LOCAL CHARACTERIZATION OF MULTICRYSTALLINE SILICON WAFERS AND SOLAR CELLS

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ABSTRACT: The current voltage characteristics of multicrystalline solar cells with individually designed front contact grids under different bias light conditions in the temperature range of 300 K to 340 K were investigated. Cells with a grid placed predominately on grain boundaries exhibit higher conversion efficiencies than cells where a great portion of the grid covers crystallites. The diode loss current observed for the first type of cells is governed by a thermal activation energy which is about 30 meV larger than found for other cells. This is attributed to a local increase of the recombination center density within grain boundaries.

Keywords: Multi-Crystalline, Silicon, Solar Cell Efficiencies.

1 INTRODUCTION

During the preparation of multicrystalline silicon (mc-Si) cells different crystal orientations as well as the region between the grains which has an extremely high density of lattice defects and accumulates impurities causes inhomogeneous chemical surface treatment and different doping conditions during diffusion steps. In the final solar cells especially the grain boundaries exhibit unwanted electrical characteristics. They tend to have a high concentration of electrically active defects which cause high recombination for minority carriers thus reducing the collection efficiency of light generated carriers [1, 2]. Furthermore grain boundaries often act as potential barriers for majority carriers which introduces an additional contribution to internal power losses of the solar cell [3]. Therefore cells of mc-Si suffer from lower conversion efficiencies and batches of cells have larger dispersion of the electrical parameter compared with monocrystalline Si cells. In order to minimize grain boundary effects on the solar cell performance electrically active defects are passivated by the introduction of atomic hydrogen frequently in combination with a thermal treatment to getter metallic impurities [4]. Recently an other approach to minimize efficiency losses due to grain boundary effects was suggested [5]. The metal grid of the front contact of a mc-Si solar cell was applied mainly above grain boundaries. Two effects were expected to take place. First the shadowing of grains with high light generated photocurrent densities is suppressed. Second the series resistance is lowered due to a reduction of current paths across grain boundaries. Previously a statistically elaborated study reported an increase of the output power between 2-5 % [6]. Content of the present work is the evaluation of techniques in order to further improve the individually processing of each mc-Si wafer to a high efficient solar cell. In the following we report about some of the results we have obtained from the investigations of individually contacted photovoltaic mc-Si devices.

2 EXPERIMENTAL

The starting material for the preparation of solar cells were p-type mc-Si wafers as delivered from Bayer or Eurosolare. The wafer surfaces were chemically polished and cleaned either by an acetic or by a hydroxide solution. The planar pn-junction was formed by a phosphorous diffusion. The back side of all cells was fully metalized by screen printing a paste containing aluminum and silver particles. In order to compare cells with different front grids pairs or triplets of subsequent wafers from one batch which have almost identical distributions of crystallites were selected. For one of these cells the surface structure was determined by an optical contrast image which was transferred to a computer. A program starts from an initial grid with rectangular lines defined by the user's input of the desired grid parameter such as line spacing, total line length and percentage of the cell area which shall be covered by the metal. Based on the information of the optical contrast image the program distorts the initial grid layout towards a grid which still maintains the inputted parameter but is located predominately (>77 %) along boundaries of high optical contrast caused by the different crystallographic orientations of the grains. Depending on the applied technique for the front contact formation which are explained later, the final layout of the grid is used to either drive a XY translation stage or to output a mask for photolithography. Currently two methods to apply the front grid are in use: (1) A Silver ink is plotted onto the grain boundaries according to the computer driven plot instructions and then burnt in or (2) a masked photoresist covers the wafer's surface leaving regions uncovered where the metal is intended to be deposited by an electrochemical deposition from a liquid solution. The grid properties of the two deposition methods are summarized in Tab. I.

TABLE I: Properties of the front metal grid.

	Electrochemical deposition	**Silver ink plotting**
Line width	210 µm	350 µm
Line height	3 - 5 µm(Ni) +10 - 15 µm (Ag)	100 µm
Line resistance	10 mΩ/cm	30 mΩ/cm
Contact resistance	1.5 mΩcm^2	11-12 mΩcm^2
Shadowed to total surface	6.0 % - 7.9 %	7.5 % - 11 %

On the first cell of a selected pair the grid was applied above the grain boundaries. These cells will be referred to as "ON cells" further on. The same grid was used for the second cell of the pair but it was rotated by 90 degrees causing an intentional misalignment of grid lines and grain boundaries (“OFF cells”). In the case of triplets a standard H-pattern grid was used for the third cell. Except of a simple surface passivation by covering the cell’s surface with a polymeric layer no advanced techniques to reduce the electrically active defect density on surfaces or within the grain boundary region were used. The optical and electrical properties of the solar cells were investigated. In Fig. 1 the map of a light beam induced current scan, LBIC, carried out on an “ON cell” with electrochemically deposited contacts illustrates how the metal lines shown as black polygons surround the crystallites shaded in grey (a).

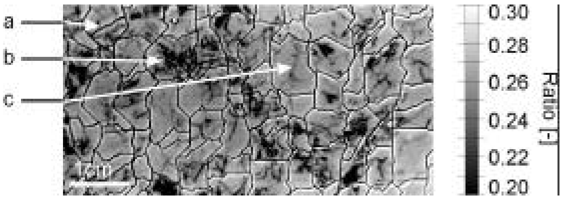

Figure 1: Grey scale map of the local variation of a light beam induced current in an “ON cell”. The shadowed areas covered by the front contact grid appear as black polygons (a). A grain with an high density of crystal defects is indicated by (b). An example of a grain boundary (c) that was invisible to optical surface contrast.

A light spot caused by two intensity modulated lasers with wavelengths at 635 nm and 905 nm respectively was scanned over the cell surface. Since the modulation frequencies of the two lasers were different two frequency locked electrical signals were extracted from the light beam induced current of the solar cell. The ratio of the two signals were shown as Grey scale contrast in the image. Displaying the ratio rather than recording the signal arising from a single laser excitation reduces misinterpretation caused by the large spatial variation of surface reflection. In some cases at each step of the solar cell preparation cycle the local light excited charge carrier density of the partly processed cells were characterized with the help of a microwave bridge. The method allowed us to estimate the local minority carrier diffusion length without any additional preparation and without the application of electrical terminals [7]. A comparison of optical contrast images which were used to define front contact grids and the maps of the microwave signal indicates that only a portion of boundaries between areas of high optical contrast are electrically active. On the other hand electrically active boundaries were sometimes invisible to an optical surface scan due to low contrast. As a consequence the grid calculation should preferably be based on minority carrier diffusion length mapping.

3 RESULTS

The electrical characteristics of the photovoltaic devices were investigated in the dark and under different bias light conditions between 300 K and 340 K. The solar cell parameter, short circuit current, I_{SC}, open circuit voltage, V_{OC}, curve fill factor, CFF, and maximal outputted power, P_m, were determined and statistically evaluated for batches of cells. As previously reported an increase in P_m of 2-5 % for “ON cells” compared with standard pattern cells was found when the front grid was plotted with silver ink [6]. However P_m for “ON cells” varied stronger with temperature than for the other types. This was ascribed to a lower series resistance, R_S observed for “ON cells”. The results reported in this paper refer to cells with electrochemically deposited front contact grid. As can be seen in Tab. 1 the line width is reduced by 40 % resulting in a reduction of shadowed cell area. Moreover the contact resistance to the underlying highly doped emitter could be significantly lowered which results in almost negligible low values for R_S for all types of cells. Nevertheless the temperature dependence of P_m for “ON cells” still was significantly larger. In order to investigate this behavior in more detail linear temperature coefficients were defined.

$$a_P = \frac{1}{P_m(300K)} \frac{\Delta P_m}{\Delta T} \tag{1}$$

Analogue to Eq. 1 which expresses the coefficient for P_m coefficients for the other solar cell parameter were defined. A statistical analysis of these coefficients showed that for P_m, V_{OC} and CFF the coefficients are systematically larger for “ON cells” whereas no differences were found for I_{SC} which suggests that the differences in the temperature dependence is caused by the diode loss currents which are located in the semiconductor below the cell area which is covered by the metal lines. Therefore the current voltage characteristics $I_{cell}(V_{cell})$ of the cells in the dark and under illumination were fitted to a single diode model as described below. Where the light generated current, I_L, practically equals the measured I_{SC}, I_D is the diode loss current and I_{SH} is a loss current caused by short circuits across the pn-junction.

$$I_{cell}(T) = I_L - I_D - I_{SH} \tag{2}$$

$$I_D(T) = I_0 \left\{ \exp\left(\frac{V_{cell} - R_S I_{cell}}{2k_B T} \right) - 1 \right\} \tag{3}$$

$$I_{SH}(T) = G_{SH}(V_{cell} - R_S I_{cell}) \tag{4}$$

$$I_0 \propto \exp\left\{ \frac{-E_{act}}{k_B T} \right\} \tag{5}$$

I_0 is the diode saturation current thermally activated by an energy, E_{act}. The shunt conductance G_{SH} as well as R_S were found to be almost temperature independent.

For 100 cm^2 cell area R_S was typically 1 mΩ – 3 mΩ, G_{SH} about 0.1 S. Since the effect of slight variations of these two parameter on the quality of data fitting was negligible no significant differences between cells types could be derived. It appears that “ON cells” have slightly lower values of R_S and slightly higher values of G_{SH}. A typical result of fitting measured $I_{cell}(V_{cell})$ data according to a recombination dominated diode loss current is shown in Fig. 2 for a pair of mc-Si cells. From the arrhenius plot of fitted I_0 values E_{act} was determined which is independent from the illumination level. The shift between results from measurements in the dark and under illumination which can be seen in Fig. 2 is likely to be caused by a change of the active area for the diode current. We found that in “ON cells” E_{act} was about 30 meV larger compared with corresponding “OFF cells” which explains the observed differences in the temperature dependence of V_{OC} very well as can be seen in Fig. 3 (top). Beside I_D also R_S and, depending on the illumination intensity, G_{SH} determine CFF. Therefore the agreement of calculated and measured temperature variations of

CFF (Fig. 3 bottom) is less accurate than it is for V_{OC}.

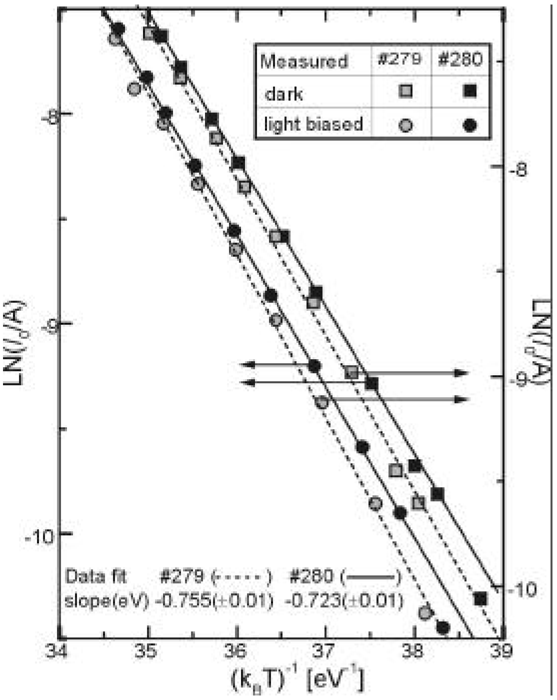

Figure 2: Arrhenius plot of the diode saturation current I_0 in order to retrieve it's activation energy E_{act}

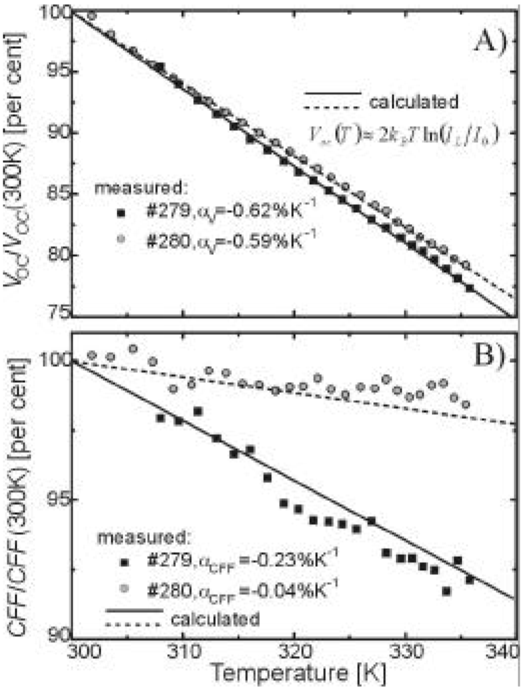

Figure 3: Calculated and measured temperature dependence of open circuit voltage, V_{OC} (A), and curve fill factor *CFF* (B) for a pair of solar cells.

4 CONCLUSIONS

We found that for the application of individually designed front contact grids an electrochemical deposition process is favourable over Silver ink drawing since statistically it yields in an improved electrical output of mc-Si solar cells. Cells having a galvanically processed grid covering predominately grain boundaries show an increase of P_m between 5-25 % compared with cells with a geometrical standard grid. This is significantly more than previously found for cells prepared by silver ink plotting [6]. Due to the high density of electrically active defects in the grain boundary region of mc-Si the thermal activation energy of the diode loss current differs from the ones within the crystallites. This was found to be the origin of larger variations of P_m, V_{OC} and *CFF* with temperature observed for "ON cells" and could potentially be suppressed by a passivation procedure of the grain boundaries during solar cell preparation.

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