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Swiss high efficient crystalline solar cell project using PSI process for sheet-ribbon Si material

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Project Partners:

Alpha Real AG, Zürich
Evergreen Solar, Waltham, USA

on behalf of
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Final Report

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Abstract

The possibility of improving the quality of Evergreen's 200µm thick p-type polycystalline silicon string ribbon (SR) using gettering and passivation schemes, is studied in this work. First, defects passivation is carried out using thin layers (~15nm) of SiO_2, H rf plasma and PECVD Si_3N_4. Solar cells are fabricated, using 1 Ω.cm resistivity SR wafers, following a simple process with uniform front emitter (n^+) at 875°C for 45 min, thermal dry SiO_2 at 870°C, back side H&Si_3N_4, photolithography, evaporated contacts, and antireflection coating of ZnS/MgF_2. Using this process a cell efficiency of **14%** (open circuit voltage of **577 mV**) is achieved on a 4 cm^2 area. Second, the impurity gettering is implemented by evaporation of 2µm of Al on the back of the wafers before the formation of the n^+ emitter at 875°C. Note, the rest of the cell's fabrication steps are exactly the same as described above. A solar cell efficiency of **15.2%** (open circuit voltage of **581 mV**) is realised on a 4 cm^2 area using a 3 Ω.cm resistivity SR wafers. It is worth mentioning here that, the optimum resistivity for polycrystalline silicon, found by most solar cell labs, is around 1 Ω.cm. Thus, if SR wafers with 1 Ω.cm were used rather than 3 Ω.cm, in the Al-gettering process, higher open circuit voltage will be obtained and an efficiency much higher than 15% would have been reached. The minority carrier diffusion length (L_n) measured with the surface photovoltage technique confirmed the cell's I-V data. A net improvement of 70% in L_n is obtained only due to H passivation, while L_n improved by 100% when Al gettering is combined with passivation.

Comparison of goals versus achievements

Goal according to proposal	Achieved in project
Charactrisation of ribbon material	Material characterised: Homogeneity, resistivity, L_n, lifetime mapping
Adaption of process parameters of PSI-sc solar cell process	Pocess parameters were changed for optimized poly-Si processing of 1-3Ωcm
Make cells with η = 15 ... 20%	Several batches made with η up to 15.2%

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The Swiss Federal Office of Energy, BfE, Bern; Elektrizitätswerk der Stadt Zürich, EWZ; Alpha-Real AG, Zürich; Evergreeen Solar, Waltham, USA; and Paul Scherrer Institute, PSI, Villigen

Zusammenfassung

Ziel dieses Projektes war die Steigerung des Wirkungsgrades von Silizium-Solarzellen, die aus 200 µm dickem, bandgezogenem Material der Fa. Evergreen Solar, Waltham, USA aufgebaut sind. Dabei sollten insbesondere Technologien zur Verbesserung des Wirkungsgrades untersucht werden, die in einem früheren Forschungsprojekt von H. Kiess am PSI zu einkristallinen Si-Zellen mit η>20% geführt hatten. Bandgezogenes Poly-Si hat den enormen Vorteil, dass es direkt als Solarzellensubstrat verwendet werden kann, ohne vorheriges sägen. läppen, ätzen usw. und dadurch den Herstellungsprozess wesentlich verbilligt. Gelingt es, mit diesem Material gleich hohe Wirkungsgrade zu erreichen, wie mit herkömmlichem Poly-Si, würde eine deutliche Reduktion des $/$W_p$-Wertes und auch der grauen Energie resultieren. Derzeit erreichen Zellen aus bandgezogenem Si aus der Fertigung etwa 10-12%.

Zunächst wurden Zellen nach Standard-Prozess auf 1Ωcm p-Material hergestellt (n-Emitter, 15 nm Passivierungsoxid), mit einer zusätzlichen, rückseitigen Passivierung mit Wasserstoff-Plasma und Plasma-Nitrid. Diese 4cm^2 -Zellen erreichten bis zu 14% unter AM 1,5-Bedingungen (V_{cc} = 577 mV).

In einer zweiten Serie von Versuchen wurden Zellen identisch prozessiert, aber zusätzlich mit einem rückseitigen Al-Getterprozess während der Eindiffusion des n-Emitters. Diese Zellen ergaben bis 15,2% auf 3Ωcm Grundmaterial (4cm^2) mit V_{oc} = 581 mV.

Es ist anzumerken, dass diese Zelle einen noch deutlich höheren Wirkungsgrad erreicht hätte, wäre sie auch auf 1Ωcm Material hergestellt worden, das aber zum Zeitpunkt dieser Versuche leider nicht verfügbar war.

Die gemessenen Verbesserungen der Diffusionslängen der Minoritätsträger sind in Einklang mit den Resultaten aus den I-V-Messungen: H-Plasma-Behandlung verbessert L_n um 70%, H-Plasma und Al-Getterung verbessert L_n um 100%.

Dieses Projekt wurde ermöglicht durch finanzielle Unterstützung von:

Bundesamt für Energie, BfE, Bern; Elektrizitätswerk der Stadt Zürich, EWZ; Alpha-Real AG, Zürich; Evergreen Solar, Waltham, USA; und das Paul Scherrer Institut, PSI, Villigen.

1. Introduction/motivation

So far silicon is the material of choice for large scale photovoltaic energy conversion because of its abundance, stability, low toxicity, etc. A large fraction of the cost of a silicon solar cell originates from the cost of the single- or poly-crystalline substrate because it is necessary to saw the wafers from large ingots. This process also increases the energy required to produce the solar cell.

Evergreen Solar, Inc. has successfully developed a low cost proprietary process that allows pulling thin polycrystalline silicon String Ribbon (SR) directly from the melt using a low cost manufacturing technique [1,2]. These silicon ribbons can be used for solar cell processing without further treatment [3,4,5]. It was the purpose of phase I and II of this project, to show that the material of Evergreen is basically suitable also for solar cells with higher efficiency. This has been demonstrated with the results obtained. As a conclusion we propose a next step (phase III and IV) where the main purpose is to look for alternatives in the passivation and gettering processes while maintaining the conversion efficiencies achieved in order to reduce production cost.

2. Experimental

In this work, we studied the possibility of improving the quality of Evergreen's 200 μm thick polycrystalline silicon ribbons using gettering and passivation schemes. Defect passivation is carried out using thin layers (~ 15 nm) of SiO_2, H rf plasma and PECVD Si_3N_4. Solar cells are fabricated with 3 Ω.cm bulk resistivity SR wafers using a simple process with uniform front emitter (n^+) of 80 Ω/□ formed at 875°C for 40 min using $POCl_3$. This is followed by growing ~15 nm of thermal dry oxide again at 875°C for 13 min, H rf plasma & PECVD Si_3N_4, photolithography, contacts formation, and antireflection coating. Impurity gettering is implemented by evaporating 3 μm of Al on the back of the wafers just before the formation of front n^+ emitter at 875°C for 40 min. Note, the rest of the fabrication steps are exactly the same as for the process described above. The cell area is 4 cm^2 and thus large compared to the grain size of the material. Details of the cell processing are given in ref. 5 resp. appendix 1 of this report.

3. Results and discussion

3.1 Defect passivation

The minority carrier diffusion length (L_n) measured with the surface photovoltage method showed that a net improvement of 70% in L_n is obtained only due to H passivation as displayed in Table 1. It is clear from Table 1 that because of the significant scatter in the diffusion length of the starting SR material, the effect of the H plasma passivation is more pronounced in some cases than in others.

3.2 Impurity gettering

The combination of Phosphorus (P) and Aluminum (AL) cogettering has been reported to be very effective in improving the quality of different polycrystalline silicon solar cells [6]. In this section, we implemented P/Al cogettering and/or H passivation to improve the SR wafers. Table 2 indicates that L_n has increased by more than 100% when the gettering is combined with passivation. One can see clearly from Table 2 that, when the proper processes are implemented the minority carrier diffusion length of the low cost SR wafers can be increased to values as high as 200 μm, which is comparable to the L_n values of the more expensive conventionally casted polycrystalline silicon wafers.

3.3 Solar cell output parameters

The illuminated I-V characteristics of the SR solar cells with P/Al gettering and H passivation schemes are depicted in Table 3. Table 3 shows that the combination of the P/Al gettering and the H passivation considerably improve the performance of the SR solar cells, which resulted in an efficiency above 15%. Figure 1 displays the illuminated I-V characteristics of the 15.2% SR solar cell measured under AM1.5-25°C standard illumination condition.

4. Conclusions and outlook

By efficiently combining the gettering and the passivation techniques a 15.2% cell efficiency is realized on low cost polycrystalline silicon string ribbon material (with 3 Ω.cm resistivity) and by implementing a simple fabrication process. It is worth mentioning here that the optimum bulk resistivity for polycrystalline silicon, found by most solar cell labs, is around 1 Ω.cm. Thus, if SR wafers with 1 Ω.cm were used rather than the 3 Ω.cm, higher open circuit voltage would be obtained and an efficiency much higher than 15% would have been reached.

As alrady pointed out in the original proposal, a continuation of the project should be envisaged if

- the milestone for the first year (phase I and II) of 15% on 4 cm2 is reached
- an increased commitment from the industrial partners is granted.

Both conditions have been met now and we would be happy to continue for one more year with phase 3 and 4 in order to reach an industrial implementation of the results.

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Publications having emerged from the project:

1. H. Elgamel and J. Gobrecht: High efficiency solar cells on sheet ribbon grown silicon material" poster, Nationale Photovoltaiktagung, Bern, Switzerland, May 5th, 1998
2. H. Elgamel and J. Gobrecht: "Improving the quality of polycrystalline silicon string ribbon for fabricating high efficiency solar cells", talk at POLYSE 98, Schwäbisch Gmünd, Germany, Sept. 13 - 18, 1998.. Paper in: *Polycrystalline Semiconductors V*, ed. By J.H. Werner, H.P. Strunk and H.W.Schock, Scitec Publications Ltd, 1999, pp 521 - 526
3. J. Gobrecht and H. Elgamel, talk at "11th Workshop on quantum solar energy concersion QUANTSOL 99", Wildhaus, Switzerland, March 14th to 19th, 1999. 2 page extended abstract in the workshop's proceedings.
4. H. Elgamel et al.: "Higly efficient solar cells on low cost sheet ribbon silicon", PSI Scientific Report 1998, Vol. 1, p.107, ISSN 1423-7296, March 1999
5. H. Elgamel and J. Gobrecht: "A Simple And Efficient Process For Fabricating High Efficiency Polycrystalline Silicon Ribbon Solar Cells", paper accepted at 11th Int. PV Science and Engineering Conf. (PVSEC-11), Sept. 20 - 24,1999, Sapporo, Japan

Internal reports having emerged from the project:

1. Project-progress reports no 1 to 5
2. A summary of the project meeting at Evergreen, USA, June 1998, by H. Elgamel
3. Travel report on 2nd world conference and exhibition on photovoltaic solar energy conversion, July 6-10, 1998, Vienna, Austria, by H. Elgamel
4. Annual report 1998 to BfE, by H. Elgamel

Table 1. The effect of the H rf plasma treatment on the L_n of the SR material.

Wafer	L_n before H passivation	L_n after H passivation
SR1	75.2 ±6.3 μm	106.1 ±5.7 μm
SR2	95 ±13.1 μm	141.5 ±2.7 μm
SR3	97.3 ±4 μm	171.6 ±7.2μm

Table 2. The effect of P/Al cogettering and/or H passivation on the L_n of the SR material.

P/Al cogettering	H passivation	L_n (avg. of 3 wafers)
No	No	91 ±7.5 μm
Yes	No	152.7±5.6 μm
Yes	Yes	191.1 ±4.7μm

Table 3. The electrical parameters of 8 SR solar cells with gettering and/or passivation.

P/Al cogettering	H passivation	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	Efficiency (%)
No	No	Best:31.3 Avg.:30.7	Best:552 Avg.:545	Best::71.5 Avg.:70.3	Best:12.4 Avg.:11.7
No	Yes	Best:33.0 Avg.:32.6	Best:567 Avg.:564	Best:74.1 Avg.:71.9	Best:13.8 Avg.:13.5
Yes	Yes	Best:33.8 Avg.:33.6	Best:581 Avg.:582	Best:77.4 Avg.:75.6	Best:15.2 Avg.:14.8

Fig. 1. The illuminated I-V characteristics of the 15.2% SR solar cell measured under AM1.5.