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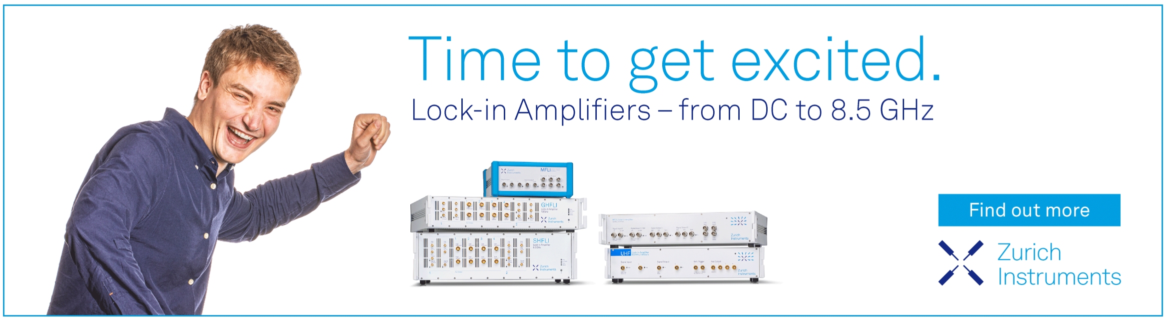

Transient Electrical Characteristics of Silicon Heterojunction Solar Cells under Fast Transient Illumination

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Abstract. For vehicle integrated photovoltaics (VIPV) there are possibly specific requirements on the speed of maximum power point tracking. However, a certain delay in the response of solar cells to fast irradiance changes might impact those requirements on the MPPT. The subject of this work is therefore the investigation of the transient electrical behaviour of state-of-the-art silicon heterojunction solar cells. We use a fast switchable LED-array and an oscilloscope to investigate the cell voltage of silicon heterojunction solar cells under transient illumination. We find that these cells have a switch-off delay that is smaller than one millisecond when operated at or close to the maximum power point. This can be assumed to be faster than the time scale on that irradiances change typically occur on a car body while driving. We also find that, after switching off the light source, the transient cell voltage does not show a simple capacitive behaviour, but a more complex characteristic. A theoretical analysis shows that this behaviour can be explained by the nonlinear dependency of the diffusion and depletion capacitance and the minority carrier lifetime on the cell voltage.

INTRODUCTION

In vehicle integrated photovoltaics (VIPV), fast irradiance changes may affect maximum power point tracking. We have previously performed test drives with fast car-mounted pyranometers in urban environment and determined the relevant frequency range to below 10 Hz [1,2]. To correlate these findings with the impact of fast changing illumination on the energy output of vehicle integrated solar cells, we investigate the electrical characteristics of solar cells under defined transient illumination conditions in our laboratory. Because the rise and fall times of the cell voltage are finite, the cell behaves as a low pass filter, so fast changes of illumination do not necessarily cause directly proportional changes in the cell voltage immediately. To measure the rise and fall time of the cell voltage we use a fast switchable light source, a similar approach to measure switch-on times of solar cell was reported in [3]. As for VIPV the usable area is very limited, it is reasonable to use high efficiency solar cells to gain a maximum of energy out of that area. Therefore, we chose silicon hetero junction solar cells exemplary for commercially available high efficiency solar cells. The cells we investigated were provided by Helmholtz-Zentrum Berlin (HZB). They feature an efficiency of 22% and a high open circuit voltage (V_{oc}) of 737 mV under standard test conditions. The high V_{oc} values are in particular worth to mention since they correspond to high effective minority carrier lifetimes in the solar cells – which could be relevant for the transient behaviour. Tab. 1 shows an overview of the electrical cell parameters.

TABLE 1. Overview of the electrical parameters of the tested silicon heterojunction solar cell, measured at a pv-tools LOANA solar cell analysis system at the Institute for Solar Energy Research in Hamelin (ISFH).

Area	V_{OC}	J_{SC}	Efficiency	FF	pFF	R_{Shunt}	R_S
4 cm²	736.8 mV	39.82 mA	22.08 %	75.25 %	80.25 %	6574 Ohm·cm²	1.08 Ohm·cm²

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EXPERIMENTAL

The test setup, shown in Fig.1, consists of a test chamber with a vacuum chuck to contact the solar cell and an LED-array, that emits infrared light with a wavelength of 950 nm and has a sub-micro second rise and fall time. This is significantly faster than necessary to emulate illumination occurring while driving [1,2]. The solar cell is connected to an adjustable (ohmic) load resistance. The cell voltage can be measured either by multimeter (steady-state) or oscilloscope (transient). The illumination is calibrated by short-circuiting the cell and adjusting the LED's supply voltage, so that the short circuit current I_{SC} matches the value at an illumination of 1000 W/m² previously measured at a pv-tools LOANA solar cell analysis system at the Institute for Solar Energy Research in Hamelin (ISFH). For measuring the transient behaviour of the cell voltage we apply a square wave signal with a frequency of 1 kHz to the light source and measure the cell voltage over time with the oscilloscope at a sampling rate of 20 MHz. Furthermore, we use the same test chamber to connect the solar cell to an impedance meter for capacitance voltage measurements, that will be discussed in the next chapter.

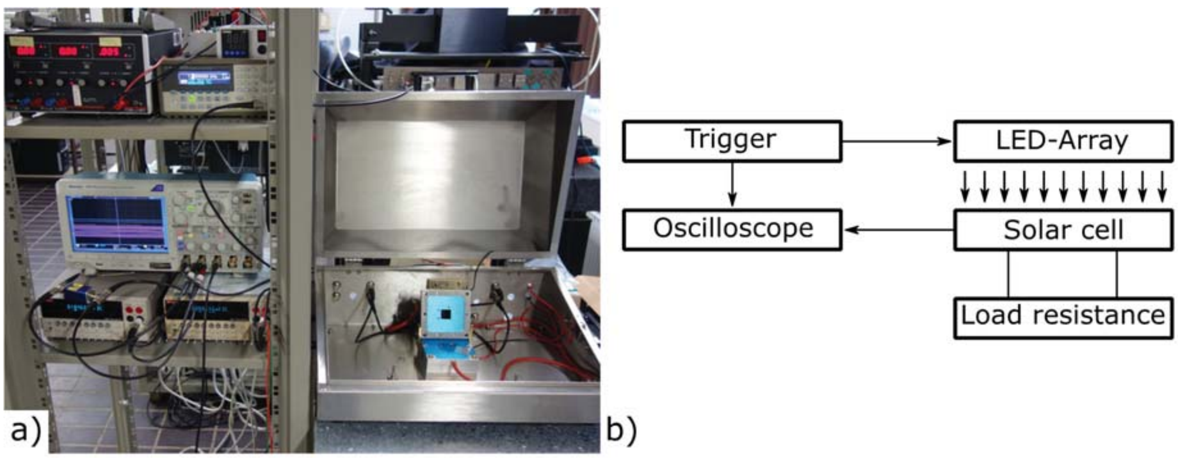

FIGURE 1. a) Photograph of the test setup. Test chamber with chuck, for contacting the solar cell, on the right and measurement electronics on the left. b) Schematic of the measurement principle. A trigger signal (square wave) is used to switch the LED-Array on and off to periodically illuminate the tested solar cell, which is connected to a load resistance. An oscilloscope, synchronised with the trigger signal, is used to measure the transient cell voltage.

The measured switch-off curves are shown in Fig. 2. At t = 0 the light source is switched off, thus no more generation occurs and the cell voltage decays to zero. The decay time heavily depends on the load resistance. With small loads the discharging occurs primarily by current over the load resistance. Around the maximum power point, the switch-off time, until the voltage reaches 10% of the initial voltage, is in the range of a few hundred microseconds. With high loads, this current is very limited so that recombination in the cell becomes relevant, with open circuit the switch-off time reaches about 20 ms.

For initial cell voltages above ~0.65 V, therefore only visible for the measurement with open circuit, we see a decreasing slope of the voltage over time curve, while for voltages between ~0.65 V and ~0.5 V the slope is slightly increasing. Around 0.5 V the slope of the curve increases rapidly for all curves until the voltage drops to ~0.2 V. Below that voltage the slope of the curve decreases again. We will discuss the reason for this behaviour in the next chapter.

The measured switch-on times (not shown here) equivalently depend on the load resistance and are shorter as the switch-off time but on a similar time scale. Therefore, we will focus on the switch-off curves in the analysis.

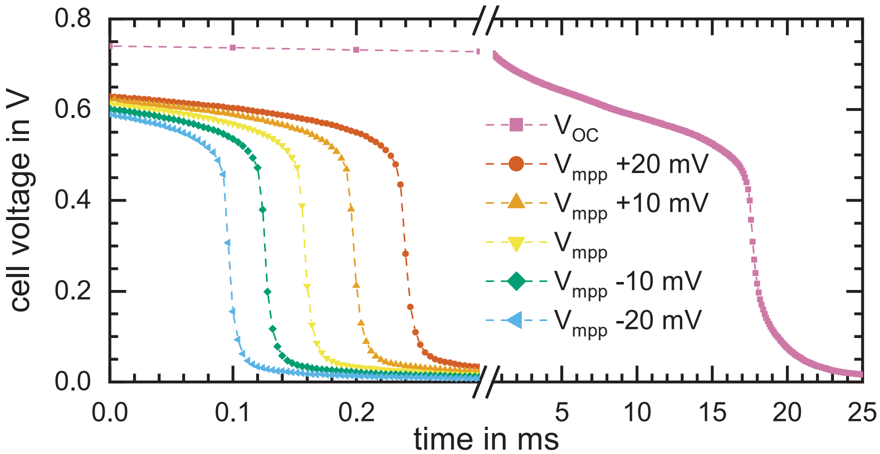

FIGURE 2. The decay of the voltage of a SHJ solar cell at abrupt change of illumination from 1000 W/m² to 0 W/m² as a function of the output voltage at t = 0. The load resistance is adjusted in a way that the static output voltage matches or is slightly above/below V_{MPP}. The initial value of the voltage and the fall time depends on the load resistance (increasing resistance from left to right curve)

THEORETICAL ANALYSIS

The measured delay, between switching off the light source and the time it takes until the cell voltage reaches zero, can be explained by charge carriers, that are stored in the volume of the solar cell. These stored charge can be described with the diffusion capacitance and the depletion capacitance of the cell. After the light switch-off, the stored carriers then either recombine via various mechanisms or are extracted via external contacts and cause a current trough a load resistance.

The voltage decrease is small at the beginning for the measurements with a load resistance. For V_{oc}, the decrease at the beginning is higher though. This is caused by decreased minority carrier life time due to Auger recombination, which is dominant at higher excess carrier density, but becomes negligible for lower voltages. For Auger recombination the lifetime increases with lower excess carrier density as it does for radiative recombination too [4]. For Shockley-Read-Hall (SRH) recombination in contrary the life time decreases with lower Δn [5]. Therefore, the effective lifetime and thus the overall recombination rate changes during the decay of the excess carriers after switching off the light source from auger-dominated to SRH-dominated.

As the excess carrier density (Δn), and thus the cell voltage, decreases, the recombination current as well as the external current should decrease accordingly. Around the MPP we see a very slight decline of the cell voltage at the beginning that becomes steeper with time until the voltage decreases very rapidly when it drops under about 0.5 V and then asymptotically approaches zero. This can partially be explained by nonlinearly dependents of the voltage on Δn, with the equation:

$$V = \frac{kT}{e} \times \ln\left(\frac{n_i^2 + \Delta n \times (p_0 + n_0) + \Delta n^2}{n_i^2}\right), \tag{1}$$

with the Boltzmann constant k, the Temperature T, the elementary charge e, the intrinsic carrier concentration n_i and the equilibrium hole and electron concentration p_0 and n_0. We use equation (1) to calculate the voltage from a given value of Δn. Further we use the equations from [5] for the carrier lifetime for SRH recombination and from [4] for carrier lifetime for the intrinsic (Auger + radiative) recombination. With the external current, which is given by the value of the load resistance and the cell voltage, we can calculate the incremental change of Δn within a time interval, assuming that the change of recombination and extrinsic current is negligibly small if the time interval is sufficiently short. Recursive calculation of the incremental change of Δn and the resulting cell voltage for time intervals of 10 µs gives the voltage over time plots shown in Fig. 3.

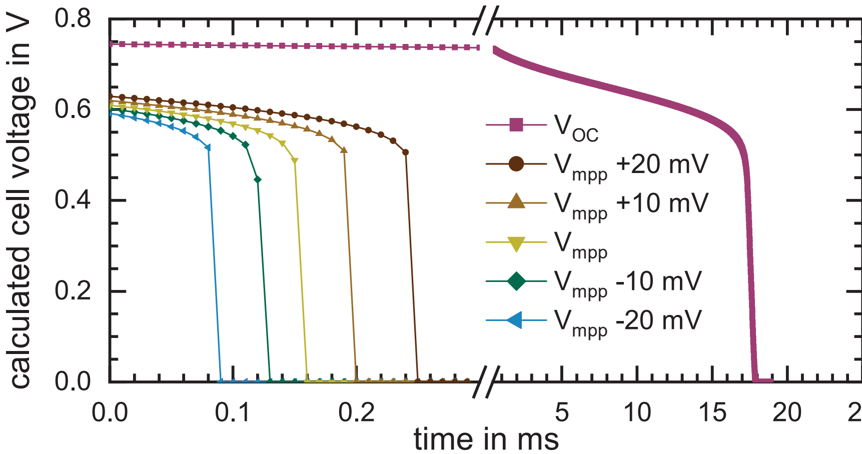

FIGURE 3. Calculated decay of the cell voltage for different starting values resulting from the initial value of the excess carrier density. The calculations consider recombination current and extrinsic current over a load resistance (except for the V_{OC} curve with recombination only).

Qualitatively the calculated curves show a similar behaviour as the one obtained from the experiment. After the voltage falls below about 0.5 V the decrease rapidly fastens. The asymptotic approach to zero cannot be reproduced within this approach. The reason is that this simple model takes only the diffusion capacitance, caused by excess carriers, into consideration, but neglects the depletion capacitance. Both capacitances are voltage dependent, as shown in Fig. 4. The diffusion capacitance depends exponentially on the voltage, while the depletion capacitance only changes with the square root of the voltage. For higher voltages, the diffusion capacitance therefore exceeds the depletion capacitance by orders of magnitude and vice-versa for lower voltages.

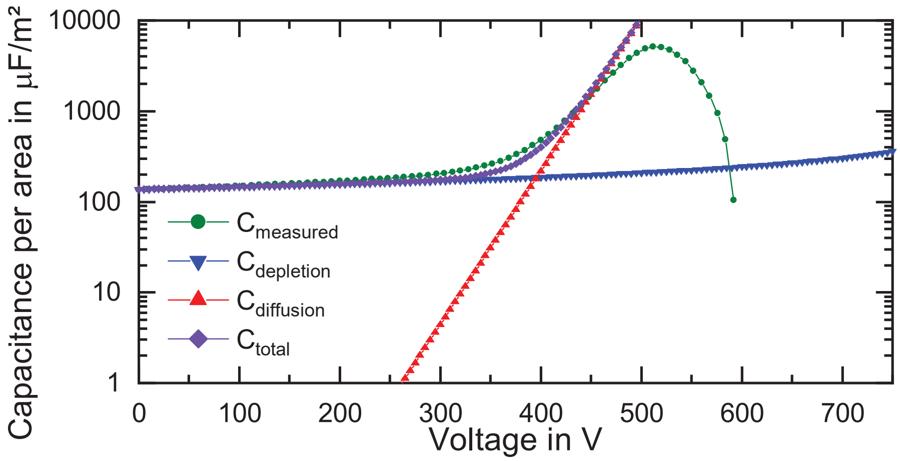

FIGURE 4. The measured capacitance voltage curve for the examined solar cells (taken at 10 kHz and 25 mV amplitude) and the calculated depletion capacitance and diffusion capacitance and the resulting total capacitance. Note that the decrease of the measured capacitance over about 450 mV is not an actual characteristic of the solar cell, but is caused due to current limitation of the used impedance meter. It is apparent, that the total capacitance is dominated by the depletion capacitance at lower voltages and by the diffusion capacitance at higher voltages.

Unlike the diffusion capacitance, which is directly dependent on the excess carrier density, the depletion capacitance is caused by the space charge in the depletion region. Therefore, it cannot easily be implemented in the simple model described above, as its calculation is based on Δn. To model the lower part of the measured voltage over time curves, we use the equation:

$$V = V_0 \times \exp\left(\frac{t}{RC}\right), \tag{2}$$

for capacitance discharge with the initial voltage V_0, which is 0.4 V in this case, as below the diffusion capacitance becomes small compared to the depletion capacitance, the time t, the resistance R (including load and internal resistances) and the capacitance C, which is the (voltage dependent) depletion capacitance in this case [6]. We then incrementally calculate the voltage change per time interval, similar to the method describe above. Fig. 5 shows the measured and calculated voltage over time.

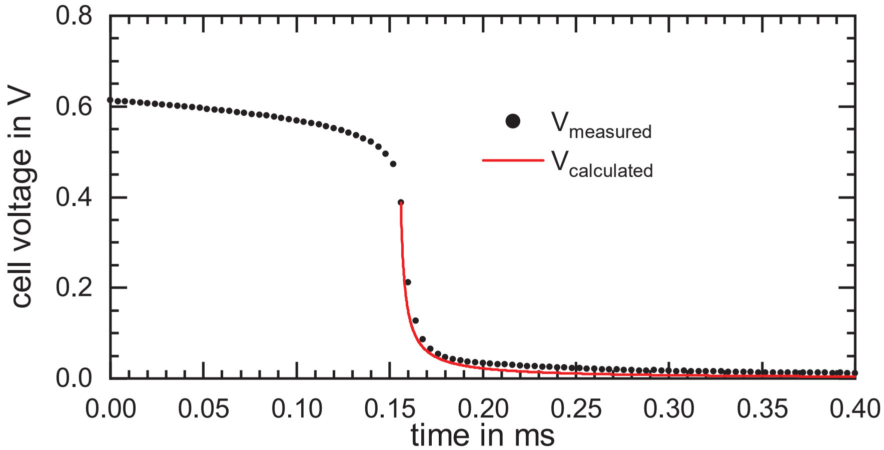

FIGURE 5. Voltage over time, measured and calculated with discharge of the voltage dependent depletion capacitance over a load resistance. The calculated curve resembles the lower part of the measured curve.

The calculated curve is in good agreement with the lower part of the measured curve at the maximum power point. Quantitatively both models are still a very rough approximation to the measured curve that can be optimised by choice of input parameters. To estimate the response time of a solar cell for system design, this might still be a sufficiently close approximation.

CONCLUSION

We measured the decay of the cell voltage of silicon heterojunction solar cells after instant light switch-off. We find the switch-off time at or close to its maximum power point to be in the range below 1 ms, corresponding to frequencies above about 1 kHz. With open circuit the fall time of the cell voltage reaches almost 20 ms. This corresponds to a frequency of 50 Hz. This leads to the conclusion, that the aforementioned effect of low pass filtering will only be significant at frequencies of 1 kHz and higher for typical loads (around the MPP). From the in-field measurements in [1,2] we can conclude that the changes of the illumination typically occur at frequencies that are at least an order of magnitude lower than would be relevant for the switching characteristic of the solar cell. To what extend additional resistive contributions of cell interconnectors in the module might have an impact on the switching characteristics is subject of ongoing work.

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