ELLIPSOMETRIC MEASUREMENTS OF THERMAL AND STRESS GRADIENTS ON A GOLD SURFACE BY A LASER

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Abstract

The knowledge of localized surface temperature of a metallic photocathode, irradiated by an intense laser beam is a necessity for its yield optimization. We propose to measure this temperature by ellipsometry. The advantage of this method is to be, also, sensitive to the surface condition and the environment (air or vacuum)

1 - Introduction

The recent use of photocathodes irradiated by high power laser, for the production of high current densities, requires the control of their behaviour.

The laser-material interaction, results in thermal gradient, stress and possibly reaction of the surface with its environment. Its application to the specified case of photocathodes causes localized effects which require an experimental study, because the classical laws cannot be applied directly.

To control all the phenomena in real time and *in situ*, we propose an original technique based on ellipsometry. We present here a first series of data derived from a thin layer of gold illuminated by a CW Ar^+ laser.

2 - Major basic data of ellipsometry

The ellisometry is the measurement of variations of the electromagnetic wave-electric field after reflection on a solid surface. The electric field results in components E_p parallel and E_s perpendicular to the plane of incidence. By a reflection on a metallic surface, the E_p and E_s components are submitted to phase shifts φ_p and φ_s respectively, the first ellipsometric parameter $\Delta = \varphi_p - \varphi_s$ is defined for the value of phases difference after reflection. The amplitudes of these two components being also modified, we measure their variations from the ratio of the E_p and E_s amplitudes after and before the reflection : A_p and A_s. The second ellipsometric parameter ψ is defined by $\mathrm{tg}\, \psi = A_p/A_s$.

For air-metal reflection, the metal is characterized by its complex index $\underline{n}$, the complex reflectances for each component E_s and E_p for incidence angle θ_i are :

$$\underline{\rho_s} = \frac{\cos\theta_i - \left[(\underline{n})^2 - \sin^2\theta_i\right]^{1/2}}{\cos\theta_i - \left[(\underline{n})^2 + \sin^2\theta_i\right]^{1/2}} = A_s\, e^{j\varphi_s}$$

$$\underline{\rho_p} = \frac{\left[(\underline{n})^2 - \sin^2\theta_i\right]^{1/2} - (\underline{n})^2\cos\theta_i}{\left[(\underline{n})^2 - \sin^2\theta_i\right]^{1/2} + (\underline{n})^2\cos\theta_i} = A_p\, e^{j\varphi_p}$$

The relative complex dielectric constant of the metal is

$$\underline{\varepsilon} = \varepsilon_1 - j\,\varepsilon_2 = (\underline{n})^2$$

$$\text{with} \quad \varepsilon_1 = \varepsilon'_r(\omega) \quad \text{and} \quad \varepsilon_2 = \varepsilon''_r(\omega) + \frac{\sigma(\omega)}{\omega\,\varepsilon_0}$$

where $\sigma(\omega)$ is the electrical conductivity for the frequency ω.
J. Shewchun and R.C. Rove [1] established the main relations between ε_1, ε_2, Δ and θ_i :

$$\varepsilon_1 = n_0 \sin\theta_i \left[1 + \mathrm{tg}^2\,\theta_i \frac{(\cos^2 2\psi - \sin^2 2\psi \sin^2\Delta)}{(1 + \sin 2\psi \cos\Delta)^2}\right]$$

$$\varepsilon_2 = n_0 \sin^2\theta_i\, \mathrm{tg}^2\,\theta_i \frac{\sin 4\psi \sin\Delta}{(1 + \sin 2\psi\cos\Delta)^2}$$

Here $n_0 \approx 1$ (air or vacuum).

The measurements of θ_i, Δ and ψ with a precision in order to 10^{-2} degree, we deduce directly the values of ε_1 and ε_2.

3 - Relation between $\underline{\varepsilon}$ and the surface temperature

Such a relation has been shown by different authors for various metals. Winsemius [2] measured ε_2 particularly, for temperatures of a gold surface from 40 K to 295 K versus the wavelength of incident radiation. We propose to use this relation to determine in real time the thermal variation of a gold surface irradiated by an intense laser beam.

4 - Experimental set-up

It was built to measure, in real time, the ellipsometric parameters of a large solid surface (some cm^2), located in air or in a vacuum chamber. The analyzed sample is then illuminated by a laser probe, here 5 mW polarized He-Ne, modulated by an acousto-optic deflector. The laser beam can be moved by a servomotor-optical scanner. A second laser, here 5 W CW Ar^+, can be focused on a small surface of the sample (Ø ~ 0.2 mm) to produce a local heating. The optical ellipsometric signal is detected by a set of monochromator - photomultiplier and lock-in amplifier, with 1 Hz bandwidth.

We use the method first proposed by R.J. Archer [3], the experimental parameters being the azimuthal angles P and A, between the direction of maximum transmission of the polarizer and the analyzer with the normal to the plane of incidence. For a compensator-azimuth C = ± π/4, the detected electrical signal is :

$$S(P, A) \propto I_\omega \left[\sin^2(A - A_i) - \sin 2A_i \ \sin 2A \ \sin^2(P - P_i) \right]$$

where I_ω is the laser-probe intensity, P_i and A_i are the values to be measured. For example, when C = + π/4

$$A_i = \psi \quad \text{and} \quad P_i = \frac{\Delta}{2} - \frac{\pi}{2}$$

The values of nulling angles A and P give the values of A_i and P_i and then that of Δ and ψ. For constant A_i, the signal is a parabolic function of difference $P - P_i$. The increase of temperature shifts the parabola to the increasing P, while the minimum of S(P, A) is conserved. In the case of chemical alteration of the surface, we will observe an irreversible shift without the conservation of the minimum. Conserving P constant close to P_i (with A and A_L constant), any modification of P_i induces a variation of S(P, A). From this variation, we can determine ΔP_i by comparison with the value for a constant P_i and a given ΔP.

5 - Experimental results

All the data reported here were obtained from a gold cathode in air.

First, we proceed to the temperature calibration. The sample is constituted by a thin gold layer (~ 200 nm), deposited on a substrate of silicium of 0.3 mm thickness. This set is glued on a copper disc of 4 mm thickness and 25 mm diameter.

A thermocouple placed in the copper disc just under the silicium, gives the temperature of all the surface because the whole piece is heated uniformly. As the heating power is constant, the temperature increases slowly. The corresponding variation of the ellipsometric signal S(P, A) is simultaneously recorded. The values of S(P,A) for different P, at room temperature were preliminarily recorded.

The influence of the convection increases with the heating time, so that if we can consider that initial evolution of surface temperature is not much perturbed ; after some tens of seconds the temperature would be much reduced. The variations of S(P, A) agree well with the $t^{1/2}$ heating law.

The ellipsometric signal S(P, A) is compared on the Figure 1 to the signal S_0 given by the thermocouple. From S_0 we deduce that 50 Kelvin rise corresponds to a variation $\Delta P = 5.10^{-2}$ degree. The resolution is ≈ ± 2.5 K.

Now we consider a local heating by the (500 ± 14 nm) CW Ar^+ laser. The beam is focused on a spot of 3.10^{-2} mm² at the center of the same disc.

A local equilibrium is established between the air and surface temperatures. For absorbed powers less than 0.25 W, after about 1 second, thermal and index gradients appear locally in air. They cause deviations of probe beam depending of relative positions of the two laser beams, it is the mirage effect [4]. For high power, the thermal variation is extended to all the surface. The probe laser beam is no more deviated, a defocalization appears, increasing with the incident power.

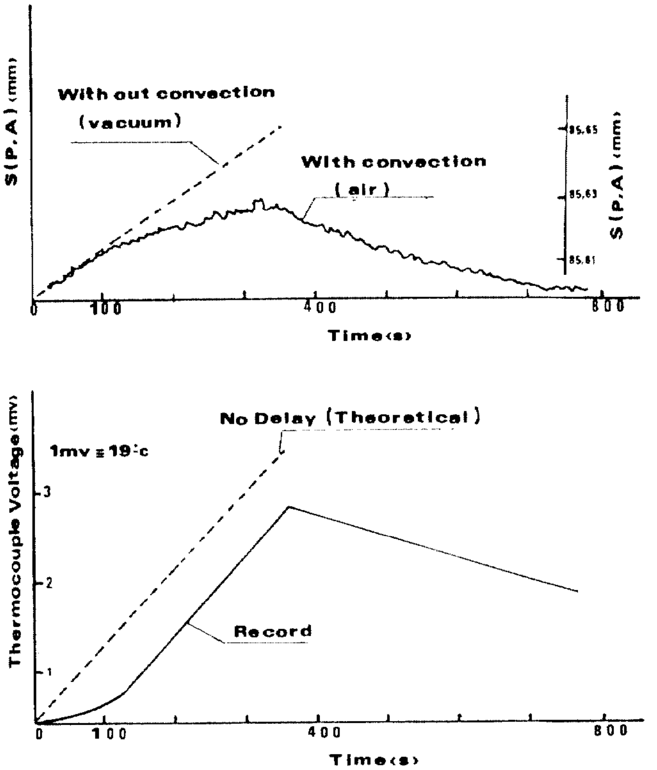

Figure 1 - Simultaneous variations of (a) the ellipsometric signal and (b) the thermocouple voltage for a gold sample heating in air.

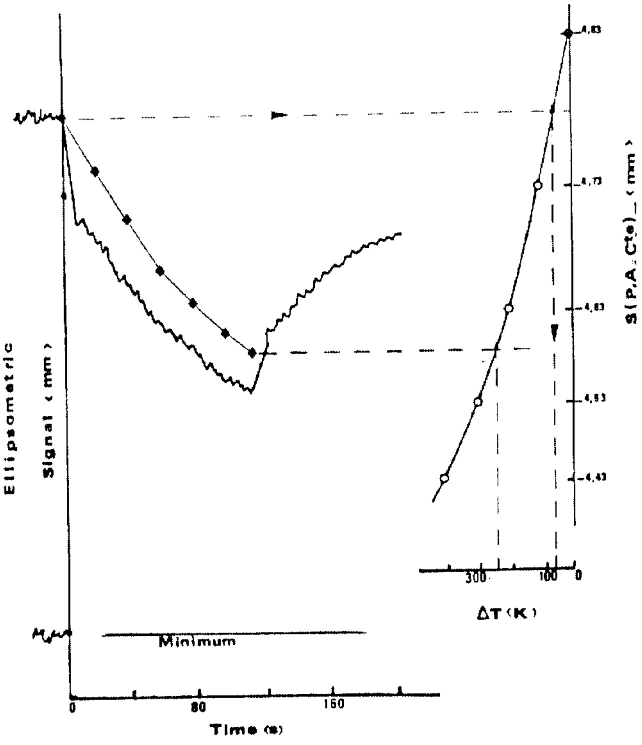

Figure 2 - Ellipsometric signal during the heating by laser, localized at the center of gold surface (Absorbed power 2 W)

The Figure 2 shows S(P, A) during the local irradiation of the sample center by 2 W absorbed power. Values of S(P, A) for different P values, at room temperature are also indicated. A P variation of ~0.1 degree corresponds to a 100 K temperature elevation. The brutal variations at the beginning and the end of the Ar^+ irradiation are imputed to the mirage effect. They correspond to a constant attenuation of the probe beam during the whole duration of irradiation. The corrected values allow the computation of the difference between room and surface temperatures. After the end of illumination the thermal gradient on the surface is lower, cancelling the mirage effect.

The main heating of an element of the gold surface close to the centre is shown on Figure 3.

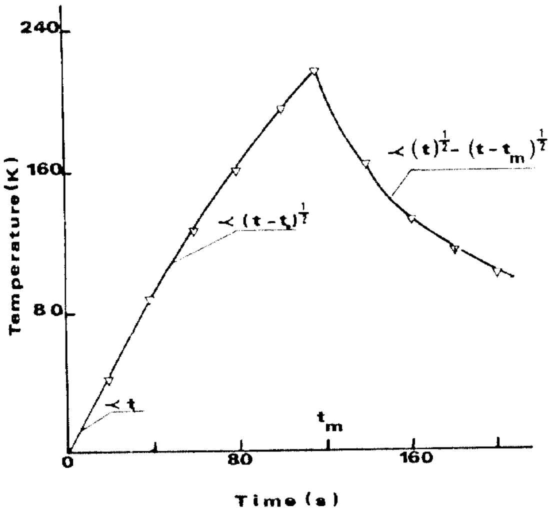

Figure 3 - Results of localized surface temperature measurements during and after heating by a laser

6 - Conclusion

We demonstrated that, in the case of metallic polished surface our ellipsometric method permits effectively the measurements of the temperature of a surface element and to know its evolution in real time. The knowledge of thermal gradients is the only means of computation to stresses.

References

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