Infrared lock-in thermography through glass substrates

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ABSTRACT

Infrared lock-in thermography of an active layer through a glass substrates is demonstrated and explained theoretically. A transition between signal generation close to the active layer and close to the back surface of the substrate is found for glass at 0.5 Hz. For higher frequencies, the signal resolution is given by the thermal diffusion length in glass, very similar to direct observation of the active layer. An experimental difficulty is that the signal is strongly influenced by a slow but strong temperature transient in the beginning of the measurement. It is shown how to correct for this effect efficiently.

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1. Introduction

Infrared lock-in thermography (LIT) is a useful characterization technique widely used in solar cell research and production [1]. An infrared camera captures a stream of temperature images of a periodically excited sample that is instantly lock-in correlated with the excitation frequency. Due to the linearity of the heat conduction process, the resulting images can be interpreted as a map of power dissipation [2].

Lock-in thermography has two main advantages compared to steady-state thermography: a greatly improved signal-to-noise ratio and a much better spatial resolution. Currently, LIT is applied at the cell level for wafer based modules as well as for thin film cells on a glass substrate prior to encapsulation [3,4], since in these cases the active layer is exposed to the camera. For a module encapsulated between two glass panes, however, the technique appears to be unsuitable since a thick layer of glass is mostly opaque for mid-wave infrared radiation (3–5 μm). In this contribution we show theoretically and experimentally that, surprisingly, this is not an obstacle for imaging the active layer.

After reviewing the basics of LIT, we will show that above a certain frequency threshold, the detected signal comes mainly from the thermal wave pattern inside the glass close the active layer. If the signal is generated close to the back surface (low frequencies), the resolution with which the signal reflects the heat source distribution cannot be higher than the glass thickness. If, however, the signal is generated close to the active layer (higher frequencies) it is approximately as good as when imaging the active layer directly.

2. Theory

2.1. General LIT correlation

The lock-in correlation of the solar cell surface temperature $T(x,y,t)$ for a measurement from time 0 to t_{int} according to

$$S(x,y) = \frac{1}{t_{int}} \int_0^{t_{int}} T(x,y,t)(2\sin\omega t + 2i\cos\omega t)\, dt \qquad (1)$$

selectively averages the first harmonic of the temperature modulation response of the solar cell to a square-wave electrical excitation at a frequency of $f = \omega/2\pi$. The excitation has to be on/off only for a well-defined operating point of the solar cell with its highly non-linear current–voltage characteristic.

The temperature modulation signal $S(x,y)$ is an array of complex numbers. It can be displayed as arrays of temperature modulation amplitude $|S(x,y)|$ and phase $\arg S(x,y)$ or alternatively as images of real and imaginary parts $\operatorname{Re} S(x,y) = S^0(x,y)$, $\operatorname{Im} S(x,y) = S^{90}(x,y)$. The correlation convention (1) gives a phase angle $\arg S(x,y) = 0°$ for a temperature modulation signal in phase with the first harmonic of an on/off square-wave excitation. It is necessary to include the factor of two such that the $|S(x,y)|$ is the amplitude of a sine-shaped temperature signal.

In all practical realizations of LIT, the correlation is not done continuously as in Eq. (1) but with a finite number n of temperature measurements (image frames from the camera) per lock-in period. For a total number of N lock-in periods, (1) is approximated by

$$S^0(x,y) = \frac{1}{nN} \sum_{i=1}^{N} \sum_{j=1}^{n} T_{i,j}(x,y) K_j^0 ,$$

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$$S^{90^\circ}(x,y) = \frac{1}{nN} \sum_{i=1}^{N} \sum_{j=1}^{n} T_{i,j}(x,y) K_j^{90^\circ}, \qquad (2)$$

where $T_{i,j}(x,y)$ denotes the temperature measurement at the time of the j-th frame in the i-th lock-in period. The weighting factors K_j are given by

$$K_j^{0^\circ} = 2\sin\left(\frac{2\pi(j-1)}{n}\right),$$

$$K_j^{90^\circ} = 2\cos\left(\frac{2\pi(j-1)}{n}\right). \qquad (3)$$

We will need these factors in the correction of the spurious effect of temperature drifts in the experimental Section 3.3.
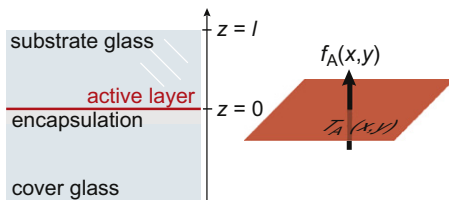
The above discussion is based on the assumption that the IR radiation detected in the camera originates from the surface of an opaque sample of known emissivity. In this contribution we are interested in the question whether information about an active layer can be deduced through a glass substrate. In the limiting case that this substrate was fully opaque, a camera looking from the back surface (opposite to the active layer) would register only the thermal wave pattern on the back surface of the glass substrate.

Since the propagation of dissipative waves is strongly damped, the amplitude there is orders of magnitudes lower than the thermal amplitude near the active side of the sample for usual lock-in frequencies of 0.1–100 Hz. Another effect of the wave propagation from the active side to the back side of an opaque substrate is a significant loss in resolution: the pattern of thermal waves at the back surface does not reflect details of the heat source distribution much smaller than the substrate thickness, since details are damped out of the signal due to lateral heat conduction. For these two considerations LIT through glass substrates was generally avoided [1].

2.2. Signal generation in the glass volume

Fortunately, however, glass is not perfectly opaque. Its transmission of 1% through a 3 mm sheet [5] corresponds to an absorption length of $L \approx 0.65$ mm. For thermal waves the attenuation is given by the thermal diffusion length $\Lambda = \sqrt{2D/\omega} \approx 0.46$ mm (D: thermal diffusivity) for an excitation frequency $f = \omega/2\pi = 1$ Hz in glass. Thus both attenuation effects are of comparable magnitude and it depends on the frequency which of the two is dominant. The fully opaque model described above is thus only a good approximation for very low excitation frequencies.

To understand signal formation inside the glass (Fig. 1), let us assume we know the distribution of temperature in the active layer and the heat flux through this layer. The fields of temperature and flux at $z=0$ contain the maximum amount of information about the heat source distribution in the active layer. The theoretical treatment shows that the signal reaching the camera is mostly generated close to the active layer above a certain frequency threshold, independent of the actual distribution of

temperature and flux there. In this case, the information about the heat source distribution is thus not lost to thermal blurring.

The propagation inside a homogeneous slab of substrate glass follows the heat equation for harmonic excitation

$$0 = D\nabla^2 T(x,y,z) - i\omega T(x,y,z). \qquad (4)$$

This equation does not include a source term as heat enters the glass substrate only from the active layer, i.e., through a boundary condition. The amplitude of the complex valued temperature $|T(x,y)|$ is the temperature modulation amplitude, the phase $\arg T(x,y)$ follows the same convention used in the correlation procedure, Eq. (1).

Through a two-dimensional (x,y) Fourier transform the heat equation (4) simplifies to

$$0 = -\eta^2 T(k_x,k_y,z) + \frac{\partial^2}{\partial z^2} T(k_x,k_y,z), \qquad (5)$$

using the wave vector-like quantity $\eta^2 = i\omega/D + k^2$. The coordinates (x,y) in the image plane are transformed to the spatial frequency vector (k_x,k_y) with the absolute value $k^2 = k_x^2 + k_y^2$. The temperature field in the glass is completely determined by the oscillating boundary values $T_A(k_x,k_y)$ and $f_A(k_x,k_y)$ at $z=0$. The solution of the heat equation for the temperature at depth z is

$$T_G(k_x,k_y,z) = T_A(k_x,k_y)\cosh(-\eta z) + \frac{f_A(k_x,k_y)\sinh(-\eta z)}{\eta\lambda}. \qquad (6)$$

If the glass is thermally thick, i.e., if $|\eta l| \gg 1$ (given for high spatial frequencies and if the thermal diffusion length Λ of the glass is small compared to its thickness) the cosh and sinh can be approximated as

$$T_G(k_x,k_y,z) \approx \exp(-\eta z)[T_A(k_x,k_y) + f_A(k_x,k_y)/\eta\lambda]/2$$
$$\propto \exp[-\mathrm{Re}(\eta)z]. \qquad (7)$$

The imaginary part of η does not influence the amplitude of the signal. This approximation is valid for most of the glass substrate volume except a slab of approximately one thermal diffusion length thickness close to the active layer of the glass. There, cosh and sinh approach 1 and 0, respectively.

The probability that a photon is emitted inside the glass is proportional to the absorption α inside the glass (Kirchhoff's law of thermal radiation, the emissivity of a thin layer dz is $\alpha\,dz$). The probability that an IR photon emitted inside the glass reaches the back $z=l$ of the glass is given by $\exp\alpha(z-l)$ (abaxial photons do not reach the camera). Therefore, the emission from a thin layer of glass at depth z that reaches the back surface is given by

$$p(k,z)\,dz = T_G(k,z) \cdot \alpha \cdot \exp\alpha(z-l) \cdot dz$$
$$\propto \exp[\alpha z - \mathrm{Re}(\eta)z]\,dz. \qquad (8)$$

Some of these photons get reflected inside the glass at the glass–air interface. Quartz glass has an index of refraction of 1.42–1.34 in the spectral range $3\ldots5\,\mu$m, corresponding to only 3% reflection at the interface [6]. Other glasses like soda-lime or borosilicate glass show similar values, leading only to insignificant reflections that affect the signal homogeneously.

Eq. (8) shows competing trends that can be understood most easily for homogeneous excitation $k=0$. Using the optical absorption length $L = 1/\alpha$ and the thermal diffusion length Λ, (8) reads

$$p(k,z)\,dz \propto \exp(z/L - z/\Lambda)\,dz. \qquad (9)$$

Seen from the back surface ($z=l$), the probability that photons reach the camera drops exponentially while the amplitude of the thermal wave (and thus the probability that photons get emitted) increases exponentially. Which of the two is dominant depends on the value of Λ, a function of the excitation frequency f. It can be seen from (9) that the signal at the camera is mostly emitted from glass near the active layer if Λ is small compared to the absorption length L. Conversely, the signal is mostly generated at

Fig. 1. Typical glass–glass solar module with geometrical conventions. Temperature and flux at the active layer $z=0$, $T_A(x,y) = T(x,y,0)$ and $f_A(x,y) = -\lambda\partial T(x,y,z)/\partial z|_{z\to 0^+}$ (taken in the substrate glass close to the active layer, λ: thermal conductivity of the glass) carry more information about the heat source distribution in the active layer than temperature and flux in any other depth z.