

4th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2014)

Energy Procedia Volume 55

**Hertogenbosch, Netherlands
25-27 March 2014**

Editors:

**Arthur Weeber
Rolf Brendel
Stefan Glunz
Jef Poortmans
Ron Sinton**

**Armin Aberle
Andres Cuevas
Giso Hahn
Pierre-Jean Ribeyron**

ISBN: 978-1-63266-985-8

Printed from e-media with permission by:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571



Some format issues inherent in the e-media version may also appear in this print version.

Copyright© by Elsevier B.V.
All rights reserved.

Printed by Curran Associates, Inc. (2014)

For permission requests, please contact Elsevier B.V.
at the address below.

Elsevier B.V.
Radarweg 29
Amsterdam 1043 NX
The Netherlands

Phone: +31 20 485 3911
Fax: +31 20 485 2457

<http://www.elsevierpublishingsolutions.com/contact.asp>

Additional copies of this publication are available from:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571 USA
Phone: 845-758-0400
Fax: 845-758-2634
Email: curran@proceedings.com
Web: www.proceedings.com

4th International Conference on Silicon Photovoltaics, SiliconPV 2014

Table of contents



Editorial to the Proceedings of the 4th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2014)

A. Weeber

Advanced characterization and simulation

Conceptual comparison between standard Si solar cells and back contacted cells 33

A. Ali, P.P. Altermatt, T. Ohrdes, H. Wagner

A roadmap for PERC cell efficiency towards 22%, focused on technology-related constraints "39

P. Altermatt, K. McIntosh

A generalized electric model for mono and polycrystalline silicon in the presence of cracks and random defects 44

I. Berardone, M. Corrado, M. Paggi

An alternative one-diode model for illuminated solar cells "52

O. Breitenstein

Influence of technological changes on the energy yield of PV modules: An outdoor study "5:

D. Buß, M. Koentopp, M. Strobel

Rear contact pattern optimization based on 3D simulations for IBC solar cells with point-like doped contacts "69

D. Carrió, R. Alcubilla, G. López, J.M. López-González, I. Martin, A. Orpella, P. Ortega, C. Voz

The recombination parameter J_0 "75

A. Cuevas

Quantitative surface recombination imaging of single side processed silicon wafers obtained by photoluminescence modeling "85

A. Fell, E. Franklin, D. Macdonald, S. Surve, D. Walter, K. Weber, X. Yang

A distributed electrical model for interdigitated back contact silicon solar cells "93

D. Giaffreda, M. Debucquoy, C. Fiegna, P. Magnone, N. Posthuma

- Dynamic photoluminescence lifetime imaging for injection-dependent lifetime measurements ""99
S. Herlufsen, K. Bothe, R. Brendel, J. Schmidt
- Spatially resolved determination of junction voltage of silicon solar cells ""7
H. Höffler, H. Al-Mohtaseb, J. Haunschild, M. Kasemann, B. Michl, N. Wöhrle
- Optimized back reflectors for rear diffused c-Si solar cells ""6
A. Ingenito, O. Isabella, J.C.O. Lizcano, S. Luxembourg, R. Santbergen, A. Weeber, M. Zeman
- Increased reliability for J_0 -analysis by QSSPC ""323
A. Kimmerle, P. Rothhardt, R.A. Sinton, A. Wolf
- 2D-modelling of metal-Si emitter interface assuming Schottky or Ohmic contact ""329
L.J. Koduvelikulathu, T. Buck, C. Comparotto, R. Kopecek, V.D. Mihailetchi
- Limitation of industrial phosphorus-diffused emitters by SRH recombination ""337
B. Min, P. Altermatt, A. Dastgheib-Shirazi, H. Wagner
- Study of photoluminescence decay by time-correlated single photon counting for the determination of the minority-carrier lifetime in silicon ""343
S. Parola, D. Blanc-Pélissier, M. Daanoune, A. Focsa, A. Kaminski-Cachopo, M. Lemiti, E. Picard, B. Semmache
- Analysis of the impact of doping levels on performance of back contact - back junction solar cells ""34:
P. Procel, G. Cocorullo, F. Crupi, C. Fiegna, V. Maccaronio, P. Magnone, M. Zanucoli
- In-line thermography for reliable hot spot detection and process control ""355
K. Ramspeck, D. Duphorn, M. Meixner, A. Metz, S. Schenk
- Improved diffused-region recombination-current pre-factor analysis ""363
A. Thomson, K. Fong-Chern, N. Grant, T. Kho
- 2D p-FF simulations for the interpretation of junction isolation's influence on silicon heterojunction solar cells ""36;
R. Varache, D. Muñoz, N. Nguyen
- A method to overcome the time step limitation of PC1D in transient excitation mode ""377
K. Wang, I. Perez-Wurfl
- A method to separate bulk lifetime and surface recombination velocity of silicon bricks based on transient photoluminescence ""383
K. Wang, H. Kampwerth
- Use of QSSPC and QSSPL to monitor recombination processes in p-type silicon solar cells ""38;
X. Wang, M. Abbott, Z. Hameiri, M. Juhl, A. Lennon, Y. Yao
- Comparison between Secondary Electron Microscopy Dopant Contrast Image (SEMDCI) and Electron Beam Induced Current (EBIC) for laser doping of crystalline silicon ""39;
L. Xu, Z. Hameiri, K. Weber, X. Yang

Advanced light management

Experimental implementation of a silicon wafer tandem solar cell "3: 8

T. Gimpel, A.L. Baumann, T. Buck, K. Günther, S. Kontermann, E. Lemp, V. Mihaiilechi, D. Rudolph, W. Schade, J. Theobald, E. Wefringhaus

Application of a silicon nanocrystal down-shifter to a c-Si solar cell "3; 2

S. Luxembourg, T. Burgers, T. Gregorkiewicz, R. Limpens, A. Weeber

Cleaning and etching

Wet-chemical treatment for improved surface passivation of textured silicon heterojunction solar cells "3; 9

D. Deligiannis, S. Alivizatos, A. Ingenito, M. Zeman, D. Zhang, M. van Seville, R. van Swaaij

Enhanced phosphorus gettering of impurities in multicrystalline silicon at low temperature "425

S. Joonwichien, S. Matsushima, I. Takahashi, N. Usami

Industrial cleaning sequences for Al₂O₃-passivated PERC solar cells ""433

C. Kranz, U. Baumann, S. Dorn, T. Dullweber, D. Pysch, S. Queisser, J. Schweckendiek, S. Wyczanowski

Evolution of the charge carrier lifetime characteristics in crystalline silicon wafers during processing of heterojunction solar cells ""43;

B. Stegemann, H. Angermann, E. Conrad, J. Kegel, L. Korte, M. Mews, U. Stürzebecher

Junction formation

Rear emitter silicon heterojunction solar cells: fewer restrictions on the optoelectrical properties of front side TCOs ""44;

M. Bivour, M. Hermle, J. Jeurink, S. Schröer, H. Steinkemper

Boron emitters from doped PECVD layers for n-type crystalline silicon solar cells with LCO ""457

J. Engelhardt, A. Frey, S. Gloger, G. Hahn, L. Mahlstaedt, B. Terheiden

The potential advantage of industrially processed boron emitters compared to phosphorus emitters ""463

Y. Komatsu, I.G. Romijn, P.R. Venema, A.H.G. Vlooswijk

Highly n-doped surfaces on n-type silicon wafers by laser-chemical processes ""469

D. Linaschke, I. Dani, U. Klotzbach, C. Leyens, N. Schilling

c-Si solar cells based on laser-processed dielectric films ""477

I. Martin, R. Alcubilla, M. Colina, A. Coll, G. López, A. Orpella, P. Ortega

Ion implantation for all-alumina IBC solar cells with floating emitter ""487

R. Müller, J. Benick, M. Hermle, C. Reichel

Influence of implantation damage on emitter recombination ""494

T. Ratcliff, A. Blakers, R. Elliman, K.C. Fong, A. Shalav

Lifetime degradation on n-type wafers with boron-diffused and SiO₂/SiN-passivated surface ""4: 2

C. Renevier, M. Forster, E. Fourmond, S. Parola, E. Picard, M. le Coz

- Codiffused bifacial n-type solar cells (CoBiN) "4: 9
P. Rothhardt, D. Biro, C. Demberger, S. Meier, A. Wolf
- Etch-back of p+ structures for selective boron emitters in n-type c-Si solar cells "4; 7
Y. Schiele, G. Hahn, S. Joos, B. Terheiden
- Front side recombination losses analysis in rear emitter silicon heterojunction solar cells 524
R. Varache, D. Muñoz, N. Nguyen, A. Valla
- Characterization of ultra-thin $\mu\text{c-Si:H}$ films for silicon heterojunction solar cells 532
H. Wernerus, M. Bivour, M. Hermle, L. Kroely, W. Wolke
- Boron implanted, laser annealed p+ emitter for n-type interdigitated back-contact solar cells "542
X. Yang, Q. Bi, R. Elliman, W. Liang, D. Macdonald, R. Müller, A. Shalav, K. Weber, L. Xu, R. Zhang
- Module integration**
- Loss analysis for laser separated solar cells "548
S. Eiternick, K. Kaufmann, J. Schneider, M. Turek
- The mechanical theory behind the peel test "553
U. Eitner, L.C. Randler
- Reliable interconnection of the front side grid fingers using silverreduced conductive adhesives "558
T. Geipel, U. Eitner, M.Z. Huq
- Aluminium foil and cold spray copper technology as cost reduction process step in back-contact module design "564
M. Goris, I. Bennett, W. Eerenstein
- Contact-free determination of ethylene vinyl acetate crosslinking in PV modules with fluorescence emission "56:
A. Morlier, S. Blankemeyer, I. Kunze, M. Köntges
- Laser-welded interconnection of screen-printed Si solar cells ""578
H. Schulte-Huxel, S. Blankemeyer, R. Brendel, S. Kajari-Schröder, V. Steckenreiter
- Two-level metallization and module integration of point-contacted solar cells "583
H. Schulte-Huxel, S. Blankemeyer, R. Brendel, S. Kajari-Schröder, Y. Larionova, A. Merkle, R. Peibst, U. Römer, V. Steckenreiter
- Rapid module component testing and quantification of performance gains "58;
M. Turek, S. Eitenrick
- Cost, efficiency and material optimisation of back-contact cell and module design "596
B. Van Aken, E. Bende, I. Bennett, M. Goris, M. Lamers
- Multi-wire interconnection of busbar-free solar cells ""5: 2
J. Walter, C. Ebert, U. Eitner, M. Tranitz, M. Volk
- Simulation of energy production by bifacial modules with revision of ground reflection "5: ;
U.A. Yusufoglu, C. Comparotto, A. Halm, L.J. Koduvelikulathu, R. Kopecek, H. Kurz, T.H. Lee, T.M. Pletzer

Process integration

- Wafer-thickness dependence of double-side contacted rear junction n-type solar cells ""5; 8
T. Ballmann, S. Bordihn, J. Cieslak, M. Kauert, C. Klenke, M. Koentopp, K.H. Küsters, V. Mertens, J. Müller, C. Peters, A. Schönmann, G. Zimmermann
- 21.8 % efficient n-type solar cells with industrially feasible plated metallization ""622
J. Bartsch, J. Benick, F. Feldmann, M. Glatthaar, S. Glunz, D. Hartleb, M. Hermle, M. Kamp, A. Mondon, A. Richter, B. Steinhauser, C. Wittich
- Laser doped screen-printed back contact solar cells exceeding 21% efficiency ""632
M. Dahlinger, K. Carstens, J.R. Köhler, J.H. Werner, R. Zapf-Gottwick
- The BOSCO solar cell: double-sided collection & bifacial operation ""638
F. Fertig, D. Biro, F. Clement, J. Greulich, K. Krauß, R. Preu, S. Rein
- Simulation based development of industrial PERC cell production beyond 20.5% efficiency ""647
G. Fischer, A. Fülle, F. Lottspeich, M. Müller, H. Neuhaus, R. Schiepe, E. Schneiderloechner, S. Steckemetz, K. Stegemann, K. Strauch, T. Weber, F. Wolny
- 21%-efficient PERL solar cells with plated front contacts on industrial 156 mm p-type crystalline silicon wafers ""653
T. Kim, J. Cho, E. Cho, M. Kim, D. Kyeong, J. Lee, W. Lee, K. Lee, J. Lim, H. Park, H. Shin
- 20.5% efficiency on large area N-type PERT cells by ion implantation ""659
A. Lanterne, M. Coig, S. Gall, J. Le Perchec, A. Tauzin, Y. Veschetti

Reliability

- Study of compatibility of silicone-based electrically conductive adhesives and conductive backsheets for MWT modules ""666
G. Beaucarne, I. Bennett, K. Broek, B. Chislea, J. Wei, Y. Yu, A. Zambova
- High-resolution optical and electro-optical microscopy for PV-modules ""673
S. Großer, C. Brzuska, M. Gläser, C. Hagendorf, F. Schippel, T. Tänzer
- Investigations of different soldering failure modes and their impact on module reliability ""678
M. Heimann, R. Bakowskie, J. Hirsch, A. Hussack, M. Junghänel, M. Köhler, S. Sachert
- Solder joint failure modes in the conventional crystalline Si module ""686
U. Itoh, Y. Takemura, K. Takeuchi, H. Tokuhisa, M. Yoshida
- Cracks in solar cell metallization leading to module power loss under mechanical loads ""68;
J. Käsewieter, F. Haase, M. Haro Larrodé, M. Köntges
- Long term stability analysis of copper front side metallization for silicon solar cells ""69:
A. Kraft, J. Bartsch, M. Glatthaar, S. Glunz, A. Lorenz, C. Wolf
- Sodium outdiffusion from stacking faults as root cause for the recovery process of potential-induced degradation (PID) ""6: 8
D. Lausch, J. Bagdahn, O. Breitenstein, A. Graff, C. Hagendorf, A. Hähnel, V. Naumann

Polymer foil additives trigger the formation of snail trails in photovoltaic modules "6; 6

S. Meyer, U. Braun, C. Hagendorf, S. Timmel

Potential-induced degradation at interdigitated back contact solar cells "6; :

V. Naumann, T. Geppert, S. Großer, C. Hagendorf, H. Krokoszinski, M. Werner, D. Wichmann

From short-term hotspot measurements to long-term module reliability "726

T. Roth, K. Meyer, R. Siebert

Comprehensive study of material dependency for silver based conductive glues "72;

A. Schneider, S. Aulehla, F. Demiralp, R. Harney, S. Koch, J. Scheurer, C. Seeger

Silicon material

Determination of acceptor ratio and iron concentration in co-doped silicon "73;

T. Bartel, M. Forster, F. Gibaja

UMG n-type Cz-silicon: influencing factors of the light-induced degradation and its suitability for PV production "748

J. Broisch, J.K. Haunschild, S. Rein, J. Schmidt

Exclusively thermal donor-doped Cz wafers for silicon heterojunction solar cell technology "755

F. Jay, S. Dubois, A. Jouini, D. Muñoz, N. Najid, J. Veirman

Internal gettering of iron at extended defects "75;

M. Knörlein, A. Atruffe, M. Di Sabatino, R. Söndenå

Low-temperature FTIR investigation of aluminum doped solargrade silicon "767

K. Lauer, T. Bartel, F. Kirscht, C. Möller

Reorganization of porous silicon: effect on epitaxial layer quality and detachment "774

N. Milenkovic, M. Driessen, E. Gust, S. Janz, S. Reber

A_{Si-Si_i} -defect model of light-induced degradation in silicon "77;

C. Möller, K. Lauer

Iron-acceptor pair kinetics in compensated n-type silicon "786

C. Möller, T. Bartel, F. Gibaja, F. Kirscht, K. Lauer

High-quality exfoliated crystalline silicon foils for solar cell applications "792

R. Niepelt, R. Brendel, J. Hensen, S. Kajari-Schröder, A. Knorr, V. Steckenreiter

A statistical analysis of the temperature coefficients of industrial silicon solar cells "79:

S. Ponce-Alcántara, J. Connolly, V. Hoffmann, J.M. Míguez, R. Ordás, G. Sánchez

Towards 20 % solar cell efficiency using silicon from metallurgical process route "7: ;

P. Preis, F. Buchholz, P. Diaz-Perez, J. Glatz-Reichenbach, K. Peter, C. Peter, S. Schmitt, A. Søiland, J. Theobald

Influence of slim rod material properties to the Siemens feed rod and the float zone process "7; 8

S. Richter, P. Dold, C. Hagendorf, R. Kunert, H. Riemann, H. Rost, F. Schaaff, M. Schley, M. Werner, F. Zobel

Irradiance dependent temperature coefficients for MC solar cells from Elkem solar grade silicon in comparison with reference polysilicon "824

M. Tayyib, J.O. Odden, T.O. Saetre

Measuring stress birefringence in small Si samples "82:

B. Wang, J. Freudenthal, A. Leadbetter, H. Seigneur, B. Seipel

Cast silicon of varying purity for high efficiency PERC solar cells "83:

F. Wolny, G. Fischer, A. Krause

Structuring and contact formation

Micro characterization and imaging of spikes in nickel plated solar cells ""846

A. Büchler, A. Brand, C. Geisler, M. Glatthaar, S. Hopman, S. Kluska

Mercury: A back junction back contact front floating emitter cell with novel design for high efficiency and simplified processing ""855

I. Cesar, J. Anker, A.R. Burgers, L.J. Geerligs, N. Guillevin, M. Koppes, A. Mewe, A.W. Weeber

Improvement on industrial n-type bifacial solar cell with >20.6% efficiency ""865

H. Chang, P. Hsieh, C. Huang, C. Li, W. Mo, S. Yu

Investigation of laser ablation induced defects in crystalline silicon solar cells '86;

C. Dang, J. Deckers, F. Duerinckx, R. Labie, J. Poortmans, M. Recaman, R. Russell, L. Tous, A. Uruena

Aluminum oxide-aluminum stacks for contact passivation in silicon solar cells "878

J. Deckers, E. Cornagliotti, M. Debucquoy, I. Gordon, R. Mertens, J. Poortmans

Continuous wave laser processing for electrical and mechanical stable solar cells with Ni-Cu metallization "887

C. Geisler, M. Glatthaar, S. Hopman, W. Hördt, S. Kluska, A. Mondon

Novel hybrid electrode using transparent conductive oxide and silver nanoparticle mesh for silicon solar cell applications ""892

M. Huang, A.G. Aberle, H. Gong, Z. Hameiri, T. Mueller, W. Wong

Plating processes on aluminum and application to novel solar cell concepts ""89;

M. Kamp, J. Bartsch, M. Glatthaar, S. Glunz, M. Jahn, R. Keding, I. Krossing, R. Müller

Influence of oxygen micro atmosphere during contact formation ""8: :

S. Koerner, M. Eberstein, U. Partsch, K. Reinhardt, U. Schmidt

Optimizing fine line dispensed contact grids ""8; 5

M. Pospischil, D. Biro, A. Brand, F. Clement, O. Doll, T. Fellmeth, H. Gentischer, M. Hörteis, M. Klawitter, M. Kuchler, M. König, S. Nold, L. Wende, R. Zengerle

Observation of the contact formation of PV frontside pastes by in-situ contact resistance measurement ""924

K. Reinhardt, M. Eberstein, R. Jurk, S. Körner, U. Partsch, U. Schmidt

Synthesis of a lead- and particle-free metal-organic ink for front side metallization of crystalline silicon solar cells "92:

Y. Tamari, S. Binder, A. Gautrein, M. Glatthaar, S.W. Glunz, C. Schmiga

- Large-area hybrid silicon heterojunction solar cells with Ni/Cu plated front contacts "937
L. Tous, M. Aleman, C. Ballif, S. De Wolf, F. Duerinckx, T. Emeraud, I. Gordon, S. Granata, J. John, R. Labie, J. Lerat, S. Martin de Nicolas, R. Mertens, T. Pletzer, J. Poortmans, R. Russell, J. Szlufcik
- Passivated busbars from screen-printed low-temperature copper paste "946
D. Wood, G. Beaucarne, A. Beucher, C. Boulord, P. Chevalier, B. Chislea, W. Deng, F. Duerinckx, Z. Feng, I. Kuzma-Filipek, N. Powell, R. Russel, J. Szlufcik, P. Verlinden, A. Zambova, N. Zeghers
- Carrier selective, passivated contacts for high efficiency silicon solar cells based on transparent conducting oxides "955
D. Young, S. Grover, V. LaSalvia, B. Lee, W. Nemeth, A. Norman, P. Stradins, H. Yuan

Surface morphology and passivation

- Feasibility of antireflection and passivation coatings by atmospheric pressure PECVD "963
J. Almeida Silva, R. Bazinette, D. Blanc-Pélissier, L. Gaudy, M. Lemiti, A. Lukianov, F. Massines, S. Pouliquen, J. Vallade
- The influence of orientation and morphology on the passivation of crystalline silicon surfaces by Al₂O₃ "972
L. Black, A. Cuevas, T. Kho, K. McIntosh
- Highly efficient multi-crystalline solar cells using rear surface passivation technology "979
Y. Chiou, F.S.F. Chen, W.K.W. Huang, K. Hung, C. Ko, H. Lin, N. Ou, C. Wu, H. Yen
- Optical and electronic properties of MAE textured nanoporous silicon "984
T.K. Chong, A.W. Blakers, K. Booker, K.J. Weber
- Deposition of a SiO_x film showing enhanced surface passivation "98;
P. Descamps, S.S. Asad, G. Beaucarne, F. Campeol, R. Delamare, F. Duerinckx, D. Flandre, V. Kaiser, R. Kotipalli, I. Kuzma-Filipek, J. Szlufcik
- MF-sputtered AZO for a-Si SHJ solar cells "999
J. Jeurink, L. Kroely, S. Park, F. Wagner, W. Wolke
- Fundamental studies of hydrogen at the silicon / silicon nitride interface "9: 8
S. Joos, H. Becker, G. Hahn, D. Rogalla, Y. Schiele, B. Terheiden
- Investigation of rear side selective laser ablation and damage etching process for industrial PERC solar cells "9; 3
J. Kim, Y. Hwang, E. Lee, J. Lim
- Investigations on the passivation mechanism of AlN:H and AlN:H-SiN:H stacks "9; 9
G. Krugel, F. Jenkner, A. Moldovan, R. Preu, J. Rentsch, W. Wolke
- Passivation properties of subnanometer thin interfacial silicon oxide films "": 27
W. Lu, H. Angermann, L. Korte, C. Leendertz, A. Töfflinger
- Neutron and x-ray reflectometry investigations of amorphous silicon-based surface passivation layers "": 35
E.S. Marstein, I.M. Hasle, H. Haug, A.J. Qviller

Thermal, structural and electrical study of the effect of annealing on the passivation by amorphous silicon of n-type crystalline (100) silicon surfaces "": 3:

H. Meddeb, I. Abdelwahab, Y. Abdulraheem, T. Bearda, H. Ezzaouia, V. Ferro, I. Gordon, B. O'Sullivan, J. Poortmans, J. Szlufcik

Hydrogen plasma treatments of amorphous/crystalline silicon heterojunctions "": 49

M. Mews, E. Conrad, S. Kirner, L. Korte, N. Mingirulli

Simple cleaning and conditioning of silicon surfaces with UV/ozone sources "": 56

A. Moldovan, F. Feldmann, C. Hagendorf, M. Hermle, K. Kaufmann, G. Krugel, J. Rentsch, A. Roth-Fölsch, M. Zimmer

PECVD- $\text{AlO}_x/\text{SiN}_x$ passivation stacks on silicon: Effective charge dynamics and interface defect state spectroscopy "": 67

J.A. Töfflinger, L. Korte, A. Laades, C. Leendertz, L.M. Montañez, B. Rech, H. Sperlich, U. Stürzebecher

Requirements to achieve field-induced anodisation for silicon surface passivation "": 77

J. Tong, A. Lennon, X. Wang

Sputtered hydrogenated amorphous silicon for silicon heterojunction solar cell fabrication "": 87

X. Zhang, A. Cuevas, S. De Wolf, B. Demareux

Wafering technologies

Room temperature spalling of thin silicon foils using a kerfless technique "": 95

P. Bellanger, J. Serra

Solar cell processing of foil produced by epoxy-induced spalling of silicon "": 9;

R. Martini, V. Depauw, M. Gonzalez, I. Gordon, S. Granata, J. Poortmans