_1 I_2} \cos \varphi_{12} + 2\sqrt{I_1 I_3} \cos \varphi_{13} + 2\sqrt{I_2 I_3} \cos \varphi_{23}, \quad (1)$$

where

$$\begin{aligned} \varphi_{12} &= \frac{4\pi}{\lambda_p} n_a l_a + 180 \text{ deg}, \\ \varphi_{23} &= \frac{4\pi}{\lambda_p} n_f l_f, \\ \varphi_{13} &= \varphi_{12} + \varphi_{23} \end{aligned} \quad (2)$$

are the phase shifts between each pair of reflected beams. In Table I the optothermal parameters for the four materials are listed. Among them, one can see that the refraction index (n_i , $i=g,a,f,c$) increases from the top of the structure to the bottom, except for the adhesive layer. This introduces an additional phase shift of 180 deg between beams 1 and 2, and between beams 1 and 3, as expressed by Eq. (2). In this equation, λ_p is the probe wavelength in vacuum ($\lambda_p = 670 \text{ nm}$), and l_i is the thickness of each layer. Now, let us write the intensities I_1 , I_2 , and I_3 in terms of I_0

$$\begin{aligned} I_1 &= R_1 I_0, \\ I_2 &= (1 - R_1)^2 R_2 I_0, \\ I_3 &= (1 - R_1)^2 (1 - R_2)^2 R_3 I_0, \end{aligned} \quad (3)$$

where R_i is the reflectivity at each interface. Although multiple reflections occur in this case, only the first one was considered for each layer. Such approximation is good enough for R_1 and R_2 are quite small ($R_1 \approx 6.2 \times 10^{-4}$ and $R_2 \approx 4.8 \times 10^{-2}$). Indeed, we make further approximations: $1 - R_1$

≈ 1 and $1 - R_2 \approx 1$. Therefore, the ratio between the reflected and incident intensities, which we call the effective reflectance, R , is

$$R = \frac{I}{I_0} = R_1 + R_2 + R_3 + 2\sqrt{R_1 R_2} \cos \varphi_{12} + 2\sqrt{R_1 R_3} \cos \varphi_{13} + 2\sqrt{R_2 R_3} \cos \varphi_{23}. \quad (4)$$

We are interested in the reflectance variation (ΔR) caused by the temperature oscillation. The local temperature at the different interfaces induces reflectance variation at the interface. Moreover, the average temperature in a given layer changes its thickness and the average refraction index, thus inducing a change in the phase shift between each pair of reflections. In other words, the temperature changes both the intensities of each reflected beam and the phase shift between the beams. By differentiating Eq. (4) with respect temperature, and multiplying each term by the appropriate temperature, the reflectance variation is found

$$\Delta R = \frac{\Delta I}{I_0} = A T_1 + B T_2 + C \langle T_{12} \rangle. \quad (5)$$

The coefficients A , B , and C are given by

$$\begin{aligned} A &= \left(1 + \sqrt{\frac{R_2}{R_1}} \cos \varphi_{12} + \sqrt{\frac{R_3}{R_1}} \cos \varphi_{13} \right) \frac{\partial R_1}{\partial T}, \\ B &= \left(1 + \sqrt{\frac{R_1}{R_2}} \cos \varphi_{12} + \sqrt{\frac{R_3}{R_2}} \cos \varphi_{23} \right) \frac{\partial R_2}{\partial T} \\ &\quad + \left(1 + \sqrt{\frac{R_1}{R_3}} \cos \varphi_{13} + \sqrt{\frac{R_2}{R_3}} \cos \varphi_{23} \right) \frac{\partial R_3}{\partial T} \\ &\quad - 2\sqrt{R_2 R_3} \sin \varphi_{23} \frac{\partial \varphi_{23}}{\partial T}, \\ C &= -2 \left(\sqrt{R_1 R_2} \sin \varphi_{12} \frac{\partial \varphi_{12}}{\partial T} + \sqrt{R_1 R_3} \sin \varphi_{13} \frac{\partial \varphi_{13}}{\partial T} \right). \end{aligned} \quad (6)$$

T_1 and T_2 are the temperatures at the interfaces between glass–adhesive and adhesive–coating, respectively, and $\langle T_{12} \rangle$ is the average temperature in the adhesive layer. Since the coating is very thin, in the frequency range we worked its thermal diffusion length is much larger than its thickness. Therefore, the temperature T_3 at the coating–cell interface was considered the same as T_2 in Eq. (5). Accordingly, the average temperature in the coating layer was also made equal

to T_2 , as well as $\langle T_{13} \rangle = \langle T_{12} \rangle$. The temperature coefficients of the reflectance are related to the refraction indexes and their temperature coefficients as

$$\frac{\partial R_i}{\partial T} = \frac{4(n_\beta - n_\alpha)n_\beta n_\alpha}{(n_\beta + n_\alpha)^3} \left[\frac{1}{n_\beta} \frac{\partial n_\beta}{\partial T} - \frac{1}{n_\alpha} \frac{\partial n_\alpha}{\partial T} \right] \quad (7)$$

with $i = 1, 2, 3$ and $\alpha, \beta = g, a, f, c$; the probe beam comes from medium α and goes to medium β . The term involving the imaginary part of the refraction index for the Si cell was neglected, since for $\lambda_p = 670$ nm it is almost two orders of magnitude smaller than that involving the real part. In the same way, the temperature coefficients for the phase shifts are given by

$$\frac{1}{\varphi_{ij}} \frac{\partial \varphi_{ij}}{\partial T} = \alpha_{T_\gamma} + \frac{1}{n_\gamma} \frac{\partial n_\gamma}{\partial T}. \quad (8)$$

Here, $\alpha_{T_\gamma} = (1/l_\gamma)(\partial l_\gamma / \partial T)$ is the thermal expansion coefficient and n_γ is the refraction index of the layer γ between interfaces i and j : $\gamma = a$ for $ij = 12$ and $\gamma = f$ for $ij = 23$. Moreover, $\partial \varphi_{13} / \partial T = \partial \varphi_{12} / \partial T + \partial \varphi_{23} / \partial T$.

As mentioned above, the optothermal parameters of the materials, which are necessary in the above calculation of the

reflectance signal, were obtained from literature^{13–18} and are listed in Table I. In order to calculate the reflectance variation, we need, however, to know the oscillating temperatures T_1 , T_2 , and $\langle T_{12} \rangle$. The temperature oscillation, at the frequency f , is produced by the Ar^+ laser beam, which is absorbed at the Si cell surface (depth of penetration smaller than one micron). Therefore, the temperature profile is obtained by solving the 3D heat diffusion equation for the three media (glass, adhesive, and cell), with a heat source at the silicon cell surface. The heat source shape was considered Gaussian, with a radius $R_e = 2 \mu\text{m}$. This value corresponds to an effective radius used in our experiments (such effective radius takes into account the extended/finite probe spot).

Since the problem presents cylindrical symmetry, the one-dimensional (1D) diffusion problem was firstly solved; afterward we converted the solution to the 3D case using Hankel transform method. The temperature at a given position (r, z) in the adhesive layer is found to be

$$T_{3D}(r, z) = \frac{P_0}{2\pi k_a} \int_0^\infty F(p, z) J_0(pr) e^{-p^2 R_e^2 / 4} p dp, \quad (9)$$

where

$$F(p, z) = \frac{1}{\xi_a} \frac{(1 - \Gamma_{ga})e^{\xi_a(z - l_a - l_f)} + (1 + \Gamma_{ga})e^{-\xi_a(z - l_a - l_f)}}{(1 + \Gamma_{ca})(1 + \Gamma_{ga})e^{\xi_a(l_a + l_f)} - (1 - \Gamma_{ca})(1 - \Gamma_{ga})e^{-\xi_a(l_a + l_f)}},$$

$$\Gamma_{ga} = \frac{k_g \xi_g}{k_a \xi_a}, \quad \Gamma_{ca} = \frac{k_c \xi_c}{k_a \xi_a},$$

$$\xi_i = \sqrt{p^2 + \sigma_i^2},$$

$$\sigma_i = (1 + j) \sqrt{\frac{\pi f}{\alpha_i}}, \quad \alpha_i = \frac{k_i}{\rho_i c_i}, \quad i = g, a, c.$$

Finally,

$$T_1 \equiv T_{3D}(r=0, z=l_a + l_f),$$

$$T_2 \equiv T_{3D}(r=0, z=0), \quad (10)$$

$$\langle T_{12} \rangle \equiv \frac{1}{l_a + l_f} \int_0^{l_a + l_f} T_{3D}(r=0, z) dz.$$

In the above expression, α_i , k_i , ρ_i , and c_i are, respectively, the thermal diffusivity, the thermal conductivity, the density, and the specific heat of each material; P_0 is the absorbed power and J_0 is the zero-order Bessel function.

The solid lines in Figs. 2 and 3 (amplitude and phase) are the result of the calculated optothermal interference signal using the geometrical, optical, and thermal parameters from Table I. The adhesive thickness was made equal to 20 μm at the initial position, and the measured slope (2.2 nm/ μm , see Sec. III) was then added, making the thickness to increase with position. Since the relative change of the thickness with position is very small, the temperature profile is not affected. Therefore, we considered that only the optical

path changes with position. Furthermore, the position of one of the maxima was adjusted to match both experimental and theoretical data.

The agreement between calculation and experiment is very good, except for the phase at 100 kHz in Fig. 3. The reason for this disagreement is that, the carrier contribution, which becomes important at high frequencies,⁵ was not considered in the calculation. Its effect is to shift down the phase, since it modulates the reflectance at the silicon/coating interface with its own phase shift in the range of 135 (1D carrier diffusion regime) and 180 deg (3D carrier diffusion regime).

Now, since our experimental data were very well described by the proposed model above, let us analyze the sensitivity of the reflectance signal to the optothermal parameters of the sample. The sensitivity to the transparent layer thickness (adhesive in our case) is very high, for the thickness, variation affects directly the optical path. The observed contrast is better at low modulation frequencies, because at low frequencies the temperature at the upper interface is relatively high, thus modulating the reflectance. At higher fre-

FIG. 4. Theoretical calculation (amplitude and phase) of the optothermal signal for a scan along the line depicted in Fig. 1 using a modulation frequency of 10 kHz. The optothermal parameters used are those of Table I, except the adhesive thermal diffusivity α_a , which was varied: 1.3×10^{-1} (upper solid line), 1.3×10^{-2} (dashed line), 1.3×10^{-3} (dotted line), and 1.3×10^{-4} cm²/s (lower solid line).

quencies, the modulation of the reflection at the upper interface is attenuated, thus reducing the contrast. As it is well known, the thermal diffusion length is the relevant parameter concerning the temperature attenuation. It depends on the modulation frequency, but also on the thermal diffusivity.

In order to verify the role of the thermal diffusivity, α_a was made variable, from 1.3×10^{-4} to 1.3×10^{-1} cm²/s, and the result of the signal calculation is shown in Fig. 4 for the modulation frequency of 10 kHz. The thermal conductivity of the adhesive was kept constant in these calculations (the more realistic case where the adhesive thermal conductivity also varies presents the same trend in the range where it is lower than the Si cell one—curves not shown). As in the case of frequency variation (see Figs. 2 and 3), one can see in the amplitude curves [Fig. 4(a)] that the lowest maxima, compared to the highest ones, are reduced when the thermal diffusivity decreases. Indeed, they completely disappear for the value of $\alpha_a = 1.3 \times 10^{-4}$ cm²/s, as in the case of Fig. 3. It is to be observed that, for such values of thermal diffusivity and frequency, the thermal diffusion length in the adhesive becomes equal to that of Fig. 3. Figure 4(b) shows the calculated signal phase for the different values of α_a , with the expected behavior, as discussed above.

Figure 4 represents the calculated signal for a situation where the adhesive thickness increases linearly with position. Now, if we want to know the influence of the thermal diffusivity keeping the layer thickness constant, we must follow the signal in a given position of Fig. 4. From curve to curve we see that the amplitude, generally, drops if the thermal diffusivity is reduced. In the same way, the phase detaches from the 360 and 180 deg values when decreasing α_a . Therefore, by using an appropriate probe wavelength we can place the experimental setup in one of the lowest maxima. In this situation, the signal variation with α_a is enhanced, as one can see from Fig. 4. Consequently, a local variation of α_a much less than one order of magnitude becomes detectable both through the amplitude and through the phase. Indeed, the evolution of the highest maxima follows quite closely the temperature in the cell-coating interface. This temperature is the signal source in the cases where no optothermal interference is verified. Therefore, our results demonstrate that, the inclusion of optothermal interference does enhance the sensitivity to the thermal properties of a film on substrate, particularly if we focus our attention on the lowest maxima.

Other relevant parameters involved in the optothermal interference signal are the refractive index and its derivative with respect to temperature. A variation in the refractive index of the adhesive, n_a , produces a change in the reflectance at the adhesive interfaces, and in the optical path in the layer. For small variations in the refractive index, the reflectance does not change very much, and the main consequence is the change in the optical path. Therefore, in this situation, by increasing n_a , for instance, the optothermal signal oscillates, both in amplitude and in phase, as in the case of increasing the layer thickness. In view of the results presented in Fig. 2, one can state that a nonuniformity in n_a of 1.5×10^{-4} ($\sim 0.01\%$) can be detected, provided the other parameters are kept constant. For this estimation, we considered a signal noise of 5% (overestimated in our measurements) and the fact that the contrast in the measurement of Fig. 2 is of 100%.

Finally, Fig. 5 shows the influence of the temperature coefficient of the refractive index, $\partial n_a / \partial T$, in the optothermal signal at 10 kHz. The geometrical and optothermal parameters used in the calculation are those of Table I, and $\partial n_a / \partial T$ was varied from 10^{-6} to 10^{-2} K⁻¹. The signal was calculated for an adhesive thickness such that it is one of the lowest maxima. At very low values of $\partial n_a / \partial T$ the reflectance modulation is strongly influenced by the coating and the Si cell (see the temperature coefficient of the refractive index in Table I). Therefore, the signal amplitude [Fig. 5(a)] does not change drastically with $\partial n_a / \partial T$ at this modulation frequency. However, when $\partial n_a / \partial T$ becomes large enough to dominate the modulation of the reflectance (above 10^{-4} K⁻¹), one can see the linear dependence of the signal amplitude, as it is expected. The phase dependence on $\partial n_a / \partial T$ is shown in Fig. 5(b). As one can see, starting with the nominal value of $\partial n_a / \partial T = 1 \times 10^{-5}$ K⁻¹, by increasing $\partial n_a / \partial T$ the phase also increases, reaching a saturation value of about -27 deg. This value is not far from the 360 deg that was observed in measurements at low modulation frequen-

FIG. 5. Theoretical calculation (amplitude and phase) of the optothermal signal for a modulation frequency of 10 kHz. The geometrical and optothermal parameters used are those of Table I, except $\partial n_a / \partial T$ that was varied from 10^{-6} to 10^{-2} K^{-1} . The signal was calculated for an adhesive thickness such that it is one of the lowest maxima.

cies for the lowest maxima [see Fig. 2(b) for 100 Hz]. This means that the weight of the influence of the upper interface of the adhesive is augmented by increasing $\partial n_a / \partial T$, in the same way it is augmented by decreasing modulation frequency. On the other hand, by decreasing $\partial n_a / \partial T$, the phase also decreases, going to a value around that obtained at high modulation frequencies for the lowest maxima, that means, 180 deg (see Fig. 3 for 100 kHz). This means that the weight of the influence of the upper interface of the adhesive is diminished, as in the case of high modulation frequencies.

V. CONCLUSIONS

In conclusion, the experimental results presented above evidence the high sensitivity of the optothermal interference signal in detecting defect and local heterogeneity in layered transparent structures, particularly the layer thickness; this application of the technique was not explored before. The proposed model describes very well the measured signals at low frequencies, from a few hertz to a few tens of kHz. For higher modulation frequencies, in the case of semiconductor substrates, the carrier contribution to the reflectance modulation has to be considered. The potential ability of the technique in detecting local differences in the optothermal pa-

FIG. 6. Experimental signal amplitude for a $135 \mu\text{m} \times 135 \mu\text{m}$ scan in a region containing one air bubble in the adhesive layer. The modulation frequency was 100 kHz. White means minimum (zero) and black means maximum amplitude.

rameters was evidenced through theoretical calculations where we varied the optothermal parameters of the transparent layer (adhesive in our case). Exceptional contrasts can be obtained by varying the refractive index, as in the case of thickness variation; significant contrast is achieved by varying thermal diffusivity and $\partial n_a / \partial T$.

A further illustration of the potentiality of the technique in detecting local defects is presented in Fig. 6. It represents the signal amplitude in a region of $135 \mu\text{m} \times 135 \mu\text{m}$, which contained one air bubble in the adhesive. The air in the adhesive implies in nonuniformity in thickness, refractive index and its temperature derivative. The whole change in the optothermal parameters resulted in a strong contrast in both amplitude and phase. The bubble is spherical, but not internally uniform, as one can see in Fig. 6. The signal phase map (not shown) also presents the same internal structure, while the conventional optical image (using 670 nm light, not shown) only displays the main features of the preceding ones. When compared with the conventional optical image, both amplitude and phase reveal to be much richer, presenting spatial oscillations as in the case of Figs. 2 and 3. This oscillatory behavior is not fully resolved in Fig. 6; indeed, one must observe that the resolution achieved with this experimental setup (of the order of one micron) is much higher than that needed in the scan of Fig. 6. Therefore, for a large area as in the present example, the whole optical image presents the main characteristics of amplitude and phase maps; amplitude contrast is of 100% (as defined above), while the optical contrast is roughly 80% for the entire image. However, when a small portion of the bubble is analyzed (a few micrometers wide), one can see the rich structure above mentioned, in amplitude and phase, while the optical image remains practically unchanged. This is because the optical image is less affected by the interference effect, and most affected by the interface angles in the bubble. The optothermal signal is, of course, influenced by the second effect, but

the former definitely determines amplitude and phase, thus originating the spatial oscillations in the internal area of the bubble. In other words, the optothermal signal accounts to very small changes in the geometrical and optothermal parameters, thus providing information to an accurate reconstruction of the defect in the micrometer scale. The optical image, on the other hand, accounts only to intense variations of thickness and refraction index.

Finally, besides this type of application, the technique is also valuable in the characterization of transparent thin films, provided the properties of the substrate are known. In the same way, it opens the possibility of investigating wetting through the determination of drops shape and their angles of contact.

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