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Capacitance effects in high-efficiency cells

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Abstract

Frequently transient measurement techniques lead to capacitance effects which complicate the accurate measurement of the performance of high efficiency solar cells. The photo-current-response measurement (PCR), developed at ESTI, offers a tool for the investigation of these capacitance effects. This paper describes the theory of capacitance effects and the diffusion capacitance as experimental results achieved by the PCR-method. The theory shows that the diffusion capacitance is strongly dependent on the minority carrier diffusion length and lifetime. In the future the PCR-method could be used for the determination of this solar cell parameter. We show, using monochromatic light pulses, that the induced diffusion capacitance charge (Q_{diff}) is exponentially dependent on the bias voltage and linearly dependent on the light intensity. Finally, the capacitance effect is made clearly visible by the generation of the current–voltage characteristic from PCR-measurements.

Keywords: Capacitance; High-efficiency cells

1. Introduction

Because of increasing quality assurance requirements on calibrations and growing importance of high-efficiency cells, a correct characterisation of photovoltaic devices is essential. It is well known that using pulsed light sources for the current-voltage (IU) characterisation of high efficiency cells, special precautions must be taken to ensure an accurate measurement [1–6]. In the past, efforts were made to develop correction procedures [1–4] for transient IU-measurements, but the physical mechanism causing

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the discrepancy between quasi-steady-state and transient measurements results is not yet fully understood. So far we know that one of the device features responsible for these distortions is the voltage-dependent capacitance. The capacitance of a PV-device is the sum of the diffusion capacitance (C_{diff}) and the depletion layer capacitance (C_{depl}). Since distortions are only observable at voltages near and greater than the maximum power point (V_{mp}), where C_{depl} can be neglected, our interest lies only in the diffusion capacitance (C_{diff}). Forward biased high-efficiency cells can show a diffusion capacitance in the range of some μF. In these cases the determination of the Fillfactor can lead to errors up to 20%. For a better understanding of the so-called capacitance effect systematic capacitance measurements of different photovoltaic devices have been performed and compared with theory. At ESTI we developed, for these types of measurements, a method to measure the light-induced diffusion capacitance charge (Q_{Diff}) in silicon solar cells [7]. The measurement is based on the photocurrent response of a photovoltaic device for fixed bias voltages. The photocurrent is induced by a square-shaped monochromatic irradiation pulse of approximately 20 μs. This paper shows the theoretical background and experimental results achieved by this transient measurement method. The dependence of the capacitance charge on the bias voltage and the light intensity has been investigated for different silicon solar cells. It is shown that the diffusion capacitance charge is exponentially dependent on the bias voltage and linearly dependent on the light intensity.

2. Theory

2.1. The diffusion capacitance

The diffusion capacitance (C_{diff}) results from the effect of excess minority carriers stored in the quasi-neutral region of a diode. This charge is compensated by an equal quantity of excess majority carriers drawn from the opposite side of the junction. For a time-dependent photocurrent induced by an irradiation pulse the excess minority charge must change, implying a capacitive effect. From open-circuit-voltage-decay tests [8] and analytical models [9] it is known that an exponential dependency exists between C_{diff} and U. C_{diff} can be expressed as

$$C_{Diff} = C_0 \exp\left(b \frac{q}{kT} U\right), \tag{1}$$

where C_0 is the base capacitance and b a fitted parameter. The base capacitance (C_0) includes the excess minority carriers diffusion length in the base (L_n) and is written as

$$C_0 = \frac{q}{kT} \frac{q n_i^2}{N_A} L_n . \tag{2}$$

We know from literature [10] that C_{diff} can also be written as a function of the diode current (I_{diode}) and τ_F. The latter is defined as $\tau_F^{-1} = \tau^{-1} + \tau_B^{-1}$, where τ is the minority carrier lifetime and τ_B the transit time of the carriers across the diode. The diffusion capacitance (C_{diff}) is directly proportional to the product of τ_F and I_{diode}, and inversely proportional to the absolute device temperature (T) and can therefore be expressed as

$$C_{\text{Diff}} = \frac{q}{kT}\tau_F I_{\text{diode}}. \tag{3}$$

The inverse transit time (τ_B^{-1}) is negligible if the solar cell base thickness (d) is greater than L_n. The diffusion capacitance (C_{diff}) is therefore directly proportional to the minority carrier lifetime (τ).

2.2. The capacitance effect

The capacitance effect can be partially explained by including the diffusion capacitance as a variable capacity in the equivalent circuit of a solar cell (see Fig. 1).

The discrepancy between quasi-steady-state and transient measurements is due to the capacitive current I_C which must be either added to or subtracted from the photogenerated current, depending on the measurement conditions. For increasing (decreasing) light intensities the cell capacitance must be charged (discharged) which results in a smaller (larger) cell current (I) as measured under quasi-steady-state conditions. The capacitive current (I_C) is given by

$$I_c = C\frac{dU}{dt} + U\frac{dC}{dt}. \tag{4}$$

Neglecting the depletion layer capacitance, assuming a fixed bias voltage (dU/dt) = 0) as it is given in our experiments and considering the serial resistance (R_s), Eq. (4), this can be written as

$$I_c(t) = -C_0 R_s \exp\left[b\frac{q}{kT}(U - I(t)R_s)\right]\left(1 + b\frac{q}{kT}(U - I(t)R_s)\right)\frac{dI(t)}{dt} \tag{5}$$

From $I_C = dQ_{\text{Diff}}/dt$ the capacitance charge (Q_{Diff}) can be derived.

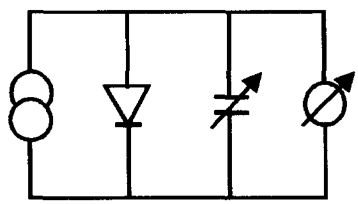

Fig. 1. Equivalent circuit of a photovoltaic device.

3. Experimental approach

3.1. The photocurrent–response measurement

The data from the photocurrent–response measurement is used for determining the capacitance charge (Q_{Diff}) value and for the IU-characteristic from different silicon solar cells. For details of the experimental set-up, see Ref. [7]. The photocurrent (I) is induced by a square-shaped monochromatic (660 nm) irradiation pulse of approximately 20μs duration and an irradiance (E) of 200 W/m^2. The rise and decay time of the induced current (Fig. 2) are observed for different bias voltages (− 0.2 to 0.6 V). The light-induced capacitance charge (Q_{Diff}) can be calculated from the experimental data and the spectral responsivity at 660 nm.

3.1.1. The capacitance charge for different single crystal silicon solar cells

Measurements of the capacitance charge were performed for different single-crystal silicon solar cells of the type n^+P or n^+pp^+ (cell thickness 300 μm, resistivity 1,5 Ω cm, cell area 4 cm^2). Their back surfaces are distinguished by the materials used (Al or Ag) and the presence of phosphorus (P) left as a residue at the rear side during the cell production. The AlP- and AgP-cell have a P-residue. For the Al- and Ag-cell the residue is removed. For comparison reasons, the I_{sc} values are all normalised on 50 mA. We defined the calculated positive capacitance charge values (+) for increasing irradiance and negative capacitance charge values (−) for decreasing irradiance.

The results (see Fig. 3) show the exponential dependence form the bias voltage and an asymmetry between the positive and the negative charge values. The theory

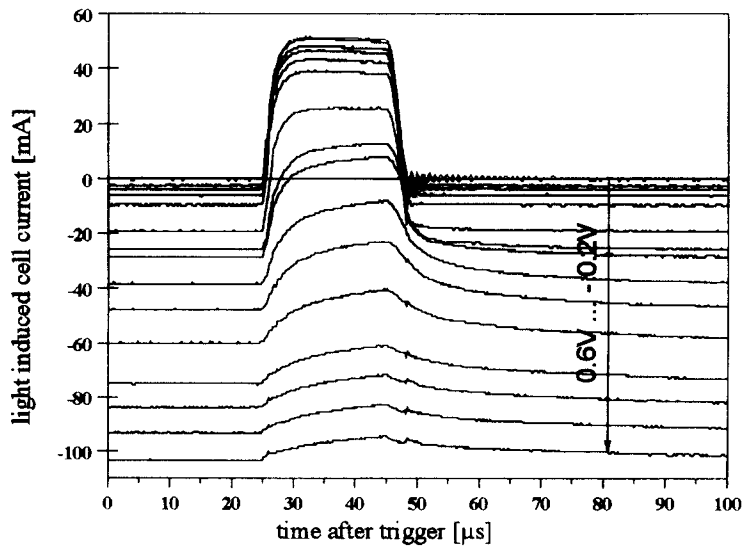

Fig. 2. Photocurrent of a solar cell at different applied voltages induced by a monochromatic light pulse (660 nm, 200 W/m^2).

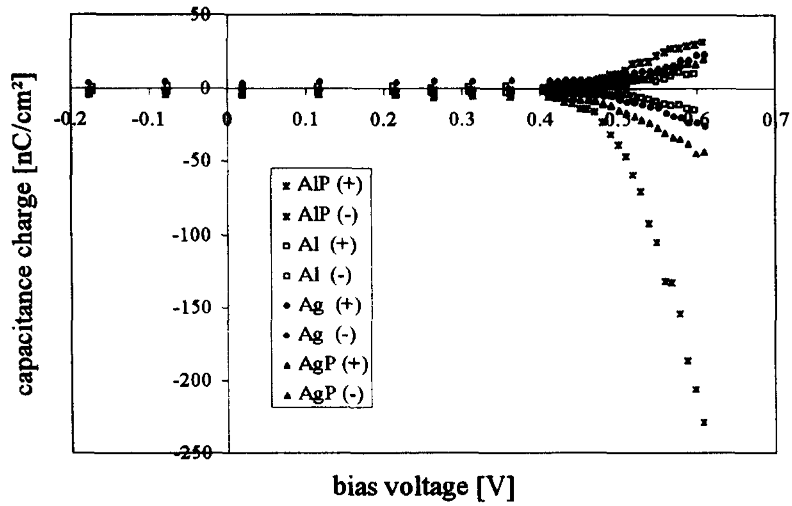

Fig. 3. Capacitance charge over the bias voltage for different solar cells measured for increasing irradiance (+) and decreasing irradiance (−).

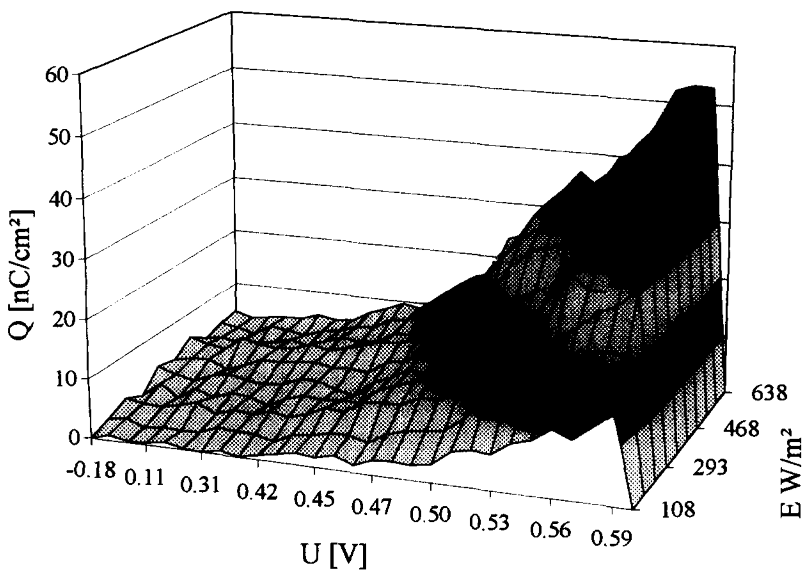

Fig. 4. Capacitance charge (Q) versus bias voltage (U) and light intensity (E).

explains the observed capacitance, but it does not explain the asymmetry between the positive (+) and the negative (−) values. One possible explanation for this asymmetry is the impurity photoconductivity [11]. This leads to a turn-on transient which is faster than the turn-off transient and depends on the illumination level. The

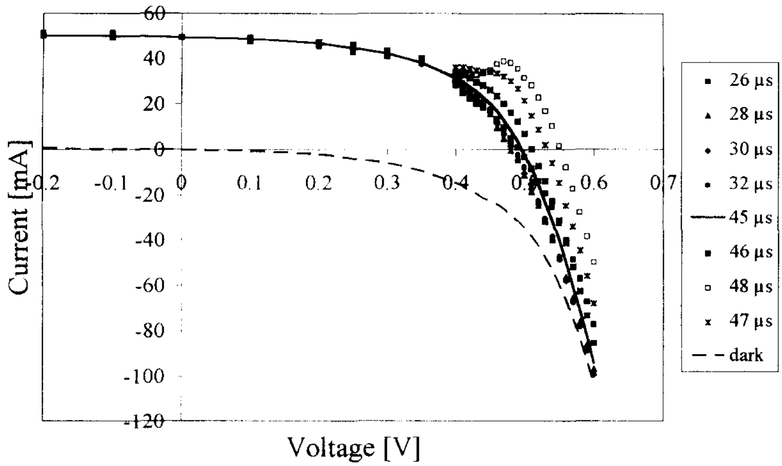

Fig. 5. *IU*-characteristics for different sampling times constructed from data points shown in (Fig. 2).

asymmetry is observed especially for the devices with a P-residue at the rear side. Deep traps could be responsible for this asymmetry, as by cleaning the rear side the asymmetry is reduced. The exponential dependency of the capacitance charge $Q(+)$ of the AlP-device versus bias voltage (U) and the linear dependency of the light intensity E (100–700 W/m^2) are shown in Fig. 4.

3.1.2. *The IU-characteristic*

From the recorded data (see Fig. 2) the current-voltage (IU) characteristic of a photovoltaic device is constructed. Dependent on the sampling time after trigger, different IU-curves are plotted (see Fig. 5). In this case, for the purpose of comparison I_{sc} values are all normalised on 50 mA. During the first 25 µs the dark IU-characteristic can be observed. After the dark period the IU-curves change shape depending on the sampling time. A set of IU-samples at the rising edge of the light pulse (26–32 µs) produces an IU-curve with lower fill factors with respect to the quasi-steady-state curve (measured at 45 µs). Higher fill factors are measured at the falling edge of the light pulse (46–48 µs).

4. Conclusions

We may conclude the following:

- The diffusion capacitance charge increases exponentially with forward bias voltage, which is proportional to the light intensity and is finally inversely proportional to the device also temperature.
- An asymmetry between the positive and the negative capacitance charge values is possibly due to impurity photoconductivity.

- The theory shows that in future PCR-measurements could be used for determining the physical parameter (e.g. minority carrier diffusion length and lifetime).

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