Infrared photocarrier radiometry, modulated photovoltage and electrical characteristics of polycrystalline Si solar cells

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Abstract. Laser-induced infrared photocarrier radiometry (PCR) was used to characterize industrial polycrystalline silicon solar cells. The ac photovoltage was measured simultaneously with the PCR signal. The PCR and ac photovoltage signals were investigated as functions of modulation frequency, excitation intensity, external dc illumination and load resistance. The interrelation and interpretation of PCR signal, ac photovoltage and static (dc) electrical parameters of solar cells are discussed.

1. Introduction
Nondestructive and noncontact methods for optoelectronic diagnostics of solar cells at all stages of the fabrication process are in strong demand. Laser-induced infrared photo-carrier radiometry (PCR) is a powerful methodology for the measurements of transport properties of semiconductors \cite{1} and is therefore very suitable for such applications at the device level. Although dc photoluminescence (PL) and electroluminescence (EL) are increasingly being used for qualitative quality control of solar cells \cite{2, 3}, PCR, as a dynamic spectrally-gated form of PL, can potentially yield precise quantitative information about transport and recombination processes in junction devices like solar cells. In this paper we report the first ever PCR investigation of industrial polycrystalline-Si solar cells. We have developed the PCR theory and interpreted our signals in terms of optoelectronic physical processes in conjunction with ac photovoltage frequency scans and electrical characteristics.

2. Materials and experimental set-up
A solar cell featuring a $p$-$n$ junction fabricated on a $p$-type industrial polycrystalline Si wafer (156 x 156 mm$^2$ area, 200 µm thickness) was irradiated with a square-wave-modulated laser beam. The wavelength of the laser and its spotsize on the solar cell were 830 nm and 387 µm, respectively. Frequency scans were performed from 2 Hz to 100 kHz at room temperature. The near infrared radiative emissions from the solar cell were detected using an InGaAs detector (spectral bandwidth 1-1.8 µm). The PCR signal and the modulated (ac) photovoltage, $V_{ph}$, were measured simultaneously using lock-in amplifiers. The experimental PCR configuration has been described elsewhere \cite{1}. The electrical connections for $V_{ph}$ and the measurement of $I$-$V$ characteristics were conventional. Additional dc illumination was provided when needed by a halogen lamp.
3. Results and discussion

Typical I-V characteristics of the investigated solar cell were measured using a load resistance box in the dc mode. The photocurrent, $I_{ph}$, was obtained with the same laser parameters as those for PCR and $V_{ph}$ measurements. The current $I$ through the load resistance $R_L$ gives rise to a voltage $V$:

$$I = I_{ph} - I_0[\exp(qV/nkT) - 1] - V/R_{sh},$$

(1)

where $n$ is the ideality factor and $R_{sh}$ is the shunt resistance [4]. $I_{ph}$ is equal to the short-circuit current, $I_{SC}$, and the dark saturation current $I_0$ can be expressed as

$$I_0 = (I_{SC} - V_{OC}/R_{sh})/[\exp(qV_{OC}/nkT) - 1].$$

(2)

$I_{SC}$ and the open-circuit voltage, $V_{OC}$, as well as $n$ and $R_{sh}$ were calculated by fitting Eq. (1) to the data. They were found to be 18.5 mA, 418.8 mV, 1.7, and 300 Ω, respectively. The voltage and current at the maximum power point were 324 mV and 15.4 mA. Eq. (1) does not take into account the variation of $I_0$ and $n$ over the I-V curve, which leads to some variation in the fitted values of $n$ and $R_{sh}$ with changing illumination level. At low illumination levels the calculated $R_{sh}$ was close to its dark value as measured with a standard procedure, $R_{sh} \approx 1700$ Ω.

In order to describe the ac characteristics of the solar cell, a suitable equivalent circuit model was used as shown in the inset of Fig.1. The ac photovoltage $V_{ph}$ can be expressed as

$$V_{ph} = I_{ph}/(1/R_j + 1/R_L + i2\pi f C_j),$$

(3)

where the junction capacitance $C_j$ is the sum of depletion layer capacitance $C_d$ and diffusion capacitance $C_d$; $f$ is the modulation frequency. The $V_{ph}$ dependence on frequency at different $V_{OC}$ values is shown in Fig. 1. At high frequencies $V_{ph}$ decreases $\propto f_c$ due to the junction capacitance-induced RC time constant.

![Figure 1. Small-signal $V_{ph}$ frequency scan. Open circuit mode using low-intensity modulated laser beam and various levels of dc illumination, resulting in various $V_{OC}$ values. (a) Amplitude; (b) phase.](image)

The cut-off frequency $f_c$, defined as

$$f_c = (R_j + R_L)/(2\pi C_j R_j R_L),$$

(4)

shifts to higher values when the voltage increases across the junction. $C_j$ lies in the range $-10.3 \mu F$ for 0 mV to $-21.5 \mu F$ for 450 mV and $R_j$ from $-1600 \Omega$ to $-1 \Omega$, respectively. The fitted $R_j$ value is very close to $R_{diff} = dV/dI$, estimated from the I-V curve measured in the dark. The large capacitance of the solar cell masks effects associated with the minority carrier lifetime in the $V_{ph(f)}$ frequency dependence, and results in shifting the well-known transition point from the $f^{-1}$ to the $f^{-3/2}$ regime for the photovoltage frequency dependence [5] beyond the measurement frequency range, Fig. 1a.

The frequency responses of $V_{ph(f)}$ at large excitation amplitude obtained with peak laser power 30.9 mW at OC and with 30.5 Ω, 20.5 Ω, and 0.5 Ω load resistance are shown in Fig. 2. The OC amplitude curve and those at high load resistance have two pronounced bending points with corresponding features in the phase-frequency responses. The behavior is different for $R_L \leq 30.5 \Omega$ (single bending point). These features can be explained through changes in the cut-off (or “knee”) frequency, $f_c$, from...
0 to $V_{oc}$. More physical insights on the origins of the $V_{ph}$ frequency response can be garnered using a digital oscilloscope (Tektronix DPO7104). Fig. 3 shows that the first bending point is caused by the growth of the signal baseline. The second bending point is due to the reduction of the peak signal. The low-frequency bending point corresponds to $f_c$ for 0 V across the junction. The second bending point corresponds to the cut-off frequency for peak junction voltage $V_p$. The calculated $f_c$ values for OC, 30.5 $\Omega$, 20.5 $\Omega$, 10.5 $\Omega$, 1.5 $\Omega$, and 0.5 $\Omega$ are also indicated in Fig. 3a. It can be seen that the difference between signal baseline $f_c$ and peak $f_c$ strongly decreases with decreasing load resistance and practically disappears for $R_L \leq 30 \Omega$. The dependence of $V_p$ on frequency can be modeled by

$$V_p = V_{ph}/2 + V_{p0}, \quad (5)$$

where $V_{ph}$ is the peak voltage at modulation frequencies $f >> f_c$. $V_{ph}$ is given by Eq. (3) for $R_p$, $C_j$ corresponding to $V_p$ at $f << f_c$, and for $I_{ph}$ such that $V_{ph} = 2(V_p - V_{p0})$ at $f << f_c$. The signal amplitude frequency scan, Fig. 3b, is practically the same shape as that measured with the lock-in amplifier, Fig. 2, as expected. The simulated amplitude represents the sum of two signals with $f_c$ for voltage $V = 0$ and $V = V_p$ correspondingly. The fitted amplitude frequency dependencies show the same features as experimental.

![Figure 2](image)

**Figure 2.** Frequency dependence of $V_{ph}$ induced with laser beam peak power 30.9 mW. (a) Amplitude; (b) phase.

![Figure 3](image)

**Figure 3.** a) Frequency dependence of peak and baseline of $V_{ph}$ induced with the same square waveform as Fig. 3 and laser peak power 30.9 mW for various values of load resistance, as measured with an oscilloscope; b) Frequency scan of the difference peak-baseline.

The frequency dependence of the PCR signal, $S_{PCR}(f)$, is presented in Fig. 4. The amplitude and phase dependencies for $R_L = 0.5 \Omega$ have shapes similar to signals obtained from plain Si substrate
wafers [1]. For \( R_L \geq 10.5 \, \Omega \), the PCR amplitudes exhibit two levels with corresponding phase features. This type of behavior is unlike plain Si wafer PCR signals and is the result of two time constants, \( \tau_1 \) and \( \tau_2 \). Comparing the \( V_{ph}(f) \) and \( S_{PCR}(f) \) frequency dependencies shows that the longer (\( \tau_1 \)) lifetime corresponds to \( f_c \) of the peak photovoltage value and its origin must be sought at the junction \( \tau_1 = (1/R_J + 1/R_L)^{-1}C_J \). The shorter (\( \tau_2 \)) lifetime is the result of minority carrier recombination in the quasi-neutral bulk p-type region. Due to the large junction capacitance of modern large size solar cells, a significant number of minority carriers are involved in near-junction charge - process leading to reduction of excess minority carriers at frequencies \( f > f_c \). As can be seen in the frequency dependence of the peak voltage \( V_p \), Fig. 3, this effect is more pronounced for \( R_L \sim 10-100 \, \Omega \) and is reflected in the emergence of two relaxation lifetimes in the PCR frequency response.

The best fitted curves yield for \( \tau_1 \) and \( \tau_2 \) values are presented in Table 1 using a simple model for two recombination lifetimes expressed by

\[
S(f) = C_1/(i2\pi f + \tau_1^{-1}) + C_2/(i2\pi f + \tau_2^{-1}),
\]

where \( C_1 \) and \( C_2 \) are constants. The \( \tau_1 \) values are close to time constants \( 2\pi f \tau_1 \sim 1 \) calculated from \( f_c \) on the \( V_{ph} \) dependences (see Table 1). Some values discrepancies are due to our use of simplified photovoltage model which ignores the change of \( f_c \) in the voltage interval from \( V_p \) to \( V_{ph0} \).

| Parameter      | DC   | PCR | AC photovoltage |
|----------------|------|-----|-----------------|
| \( \tau_1 \) (OC) | 0.15 ms | 0.044 ms |
| \( \tau_1 \) (30.5 \, \Omega) | 0.24 ms | 0.12 ms |
| \( \tau_1 \) (20.5 \, \Omega) | 0.26 ms | 0.16 ms |
| \( \tau_2 \) (OC) | 5.2 \, \mu s |
| \( \tau_2 \) (30.5 \, \Omega) | 2.8 \, \mu s |
| \( \tau_2 \) (20.5 \, \Omega) | 1.9 \, \mu s |
| \( R_L \) for max power | 21 \, \Omega | 17 \, \Omega at 0.01 kHz |
|                |      | 27 \, \Omega at 100 kHz |

To reduce the influence of the capacitance it is necessary to apply a forward bias voltage, generated by, e.g., a dc bias light. We found that PCR frequency dependencies are not sensitive to capacitive time constant at intense dc illumination due to probably \( \tau_1 < \tau_2 \).
The PCR amplitude dependence on load resistance at various frequencies is presented in Fig. 5a. For all frequencies the PCR signal increases with increasing resistance and saturates at OC. According to [2] the photovoltage generated across the solar cell is proportional to $ln(I_{PL,rel})$, where $I_{PL,rel}$ is the relative PL signal. Therefore, the current through the load resistance $R_L$ is proportional to $PCR(OC) - PCR(R_L)$. On the basis of this discussion, the quantity $(PCR(OC)-PCR(R_L))^2 R_L$ reflects the solar cell power at $R_L$.

The dependence $(PCR(OC)-PCR(R_L))^2 R_L$ on $R_L$ is presented in Fig. 5b. The curves for 0.01 kHz and 0.1 kHz are identical. The maximum power point is essentially the same as for dc measurements (see Table 1). That point is shifted to higher load resistances with increasing frequency. Probably, this shift occurs due to effect of capacitance on the PCR signal for frequencies near $\tau_1$.

4. Conclusions
The first application of photocarrier radiometry to polycrystalline Si solar cells is demonstrated to be a quantitative non-contacting and non-destructive diffusion-wave method for optoelectronic transport and equivalent electrical circuit diagnostics with potential application to the control of solar cell parameters. Aided by the correlation of PCR and modulated photovoltage signals, the frequency dependence of the PCR signal on minority carrier recombination lifetime in the quasi-neutral region (bulk), junction capacitance and load resistance was explored. It was shown that the dependence of the solar cell power on load resistance can be quantified from the PCR measurements. Further theoretical calculations of the photocarrier transport equations in the solar cell circuit is under way.

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