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Fill Factor Losses in mc-Si Solar Cells

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Non-fundamental losses in mc-Si solar cells have been studied. These efficiency losses significantly depend on diode quality and parasitic ohmic resistances that result in the fill factor losses. The fill factor losses in mc-Si solar cells were analyzed by testing of the industrial solar cell lot under AM1.5 conditions. The observed fill factor reduction due to both dark saturation current and diode ideality factor increasing is explained by their exponential relationship which has been found experimentally. Additionally, solar cell maximum power losses through the parasitic ohmic resistances have been estimated and discussed. The obtained results may be used to a solar cell efficiency enhancement and hence reduction in a solar electricity cost.

Keywords: Solar cell, mc-Si, Fill factor losses, Parasitic ohmic resistance, Dark saturation current, Diode ideality factor.

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1. INTRODUCTION

The low cost and high quality of multicrystalline silicon (mc-Si) based on directional solidification has become the main stream in photovoltaic industry. The best achievements in 17-18 % efficiency of the industrial mc-Si solar cells (SCs) [1, 2] are still well below 25.6 ± 0.5 % efficiency which were obtained for the aperture or designated illumination SC areas [3]. Fundamental loss processes occurring in solar cells were analyzed in details [4]. Efficiency limit dependence on an energy band gap (E_g) was quantified by taking into account the «below E_g», electron thermalisation, fill factor and thermodynamic loss processes. Thermodynamic losses include electron kinetic, Fermi level and etendue losses which were considered by several authors [5, 6]. Fill factor loss is a result of operating at the maximum power point of a solar cell. It is generally limited by diode quality and parasitic ohmic resistances [7]. Fundamental losses except fill factor are unavoidable in the single junction semiconductor device under one sun illumination without a changing device design.

Non-fundamental losses are theoretically avoidable and must be studied. Analysis of the resistance and diode quality losses in solar cells is essential to improving their efficiency. It is especially important for multicrystalline solar cells because there are many grain boundaries intersecting p-n junction and hence a diode quality may greatly reduced.

This article presents the statistical analysis results of the industrial SC lot tests under AM1.5 conditions. Besides the fill factor loss correlations with diode quality parameters and parasitic resistances have been studied and the main causes of these losses have been discussed.

2. EXPERIMENTAL

The industrial lot of the 1400 mc-Si SCs was fabricated by standard screen printing technology with p^+- p back surface field (BSF) on the automatic Schmidt GmbH production line. The 156 × 156 mm^2 and 210-230 μm thickness wafers were used. They were cut from the electronic grade mc-Si ingots by a multi-wire wafering technique. The main details on resistivity, lifetime, contaminations and wafer grain structure have been published earlier [8].

The whole SC lot has been tested at AM1.5 Global spectrum (ASMG173) and integrated power of 1000 W/m^2 by the measuring station with solar simulator that is included in the automatic production line. The H.A.L.M. electronic GmbH measuring station consists of the cetisPV-CT-L1 photovoltaic *I-V* curve measuring system and the cetisPV-XF2 control units with the self-adjusting xenon flasher for a solar simulation. This modulator station provides *I-V* curve measurements at three conditions: the forward measurement with light, the reverse measurement in dark and the combination – forward measurement with light and in dark. All test operations were carried out with continuous monitoring of the radiation and the cell / room temperatures then the irradiance-current-voltage correction procedures were performed simultaneously.

The open circuit voltage U_{oc}, short circuit current I_{sc}, voltage U_{mpp} and current I_{mpp} in the maximum power point, the series R_s and shunt R_{sh} resistances of the solar cells have been measured. The series and shunt (parallel) resistances were determined due to light *I-V* curve measurements. The *I-V* curve parts were analyzed via linear regressions within the U_{oc} range for series resistance and within the I_{sc} range for shunt resistance. The measuring station ensures that these *I-V* curve parts contain at least 100 and 200 measuring points for the shunt and series resistance determinations respectively.

The main solar cell parameters such as efficiency, maximum power and fill factor are easily calculated by generally known relations [9] using the measured values. To evaluation the *p-n* junction quality additional measurements of the *I-V* curve within the maximum power voltage range were performed. The measured cell currents $I_{vld1/2}$ have been determined at 0.5 and 0.6 volts of the load voltages $U_{vld1/2}$. The max power voltage usually is between these voltages and therefore that is SC operate part of the light *I-V* curve. Then the dark saturation current I_0 and diode ideality factor A were calculated for this section of the *I-V* curve.

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A shape of the real-diode *I-V* curve is well known to depend on the *p-n* junction quality parameters I_0 and A as well as on the parasitic resistance R_s and R_{sh}. Therefore the junction quality parameters estimates were performed by measured values $U(I)_{vld1/2}$ with exception of the parasitic resistance influences by the equations:

$$A = \frac{e}{kT}\frac{\left(U_2 - U_1 - R_s\left(I_2 - I_1\right)\right)}{\ln\left(\frac{\left(I_{SC} - I_2\right) - \left(U_2 - I_2 \times R_{ser}\right)/R_{sh}}{\left(I_{SC} - I_1\right) - \left(U_1 - I_1 \times R_s\right)R_{sh}}\right)} \quad (1)$$

$$I_0 = \frac{(I_1 - I_2 + \left[(U_1 - I_1 \times R_s) - (U_2 - I_2 \times R_s)\right]/R_{sh})}{\exp\frac{e(U_2 - I_2 \times R_s)}{AkT} - \exp\frac{e(U_1 - I_1 \times R_s)}{AkT}}, \quad (2)$$

where T – the each cell temperature at the time of measurement, $I_{1(2)}$ – SC currents at voltages $U_{1(2)}$, U_1 and U_2 – 0.5 and 0.6 Volts, respectively.

These ratios have been derived by comparing the diode *I-V* equation for two load voltages within U_{mpp} range. The additional voltage drop $I \times R_s$ outside of the *p-n* junction and the current U / R_{sh} supplemented to that through junction is also taken into account. The diode ideality factor calculations must precede the dark saturation current definition so it depends on this factor according to equation (2) while the A can be found without I_0 by the equation (1).

3. RESULTS AND DISCUSSION

The solar cell distributions on diode ideality factor A and dark saturation current density j_0 have been analyzed. These distributions are significantly different. The A distribution is Gaussian with the same mean, median and mode about 2.3. Thereby the recombination processes in depleted zone of the *p-n* junction are essential and this current component is dominant near the maximum power point of the mc-Si SCs. The j_0 distribution is lognormal and the 99 percent of all solar cells have these current densities less than 4 μA/mm^2.

The open circuit voltage U_{oc} was associated with the diode ideality factor A, dark saturation current I_0 and short circuit current I_{sc} by the simple equation – $U_{oc} = (AkT / e)ln[(I_{sc} - I_0) / I_0]$. Thus the open circuit voltages have been calculated and compared with that experimentally measured. The calculated and measured values U_{oc} have been found to correspond satisfactorily and their ratios are within 0.9-1.1 range that confirms the accuracy of the defined diode ideality factor and dark saturation current. The best voltage match was observed for U_{oc} about 0.6 V.

It is quite clear that the diode *I-V* curve area should increase with increasing of the ideality factor according to diode *I-V* equation and thus the factor A rising must be followed by the fill factor increasing [10]. Conversely, increasing of the dark saturation current I_0 will reduce a fill factor thereby resulting in SC efficiency losses. The experimental fill factor dependencies on the ideality factor A and the saturation current density j_0 for SC sublot with similar short circuit currents and with shunt resistances more than 40 ohms are shown in Fig. 1 a, b. The fill factor reduction from 0.78 up 0.75 was observed for both j_0 and A parameters increasing.

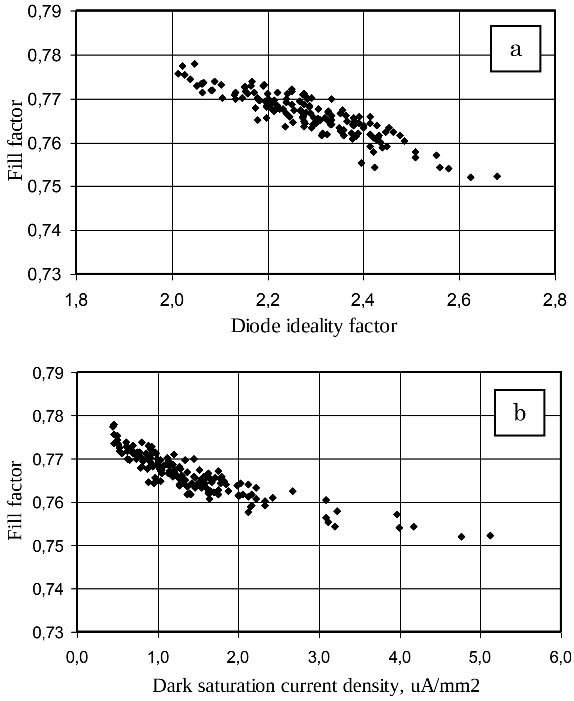

Fig. 1 – The fill factor dependencies on the diode ideality factor (a) and the dark saturation current density (b) for solar sells with I_{sc} = 7.83-7.87 A and $R_{sh} \geq 40$ ohms

But this discrepancy easily eliminated if the exponential increasing of the density j_0 with ideality factor A for the equal *p-n* junction currents will be taken into account. The experimental correlation between the dark saturation current density and the modified ideality factor has been studied and is shown in Fig. 2. The modified diode ideality factor is the ratio $(U_{mpp} - I_{mpp} \times R_s) / A$, where U_{mpp} and I_{mpp} are voltage and current at the maximum power point of a solar cell. Fig. 2 presents the correlation between j_0 and A which described by an exponential dependence with good approximation reliability $R^2 = 0.92$ and with the exponent coefficient of 35.8, that is close to $e / kT = 38.8$ at 300 K. Thus *I-V* curve of the multicrystalline silicon solar cells is satisfactorily characterized by the diode diffusion theory equations and the factor A magnification results in the fill factor losses due to exponential saturation current increase with the ideality diode factor.

The SC maximum power is limited also by the parasitic ohmic resistances. Relative fractions of the power dissipation have been calculated with using the voltage and current at maximum power point, the series and shunt resistances which have been measured during the SC tests.

Therefore the concentrated parasitic resistance approximation [10] also was used. The maximum power loss dependencies on the series and shunt resistances are presented in Fig. 3 a, b respectively.

The maximum power losses up to 12 % occur on the series resistance whereas the shunt resistance losses are an order of magnitude less and insignificant. Power dissipations originate due to a voltage drop across the series resistance and a leakage current thru the shunt resistance, so the dependencies are differ in Fig. 3.

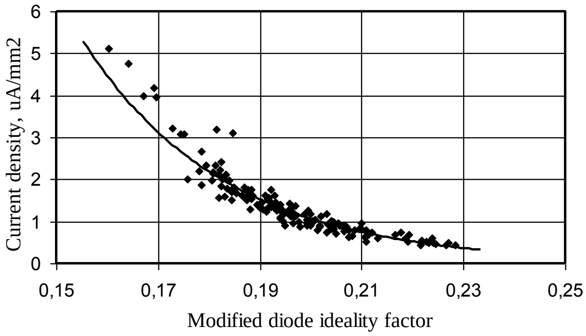

Fig. 2 – The correlation between the dark saturation current density and the diode ideality factor for solar sells with *Isc* = 7.83-7.87 A and *Rsh* ≥ 40 Ohm

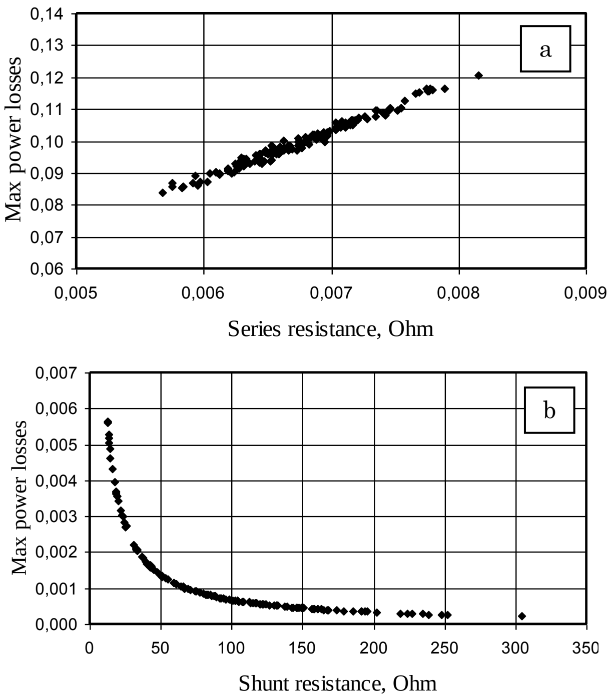

Fig. 3 – The maximum power losses dependencies on series (a) and shunt (b) resistances for solar sells with I_{sc} = 7.83-7.87 A and R_{sh} ≥ 40 ohms (a), R_{ser} ≤ 0.007 ohm (b)

There are many grain boundaries intersecting the *p-n* junction in the silicon multicrystalline solar cells. It is reliably established now that grain boundaries accumulate the metal trace impurities [11-13] and partially shunt the *p-n* junction [14, 15]. Furthermore they exhibit appreciable recombination activity [16-18] and create potential barriers for the charge carries [19].

According to solar cell tests analysis the main efficiency losses are caused by the recombination processes in the *p-n* junction depletion zone that resulting in the fill factor reduction (see Fig. 1). While the SC power losses due to *p-n* junction shunting that is caused by impurity segregation at the grain boundaries were negligible compared with the series resistance losses (see Fig. 3).

4. SUMMARY

The *p-n* junction non-ideality and parasitic ohmic resistances result in fill factor losses of solar cell efficiency. Both the dark saturation current density j_0 and the diode ideality factor *A* were found to increase in fill factor losses in multicrystalline silicon solar cells. Theoretically predicted improving of the fill factor with the diode ideality factor rise was not observed owing to exponential dark saturation current growth with a diode ideality factor that has been observed experimentally.

Additionally the solar cell maximum power is limited by the parasitic ohmic resistances. These losses reach quantity up to 12 % solar cell maximum power. The parasitic series resistance results in the most power losses whereas the shunt resistance losses are an order of magnitude less. The mc-Si solar cell efficiency may be quite improved by reduction of the diode ideality factor and parasitic series resistance.

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Втрати фактору заповнення в сонячних елементах із мультикристалічного кремнію

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Досліджено нефундаментальні втрати ефективності сонячних елементів із мультикристалічного кремнію. Вони значною мірою визначаються якістю діоду і паразитними омічними опорами, що приводять до зменшення коефіцієнту заповнення. Втрати фактору заповнення сонячних елементів із мультикристалічного кремнію були проаналізовані за допомогою випробувань промислової партії сонячних елементів в умовах випромінювання AM1.5. Спостережуване зменшення фактору заповнення при збільшені як струму насичення, так і фактору ідеальності діоду пояснюється їхньою експоненціальною залежністю, яка була встановлена експериментально. Додатково, було оцінено і обговорено втрати максимальної потужності сонячних елементів через омічні паразитні опори. Отримані результати можуть бути використані для підвищення ефективності сонячних елементів і, таким чином, знизити вартість сонячної електроенергії.

Ключові слова: Сонячний елемент, mc-Si, Втрати фактору заповнення, Паразитний омічний опір, Темновий струм насичення, Фактор ідеальності діоду.

Потери фактора заполнения в солнечных элементах с мультикристаллического кремния

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Исследованы нефундаментальные потери эффективности солнечных элементов с мультикристаллического кремния. Они в значительной мере определяются качеством диода и паразитными омическими сопротивлениями, приводящих к уменьшению коэффициента заполнения. Потери фактора заполнения солнечных элементов с мультикристаллического кремния были проанализированы с помощью испытаний промышленной партии солнечных элементов в условиях излучения AM1.5. Наблюдаемое уменьшение фактора заполнения при увеличении как тока насыщения, так и фактора идеальности диода объясняется их экспоненциальной зависимостью, которая была установлена экспериментально. Дополнительно, было оценено и обсуждены потери максимальной мощности солнечных элементов через омические паразитные опоры. Полученны результаты могут быть использованы для повышения эффективности солнечных элементов и, таким образом, снизить стоимость солнечной электроэнергии.

Ключевые слова: Солнечный элемент, mc-Si, Потери фактора заполнения, Паразитное омическое сопротивление, Темновой ток насыщения, Фактор идеальности диода.

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