STUDY OF SOLAR CELLS
BASED ON UPGRADED METALLURGICAL GRADE SILICON

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Summary

In this work we present a study on the applicability of diffused solar cells when cast upgraded metallurgical grade silicon (UMG-Si) is used. Cells have been prepared from differently processed UMG-Si and for comparison from high purity FZ-Si. The material was characterized by the minority carrier diffusion length, which was obtained from spectral response measurements. A two-diode equivalent circuit model was used in order to evaluate pn-junction characteristics under illumination and in the dark.

1. INTRODUCTION

At present the diffusion technology is the cheapest approach to manufacture large area solar cells on a large scale production line. The use of upgraded metallurgical grade silicon as a starting material can reduce the total energy consumption necessary for solar cell manufactoring up to 50% compared to high purity silicon. Until now only sliced wafers of UMG-Si grown by different methods have reached satisfactory quality. Continuous sheet growth techniques are still in evaluation. Therefore the results of this work are restricted to thick ($d \sim 400$ µm) sliced wafers where the minority carrier diffusion length is one order of magnitude smaller ($L \sim 50$ µm) than the cell thickness. As a consequence additional process steps that can increase the solar cell output such as applying a back surface field (1) have negligible influence on these cells. In our experiments the solar cells (area 1 - 4 cm^2) were made on wafers delivered "as cut" from differently processed UMG-Si (Tab.I.). Standard techniques have been used for surface preparation, pn-junction diffusion, metallization, and AR-layer deposition.

2. DATA ANALYSES

The UMG-Si quality is described by the diffusion length (L) of the minority carriers in the base region.

$$L = \sqrt{\tau D} \qquad (2.1)$$

D ... Diffusion coefficient
τ ... lifetime of carriers

The absorption coefficient of Si for wavelengths smaller than the wavelength corresponding to the gap energy ($\varepsilon_g = 1.12$ eV at 300 K) is nearly independent of defects incorporated in the material. Therefore the generated photo current density (j_L) depends only on L and the incident light distribution (1). The diffusion length was obtained from spectral response

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measurements (2). The correlation between L of the examined wafers and the short sircuit current density ($j_{SC} \approx j_L$) is shown in Fig.1 for AM1.5 irradiation at 27°C. The results are in good agreement with results obtained on pure Si (3) and therefore show that the quality of UMG-Si can be sufficiently well described by L.

To study the influence of the pn-junction characteristics on solar cell parameters a two-diode equivalent DC-circuit model was used (Fig.2).

$$j_{ext} = j_L - j_{rg} - j_{diff} - j_{SH} \tag{2.2}$$

$$V_{ext} = V_{int} \pm j_{ext} R_S \tag{2.3}$$

$$j_{rg} = j_{01}\left[\exp(q\, V_{int}/2kT)-1\right] \tag{2.4}$$

$$j_{01} \propto W \Sigma \sigma_T N_T \tag{2.5}$$

$$j_{diff} = j_{02}\left[\exp(q\, V_{int}/kT)-1\right] \tag{2.6}$$

$$j_{02} \approx n_i^2\, q \left[\frac{D_p}{L_p\, N_D} + \frac{D_n}{L_n\, N_A}\right] \tag{2.7}$$

$$j_{SH} = G_{SH} V_{int} (G_{SH} = R_{SH}^{-1}) \tag{2.8}$$

q ... electron charge
k ... Boltzmann's constant
w ... width of space charge region
σ_T ... capture cross section of a deep level
N_T ... concentration of a deep level.

For a more detailed treatment see for example (4). Under the following assumptions upper limits of solar cell parameters (CFF, V_{OC}, η) was calculated using Eq.(2.2). (i) $R_S = G_{SH} = 0$; (ii) $j_L \approx j_{SC}$, the highest measured values are taken; (iii) $j_{01} = 1.10^{-7}\,Acm^{-2}$ taken from the best results obtained on pure FZ-Si; (iv) j_{02} was calculated using (2.7) and values of (5). The results are summarized in Tab.II and the calculated efficiencies are shown in Fig.3.

3.RESULTS

From the processed solar cells I-V curves in the dark (a) and under illumination (b) were recorded. V_{OC} and j_{SC} were measured as a function of light intensity (c). The j-V curves were fitted by the diode parameters j_{01}, j_{02}, R_S, and G_{SH} from the equivalent circuit model to match all three j-V curves (a, b, and c) with one set of parameters according to (6). Results are shown in Tab.III. In Tab.IV the measured solar cell parameters are summarized. In each run 5 arbitrarily chosen samples together with one reference cell (pure FZ-Si) were made. Out from a typical run the parameters of the cell with the highest (+) and the lowest (-) collection efficiency are given. Furthermore the values of the best cells are expressed in per cent of the calculated values (Tab.II and Fig.3). Mean value, $\langle x \rangle_5$, are given in order to show material inhomogeneities. The cell with the lowest efficiency made from HEM-Si exhibits 2 etch pits typical for localized particles (7). These localized particles together with the high defect density observed on surfaces of HEM-Si wafers are probably the reason for the large variation of solar cell parameters.

4. CONCLUSIONS

From the results the following conclusions are drawn :

(i) Starting from commercially available metallurgical grade silicon (mg-Si) ingots, 2×CZ pulling is not sufficient to produce silicon of a quality necessary to reach 10% conversion efficiency.

(ii) Even without using selected mg-Si the Heat Exchanger Method is able to produce silicon of better quality than it can be done by 2×CZ. Furthermore only one recrystallization cycle is necessary.

(iii) Major difficulties using HEM material are : inhomogeneities of impurity distribution and localized defects partly due to enclosed particles. Since HEM is a new technology further improvements can be expected.

(iv) Using a sequence of 2×CZ + 2×FZ can produce silicon with a quality close to high purity Si. This material can be considered to give an upper limit of possible purification of mg-Si by recrystallization techniques only.

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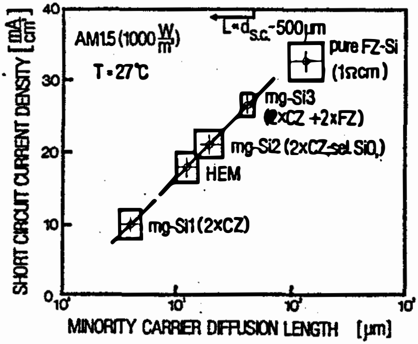


Fig.1.: Measured short circuit current density versus measured minority carrier diffusion length for differently processed UMG-Si.

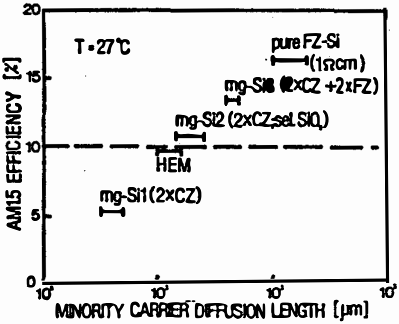
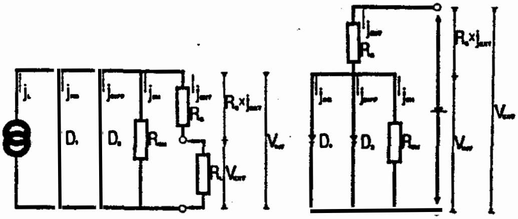


Fig.3.: Calculated upper limit of conversion efficiency versus minority carrier diffusion length of UMG-Si.



a) b)

Fig.2.: Two-diode equivalent circuit model
a) under illumination,
b) in the dark.

Table I.: Material Characteristics

Producer	Siemens$^{1)}$	Crystal Systems$^{2)}$	Siemens$^{1)}$	Siemens$^{1)}$	Wacker Chemitronic$^{3)}$
Starting material	com.av.	com.av.	select.SiO_2	com.av.	
Crystal growth	2×CZ	1×HEM	2×CZ	2×CZ+2×FZ	FZ
Crystallinity	s.	nearly s.$^{o)}$	s.	s.,d.f.	s.,d.f.
Resistivity/Ωcm	p/0.025	p/0.13-0.25	n/0.15	p/0.12-0.18	p/1-2
Diff.length/µm	3-8	7-15	10-20	40-50	> 100
Notation	mg-Si1	HEM	mg-Si2	mg-Si3	pure FZ Si

[1)] München,FRG

[2)] Salem,Mass.USA

[3)] Burghausen,FRG

com.av. ... commercial available

s. ... single crystal

d.f. ... dislocation free

CZ ... Czochralski pulling

FZ ... Float zone process

HEM ... Crystal growth by Heat Exchanger Method

[o)] 1 out of 10 5×5 cm² wafers show grain boundaries (~3 cm)

Table II.: Calculated Solar Cell Parameters

	mg-Si1	HEM	mg-Si2	mg-Si3	pure FZ Si
j_L $\times 10^{-2}$ Acm^{-2}	1.18	2.09	2.35	2.84	34.3
$j_{02} \times 10^{-13}$ Acm^{-2}	1.5	1.5	10	1.5	39
V_{oc} V	0.600	0.625	0.605	0.635	0.590
CFF	0.727	0.739	0.762	0.748	0.786
V_{max} V	0.480	0.510	0.500	0.520	0.500
j_{max} $\times 10^{-2}$ Acm^{-2}	1.1	1.9	2.2	2.6	3.2

Table III.: Fitted Diode Parameters at T = 300K

	HEM		mg-Si3		pure FZ Si	
	-	+	-	+	o	th
$j_{01} \times 10^{-7} Acm^{-2}$	5.10	2.85	5.60	3.35	1.05	1.0
$j_{02} \times 10^{-11} Acm^{-2}$	2.05	0.605	1.65	1.20	1.70	0.39
R_S Ωcm^2	3.7	0.97	0.83	0.45	0.60	0
$G_{SH} \times 10^{-3} \Omega^{-1} cm^{-2}$	19	0.054	3.3	0.068	0.004	0

best (+), worst (-), typical (o) cell out of 5

th ... values for calculating the upper limit of AM1.5 efficiency

Table IV.: Solar Cell Parameters (AM1.5 conditions, P_{inc}=1kWm^{-2}, T=27°C)

		-	+	x_{exp}/x_{th} *)	$\langle x \rangle_5$	Δx *)
mg-Si3	j_{sc} $mAcm^{-2}$	28.3	26.4		26.7	5.6
	V_{oc} V	0.530	0.545	85.8	0.539	1.3
	CFF	0.66	0.73	97.6	0.70	8.1
	Eff.%	9.9	10.5	78.9	10.1	4.9
HEM	j_{sc} $mAcm^{-2}$	20.8	20.2		20.3	6.8
	V_{oc} V	0.495	0.550	88.0	0.525	7.1
	CFF	0.41	0.71	96.1	0.58	26.3
	Eff.%	4.3	7.9	81.4	5.8	32.2
pure FZ-Si	j_{sc} $mAcm^{-2}$		34.0			
	V_{oc} V		0.555	94.1		
	CFF		0.76	96.4		
	Eff.%		14.3	88.3		

*) in per cent