Photopyroelectric versus photoacoustic characterization of photovoltaic cells

I. F. Faria, Jr., C. C. Ghizoni, and L. C. M. Miranda
Instituto de Estudos Avançados. Centro Técnico Aeroespacial. 12200 S. J. Campos, SP, Brazil

H. Vargas
Instituto de Física, Universidade Estadual de Campinas, 13100-Campinas, SP, Brazil

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The photothermal pyroelectric technique is applied to the characterization of photovoltaic cells and a comparison with the photoacoustic detection is presented. The difference between the photoacoustic and the pyroelectric data is interpreted in terms of a simple model for a junction-type solar cell.

In the last few years a great deal of effort has been devoted to the development of the so-called photothermal spectroscopies (PTS). The basic principle underlying these spectroscopic techniques is the detection of the heat produced in a sample, due to nonradiative deexcitation processes, resulting from the absorption of modulated light. The different techniques employed in the photothermal spectroscopy are named according to the mechanism used for detecting the thermal wave. Since the pioneering photoacoustic (PA)1 and piezoelectric2 detection techniques, several mechanisms have been proposed for the PTS. These include the photodisplacement spectroscopy,3,4 the beam deflection spectroscopy,5,6 the photothermal radiometry,7,8 and the newly developed photopyroelectric spectroscopy9-11 (PPS). The common feature of all these techniques is that their signals are proportional to the light into heat conversion efficiency and therefore complementary to the other photoinduced energy conversion processes. This aspect of the thermal wave signal has been explored by several authors for investigating photoinduced energy conversion processes. These investigations range from the study of photosynthetic processes in leaves12,13 to the monitoring of photovoltaic conversion efficiency of solar cells,14,15 and the study of nonradiative recombination processes in semiconductors.16 Except for a few works17,18 using the photothermal radiometry, most of these works on photoinduced conversion efficiency have been carried out using photoacoustics.

In this paper we report on the use of the recently developed PPS9-11 to the characterization of photovoltaic cells. This technique consists of using a thin pyroelectric film (e.g., polyvinylidene difluoride, PVF2) in intimate contact with the (nonilluminated) back surface of a solar cell. Following the absorption of modulated light, the nonradiative deexcitation processes within the cell cause its temperature to fluctuate and through heat diffusion to the surrounding pyroelectric film, the cell-pyroelectric film interface temperature fluctuates. As a result of this temperature fluctuation a pyroelectric signal is produced which is proportional to the temperature change in the film. The generated signal in the PVF2 film due to the internal heat generation in a resistively loaded solar cell is written as $S(R_L) = S_{OC}(1 - \gamma)$, where $S_{OC}$ is the open-circuit signal which depends on the internal loss mechanisms and $\gamma$ is the photovoltaic conversion efficiency to an external load $R_L$. Figure 1 shows the results for $\gamma$ for a p-n solar cell illuminated at 18 Hz by a 5.2-mW He-Ne laser, using both the PP and the PA techniques. The PA data was obtained using a conventional gas-microphone PA chamber with the back contact of the Si cell flushed against the back wall of the PA chamber. Both curves in Fig. 1 show a clear maximum around the optimal load resistance $R_P$. The PA-determined optimal load resistance, $R_P(\text{PA}) = 350 \Omega$, agrees quite well with that determined from electrical measurements, whereas the PP-determined optimal load resistance, $R_P(\text{PP}) = 400 \Omega$, is slightly higher. Two other significant differences between the PA

![Graph](https://example.com/graph.png)

**FIG. 1.** Photopyroelectric $\gamma_{PP}$ (solid) and photoacoustic $\gamma_{PA}$ (dashed) conversion efficiencies as a function of the load resistance $R_L$ for a 500-μm-thick p-n solar cell, at 18 Hz under 5.2 mW He-Ne laser illumination. At 350 Ω the PA-determined conversion efficiency is ~12%, whereas the PP-determined optimal conversion efficiency is ~5% at 400 Ω.
and PP conversion efficiencies were observed. First, the value of $\gamma$ at the optimal load resistance obtained from the PA measurement is about 12%, whereas the corresponding PP optimal conversion efficiency is 5%. Second, the PP-determined $\gamma$ becomes negative for $R_L \leq 200 \, \Omega$. This latter feature suggests that the pyroelectric measurement is sensitive to some additional heat sources resulting from the illumination. The difference between the PP and PA normalized signals, $\Delta S/S(OC) = \gamma_{PA} - \gamma_{PP}$, as a function of the load resistance is shown in Fig. 2. This figure shows that the excess PP signal is a monotonically decreasing function of the load resistance. In contrast, as recently suggested by Caben and Halle, the PA measurement seems to be sensitive only to the heat generated close to the surface. This is confirmed by our results at high modulation frequencies for which our sample is no longer thermally thin. Our PA results at 200 Hz, for which the thermal diffusion length $\mu_{th}$ is 360 $\mu$m ($<l = 500 \, \mu$m), yielded the same optimal conversion efficiency and load resistance as that at 18 Hz.

To explain the observed differences between the PA and PP conversion efficiencies we resort to the simple model for a $p-n$ junction-type solar cell shown in Fig. 3. The radiation absorbed within one carrier diffusion length from the junction generates a current $I_{SC}$ and a voltage $V_J$. This current splits into two components—one, $I_L$, which flows through the diode to the load, and another one, $I_J$, which is injected across the junction. The additional heating which seems to be detected by the PP measurements may be attributed to two main sources. One is the heating in the cell and contacts caused by the current $I_L$. This contribution corresponds to the current dissipation at the internal resistance $R_s$ of Fig. 3 given by $Q = R_s I_L^2$. The second heat source may be the nonradiative surface recombination at the back surface of the cell. Assuming the carrier relaxation time in a Si solar cell to be typically about $10^{-4}$ s, the electron (hole) diffusion length would be of the order of 600 (350) $\mu$m, so that the carriers generated at the top portion of the cell would eventually diffuse deeper into the base of the cell. To check for these two possibilities we have measured the PP signal at 200 Hz. At this frequency the sample is thermally thick so that the PP signal dependence on $R_L$ would eventually single out the dominant heating mechanism. In Fig. 4(a) we show the dependence of the normalized PP signal, $S(R_L)/S(OC)$, as a function of $R_L$. Here, we note that the PP signal is a monotonically decreasing function of $R_L$ exhibiting no minimum. This is evidence that at this modulation frequency no photovoltaic effect is being detected by pyroelectric film. In Fig. 4(b) we show the dependence of $I_L^2$ on the load resistance as obtained from the electrical measurements. The remarkable similarity between Figs. 4(a) and 4(b) suggests that the dominant additional heating detected by the PVF2 film is due to the dissipation of $I_L$ through $R_s$, as suggested above, with the surface recombination being apparently negligible. This additional heating sensed by the PP technique is also responsible for the difference observed in the PA- and PP-determined values of the optimum conversion efficiencies. The electrical measurements yielded an optimum conversion efficiency of 10.7% at the optimum load resistance as the PA measured one ($\approx 350 \, \Omega$). This value is quite close to the PA-determined optimum conversion efficiency of 12% (with an error of $\pm 15\%$), and differs by a factor of roughly 2 from the PP-determined value of 5%. The Joule heating is mainly generated in the base region (the widest of the three regions) of the solar cell and could, in principle, also contribute to the PA signal. The PA measurements, both at low and high modulation frequencies, show, however, that this additional heating is strongly damped so that the PA signal senses only the front surface contribution. One possible explanation for this is that there is a preferential flow, towards the back silvered contact, for the heat generated in the base region. The thermal conductance to the silvered back contact is roughly three times ($k_{Ag}/k_{Si} \approx 2.8$) larger than that of Si, so that the
Correspondence between coherently strained multilayers and a single coherently strained layer on lattice mismatched substrate

R. People
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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The equilibrium in-plane lattice parameter for lattice mismatched multilayers, as first derived by Matthews and Blakeslee [J. Cryst. Growth 32, 265 (1976)], has been used to obtain an expression for the misfit between the multilayers as a whole and a lattice mismatched substrate. The resulting expression immediately suggests a correspondence between the multilayers as a whole and a single coherently strained layer of equal thickness but having a misfit equal to the misfit between the constituent layers spatially averaged over a single repeat distance. The present results are obtained without reference to the energy density of a misfit dislocation. In particular, the present correspondence allows one to predict the critical thickness of coherently strained multilayers if single-layer critical thicknesses are known.

Coherently strained multilayers consist of thin alternating layers of materials which are lattice mismatched in bulk form but which elastically strain to uniformly match up the lattice constants of the materials in the planes parallel to the heterointerfaces. An unstrained set of mismatched layers and the corresponding set of strained layers are shown schematically in Fig. 1. The resulting value of the in-plane lattice constant \( a^\parallel \) is intermediate between the unstrained lattice constants of the multilayer constituents. Matthews and Blakeslee\(^1\) have obtained an expression for \( a^\parallel \) by minimizing the total elastic strain energy of a single pair of layers. If it is assumed that \( a_1 < a_B \), then

\[
a^\parallel = a_A \left( 1 + f \frac{1 + G_A h_A}{G_B h_B} \right),
\]

where \( A \) and \( B \) refer to the layers, \( f \) is the volume fraction of layer \( A \), and \( G \) is the shear modulus of each layer.