EFFICIENCY OF BIFACIAL SI SOLAR CELLS AT LOW IRRADIANCE.
EFFECT OF DESIGN AND FABRICATION TECHNOLOGY FACTORS

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ABSTRACT: There are applications of solar cells under illumination conditions for lower than “one sun”. Solar cell efficiency decreases with decreasing irradiance. Several factors affecting conversion efficiency at low irradiances (down to ~0.01 sun) are studied. Experiments were performed with bifacial n+–p–p+ Si solar cells, fabricated using an ion implantation procedure for BSF formation. Optimal resistivity of the starting Si is evaluated taking into consideration recombination in the ion induced defect layer. Use of high resistivity Si eliminates the influence of this defect layer on recombination in the base region. Lifetime dependence on injection level can cause current non linearity and therefore an additional efficiency drop at low irradiance. Light induced defects can be responsible for this effect. The quality of the p–n junction as expressed by the ideality factors of the two-diode model is one of the most important factors affecting solar cell conversion efficiency at low light intensities.

Keywords: Silicon Solar Cell, Low Irradiance, Bifacial, Ion Implantation

1 INTRODUCTION

The accepted standard irradiation for solar cell or module characterization and certification (sun’s spectral distribution of AM 1.5, irradiance of 1000 W/m²) is not achievable during most of the operating time of terrestrial modules. Power generated at irradiance levels down to 100 W/m² contributes a significant amount to the real part of the complete energy production of a PV system [1, 2]. Moreover, there are many solar cell applications, such as remote detectors, mobile phones, road markers, where the working illumination can be far lower than "one sun". Actual irradiance varies due to season, time of day as well as environmental reasons (position on earth, tilt angle, dust, etc.).

Solar cell efficiency decreases with decreasing irradiance. Theoretically, as a first approximation, assuming the linearity of short circuit current, Iₓ, vs irradiance, E, this decrease is the result of the logarithmic function of open circuit voltage, Vₒc vs E, as well as fill factor degradation.

In practice additional factors can significantly affect solar cell efficiency at non standard low irradiation conditions. The influence of the starting properties of single and multi crystalline Si on cell efficiency at low irradiance levels was investigated by the authors of [2, 3]. The dependence of bulk minority carrier lifetime and surface recombination on injection level can cause a further decrease in solar cell efficiency at lower irradiance [4, 5]. This effect is less pronounced in n-Si. The superiority of n-conductivity type of Si crystals as a starting material for solar cells intended for low irradiance applications was theoretically discussed based on differences of injection level recombination dependences in n- and p-Si [6]. Experimentally measured superior performance of n-based over p-based cells at low illumination levels is explained by the authors as due to this effect.

Cell design and fabrication technology are also factors which may control solar cell efficiency at low illumination levels. For instance, solar cells are very sensitive to edge recombination, particularly in the space charge region, when the border to area ratio is large [7]. Shunt resistance is another factor influencing cell efficiency, increasing with decreasing irradiance [8].

Among different designs the bifacial cell excites special interest. Use of bifacial cells in most of the above applications is advisable due to the fact that scattered (diffused) radiation is a significant component of complete incident radiation, and the contribution of both cell sides may be comparable [9]. One of the promising Si solar cell fabrication technologies is a thermal diffusion – ion implantation procedure combining thermal diffusion of phosphorous and implantation of boron ions [10].

Factors affecting the efficiency at low irradiances (down to ~0.01 sun) of bifacial n+–p–p+ Si solar cells, fabricated using the ion implantation procedure, are discussed in this paper.

2 EXPERIMENTAL

4 cm² bifacial n+–p–p+ Si cells with passivated front and rear surfaces were used as experimental samples. The resistivity range of the starting Si was 1–25 Ω.cm. Combined thermal diffusion – ion implantation technology was used for solar cell fabrication: open tube P diffusion with POCl₃ as a diffusant source and 30 keV B ion implantation with subsequent annealing and impurity drive-in. Front and back contacts are made by grids. They were fabricated by subsequent vacuum thermal evaporation of Ti, Pd and Ag layers followed by Ag plating.

I-V curve measurements were made using a solar simulator (model 81171 of Oriel) with AM 1.5 sun spectrum illumination. Irradiance in the range 0.01 to 1 sun was controlled by gray filter combinations. Samples were held on a temperature stabilized brass block by vacuum hold-down. Solar cell spectral response data were used for bulk minority carrier lifetime determinations vs. injection level as well as for correction
of the irradiance setting for the given (calculated) solar cell short circuit current. Measurements were processed by the Fraunhofer ISE IODI Measurement system using a four probe circuit. The same electronic setup and circuit was used for I-V curve measurements in the dark.

3 EXPERIMENTAL RESULTS

3.1 Starting Si resistivity optimization

The fundamental parameters of starting Si resistivity, $\rho$, and minority carrier lifetime, $\tau$, were used for solar cell optimization using the PC1D simulation program. Dependences of solar cell efficiency, $\eta$, on $\tau$ for Si of different resistivities in the range $1 \rightarrow 10 \ \Omega \cdot cm$ are shown in Fig. 1a and b for one and 0.1 sun illumination, respectively. The unbroken lines are calculated without introduction of recombination in the back defect layer which can be formed as result of B ion implantation [11]. According to the calculations, low $\rho$ Si is the preferable starting material for highest efficiency cell fabrication. However, the possibility of defect layer formation leading to different conclusions should be taken into consideration. Dotted curves in Fig. 1 are calculated for a $1 \ \Omega \cdot cm$ Si cell, which has a defect layer in the base region near the back.

![Graph showing efficiency as function of bulk lifetime for different starting Si resistivity.](image)

**Figure 1**: Efficiency as function of bulk lifetime for different starting Si resistivity.

The effective surface recombination due to this layer, $S_{ef}$, was assumed to be 950 or 1000 cm/s for 100 and 10 mW/cm² irradiance, respectively (data for B ion implantation with subsequent 950 °C annealing). If a solar cell is fabricated using higher resistivity Si, the recombination in the defect layer decreases, in a $10 \ \Omega \cdot cm$ Si cell, it is not detectable. Therefore, as can be seen in Fig. 1, the preferable $\rho$ for solar cells with BSF fabricated using B ion implantation is higher than $1 \ \Omega \cdot cm$, and close to $10 \ \Omega \cdot cm$. This positive effect of using high $\rho$ Si is more pronounced when solar cells are used at low irradiance due to a higher recombination rate in the defect layer at low injection levels.

3.2 Effect of photocurrent non-linearity

Lifetime dependence on injection level can result in a sub linear decrease of photo generated current $I_{ph}$, and corresponding efficiency degradation with decreasing irradiance, $E$. Small nonlinearity of short circuit current, $I_{sc}$, vs. irradiance was seen due to an increase of $S_{ef}$ with irradiation decrease in solar cells with a back defect layer introduced by B ion implantation.

Much more significant $I_{sc}$ non linearity was measured for solar cells with light introduced defects. Fig. 2 illustrates the effect. The sample is a solar cell fabricated using FZ $22 \ \Omega \cdot cm$ Si. After a 3 hr one sun exposure, the bulk lifetime was degraded more than an order of magnitude, when measured at low injection levels [12]. The introduced defects are characterized by a very drastic dependence of recombination rate on injection level. Due to this defect property, the solar cell demonstrates large non linearity of sun photo response.

![Graph showing sun light response of solar cell before and after light degradation.](image)

**Figure 2**: Sun light response of solar cell before and after light degradation.

The data shown in Fig. 2 for such a cell are presented in the form of irradiance dependences of relative sun photo response, $\left(J_{sc}/E\right)/\left(J_{sc1}\right)$, where $J_{sc}$ is the current density at irradiance $E$, and $J_{sc1}$ - is the current density at 100 mW/cm² solar irradiance. Photo response of a solar cell before light degradation does not change with
irradiance.

Light degraded cells demonstrate a decrease of photo response of ~ 7% at front illumination and ~ 56% at back illumination, when irradiance drops to ~ 1 mW/cm². The efficiency decrease is obviously even more drastic. In other words, the solar cell efficiency, determined at one sun illumination can drop dramatically with a decrease in irradiance, when specific defects such as light induced recombination centers control the bulk lifetime.

3.3 p-n junction quality

Parameters of the p-n junction are important factors affecting the efficiency dependence on irradiance. The following data illustrate this. Three curves in Fig. 3 show calculated and measured solar cell efficiencies vs. solar irradiance. The upper one represents PC1D simulation results for a 1 Ω.cm Si solar cell. The starting parameters for simulation were chosen corresponding to the best samples of this group. Two other curves reflect the experimental dependences \( \eta \) (E) for cells, which are characterized by the ~ same efficiency at one sun illumination.

**Figure 3: Irradiance dependence of solar cell efficiency for samples with different properties of p-n junction**

As can be seen, the cells are very different at low irradiance. While the efficiency of one (F-25-2) fits quite well to simulated irradiance dependence, the efficiency of another (F-16-2) dramatically drops with decreasing irradiance. Measurement of photocurrent vs. irradiance does not justify attributing this drop to the photocurrent non-linearity effect. The difference between experimental samples can be attributed to a difference in their I-V characteristics.

Dark I-V curves of "good" (F-25-2) and "bad" (F-16-2) cells are demonstrated in Fig. 4 and 5. Measurement results were described by the two exponential (two diode) equations. Whereas measured I-V curve data of the first fit very well to the classical equation with \( A_1 = 1 \) and \( A_2 = 2 \) (see, for instance, [13]), an equation with \( A_2 = 3 \) is required for accurate description of the measurements of sample F-16-2. Therefore, less perfect p-n junction parameters, i.e. an increase of recombination in the depletion region, is responsible for the second diode parameters with \( A_2 \) equal or exceeding 2.

**Figure 4: Dark I-V curve of the sample F-25-2. Two diode equation with \( A_2 = 2 \) for the second diode fit well measured data**

**Figure 5: Dark I-V curve of sample F-16-2. Two diode equation with \( A_2 = 3 \) for the second diode fit well measured data**

4 DISCUSSION

There are several factors which could significantly affect the efficiency of Si solar cells when they are illuminated by lower than standard one sun (100 mW/cm²). These factors should be taken into consideration during cell design, fabrication, test and application.

Optimal starting Si resistivity obviously depends on design and cell fabrication technology. Low resistivity Si is best for providing high front efficiency, if minority carrier lifetime is relatively low. For high quality Si (i.e. FZ refined) with high \( \tau \), independent of \( \rho \), there is no significant effect of Si on photovoltaic performance. This is correct for standard solar illumination as well as for lower illumination (Fig. 1). However, high resistivity Si is preferred as a starting material for solar cells fabricated using ion implantation for BSF formation, since this processing may result in detectable formation of a detectable layer in the base region.

Dotted curves in Fig. 1 demonstrate a significant decrease of low resistivity Si solar cells caused by the back defect layer. Due to injection level dependence of recombination in this layer [11], formation of such a layer has a more negative effect on cell efficiency when irradiance is low. Use of Si with higher \( \rho \) (~10 Ω.cm) prevents formation of a detectable defect layer [11]. Hence, cell fabrication technology included the ion implantation process requires higher
resistivity Si, especially for solar cells intended for low illumination applications. This requirement coincides with choice of Si for bifacial cell fabrication. Long bulk diffusion lengths needed for high back cell efficiency can be more easily achieved when higher p Si is used.

An additional decrease of conversion efficiency at low illumination levels can be caused by a factor not connected directly with Si resistivity. This factor is non linearity of photocurrent vs. irradiance due to the injection dependence of the recombination rate. The recombination centers responsible for such non linearity, can be light induced defects as demonstrated in this study. Their influence on front efficiency can be substantial, however degradation of back characteristics at low irradiance can be especially large (Fig. 2). The sample demonstrated in this study is quite special. It was fabricated using high resistivity FZ Si, in which formation of light induced defects should be minimal, according to the accepted light degradation model [14].

And, in fact, after light degradation, its bulk lifetime at standard solar illumination is ~150 µs. Whereas at 0.01 sun illumination the light induced defects actively participate in the recombination process, leading to a lifetime drop to ~20 µs. Therefore there is no significant solar cell parameter degradation at regular solar illumination, but very pronounced degradation at low irradiances. Therefore front and back current linearity, and the effect on this linearity of light induced defects, should be tested for bifacial (as well as regular) solar cells intended for low illumination applications.

The quality of the p-n junction as expressed by the ideality factors A1, which is usually equal to 1, and A2, which varies from ~2 to significantly higher values, is one of the most important factors affecting solar cell conversion efficiency at low light intensities. The above experimental data (Fig. 3 – 5) demonstrate very clearly that low irradiance cell efficiency is reduced when A2 > 2. The explanation of A2 increasing above the theoretical value (A2 = 2) is due to an introduction of recombination centers with different capture cross sections for electrons and holes into the diode space charge region (see, for example, [15]). Non controllable impurities can be the source of these additional recombination centers introduced at high temperature stages of cell fabrication. Cleaner processing conditions, lower doping levels, more controllable contact firing should keep A2 = 2 and maximize cell efficiency at low irradiance.

Lifetime dependence on injection level can cause current non linearity and therefore an additional efficiency drop at low irradiances. This effect is more pronounced for the back efficiency of bifacial cells. Light induced defects can be responsible for such effects.

p-n junction quality dramatically affects the decrease in cell efficiency at lower irradiance. For solar cells described by the two diode model, A2 values exceeding 2 are the sign of unsatisfactory characteristics at low irradiances.

6 REFERENCES


[12] L. Kreinin, N. Bordin, N. Eisenberg, Spectral response of Si solar cells at different light and voltage