Degradation of polycrystalline Si solar cell efficiency with increased incident optical power – experiments and theory

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***Abstract* — In this paper we discuss our experimental data obtained for several Si PV cell samples. From the I-V curves measured under various optical irradiance levels, we extracted the fill factors and the series and shunt resistances of the solar cells. For some of our samples, the solar cell efficiencies decrease even at illuminating power densities less than 1 Sun due to reductions in fill factors. Theoretical analysis suggests the reason for the observed dependences of PV cell circuit parameters on optical injection can be defect-mediated carrier recombination.**

Abstract* — *Silicon, non-radiative recombination, concentrator photovoltaics.

I. INTRODUCTION

Solar concentrator photovoltaic technologies have been in use for a number of years. The significance of concentrator PV comes from the fact that the optical power density of sunlight at the Earth surface does not exceed 1500 W/m^2. At the same time, semiconductor-based PV solar cells can operate and produce photocurrent at much higher densities of the incident optical power. The concentration of incident optical power promises significant reductions in the PV solar cell area requirements, that can allow significant decrease in the costs of materials used to manufacture the solar panels.

If the materials used to make the cells have perfect monocrystalline structure, the PV conversion efficiency should increase with the incident optical power density. This is due to the increase in the short-circuit photocurrent density, J_{sc}, and the open-circuit voltage, V_{oc}, for a monocrystalline solar cell as a function of the optical irradiance.

Most of the carrier recombination in Si at room temperature is attributed to the non-radiative (NR) mechanisms, since the energy bandgap for this material is much larger than the thermal energy kT. The degree of crystallinity of Si is known to affect the effective mobility and charge carrier NR recombination rates, specifically, when the incident optical irradiance is high [1]-[3]. One of the mechanisms for the recombination is the carrier trapping at grain boundaries [3].

Another mechanism that can be responsible for the cell efficiency degradation is associated with illumination-dependent carrier lifetimes in silicon PV cells is due to interstitial defects, for instance, iron impurities in silicon [4].

Therefore, when one designs and fabricates PV cells for working under high-intensity illumination, it is very important to understand how semiconductor microstructure affects the charge recombination, how it is related to changes in the quasi-Fermi levels and the PV cell open-circuit voltages.

II. THEORETICAL BACKGROUND

Considering a monocrystal Si solar cell, one can predict that as the illuminating optical power, P_{opt} increases, the photocurrent, I, should also increase with it. The open-circuit voltage is then found as [5]:

$$V_{oc} = \frac{nkT}{e} \ln(\frac{I_L}{I_s} + 1), \quad (1)$$

where n is the PV cell non-ideality factor, I_L is the photocurrent, I_s is the dark current, e is the electron charge, k is the Boltzmann's constant, T is temperature.

According to [5], the fill factor, of the cell, FF, can be calculated using the normalized open-circuit voltage, $V_{oc}^{'}$:

$$V_{oc}^{'} = \frac{e}{nkT} V_{oc} \quad (2a)$$

$$FF = \frac{V_{oc}^{'} - \ln(V_{oc}^{'} + 0.72)}{V_{oc}^{'} + 1} = \frac{V_m I_m}{V_{oc} I_L} \quad (2b)$$

where V_m and I_m are the voltage and the current of a loaded PV cell operating at the maximum power transfer point.

Since V_{oc} is a monotonically growing function of the photocurrent I_L, which, in turn, increases linearly with the optical power, and the fill factor also increases with V_{oc}, the efficiency of the solar cell, given as:

$$\eta = \frac{V_m I_m}{P_{opt}} = FF \frac{V_{oc} I_{sc}}{P_{opt}}, \quad (3)$$

should also increase with the incident optical power, P_{opt}.

The dependences of solar cell efficiencies on incident power calculated in accordance with (3) will be compared with experimental data for the actual polycrystalline solar cell samples.

III. EXPERIMENTAL RESULTS

Three commercially-available 1.5W polycrystalline solar cell samples were characterized using a low-cost solar simulator from ABET Technologies, Inc. with an AM 1.5G filter. This solar simulator can produce a variable-intensity output, covering the range of illumination power densities from 0 to 3 Suns. The output optical power level was monitored using Lambda Scientific LLM-2 light power meter. I-V characteristics were measured under various illuminating powers using a DC variable load from Chroma Systems. The temperature of the samples was measured using remote IR thermometers from PASCO.

From the measured I-V curves we found the short-circuit currents I_{sc}, open circuit voltages, $V_{oc.}$ Currents and voltages at the maximum power transfer points, I_m and V_m, respectively. Figure 1 shows a comparison between our experimental solar cell efficiency data, for one of the samples and theoretical efficiency predicted using (3) with contributions from (1) and (2b).

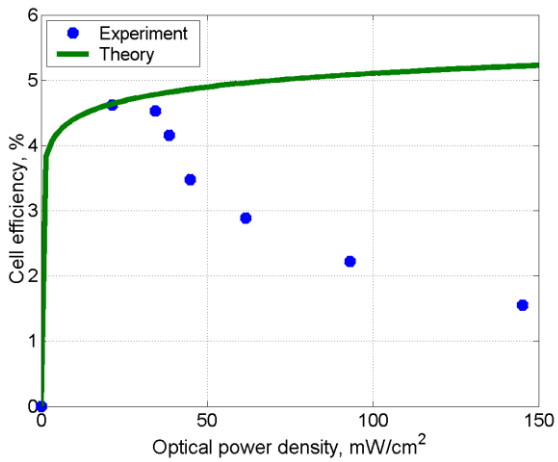
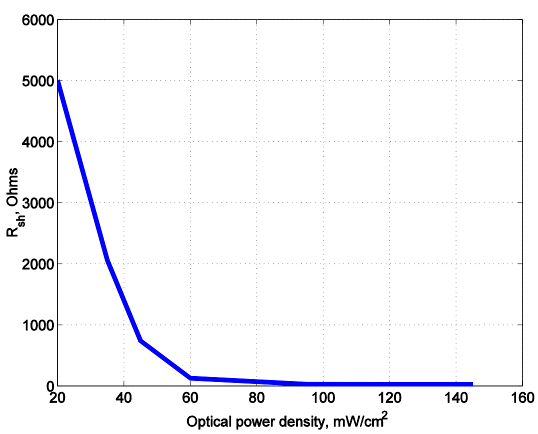


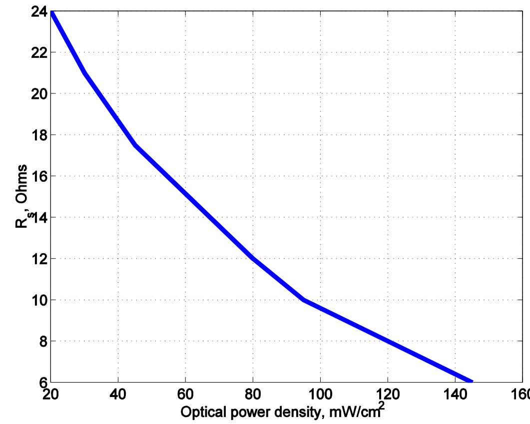
Fig. 1. Experimental and theoretical maximum photovoltaic conversion efficiencies as functions of the incident optical power density.

In order to better understand how the optical injection affects the electrical properties of silicon, we also extracted the PV cell shunt resistance from our data using the slope of the I-V curve near the short-circuit point.

Figures 2a and 2b show the dependence of the shunt and series resistances of a solar cell sample, as a function of incident optical power density.



a)



b)

Fig. 2. Experimental a) shunt resistance, b) series resistance of a solar cell sample as a function of the incident optical power density.

As one can observe, the shunt resistance decreases much faster with the illumination than the series resistance.

Figure 3 displays our results for the short-circuit photocurrent produced by the same cell as in the previous two graphs as a function of incident irradiance.

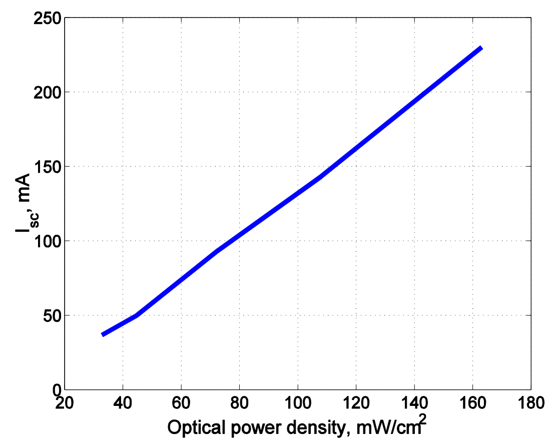


Fig. 3. Experimental short-circuit photocurrent of a solar cell sample as a function the incident optical power density.

The short-circuit photocurrent in Figure 3 changes almost linearly with the irradiance. This can provide some additional information for our analysis and discussion of solar cell efficiency degradation with optical power.

We also found that the open-circuit voltage increases with the irradiance from 1.917 V at I_{opt}=20 mW/cm^2 to 2.05 V at I_{opt}=145 mW/cm^2, as it is expected to. The fill factor, FF, over the same range of irradiances, decreases from 0.778 to 0.38, whereas the model based on (2b) predicts that is should increase by roughly 3 per cent over the same range of irradiances.

Thus, the fill factor degradation is the main reason for the decline in the PV conversion efficiency. Since the short-circuit photocurrent is practically linearly dependent on the illumination, some phenomena that affect the carrier transport should be responsible for the efficiency degradation that we one can observe in Figure 1.

IV. Analysis and Discussion

For our analysis we specifically selected low-cost and low-grade polycrystalline Si PV solar cell samples. Our intention was to study the performance of these cells under concentrated sunlight. Photovoltaic cell samples that are made from silicon with high degree of crystallinity may perform as predicted by the idealized theory at relatively low concentration factors but may also show reductions in conversion efficiency when sunlight is more concentrated.

After analyzing our data, we found that the efficiencies of all the three solar cell samples under variable irradiance show significant discrepancies compared to what one expect based on the idealized theory described by equations (1)–(3).

As one can see from Figure 1, the departure of the measured solar cell efficiency from the theoretical curve begins already at about 40 mW/cm^2 irradiance levels, and at irradiance of about 100 mW/cm^2, the cell conversion efficiency decreases to roughly 45% of its predicted theoretical value.

Using extracted electric circuit parameters, we also observed that the shunt resistance R_{sh} declines with the increasing incident irradiance (Figure 2), from 5100 Ohms at I_{opt}=20 mW/cm^2 to 27 Ohms at I_{opt}=145 mW/cm^2. For the same range of incident optical power densities, the series resistance R_s changes from 25 Ohms to 6 Ohms. The shunt resistance decreases over the same range of irradiances much more severely, by the factor of about 189, compared to the series resistance that only decreases by the factor of about 4. This indicates that the optical injection alone cannot explain the reduction in the shunt resistance with illumination.

To determine what actually causes the difference between theory and experiment, one needs to gain more knowledge of the polycrystalline Si microstructure. Both the grain boundaries and the point defects that can trap charge carriers and mediate the non-radiative recombination in Si PV cells.

Several theoretical models [3], [4] have been proposed to describe carrier transport in semiconductor solar cells under illumination.

The model by Joshi and Bhatt [3] widely used to describe grain boundary recombination under illumination appears to predict the linear dependence of the non-radiative carrier recombination rate on the carrier generation rate, (Figure 8 in [3]). It can explain the dependence of the short-circuit current density on the irradiance that we observe, however, it cannot provide a direct explanation for the reduction in the cell fill factor.

Experimental results for the cell fill factor degradation with the irradiance similar to ours were also presented and discussed in [4]. In that study, the carrier injection level was found to affect the bulk recombination lifetimes. The authors of [4] attribute the changes in the recombination lifetimes to the presence of interstitial Fe atoms in Si. This does not imply that the interstitials are the only cause for the reduction of the fill factors with the irradiance. However, this mechanism allows for the non-linear dependence of the non-radiative recombination rates on the irradiance.

V. Summary of the work

In this paper we present the analysis of experimental I-V curves for low-cost polycrystalline Si solar cells obtained at various incident optical power densities. Our data suggest that for some samples the fill factor decreases with the irradiance, while their short-circuit currents increase practically linearly with it, and the open-circuit voltages increase.

Two main types of illumination-dependent recombination - at polycrystal grain boundaries and at transition metal interstitials in silicon can be responsible for the effects we observed. A simple carrier recombination model for polycrystal grain boundaries does not seem to reproduce our results. However, models that take into account bulk recombination lifetimes and describe effects of both grain boundaries and interstitials have a better chance to explain our experimental findings. Future computational modeling work, including atomistic calculations will be required to better explain our experimental results.

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