



CONFERENCE RECORD OF THE TWENTY SIXTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE - 1997

**ANAHEIM MARRIOTT
ANAHEIM, CA**

29 September - 03 October 1997



SPONSORED BY THE IEEE ELECTRON DEVICES SOCIETY (USA)



HANWHA 1019

Copyright and Reprint Permission: Abstracting is permitted with credit to the source. Libraries are permitted to photocopy beyond the limit of U.S. copyright law for private use of patrons those articles in this volume that carry a code at the bottom of the first page, provided the per-copy fee indicated in the code is paid through Copyright Clearance Center, 27 Congress Street, Salem, MA 01970. For other copying, reprint or republication permission, write to IEEE Copyrights Manager, IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331. All rights reserved.

Copyright © 1997 by the Institute of Electrical and Electronics Engineers, Inc.

TWENTY-SIXTH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE - 1997

IEEE Catalog Number: 97CB36026

ISBN: 0-7803-3767-0
0-7803-3768-9

**Casebound Edition
Microfiche Edition**

Library of Congress: 84-640812

ISSN: 0160-8371

TABLE OF CONTENTS

CHERRY AWARD ADDRESS

Crystalline Thin Silicon Cells	1
A. Goetzberger	

1. BULK CRYSTALLINE SILICON DEVICES AND MATERIALS

MC - Silicon Solar Cells with > 17% Efficiency	7
H. Lautenschlager, F. Lutz, C. Schetter, U. Schubert and R. Schindler	
Investigation of Carrier Lifetime Instabilities In CZ-Grown Silicon	13
Jan Schmidt, Armin G. Aberle and Rudolf Hezel	
Simultaneous P and B Diffusion, <i>In-Situ</i> Surface Passivation, Impurity Filtering and Gettering for High-Efficiency Silicon Solar Cells	19
Thomas Krygowski, Ajeet Rohatgi and Douglas Ruby	
Mechanism(s) of Hydrogen Diffusion in Silicon Solar Cells During Forming Gas Anneal	25
Bhushan Sopori, M.I. Symko, Robert Reedy, Kim Jones and Rick Matson	
18.5% Efficient First-Generation MIS Inversion-Layer Silicon Solar Cells	31
Axel Metz, Rüdiger Meyer, Burkhard Kuhlmann, Manfred Grauvogl and Rudolf Hezel	
16.6% Efficient Silicon-Film™ Polycrystalline Silicon Solar Cells	35
Yibin Bai, David H. Ford, James A. Rand, Robert B. Hall and Allen M. Barnett	
Recent Progress on the Self-Aligned, Selective-Emitter Silicon Solar Cell	39
D.S. Ruby, P. Yang, M. Roy and S. Narayanan	
Mechanically V-Textured Low Cost Multicrystalline Silicon Solar Cells with a Novel Printing Metallization	43
C. Gerhards, C. Marckmann, R. Tölle M. Spiegel, P. Fath, G. Willeke and E. Bucher	
Surface Texturing Using Reactive Ion Etching For Multicrystalline Silicon Solar Cells	47
K. Fukui, Y. Inomata and K. Shirasawa	
Many-Body Theory Applied to Solar Cells: Excitonic and Related Carrier Correlation Effects	51
Martin A. Green	
Numerical Simulations of Transient Photoconductance Decay	55
T.H. Wang, T.F. Ciszek	
Minority-Carrier Lifetime Degradation in Silicon Co-doped with Iron and Gallium	59
T.F. Ciszek, T.H. Wang, W.A. Doolittle and A. Rohatgi	
Optimized Aluminum Back Surface Field Techniques for Silicon Solar Cells	63
S. Narasimha, A. Rohatgi	
Multicrystalline Silicon Solar Cells with Low Rear Surface Recombination	67
Matthew Stocks, Andrew Blakers and Andres Cuevas	

Characterization of Silicon Solar Cells with Interdigitated Contacts	71
J.O. Schumacher, J. Dicker, S. Glunz, C. Hebling, J. Knobloch, W. Warta and W. Wettling	
Improvement of MC Si Solar Cells by AL-Gettering and Hydrogen Passivation	75
G. Hahn, W. Jooss, M. Spiegel, P. Fath, G. Willeke and E. Bucher	
Characterization and Optimization of the Al/SiO ₂ /p-Si MIS Contact in MIS-IL Silicon Solar Cells	79
Burkhard Kuhlmann, Armin G. Aberle and Rudolf Hezel	
Comparison of Bulk and Surface Passivation Properties of Plasma Nitrides on Si and SiGe Solar Cells	83
K. Said, G. Beaucarne, M. Libezny, W. Laureys, K. Vinckler, J. Nijs and J. Poortmans	
Characterization and Application of Rapid Thermal Oxide Surface Passivation for the Highest Efficiency RTP Silicon Solar Cells	87
P. Doshi, J. Moschner, J. Jeong, A. Rohatgi, R. Singh and S. Narayanan	
Microstructural Analysis of the Crystallization of Silicon Ribbons Produced by the RGS Process	91
I. Steinbach and H.-U. Höfs	
Commercialization of Silicon Sheet via the String Ribbon Crystal Growth Technique	95
R. Janoch, R. Wallace and J. I. Hanoka	
Thin Silicon String Ribbon for High Efficiency Polycrystalline Solar Cells	99
R.L. Wallace, J.I. Hanoka, S. Narasimha, S. Kamra and A. Rohatgi	
Growth and Properties of Silicon Filaments for Photovoltaic Applications	103
T.F. Ciszek and T.H. Wang	
Lift-Off of Silicon Epitaxial Layers for Solar Cell Applications	107
K.J. Weber, K. Catchpole, M. Stocks and A.W. Blakers	
Growth and Characterization of 200 kg Multicrystalline Silicon Ingots by HEM	111
Chandra P. Khattak and Frederick Schmid	
Relationships Between Room Temperature Photoluminescence and Electronic Quality in Multicrystalline Silicon	115
Y. Koshka, S. Ostapenko, J. Cao and J. P. Kalejs	
Contactless Measurement of Recombination Lifetime in Photovoltaic Materials	119
R.K. Ahrenkiel and Steven Johnston	
Process Monitoring of Multicrystalline Silicon Solar Cells with Quasi-Steady State Photoconductance Measurements	123
Matthew Stocks, Andres Cuevas and Andrew Blakers	
LBIC Characterization of Twin Boundaries in Tricrystalline Silicon Solar Cells	127
P. Wawer, S. Irmscher and H.-G. Wagemann	
Diffusion Length of Tri-Crystalline Silicon During Solar Cell Processing	131
W. Kusian, H.-C. Ostendorf, J. Palm and A.L. Endrös	

Large Area, Screen Printed Silicon Solar Cells with Selective Emitter Made by Laser Overdoping and RTA Spin-On Glasses.	135	Determination of the Diffusion Length and Surface Recombination Velocity: Two Simple Methods	195
U. Besi-Vetrella, L. Pirozzi, E. Salza, G. Ginocchietti, F. Ferrazza, L. Ventura, A. Slaoui and J.C. Muller		J.C. Durán, G.L. Venier, M.J.L. Tamasi, C.G. Bolzi, J.C. Plá and E.M. Godfrin	
A Simple Processing Sequence For Selective Emitters	139	Simple Flashlamp I-V Testing of Solar Cells	199
J. Horzel, J. Szlufcik, J. Nijs and R. Mertens		William Keogh and Andrés Cuevas	
Modeling the Growth of PECVD Silicon Nitride Films for Crystalline Silicone Solar Cells Using Factorial Design and Response Surface Methodology	143	New Method of Parameters Extraction from Dark I-V Curve	203
Kjell Nybergh, Teemu Marjamäki and Eija Skarp		A. Kaminski, J.J. Marchand, A. Fave and A. Laugier	
Screen Printed Multicrystalline Silicon Solar Cells with Porous Silicon Antireflection Coating	147	PC1D Version 5: 32-Bit Solar Cell Modeling on Personal Computers	207
R.R. Bilyalov, B. Groh, H. Lautenschlager, R. Schindler and F. Schomann		Donald A. Clugston and Paul A. Basore	
Implementation of Hydrogen Passivation in an Industrial Low-Cost Multicrystalline Silicon Solar Cell Process	151	Collection Probability Equals Dark Minority Carrier Concentration and Other Surprising Solar Cell Relations	211
M. Spiegel, R. Tölle, C. Gerhards, C. Marckmann, N. Nussbaumer, P. Fath, G. Willeke and E. Bucher		Martin A. Green	
The Effect of Gettering on Areal Inhomogeneities in Large-Area Multicrystalline-Silicon Solar Cells	155	Impurity Photovoltaic Effect in Crystalline Silicon Solar Cells	215
James M. Gee and Bhushan L. Soporì		Hiroto Kasai, Toshiyuki Sato and Hideki Matsumura	
Dry Processing of mc-Silicon Thin-Film Solar Cells on Foreign Substrates leading to 11% Efficiency	159	Optimizing Metalization Patterns for Yearly Yield	219
Ralf Lüdemann, Sebastian Schaefer, Corina Schüle and Christopher Hebling		A.R. Burgers and J.A. Eikelboom	
Silicon Solar Cells with Chromium-Copper Contacts	163	Temperature Behavior of Monofacial and Bifacial Silicon Solar Cells	223
J. Härkönen, M. Yli-Koski, E. Tuominen, Y. Ezer, J. Sinkkonen, T. Marjamäki and J. Kaitila		Andreas Hübner, Armin G. Aberle and Rudolf Hezel	
Isotropic Texturing of Multicrystalline Silicon Wafers with Acidic Texturing Solutions	167	18.2% Efficient Multicrystalline Silicon Cell	227
R. Einhaus, E. Vazsonyi, J. Szlufcik, J. Nijs and R. Mertens		Jianhua Zhao, Aihua Wang, Pietro P. Altermatt and Martin A. Green	
Si Texturing With Sub-Wavelength Structures	171	The Range of High-Efficiency Silicon Solar Cells Fabricated at Fraunhofer ISE	231
Saleem H. Zaidi and S.R.J. Brueck		S.W. Glunz, J. Knobloch, C. Hebling and W. Wettling	
Twodimensional Solar Cell Simulations by Means of Circuit Modelling	175	Back Surface Field and Emitter Passivation Effects in the Record High Efficiency N-Type Dendritic Web Silicon Solar Cell	235
E. Van Kerschaver, J. Nijs, R. Mertens and M. Ghannam		S. Narasimha, G. Crotty, T. Krygowski, A. Rohatgi and D.L. Meier	
Establishing an Accurate Numerical Model for the 2D-Simulation of Buried Contact Cells	179	Progress on the Lope (Local Point Contact and Shallow Angle Evaporation) Silicon Solar Cell	239
Pietro P. Altermatt, Gernot Heiser, Tobias Kiesewetter, Keith R. McIntosh, Christiana B. Honsberg, Stuart R. Wenham and Martin A. Green		B. Terheiden, R. Kühn, C. Zechner, P. Fath, G. Willeke and E. Bucher	
Accurate Modeling of Light Trapping in Thin Film Silicon Solar Cells	183	Systematic Study Towards High Efficiency Multicrystalline Silicon Solar Cells with Mechanical Surface Texturization	243
A.A. Abouelsaood, M.Y. Ghannam, J. Poortmans and R.P. Mertens		C. Zechner, G. Hahn, W. Jooss, M. Wibrall, B. Bitnar, S. Keller, M. Spiegel, P. Fath, G. Willeke and E. Bucher	
Ray Tracing vs. Electromagnetic Methods in the Analysis of Antireflective Textured Surfaces	187	Characterisation and Measurement of Silicon Solar Cells with Floating Junction Passivation	247
J.C. Plá, J.C. Durán, D.C. Skigin and R.A. Depine		Christiana B. Honsberg, Keith R. McIntosh, Ganokwan Boonprakaikaew, Seyed Ghozati and Stuart R. Wenham	
A New Method for the Determination of the Minority Carrier Lifetime Based on a Biased OCV Technique	191	Rear Surface Passivation in Buried Contact Solar Cells	251
C.J. Bruno, M.G. Martínez Bogado, J.C. Plá and J.C. Durán		Y H Tang, X M Dai, J H Zhao, A H Wang, S R Wenham and C B Honsberg	
		23.5% Efficient Silicon Solar Cell with Rear Micro Contacts of c-Si/μc-Si:H Heterostructure	255
		S. Okamoto, M. Nishida, T. Shindo, Y. Komatsu, S. Yasue, M. Kaneiwa and T. Nanmori	
		Increase in Efficiency and Material Yield by Use of PECVD Silicon Nitride in a Simple Screen Printing Process on Solarex Material	259
		F. Duerinckx, R. Einhaus, E. Van Kerschaver, J. Szlufcik, J. Nijs, R. Mertens, M. Roy and S. Narayanan	

Novel Light Trapping Scheme for Thin Crystalline Cells Utilizing Deep Structures on Both Wafer Sides	263	Effect of Reduced Deposition Temperature, Time, and Thickness on Cu(InGa)Se₂ Films and Devices	331
Anders M. Jorgensen, Thomas Clausen and Otto Leistikio		W.N. Shafarman, R.W. Birkmire, S. Marsillac, M. Marudachalam, N. Orbey and TWF Russell	
Cost-Effective Thin Film Solar Cell Processing on Multicrystalline Silicon	267	Pilot Production of CIGS Photovoltaic Modules	335
T. Vermeulen, F. Duerinckx, K. De Clercq, J. Szlufcik, J. Poortmans, P. Laermans, M. Caymax, J. Nijs and R. Mertens		J.S. Britt, A.E. Delahoy and Z.J. Kiss	
Solar Cell Preparation in Thin Silicon Membranes	271	CdS: Characterization and Recent Advances in CdTe Solar Cell Performance	339
M. Lfibežny, J. Poortmans, M. Caymax, G. Beaucarne, W. Laureys and J. Nijs		C. Ferekides, D. Marinskiy and D.L. Morel	
Boron-Doped Back-Surface Fields Using an Aluminum-Alloy Process	275	16.0% Efficient Thin-Film CdS/CdTe Solar Cells	343
James M. Gee, Michel D. Bode and Beverly L. Silva		Hideaki Ohyama, Tetsuya Aramoto, Seiji Kumazawa, Hiroshi Higuchi, Takashi Arita, Satoshi Shibutani, Tuyoshi Nishio, Junji Nakajima, Miwa Tsuji, Akira Hanafusa, Takeshi Hibino, Kuniyoshi Omura and Mikio Murozono	
Silicon Solar Cell Emitters: Optimization and Comparison of Two Different Technologies	279	Application of Cd₂SnO₄ Transparent Conducting Oxides in CdS/CdTe Thin-Film Devices	347
M. Cid and N. Stem		X. Wu, P. Sheldon, T.J. Coutts, D.H. Rose and H.R. Moutinho	
Record Efficiencies Above 21% for MIS-Contacted Diffused Junction Silicon Solar Cells	283	Back Contact Effects on Junction Photoluminescence in CdTe/CdS Solar Cells	351
Axel Metz and Rudolf Hezel		D.H. Levi, L.M. Woods, D.S. Albin, T.A. Gessert, D.W. Niles, A. Swartzlander, D.H. Rose, R.K. Ahrenkiel and P. Sheldon	
21.9% Efficient Silicon Bifacial Solar Cells	287	Economic Recycling of CdTe Photovoltaic Modules	355
C.Z. Zhou, P.J. Verlinden, R.A. Crane, R.M. Swanson and R.A. Sinton		John Bohland, Igor Anisimov and Todd Dapkus	
Multiinterface Si Solar Cells with Active Substructures and Active Interfaces	291	On The Role of Na and Modifications to Cu(In,Ga)Se₂, Absorber Materials Using Thin-MF (M=Na, K, Cs) Precursor Layers	359
Z.T. Kuznicki		Miguel A. Contreras, B. Egaas, P. Dippo, J. Webb, J. Granata, K. Ramanathan, S. Asher, A. Swartzlander and R. Noufi	
2. II-VI MATERIALS AND DEVICES			
Recent Progress and Critical Issues in Thin Film Polycrystalline Solar Cells and Modules	295	High Efficiency CIGS and CIS Cells with CVD ZnO Buffer Layers	363
Robert W. Birkmire		Larry C. Olsen, Wenhua Lei, F. William Addis, William N. Shafarman, Miguel A. Contreras and Kannan Ramanathan	
Current Status of Polycrystalline Thin-Film PV Technologies	301	Comparison Study of Close-Spaced Sublimated and Chemical Bath Deposited CdS Films: Effects on CdTe Solar Cells	367
Harin S. Ullal, Kenneth Zweibel and Bolko von Roedern		D. Albin, D. Rose, R. Dhere, D. Levi, L. Woods, A. Swartzlander and P. Sheldon	
CdTe_{1-x}S_x Absorber Layers for Thin-Film CdTe/CdS Solar Cells	307	Metastable Changes of the Electrical Transport Properties of Cu(In,Ga)Se₂	371
Brian E. McCandless and Robert W. Birkmire		Th. Meyer, M. Schmidt, R. Harney, F. Engelhardt, O. Seifert, J. Parisi, M. Schmitt and U. Rau	
Revisiting the Defect Physics in CuInSe₂ and CuGaSe₂	313	Effect of Light Intensity on Current Collection in Thin-Film Solar Cells	375
Alex Zunger, S.B. Zhang and Su-Huai Wei		T.J. McMahon and B. von Roedern	
Advances in the CIS Research at NREL	319	The Use of Ga in Two-Step Processing to Optimize the Electronic Properties of CuInGa_{1-x}Se₂ Solar Cells	379
K. Ramanathan, R.N. Bhattacharya, J. Granata, J. Webb, D. Niles, M.A. Contreras, H. Wiesner, F.S. Hasoon and R. Noufi		S. Zafar, H. Sankaranarayanan, A. Jayapalan, R. Narayanaswamy, C.S. Ferekides and D.L. Morel	
New Aspects of Phase Segregation and Junction Formation in CuInSe₂	323	The Dependence of Reactively Sputtered ZNO Electronic Properties on Growth Parameters for Use as Buffer Layers in CuInGa_{1-x}Se₂ Solar Cells	383
R. Herberholz, H.W. Schock, U. Rau, J.H. Werner, T. Haalboom, T. Gödecke, F. Ernst, C. Beilharz, K.W. Benz and D. Cahen		R. Bhatt, H. Sankaranarayanan, C.S. Ferekides and D.L. Morel	
Improved FF of CIGS Thin-Film Mini-Modules with Zn(O,S,OH)_x Buffer by Post-Deposition Light Soaking	327	Quantitative Incorporation of Sodium in CuInSe₂ and Cu(In,Ga)Se₂ Photovoltaic Devices	387
Katsumi Kushiya, Muneyori Tachiyuki, Takahisa Kase, Yoshinori Nagoya, Tadayuki Miura, Daisuke Okumura, Masao Satoh, Ichirou Sugiyama and Osamu Yamase		J.E. Granata, J.R. Sites, S. Asher and R.J. Matson	

MOVPE of CuGaSe₂ for Photovoltaic Applications	391	Study of the Defect Levels, Electrooptics, and Interface Properties of Polycrystalline CdTe and CdS Thin Films and their Junction	451
T. Kampschulte, A. Bauknecht, U. Blieske, M. Saad, S. Chichibu and M. Ch. Lux-Steiner		F.A. Abulfotuh, A. Balcioglu, T. Wangestein, H.R. Moutinho, F. Hassoon, A. Al-Douri, A. Alnajjar and L.L. Kazmerski	
Growth of CuIn₃Se₅ Layer on the CuInSe₂ Film and Its Effect on the Photovoltaic Properties of In₂Se₃/CuInSe₂ Solar Cells	395	Isothermal Grain Growth of CdTe in CdCl₂ and Te Fluxes	455
Se Han Kwon, Sung Chan Park, Byung Tae Ahn, Kyung Hoon Yoon and Jinsoo Song		J. Hiie, M. Altosaar, E. Mellikov, J. Mädasson, J. Sapogova and V. Mikli	
FTIR, EPMA, AUGER, and XPS Analysis of Impurity Precipitates in CDS Films	399	Thin Film CdS/CdTe Solar Cells Prepared by Electrodeposition Using Low Cost Materials	459
John D. Webb, Doug H. Rose, David W. Niles, Amy Swartzlander and Mowafak M. Al-Jassim		F.J. Alvarez, N. Di Lalla and A. Lamagna	
Large-Area Copper Indium Diselenide (CIS) Process, Control and Manufacturing	403	Determining the Voltage Dependence of the Light Generated Current in CuInSe₂ - Based Solar Cells Using I-V Measurements Made at Different Light Intensities	463
T.J. Gillespie, B.R. Lanning, C.H. Marshall and M. Contreras		J.E. Phillips, J. Titus and D. Hofmann	
Investigation of Buffer Layer Process on CIGS Solar Cells by Dual Beam Optical Modulation Technique	407	ZnO(CdS)/CIS/Mo Solar Cells Characterized by Modulation Capacitance Voltage Measurements	467
C.H. Huang, Sheng S. Li, B.J. Stanbery, C.H. Chang and T.J. Anderson		Ngo Duong Sinh, R. Scheer, K. Kliefoth, W. Füssel and W. Fuhs	
Modification of Dead Layer on Surfaces of CuInSe₂ and Its Alloys	411	Solar Cell Spectral Response Measurement Errors Related to Spectral Band Width and Chopped Light Waveform	471
S. Menezes, J-F. Guillemoles, B. Canava, J. Vedel and D. Lincot		Halden Field	
CuInSe₂ Cell with CdO Window Layer	415	Interpretation of Dual Beam Optical Modulation (DBOM) Measurements in Thin-Film Materials	475
A.A. Al-Quraini and C.H. Champness		Thomas K. Simacek and Jeffery L. Gray	
Studies of ZnTe Back Contacts to CdS/CdTe Solar Cells	419	Influence of Na on the Electro-Optical Properties of Cu(In,Ga)Se₂	479
T.A. Gessert, P. Sheldon, X. Li, D. Dunlavy, D. Niles, R. Sasala, S. Albright and B. Zadler		Brian M. Keyes, Falah Hasoon, Pat Dippe, Ahmet Balcioglu and Fuad Abulfotuh	
RF Sputtered Back Contacts for CdTe/CdS Thin Film Solar Cells	423	CIGS Films via Nanoparticle Spray Deposition: Attempts at Densifying a Porous Precursor	483
C.S. Ferekides, V. Viswanathan and D.L. Morel		Douglas L. Schulz, Calvin J. Curtis, Alan Cram, Jeffrey L. Alleman, Alice Mason, Richard J. Matson, John D. Perkins and David S. Ginley	
The Effect of SnO₂ Roughness on the Properties of CdTe/CdS Solar Cells	427	Reactive Magnetron Sputtering of Transparent and Conductive Zinc Oxide Films Deposited at High Rates onto CIS/CIGS Photovoltaic Devices	487
C. Ferekides, U. Poorsala and D.L. Morel		T.J. Gillespie, W.A. Miles and J.A. del Cueto	
Studies of Recrystallization of CdTe Thin Films after CdCl₂ Treatment	431	Wavelength and Pulse Duration Effects in Laser Scribing of Thin Films	491
H.R. Moutinho, M.M. Al-Jassim, F.A. Abulfotuh, D.H. Levi, P.C. Dippo, R.G. Dhere and L.L. Kazmerski		I. Matulionis, S. Nakade and A.D. Compaan	
Influence of CdS/CdTe Interface Properties on the Device Properties	435	The Oxidation of Copper-Indium Diselenide Surfaces	495
R. Dhere, D. Rose, D. Albin, S. Asher, M. Al-Jassim, H. Cheong, A. Swartzlander, H. Moutinho, T. Coutts, R. Ribelin and P. Sheldon		A.S.A.C. Diniz	
Properties of ZnTe:Cu Thin Films and CdS/CdTe/ZnTe Solar Cells	439	XPS Studies of Sodium Compound Formation and Surface Segregation in CIGS Thin Films	499
J. Tang, D. Mao, T.R. Ohno, V. Kaydanov and J.U. Trefny		B.J. Stanbery, E.S. Lambers and T.J. Anderson	
Electrodeposited CdS Thin Films and their Application in CdS/CdTe Solar Cells	443	New Concepts of NANO-Crystalline Organic Photovoltaic Devices	503
Figen Kadirgan, D. Mao, A. Balcioglu, B.E. McCandless, W. Song, T.R. Ohno and J.U. Trefny		M. Späth, J.M. Kroon, P.M. Sommeling, J.A. Wienke, J.A.M. van Roosmalen, T.B. Meyer, A.F. Meyer and O. Kohle	
Properties of CdS Te_{1-x} Alloy Films	447	Photochemical Solar Cells Based on Dye-Sensitization of Nanocrystalline TiO₂	507
A. Fischer, X. Deng, D. Grecu, K. Makhratchev, X. Ma, R. Wendt, D. Zuo, A.D. Compaan and R.G. Bohn		S.K. Deb, S. Ferrere, A.J. Frank, B.A. Gregg, S.Y. Huang, A.J. Nozik, G. Schlichthörl and A. Zaban	

Polycrystalline GaAs Solar Cells on Low-Cost Silicon-Film™ Substrates	511	Thin Film Poly-Si Solar Cell with "Star Structure" on Glass Substrate Fabricated at Low Temperature	575
Michael G. Mauk, Bryan W. Feyock, Robert B. Hall, Kathleen Dugan Cavanaugh and Jeffrey E. Cotter		Kenji Yamamoto, Masashi Yoshimi, Takayuki Suzuki, Yoshifumi Okamoto, Yuko Tawada and Akihiko Nakajima	
Tin Sulphide Films for Solar Cell Application	515	Progress in Growth of High Quality Amorphous Silicon Materials	581
N. Koteswara Reddy and K.T. Ramakrishna Reddy		W. Futako, K. Fukutani, M. Kannbe, T. Kamiya, C.M. Fortmann and I. Shimizu	
Characterization of SnO₂ Thin Films Through Thermoelectric Power Measurements	519	An Approach to Selfconsistent Analysis of A-Si:H Material and P-I-N Solar Cell Properties	587
G. Gordillo, B.A. Paez, C.E. Jácome, L.C. Hernández, J.M. Flórez and H. Méndez		C.R. Wronski, Zhou Lu, Lihong Jiao and Yeeheng Lee	
Polycrystalline CdS Thin Film Prepared by Metalorganic Chemical Vapor Deposition	523	Improved μ-Si p-Layer and a-Si i-Layer Materials Using VHF Plasma Deposition	591
Hiroshi Uda, Takayuki Fujii, Seiji Ikegami and Hajimu Sonomura		X. Deng, S.J. Jones, T. Liu, M. Izu and S.R. Ovshinsky	
Electronic and Mechanical Properties of Ge Films Grown on Glass Substrates	527	Irreversible Light-Induced Degradation in Amorphous Silicon Solar Cells	595
R.K. Ahrenkiel, S.P. Ahrenkiel and M.M. Al-Jassim		D.E. Carlson, K. Rajan and D. Bradley	
Effect of CdS Annealing in (CdCl₂ + CdS) Atmosphere on CdTe Cells	531	Real Time Spectroscopic Ellipsometry Studies of the Top Junctions of a-Si:H-Based Solar Cells	599
Sung Chan Park, Byung Wook Han, Jin Hyung Ahn, Byung Tae Ahn and Donghwan Kim		H. Fujiwara, Joohyun Koh, Yeeheng Lee, C.R. Wronski and R.W. Collins	
Photoconductive Lifetime of CdS used in Thin-Film Solar Cells	535	Improving Performance of Superstrate p-i-n a-Si Solar Cells by Optimization of n/TCO/Metal Back Contacts	603
R.K. Ahrenkiel, D.H. Levi, S. Johnston, W. Song, D. Mao and A. Fischer		Steven S. Hegedus, Wayne A. Buchanan and Erten Eser	
Influence of the Ultrasonic Agitation on Chemical Bath Deposition of Cadmium Sulfide Thin Films	539	Triple-Junction Amorphous Silicon Alloy PV Manufacturing Plant of 5 MW Annual Capacity	607
Jun Young Choi, Kang-Jin Kim and Donghwan Kim		S. Guha, J. Yang, A. Banerjee, K. Hoffman, S. Sugiyama, J. Call, S.J. Jones, X. Deng, J. Doehler, M. Izu and H.C. Ovshinsky	
The Morphology of CdS Thin Films Deposited on SnO₂-Coated Glass Substrates	543	Improvement of Large-Area SCAF Structure A-Si Solar Cells with Plastic Film Substrate	611
F.S. Hasoon, M.M. Al-Jassim, A. Swartzlander, P. Sheldon, A.A.J. Al-Douri and A.A. Alnajjar		K. Tabuchi, S. Fujikake, H. Sato, S. Saito, A. Takano, T. Wada, T. Yoshida, Y. Ichikawa, H. Sakai and F. Natsume	
Photoluminescence Study of Highly Efficient CdTe Thin Film Solar Cells	547	Optical Confinement and Optical Loss in High-Efficiency a-Si Solar Cells	615
T. Okamoto, N. Amin, A. Yamada, M. Konagai, T. Aramoto, H. Ohyama, A. Hanafusa, M. Murozono, R. Asomoza and A. Merkulov		Y. Hishikawa, T. Kinoshita, M. Shima, M. Tanaka, S. Kiyama, S. Tsuda and S. Nakano	
Thermosensoric Localization of Defects in CIS Solar Modules	551	Texture Etched ZnO:Al Films as Front Contact and Back Reflector in Amorphous Silicon P-I-N and N-I-P Solar Cells	619
W. Gross, J. Zettner, H. Scheuerpflug, Th. Hierl, M. Schulz and F. Karg		B. Rech, S. Wieder, C. Beneking, A. Löffl, O. Kluth, W. Reetz and H. Wagner	
Properties of ZnO Thin Films for Solar Cells Grown by Chemical Bath Deposition	555	Oriented Recrystallization of Silicon Layers for Silicon Thin-Film Solar Cells	623
Mauricio Ortega-López and Arturo Morales-Acevedo		C. Hebling, S. Reber, K. Schmidt, R. Lüdemann and F. Lutz	
Electrodeposited CuInSe₂ Thin Film Devices	559	Polycrystalline Silicon Films Formation on Foreign Substrates by A Rapid Thermal-CVD Technique	627
Ryne P. Raffaele, James G. Mantovani, Robert B. Friedfeld, Sheila G. Bailey and Seth M. Hubbard		A. Slaoui, R. Monna, D. Angermeier, S. Bourdais and J.C. Muller	
3. AMORPHOUS AND THIN-FILM SILICON		Development of Light-Trapped, Interconnected, Silicon-Film Modules	631
Recent Progress in Amorphous Silicon Alloy Leading to 13% Stable Cell Efficiency	563	D.H. Ford, J.A. Rand, A.M. Barnett, E.J. DelleDonne, A.E. Ingram and R.B. Hall	
Jeffrey Yang, Arindam Banerjee, Troy Glatfelter, Shuichiro Sugiyama and Subhendu Guha			
Recent Progress on Micorcrystalline Solar Cells	569		
A. Shah, J. Meier, P. Torres, U. Kroll, D. Fischer, N. Beck, N. Wyrsh and H. Keppner			

Transport Analysis for Polycrystalline Silicon Solar Cells on Glass Substrates	635	Improved Thermal Control for a-Si:H Photovoltaic Cells Fabricated on Polymeric Substrates	699
R. Brendel, R. B. Bergmann, B. Fischer, J. Krinke, R. Plieninger, U. Rau, J. Reiß, H. P. Strunk, H. Wanka and J. H. Werner		J.R. Huang, Y. Lee, C.M.C Toporow, G.J. Vendura, Jr., T.N. Jackson and C.R. Wronski	
Laser Induced Crystallization: A Method for Preparing Silicon Thin Film Solar Cells	639	Analysis and Optimization of High Efficiency Multijunction a-Si:H Solar Cells	703
G. Andrä, J. Bergmann, F. Falk and E. Ose		Richard E. Rocheleau, Moe Tun and Steven S. Hegedus	
The Application of Low-Frequency Glow Discharge to High-Rate a-Si:H Deposition	643	Large Area a-Si/a-Si Tandem Module with 9.1% Conversion Efficiency	707
Boris G. Budaguan, Andrei Yu. Sazonov, Arcady A. Aivazov, Arcady E. Berdnikov and Alexander A. Popov		E. Terzini, C. Privato and S. Avagliano	
Large Area Deposition Technique for PECVD of Amorphous Silicon	647	Fast Deposited Microcrystalline Silicon Solar Cells	711
U. Stephan, J. Kuske, W. Frammelsberger, P. Lechner, W. Psyk and H. Schade		P. Torres, J. Meier, U. Kroll, N. Beck, H. Keppner and A. Shah	
Preparation of High-Quality μc-Si:H Films by a Hydrogen-Radical CVD Method	651	Texture Etched Al-Doped ZnO: A New Material for Enhanced Light Trapping in Thin Film Solar Cells	715
Liang-Fu Lo, Maki Hatta, Nobuyuki Andoh, Hiroshi Nagayoshi and Koichi Kamisako		O. Kluth, A. Löffl, S. Wieder, C. Beneking, W. Appenzeller, L. Houben, B. Rech, H. Wagner, S. Hoffmann, R. Waser, J.A. Anna Selvan and H. Keppner	
New Regime of RF PECVD for the Growth of a-Si:H and Its Alloys with Improved Electronic Properties	655	A-Si:H Solar Cells Using the Hot-Wire Technique-How to Exceed Efficiencies of 10%	719
A.R. Middya, S. Hazra, S. Ray, C. Longeaud, J.P. Kleider		S. Bauer, W. Herbst, B. Schröder and H. Oechsner	
Use of Gas Jet Deposition Technique to Prepare a-Si:H Solar Cells	659	Optical Optimization of a-Si:H Solar Cells Using Planar Junctions and Diffuse Rear Reflectors	723
S.J. Jones, A. Myatt, H. Ovshinsky, J. Doehler, M. Izu, A. Banerjee, J. Yang and S. Guha		K. Winz, C.M. Fortmann, Th. Eickhoff and H. Wagner	
$QE(\lambda, V_p)$ and $I(V_p)$ Measurements on Single and Triple-Junction a-Si:H Solar Cells	663	Automated Screening for Severe Shunting Defects in Encapsulated Series-Connected Modules	727
James R. Woodyard		Ingrid Eisgruber, Rick Matson and T.J. McMahon	
Development and Application of Low Temperature RF Magnetron Sputtered ITO Thin Films for a-Si:H Based p/i/n Junction Solar Cells	667	Poly-Silicon Thin Films and Solar Cells Prepared by Rapid Thermal CVD	731
E. Terzini, G. Nobile, T. Polichetti and P. Thilakan		Yuwen Zhao, Xinian Jiang, Wenjing Wang, Zhongming Li, Yuan Yu and Xianbo Liao	
Influence of Hydrogen on Optical Properties of LPCVD Amorphous Silicon Films	671	Recrystallized and Epitaxially Thickened Poly-Silicon Layers on Graphite Substrates	735
B. Mroz, B.Y. Moon, J. Jang and S.M. Pietruszko		Thomas Kunze, Stefan Hauttmann, Jörg Seekamp and Jörg Müller	
Amorphous and Microcrystalline Silicon by ECR-CVD using Highly Dilute Silane Mixtures	675	Improved Performance of Thin-Film Silicon Solar Cells on Graphite Substrates	739
B. Jagannathan, R.L. Wallace, W.A. Anderson and R.N. Ahrenkeil		R. Auer, J. Zettner, J. Krinke, G. Polisski, Th. Heirl, R. Hezel, M. Schulz, H.-P. Strunk, F. Koch and D. Nikl and H. v. Campe	
Microcrystalline Silicon from Very High Frequency Plasma Deposition and Hot-Wire CVD for 'Micromorph' Tandem Solar Cells	679	High Rate Deposition of Silicon Films for Solar Cells by Plasma-Enhanced CVD from Trichlorosilane	743
H. Brummack, R. Brüggemann, H.N. Wanka, A. Hierzenberger and M.B. Schubert		Martin Rostalsky, Thomas Kunze, Nicole Linke and Jörg Müller	
Contributions of Bulk, Interface and Built-In Potential to the Open Circuit Voltage of a-Si:H Solar Cells	683	Effect of Hydrogen Content on the Crystalline Quality of PECVD-Deposited Silicon for Solar Cells	747
Yeeheng Lee, Andre S. Ferlauto and C.R. Wronski		Tadashi Ito, Mitsuru Imaizumi, Ichiro Konomi and Masafumi Yamaguchi	
High Efficiency P-I-N Solar Cells with <I> Layer Deposited by Hot-Wire Technique	687	Laser Crystallisation of a-Si Using Copper Vapour Lasers: A Different Option for Photovoltaic Applications	751
Y. Ziegler, S. Dubail, C. Hof, U. Kroll and A. Shah		Matt Boreland	
Improved Micromorph Tandem Cell Performance Through Enhanced Top Cell Currents	691	SI-Homoepitaxy by Electron Cyclotron Resonance CVD	755
Rainer Platz, N. Pellaton Vaucher, D. Fischer, J. Meier and A. Shah		E. Conrad, L. Elstner, W. Fuhs, W. Henrion, P. Müller, B. Selle and U. Zeimer	
Properties of a-Si:H and a-(Si,Ge):H Solar Cells Prepared Using ECR Deposition Techniques	695		
Vikram L. Dalal, Tim Maxson and Kay Han			

SiGe Layer Structures for Solar Cell Application Grown by Liquid Phase Epitaxy	759	GaInP/GaAs Cascade Solar Cells Grown by Molecular Beam Epitaxy	823
A. Gutjahr, I. Siller, N. Rollbühler, M. Konuma, F. Banhart, K. Said and J. Poortmans		J. Lammasniemi, A.B. Kazantsev, R. Jaakkola, M. Toivonen, M. Jalonen, R. Aho and M. Pessa	
Thin, Substrate-Based Crystalline Silicon Solar Cells with No Grid Shading	763	Advances in Production of Cascade Solar Cells for Space	827
Daniel J. Aiken and Allen M. Barnett		Y.C.M. Yeh, F.F. Ho, C.L. Chu and P.K. Chiang	
Thin Crystalline Silicon Solar Cell with Back Surface Gate Electrode	767	Testing of Dual-Junction Scarlet Modules and Cells Plus Lessons Learned	831
David D. Smith and Allen M. Barnett		Michael I. Eskenazi, David M. Murphy, Eugene L. Ralph and Henry I. Yoo	
Properties of Silicon Thin Films Grown by the Temperature Difference Method (TDM)	771	Microscopic Analysis of Carrier Removal in Heavily Irradiated Silicon Solar Cells	835
B. Thomas, G. Müller, P.-M. Wilde and H. Wawra		S.J. Taylor, M. Yamaguchi, M. Imaizumi, M.J. Yang, T. Ito, T. Yamaguchi, S. Watanabe, K. Ando, S. Matsuda and T. Hisamatsu	
Fused-Salt Electrodeposition of Thin-Layer Silicon	775	The Effect of Test Conditions on the Degradation of Proton Irradiated Solar Cells	839
J.T. Moore, T.H. Wang, M.J. Heben, K. Douglas and T.F. Cizek		V A Wilkinson and C Goodbody	
Fabrication of High Stabilized Efficiency a-Si Solar Cells by Using SiH₂Cl₂ Addition	779	Radiation Response of Single and Dual Junction p⁺n InGaP/GaAs Space Solar Cells	843
Koji Dairiki, Akira Yamada, Makoto Konagai, A. Merkulov and Rene Asomoza		R.J. Walters, M.A. Xapsos, G.P. Summers, H.L. Cotal and S.R. Messenger	
Modeling of Multilayer SiGe Based Thin Film Solar Cells	783	Front Surface Engineering of High Efficiency Si Solar Cells and Ge TPV Cells	847
E. Christoffel, L. Debarge and A. Slaoui		Mircea Faur, Maria Faur, S.G. Bailey, D.J. Flood, D.J. Brinker, D.R. Wheeler, S.A. Alterovitz, D. Scheiman, G. Mateescu, J. Faulk, C. Goradia and M. Goradia	
4. SPACE CELLS AND SYSTEMS AND III-V DEVICES			
Progress Toward Technology Transition of GaInP₂/GaAs/Ge Multijunction Solar Cells	787	Inflatable Lenses for Space Photovoltaic Concentrator Arrays	853
Captain David N. Keener, Dr Dean C. Marvin, David J. Brinker, Henry B. Curtis and P. Michael Price		Mark J. O'Neill and Michael F. Piszczor	
Anti-Phase Domain-Free GaAs on Ge Substrates Grown by Molecular Beam Epitaxy for Space Solar Cell Applications	793	Uncertainty Analysis of High Altitude Aircraft Air Mass Zero Solar Cell Calibration	857
S.A. Ringel, R.M. Sieg, S.M. Ting and E.A. Fitzgerald		Phillip Jenkins, David Brinker and David Scheiman	
InGaAs Monolithic Interconnected Modules (MIMs)	799	Scarlet: Design of the Fresnel Concentrator Array for New Millennium Deep Space 1	861
Navid S. Fatemi, David M. Wilt, Phillip P. Jenkins, Victor G. Weizer, Richard W. Hoffman, Jr., Christopher S. Murray, David Scheiman, David Brinker and David Riley		David M. Murphy and Michael I. Eskenazi	
Characterization Testing of Dual Junction GaInP₂/GaAs/Ge Solar Cell Assemblies	805	Dust on Mars: Materials Adherence Experiment Results from Mars Pathfinder	865
Michael R. Brown, Leland J. Goldhammer, George S. Goodelle, Charlene U. Lortz, John N. Perron, Joseph S. Powe, Joel A. Schwartz, B. Terence Cavicchi, Mark S. Gillanders and Dmitri D. Krut		Geoffrey A. Landis and Phillip P. Jenkins	
20% (AM1.5) Efficiency GaAs Solar Cells on Sub-mm Grain-Size Poly-Ge and Its Transition to Low-Cost Substrates	811	A Numerical Model Based Analysis of the Design and Operation of A GaInP/GaAs Tandem Monolithic Solar Cell	871
R. Venkatasubramanian, B.C. O'Quinn, E. Siivola, B. Keyes and R. Ahrenkiel		Richard J. Schwartz and Jeffery L. Gray	
Improved Performance of p/n InP Solar Cells	815	Projected Performance of Three- and Four-Junction Devices Using GaAs and GaInP	875
Richard W. Hoffman, Jr., Navid S. Fatemi, Phillip P. Jenkins, Victor G. Weizer, Mark A. Stan, Steven A. Ringel, David A. Scheiman, David M. Wilt, David J. Brinker, Robert J. Walters and Scot R. Messenger		Sarah R. Kurtz, D. Myers and J.M. Olson	
Effect of Front-Surface Doping on Back-Surface Passivation in Ga_{0.5}In_{0.5}P Cells	819	Effects of Stress in III-V Solar Cells	879
Sarah R. Kurtz, J.M. Olson, D.J. Friedman and R. Reedy		C.L. Chu and G.I.C. Chen	
		Effects of Reverse Bias on Multijunction Cells	883
		H.I. Yoo and P.A. Iles	
		High-Efficiency Radiation-Resistant InGaP/GaAs Tandem Solar Cells	887
		T. Takamoto, M. Yamaguchi, S.J. Taylor, E. Ikeda, T. Agui and H. Kurita	
		Comparison of Al_{0.51}In_{0.49}P and Ga_{0.51}In_{0.49}P Window Layers for GaAs and GaInAsP Solar Cells	891
		R. Jaakkola, J. Lammasniemi, A.B. Kazantsev and K. Tappura	
		Wafer Bonding for Use in Mechanically Stacked Multi-Bandgap Cells	895
		P.R. Sharps, M.L. Timmons, J.S. Hills and J.L. Gray	

Three-Junction Solar Cells Comprised of a Thin-Film GaInP/GaAs Tandem Cell Mechanically Stacked on a Si Cell	899	Optical Characterization of Epitaxial Ga_xIn_{1-x}As Suitable for Thermophotovoltaic (TPV) Converters	967
Y. Yazawa, K. Tamura, S. Watahiki, T. Kitatani, H. Ohtsuka and T. Warabisako		T.L. Wangenstein, M.W. Wanlass, J.J. Carapella, H.R. Moutinho, Alice R. Mason, J.D. Webb and F.A. Abulfotuh	
A Comparative Study on Photon Recycling Effects in N⁺-P and P⁺-N InP Solar Cells with Bragg Reflector	903	Long-Wavelength Laser Power Converters for Optical Fibers	971
A. Yamamoto, M. Kurizuka, Md. M. Murshid and A. Hashimoto		Steven J. Wojtczuk	
Hydrogen-Interstitial Zn Defect Complexes and Their Effects on the Device Characteristics of Heteroepitaxial P⁺N InP Cell Structures	907	Effect of Crystal Defects on Minority Carrier Diffusion Lengths in 6H SiC	975
B. Chatterjee, S.A. Ringel and R.W. Hoffman, Jr.		S.M. Hubbard, M. Tabib-Azar, S. Bailey, G. Rybicki, P. Neudeck and R. Raffaele	
Thin-Base High Efficiency InAs_xP_{1-x}/InP Multi Quantum Well Solar Cells	911	Adaptation of Thin-Film Photovoltaic Technology for Use in Space	979
A. Freundlich, M.F. Vilela, C. Monier, L. Aguilar, F. Newman and I. Serdiukova		E.S. Fairbanks and M.T. Gates	
Properties of GaAs/InGaAs Quantum Well Solar Cells Under Low Concentration Ratios	915	Analysis of the Spectral Response of Silicon Solar Cells Irradiated with High Fluence Electrons/Protons	983
Ming-ju Yang and Masafumi Yamaguchi		Mitsuru Imaizumi, Stephen J. Taylor, Masafumi Yamaguchi, Tadashi Hisamatsu, Sumio Matsuda and Osamu Kawasaki	
Reduced Radiative Currents from GaAs/InGaAs and AlGaAs/GaAs p-i-n Quantum Well Devices	919	Displacement Damage Analysis of Single Crystal 50μm Thick Silicon Solar Cells	987
J. Nelson, I. Ballard, J. Barnes, N. Ekins-Daukes, K.W.J. Barnham, B.G. Kluitinger, E.S.M. Tsui, C.T. Foxon, T.S. Cheng and J.S. Roberts		M. Yamaguchi, S.J. Taylor, M. Imaizumi, M.J. Yang, T. Ito, S. Matsuda and T. Hisamatsu	
Dark Currents in Double-Heterostructure and Quantum-Well Solar Cells	923	Thermal Recovery of Degraded Space Silicon Solar Cells Due to Large Fluence Irradiation	991
Richard Corkish and Christiana B. Honsberg		Tadashi Hisamatsu, Sumio Matsuda, Tetsuya Nakao, Yusuke Matsumoto, Stephen J. Taylor and Masafumi Yamaguchi	
Monolithic Two-Junction AlGaAs/GaAs Solar Cells	927	Spectral Response of InP/Si Solar Cells Irradiated to High Proton Fluences	995
V.M. Andreev, V.P. Khvostikov, V.D. Rumyantsev, E.V. Paleeva and M.Z. Shvarts		S.R. Messenger, M.A. Xapsos, R.J. Walters, H.L. Cotal, S.J. Wojtczuk, H.B. Serreze and G.P. Summers	
Over 31%-Efficient GaAs/GaSb Tandem Concentrator Solar Cells	931	3.75 MeV Electron Irradiation of III-V Concentrator Tandem Cells	999
A.W. Bett, S. Keser, G. Stollwerck, O.V. Sulima and W. Wettling		V.M. Andreev, O.I. Chosta, V.P. Khvostikov, E.V. Paleeva and M.Z. Shvarts	
Tandem GaSb/InGaAsSb Thermophotovoltaic Cells	935	Proton Irradiated MBE Grown GaInP/GaAs Single Junction and Tandem Solar Cells	1003
V.M. Andreev, V.P. Khvostikov, V.R. Larionov, V.D. Rumyantsev, S.V. Sorokina, M.Z. Shvarts, V.I. Vasil'ev and A.S. Vlasov		A.B. Kazantsev, J. Lammasniemi, R. Jaakkola, M. Pessa, M. Rajatora and R.K. Jain	
n-ZnSe/p-GaAs Heterojunction Solar Cells	939	Radiation Hard In_{0.53}Ga_{0.47}As Solar Cells with Zn Diffused Emitters	1007
U. Blieske, T. Kampschulte, A. Bauknecht, M. Saad, J. Söllner, A. Krost, K. Schatke and M. Ch. Lux-Steiner		L.B. Karlina, P.A. Blagnov, M.E. Boiko, V.V. Kozlovskii, Yu.A. Kudriavtsev, V.A. Solov'ev, C. Vargas-Aburto, R.M. Uribe and D.J. Brinker	
Effect of the Irradiation Temperature on the Spectral Response of Si Solar Cells	943	Solar Cell Coverglasses for Satellites in the Intermediate Earth Orbit	1011
Jacques C. Bourgoin		C. Kitchen, K. Mullaney, M. Price, A. Dollery, K. Fyles, H. Eaves, R. Crabb and P. Buia	
Measurement of Multijunction Cells under Close-Match Conditions	947	Experimental Solar Cells on the Sunsat Microsatellite	1015
V A Wilkinson, C Goodbody and W G Williams		C Hardingham, J Simpson, S Wood, TA Cross and JF Uys	
Performance of Dark I-V Tests to Determine the Condition of Spacecraft Solar Arrays	951	Solar Array Model Corrections from Mars Pathfinder Lander Data	1019
Edward M. Gaddy		Richard C. Ewell and Dale R. Burger	
Novel Techniques for Evaluation of Interconnections in Solar Cells used for Spacecraft Power Generation	955	Rigid Type Solar Array Panels	1023
Robert J. Ferro, Robert W. Francis, Eric B. Frasco, Robert B. Pan, Enold Pierre-Louis, Charles Sve and Martin Berghaus		Taku Horie, Mitsuru Okubo and Masayoshi Goto	
Numerical Modeling of Thermophotovoltaic Cells and Systems	959	The Scarlet™ Array for High Power GEO Satellites	1027
All M. Et-Husseini and Jeffery L. Gray		Brian R. Spence, P. Alan Jones, Mike I. Eskenazi and David M. Murphy	
Strained In_{0.53}Ga_{0.47}As/In_xGa_{1-x}As (x>0.6) Multi-quantum Well Thermophotovoltaic Converters	963		
I. Serdiukova, F. Newman, L. Aguillar, M.F. Vilela, C. Monier and A. Freundlich			

InGaP/GaAs and InGaAs Mechanically-Stacked Triple-Junction Solar Cells	1031	AC Photovoltaic Module Magnetic Fields	1097
T. Takamoto, E. Ikeda, T. Agui, H. Kurita, T. Tanabe, S. Tanaka, H. Matsubara, Y. Mine, S. Takagishi and M. Yamaguchi		Christina Jennings, Gregory J. Chang, Antonio B. Reyes and Charles M. Whitaker	
18.3% Efficient Silicon Solar Cells for Space Applications	1035	PVUSA Operations Experience with Trace Technologies PV Inverters	1101
G.T. Crotty, P.J. Verlinden, M. Cudzinovic, R.M. Swanson and R.A. Crane		Jeff Newmiller and Brian Farmer	
Verification of Mars Solar Radiation Model Based on Mars Pathfinder Data	1039	Blocking Diodes and Fuses in Low-Voltage PV Systems	1105
Joseph Appelbaum, Tal Segalov, Phillip P. Jenkins, Geoffrey A. Landis and Cosmo R. Baraona		John C. Wiles and David L. King	
Results from the First International Round Robin Calibration and Measurement of Space Solar Cells	1043	Maximum Power Point Tracking Charge Controllers for Telecom Applications - Analysis & Economics	1109
S. Matsuda, D. Flood, T. Gomez and Yang Yiqiang		Dr. Robert H. Wills	
		Measuring Solar Spectral and Angle-of-Incidence Effects on Photovoltaic Modules and Solar Irradiance Sensors	1113
		David L. King, Jay A. Kratochvil and William E. Boyson	
		Optical Changes in Cerium-Containing Glass as a Result of Accelerated Exposure Testing	1117
		D.E. King, F.J. Pern, J.R. Pitts, C.E. Bingham and A.W. Czandema	
		Effects of Soiling on PV Module and Radiometer Performance	1121
		R. Hammond, D. Srinivasan, A. Harris, K. Whitfield and J. Wohlgemuth	
		Dark Current-Voltage Measurements on Photovoltaic Modules as a Diagnostic or Manufacturing Tool	1125
		D.L. King, B.R. Hansen, J.A. Kratochvil and M.A. Quintana	
		Hot Spot Investigations on PV Modules - New Concepts for a Test Standard and Consequences for Module Design with Respect to Bypass Diodes	1129
		W. Herrmann, W. Wiesner and W. Vaaßen	
		22.7% Efficient PERL Silicon Solar Cell Module with a Textured Front Surface	1133
		Jianhua Zhao, Aihua Wang, Patrick Campbell and Martin A. Green	
		Reverse Characteristics of Commercial Silicon Solar Cells - Impact on Hot Spot Temperatures and Module Integrity	1137
		M. Danner and K. Bücher	
		Fabrication and Properties of a Glass-Lens, Static-Concentrator Mini-Module	1141
		K. Yoshioka, T. Nikaido, T. Saitoh, M. Kanai and I. Hide	
		DSMTS: A Novel Linear PV Concentrator	1145
		P. Benítez, R. Mohedano and J.C. Miñano	
		Ultralight Photovoltaic Modules for Unmanned Aerial Vehicles	1149
		Michael J. Nowlan, John C. Maglitta, Ghazi Darkazalli and Thomas Lamp	
		1/2 KWp Smart Array Controller Development	1153
		Bradley E. O'Mara	
		The AES Advanced 60KW PV-Diesel Hybrid Inverter	1157
		Dr. Robert H. Wills	
		A Process to Recycle Thin Film PV Materials	1161
		Robert E. Goozner, William F. Drinkard, Mark O. Long and Christi M. Byrd	
		PV Batteries and Charge Controllers: Technical Issues, Costs, and Market Trends	1165
		R.L. Hammond, J.F. Turpin, G.P. Corey, T.D. Hund and S.R. Harrington	
5. TERRESTRIAL MODULES AND BOS COMPONENTS			
Photovoltaic System Reliability	1049		
Alexander B. Maish, Christopher Atcitty, Steve Hester, Daniel Greenberg Don Osborn David Collier			
Progress in Solarex's Crystalline Silicon PVMaT Program	1055		
J.H. Wohlgemuth, D. Whitehouse, T. Koval, J. Creager F. Artigliere and T. Tomlinson, J. Cliber, A. Buckman, M. Perry, S. Narayanan, S. Shea, M. Roy, G. Kelly, M. Brisson, R. Dominguez and M. Conway			
Market Impact of a Large-Scale PV Buildings Program	1061		
James E. Rannels			
Disposal and Recycling of End-of-Life PV Modules	1067		
Chris Eberspacher and Vasilis M. Fthenakis			
Progress Update on the U.S. Photovoltaic Manufacturing Technology Project	1073		
Richard L. Mitchell, C. Edwin Witt, Holly P. Thomas, Douglas S. Ruby, Richard King and Clay C. Aldrich			
EFG Manufacturing Line Technical Progress and Module Cost Reductions Under the PVMaT Program	1077		
J. Cao, R. Gonsiorawski, M. Kardauskas, J. Kalejs, C. O'Brien, M. Prince and E. Tornstrom			
Low Cost Module and Mounting Systems Developed Through Evergreen Solar's PVMaT Program	1081		
J.I. Hanoka, P.E. Kane, J. Martz and J. Fava			
Simplified Module Assembly Using Back-Contact Crystalline-Silicon Solar Cells	1085		
James M. Gee, Stephen E. Garrett and William P. Morgan			
Improved Photostability of NREL-Developed EVA Pottant Formulations for PV Module Encapsulation	1089		
F.J. Pern and S.H. Glick			
Balance-of-System Improvements for Photovoltaic Applications Resulting from the PVMaT Phase 4A1 Program	1093		
Ward Bower, Holly Thomas, Ben Kroposki, Russ Bonn and Tom Hund			

Large-Area Silicon-Film™ Manufacturing under the PVMaT Program	1169	The Team-Up Initiative: Status and Results from the Field	1243
J.A. Rand, Y. Bai, J.C. Checchi, J.S. Culik, D.H. Ford, C.L. Kendall, P.E. Sims, R.B. Hall and A.M. Barnett		S. Hester, J. Bigger, B. Gibson and M. Cheney	
Possibility of Recycling Silicon PV Modules	1173	Extended Performance Analysis of 70 PV Systems in Japanese Field Test Program	1249
John R. Bohland and Igor I. Anisimov		Kosuke Kurokawa, Hisashi Sugiyama, Daisuke Uchida, Koichi Sakuta, Kiyoshi Sakamoto, Toshimitsu Ohshiro, Tamon Matsuo and Toshio Katagiri	
Performance of a 2× CUSP Concentrator PV Module Using Bifacial Solar Cells	1177	Application and Validation of a New PV Performance Characterization Method	1253
Ugur Ortbas		Charles M. Whitaker, Timothy U. Townsend, Jeffrey D. Newmiller, David L. King, William E. Boyson, Jay A. Kratochvil, David E. Collier and Donald E. Osborn	
Temperature Coefficients for PV Modules and Arrays: Measurement Methods, Difficulties, and Results	1183	Evaluation of Tracking Flat Plate and Concentrator PV Systems	1257
David L. King, Jay A. Kratochvil and William E. Boyson		Tom Lepley, Bob Hammond and Alex Harris	
RRC Module Energy Rating: A Module Survey	1187	The U.S. Army YUMA Proving Ground 900-KVA Photovoltaic Power Station	1261
K. Bücher, G. Kleiss and D. Bätzner		Roch Ducey, Richard Chapman and Samuel Edwards	
The Fraunhofer ISE PV Charts: Assessment of PV Device Performance	1193	SunSine300, Utility Interactive AC Module Anti-Islanding Test Results	1265
K. Bücher and S. Kunzelmann		Gregory A. Kern	
Analysis of Photovoltaic Module Energy Output under Operating Conditions in South Africa	1197	Economic Analysis of PV Hybrid Power System: Pinnacles National Monument	1269
E. Ernest van Dyk, Edson L. Meyer, Bernard J. Scott, Daniel A. O'Connor and Johan B. Wessels		Andrew Rosenthal, Steven Durand, Michael Thomas and Harold Post	
Measured vs. Ideal Insolation on PV Structures	1201	The Indo-US. Cooperative Photovoltaic Project	1273
Timothy U. Townsend and Charles M. Whitaker		Jack L. Stone, Harin S. Ullal and E.V.R. Sastry	
Performance of Single-Junction A-Si Modules Under Varying Conditions in the Field	1205	Photovoltaics for Rural Electrification in the People's Republic of China	1277
J.A. del Cueto and T.J. McMahon		William L. Wallace and Y. Simon Tsuo	
The World Photovoltaic Scale: An International Reference Cell Calibration Program	1209	AMP-Hour Counting Charge Control for Photovoltaic Hybrid Power Systems	1281
C.R. Osterwald, S. Anevsky, A.K. Barua, P. Chaudhuri, J. Dubard, K. Emery, B. Hansen, D. King, J. Metzendorf, F. Nagamine, R. Shimokawa, Y.X. Wang, T. Wittchen, W. Zaiman, A. Zastrow and J. Zhang		Thomas D. Hund and Bruce Thompson	
Evaluation of PV Module Designs at Irregular Operation Conditions	1213	Silicon-Photodiode Pyranometers: Operational Characteristics, Historical Experiences, and New Calibration Procedures	1285
Werner Knaupp		David L. King and Daryl R. Myers	
Correlation Between Surface Carbon Concentration and Adhesive Strength at the Si Cell/EVA Interface in a PV Module	1217	Development of Building-Integrated PV Modules Using Color Solar Cells for Various Exterior Walls	1289
Neelkanth G. Dhere, Mark E. Wollam and Kaustubh S. Gadre		N. Ishikawa, M. Kanai, I. Hide, T. Nagai, T. Ito, H. Izumiyama, T. Yoshida, T. Nii, K. Tazawa and T. Harada	
Yellowing Reaction in Encapsulant of Photovoltaic Modules	1221	Hybrid Collectors Using Thin-Film Technology	1293
T. Shigekuni and M. Kumano		R. Platz, D. Fischer, M.-A. Zufferey, J.A. Anna Selvan, A. Haller, A. Shah and E. Schweizer	
6. TERRESTRIAL SYSTEMS AND APPLICATIONS		Determination of the Curvature Derating Factor for the Georgia Tech Aquatic Center Photovoltaic Array	1297
The Infrastructure Path to a Sustainable World Market for Photovoltaics	1225	M.E. Ropp, M. Begovic and A. Rohatgi	
Mark C. Fitzgerald and Mark Mrohs		Commercial Building Integrated Photovoltaics: Market and Policy Implications	1301
Successful Dissemination Programs for Residential PV Applications—An International Survey	1231	John Byrne, Steven Letendre, Lawrence Agbemabiese, David Redlin and Ralph Nigro	
Reinhard Haas		Photovoltaic Covered-Parking Systems Using Lightweight, Thin-Film PV	1305
Photovoltaic Industry-Proposed Changes for the 1999 National Electrical Code for PV Applications	1237	Tom Lepley and Prem Nath	
Ward Bower and John C. Wiles			

P. V Technology and Success of Solar Electricity in Vietnam	1309	PVUSA's Small System Test Center	1353
Trinh Quang Dung		P.A. Hutchinson, A.B. Reyes, D.E. Collier, D.D. Whitney and D.E. Osborn	
A 3kW PV-Thermal System for Home Use	1313	Technical Evaluation of Four Amorphous Silicon Systems at NREL	1357
Ming-ju Yang, Hisao Izumi, Mikihiro Sato, Shigenobu Matsunaga, Tatsuya Takamoto, Kouye Tsuzuki, Takashi Amono and Masafumi Yamaguchi		B. Kroposki and R. Hansen	
Photovoltaic Energy Program in the State of Minas Gerais - Brazil	1317	Environmental Impacts of PV Systems—Ground-Based vs BIPV	1361
A.S.A.C. Diniz, A.E. Prado, M.S.C.C. Mendonça, F.Q. Almeida and C.A. Alvarenga		A.E. Baumann, R. Hill and K.M. Hynes	
M.P.P.T for Temperature Compensation of Photovoltaic System with Neural Networks	1321	Team-Up PV-Friendly Pricing Projects: Validation of Market Research and Market Development	1365
In-Su Cha, Jang-Gyun Choi, Gyun-Jong Yu, Myung-woong Jung, Hyung-Lae Baek and Dong-Hyee Kim		J.E. Bigger and S.L. Hester	
Load Sharing Operation of a 14KW Photovoltaic/Wind Hybrid Power System	1325	A 50 Kilowatt Distributed Grid-Connected Photovoltaic Generation System for the University of Wyoming	1369
Sikyung Kim, Changbong Kim, Jinsoo Song, Gwonjong Yu and Youngseok Jung		B.H. Chowdhury, S. Muknahallipatna, T. Dinwoodie, J.J. Cupal, D. Shugar and J.C. Hamann	
Design of a Photovoltaically Operated Reverse Osmosis Plant in Off-Grid Operation for Desalination of Brackish Water	1329	Long-Term Reliability Concerns Resolved by Third Generation Integrated High-Concentration PV Systems	1373
C. Bröker, P.C.M. Carvalho, K. Menne, E. Ortjohann, L. Temme and J. Voß		V. Garboushian, D. Roubideaux, G. Turner and J. Allen Gunn	
Overall Evaluation for R&D of PV Modules Integrated with Construction Materials	1333	Performance of a Grid Connected Residential Photovoltaic System with Energy Storage	1377
Sadami Toyokawa and Shinji Uehara		G. Ernest Palomino, John Wiles, John Stevens and Frank Goodman	
Optimization of the PV-Yield in Solar Facades by Different Directions	1337	Estimation of Output Enhancement of a Partially Shaded BIPV Array by the Use of AC Modules	1381
Werner Hiller, Dietrich Amft and Gunter Ebest		M.A. Gross, S.O. Martin and N.M. Pearsall	
Building Integrated Photovoltaic Roofing Element for Covered Parking Structures	1341	Integration of PV Technology into the Building Environment: A Model for the Thermal Regulation of PV-Roof Integrated Systems	1385
P. Nath, C. Vogeli, A. Singh and S. Guha		Dr. Manuel Fuentes and Dr. Susan Roaf	
The Potential Electricity Generating Capacity of BIPV in Hong Kong	1345	Prospect of Domestic Grid Connected PV Systems Under Existing Tariff Conditions	1389
You Shijun and Yang Hongxing		Kame Khouzam	
Technical Guidelines for the Interconnection of PV Generation Systems in Queensland	1349	Heliodon Prediction of Shading on Building Integrated Photovoltaic Systems	1393
Kame Khouzam and Keith Hoffman		Tyandra Blewett, Margaret Horne and Robert Hill	

SIMULTANEOUS P AND B DIFFUSION, *IN-SITU* SURFACE PASSIVATION, IMPURITY FILTERING AND GETTERING FOR HIGH-EFFICIENCY SILICON SOLAR CELLS

Thomas Krygowski, Ajeet Rohatgi

Georgia Institute of Technology, Atlanta Georgia 30332

Douglas Ruby

Sandia National Laboratories, Albuquerque New Mexico 87123

ABSTRACT

A technique is presented to simultaneously diffuse boron and phosphorus in silicon, and grow an *in-situ* passivating oxide in a single furnace step. It is shown that *limited* solid doping sources made from P and B Spin-On Dopant (SOD) films can produce optimal n^+ and p^+ profiles simultaneously without the deleterious effects of cross doping. A high quality passivating oxide is grown *in-situ* beneath the thin (~ 60 Å) diffusion glass, resulting in low J_0 values below 100 fA/cm^2 for transparent ($\sim 100 \Omega/\square$) phosphorus and boron diffusions. For the first time it is shown that impurities present in the boron SOD film can be effectively filtered out by employing separate source wafers, resulting in bulk lifetimes in excess of 1 ms for the sample wafers. The degree of lifetime degradation in the sources is related to the gettering efficiency of boron in silicon. This novel simultaneous diffusion, *in-situ* oxidation, impurity filtering and gettering technique was successfully used to produce 20.3% Fz, and 19.1% Cz solar cells, in one furnace step.

I. INTRODUCTION

High temperature thermal processing can limit the throughput of a cell manufacturing line and potentially reduce cell efficiency through bulk lifetime degradation. To fabricate high efficiency solar cells with minimal thermal processing, simultaneous diffusion techniques can be employed to co-diffuse the emitter and Back Surface Field (BSF). Researchers at Sandia National Laboratories [1] have demonstrated an aluminum and phosphorus diffusion technique in which one high temperature ($>800^\circ\text{C}$) POCl_3 diffusion step is used to co-diffuse the emitter and pre-alloyed BSF, and grow a thick thermal oxide beneath the remaining phosphosilicate glass. Workers at IMEC have simultaneously diffused boron and phosphorus in an RTP using CVD doped oxides on opposite sides of a silicon wafer [2]. Using boron and phosphorus Spin-On Dopant (SOD) films in a conventional diffusion furnace, researchers at UNSW have simultaneously formed the front and back groove diffusions for the double sided buried contact structure [3], reducing the number of thermal cycles from three to two. All of the above techniques result in a thick layer of diffusion glass on the wafer surfaces. This thick diffusion glass leads to a high reflectance when incorporated into a module and is therefore usually removed, thus eliminating

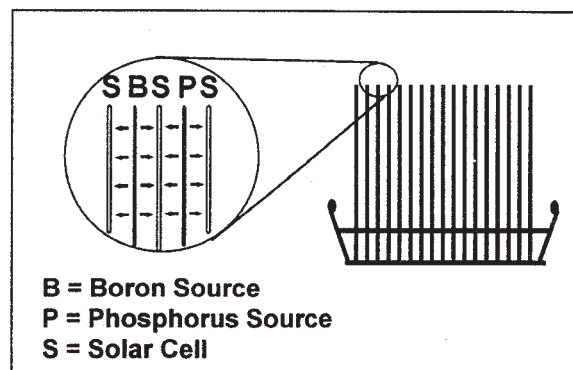


Figure 1. Wafer stacking arrangement for simultaneous P and B diffusion technique. The front sides of the Solar cells (S) face the Phosphorus (P) source wafers and the back sides face the Boron (B) source wafers.

any possibility for *in-situ* surface passivation. In addition, POCl_3 as well as the gasses typically used in CVD processes such as SiH_4 , B_2H_6 and PH_3 are highly toxic, and require significant expertise in handling and disposal. Our approach toward simultaneous diffusion, named the Dopant Oxide Solid Source (DOSS) technique [4], employs separate boron and phosphorus doping sources, which are interleaved with the solar cell wafers to simultaneously form a phosphorus emitter and boron BSF in a single furnace cycle. In the DOSS technique, the back sides of the solar cells (S) face the boron sources (B), and the front sides face the phosphorus sources (P) in a stacking arrangement shown in Figure 1. The B and P sources are fabricated in house from silicon wafers on which a controlled amount of the dopant oxide (P_2O_5 and B_2O_3) is deposited. The DOSS technique, which was first presented at the 25th Photovoltaics Specialists Conference [5], allows one to independently control the emitter and BSF doping profiles for a fixed thermal budget, by tailoring the concentration of P_2O_5 and B_2O_3 on the source wafers. In our earlier work [4] sources were made by depositing P_2O_5 or B_2O_3 on the source wafers using the liquid dopants POCl_3 and BBr_3 respectively in a pre-deposition step. In contrast to conventional solid, liquid, CVD or spin-on doping techniques, the residual phosphorous glass on the solar cell wafers was extremely thin (~ 60 Å). This allowed for a thin thermal passivating oxide to be grown *in-situ*, while maintaining a total oxide thickness below about 150 Å, which will not significantly increase the reflectance of an AR-coated cell when

incorporated into a module. This *in-situ* oxide was shown [5] to provide excellent surface passivation for light phosphorus diffusions ($\sim 90 \Omega/\square$), resulting in virtually the same saturation current densities (J_0 's) for *in-situ* as well as re-grown thermal oxide passivation.

The goal of this paper is to present recent advances in the DOSS simultaneous diffusion technique in which the solid doping sources are fabricated using phosphorus and boron Spin-On Dopant (SOD) films in place of POCl_3 and BBr_3 . It will be shown that in addition to forming optimal emitter and BSF profiles simultaneously, and providing *in-situ* oxide surface passivation, one can obtain high minority carrier lifetimes from a relatively impure boron SOD film through a powerful contamination filtering action. Several efficiency-enhancement features are combined in the DOSS technique to produce 19-20% efficient solar cells in one thermal cycle, using commercially available spin-on dopant films and a conventional diffusion furnace.

II. EXPERIMENTAL

Boron and phosphorus solid diffusion sources were made prior to each diffusion cycle by applying the same SCD film (B or P) to each side of a silicon source wafer. The source wafers are depleted after each diffusion cycle, and recycled (as sources) by a brief dip in 10% dilute HF to remove any residual glass. As shown below, the limited nature of these solid doping sources enables several high efficiency features to be realized in one furnace step using this simultaneous diffusion technique.

It should be recognized that at no point are the SOD films applied to the solar cell wafers. By applying the same SOD film to each side of a source wafer, as opposed to applying P and B films to opposite sides of a solar cell wafer, we eliminate the potential for cross doping during the film application process, and in addition reduce the handling requirements for the solar cell wafers. In production this would appear to be a distinct advantage over competing technologies since the sources could be made using high throughput techniques such as dip coating or spraying the dopants onto the sources, while the solar cell wafers are processed in parallel via cassette loading techniques.

III. RESULTS AND DISCUSSION

III-A Diffusion Profile Engineering Using DOSS Technique

To demonstrate the flexibility of the DOSS diffusion technique, a range of diluted phosphorus and boron SCD films were used to fabricate sources, followed by a 60 min diffusion cycle at 1000°C in N_2 . All of the SOD films used in this work are commercially available, and were provided by Filmtronics Corporation, under the product name Boron-A for the boron films and the P500 series for the phosphorus films. Figure 2 shows the resulting sheet resistance dependence on % P_2O_5 in the phosphorus SOD film, and the % of concentrated Boron-A in the boron SOD film. As shown in figure 2 one can

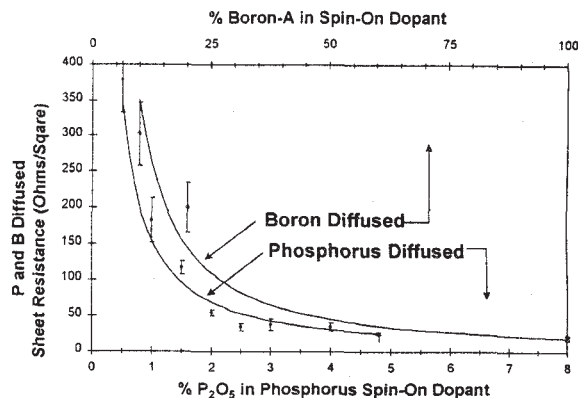


Figure 2. Dependence of sample sheet resistance on source concentration for sources made using B and P SOD films.

simultaneously achieve optimal emitter and BSF profiles, in the range of 20 to $300 \Omega/\square$ by tuning the dopant concentration of the SOD film used to fabricate the source wafers.

The dependence of diffused sheet resistance on source concentration displayed in figure 2 is quite different than what is observed with conventional phosphorus or boron solid sources. Conventional solid sources deposit large quantities of the respective dopant compound (P_2O_5 or B_2O_3) so that the surface concentration is fixed by the solid solubility of the impurity at a given temperature. Thus one is severely restricted in designing a simultaneous diffusion process with conventional solid sources, since the surface concentration of *both* impurities are pinned at the solid solubility at the diffusion temperature.

The solid sources developed in this work are *limited* in the concentration of dopant oxides transferred from source to sample, and do not behave as "infinite" solid sources over a wide range of concentrations. This unique feature for solid doping sources allows one to tune the dopant surface concentration to produce optimal emitter and BSF profiles by simply adjusting the dopant concentration of the SOD film used to fabricate the sources. The upper limit for surface concentration is dictated by the solid solubility, at which point the sources behave as conventional solid sources.

III-B. Residual Oxide Thickness

Figure 3 shows the residual oxide thickness for boron and phosphorus diffused samples resulting from the limited solid doping sources developed in this work. The two sets of data are for boron and phosphorus diffusions at 1000°C for 60 min in N_2 only, with no *in-situ* oxide formation. From figure 3 it is clear that the residual glass thickness is very small, and is approximately the same value for both dopants, for sheet resistance (ρ_s) values greater than about $30 \Omega/\square$. For ρ_s values below about $30 \Omega/\square$, the glass thickness rises sharply with decreasing ρ_s , and the differences in glass thickness between boron and phosphorus diffused samples becomes more pronounced. For most phosphorus emitters of interest, having ρ_s values

in the range of 40-100 $\Omega/\square$, the residual glass thickness ranges from 65-90 Å. This is about an order of magnitude lower than what is obtained when using conventional solid, liquid, CVD or spin-on doping sources.

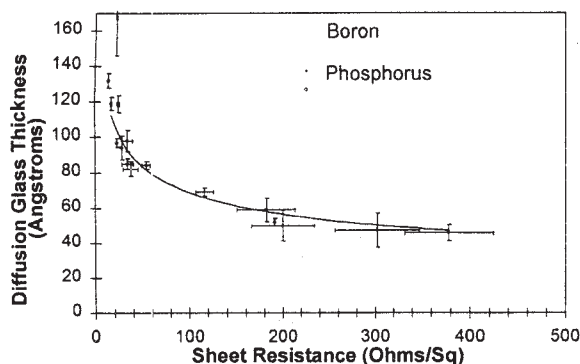
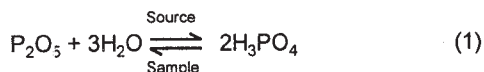


Figure 3. Residual oxide thickness for P and B diffused wafers with no in-situ oxidation.

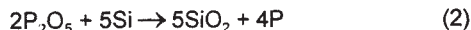
A physical model is presented below to explain two unique features of the DOSS technique; the tunability of the surface concentration below the solid solubility, figure 2, and the resulting thin diffusion glass shown in figure 3. These attributes are used to obtain optimal profiles and *in-situ* surface passivation resulting in low J_0 values.

III-C. Proposed Model for DOSS Diffusion

The phosphorus SOD used in this work is an industry-standard solution of P_2O_5 , H_2O , tetraethylorthosilane (TEOS), and ethanol. The hotplate bake prior to diffusion serves to drive off the ethanol solvent leaving a glassy film of P_2O_5 , H_2O and TEOS. At diffusion temperatures above about 700 °C, TEOS reacts to form SiO_2 , H_2O and C_2H_4 [6,7]. It is well known that P_2O_5 is extremely hygroscopic [8], and will react with H_2O intentionally added to the SOD film, as well as with humidity in the laboratory environment and trace amounts of moisture in the process gasses, to form the volatile species H_3PO_4 (phosphoric acid), which has a boiling point of about 400 °C. It is assumed that this is the phosphorus containing species that is transported from the source to the sample wafer. The reverse reaction takes place on the sample wafer resulting in a film of P_2O_5 on the sample surface with H_2O as a by-product; a process which was found to occur during the direct vaporization of H_3PO_4 at elevated temperatures [9]:

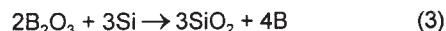


The oxide of phosphorus, P_2O_5 , deposited on the sample surface proceeds to react with silicon to form SiO_2 and P, which preferentially diffuses into silicon:



For the case of limited doping sources, we propose that the starting thickness of P_2O_5 formed on the sample surface is extremely thin, and is limited by the dose of H_3PO_4 . During the diffusion cycle, reaction (2) is essentially driven to completion, resulting in a thin layer of SiO_2 rich glass on the sample surface, and the surface concentration of P below the solid solubility. Thus by controlling the concentration of P_2O_5 in the SOD film, we can limit the dose of H_3PO_4 , and thus the thickness of P_2O_5 on the sample, allowing the underlying silicon to consume virtually all of the available phosphorus for concentrations below the solid solubility. This result is notably different than conventional SiP_2O_7 -based solid sources which are designed to be reused for hundreds of hours. These conventional solid sources continually deposit a stream of P_2O_5 on the sample wafers, which results in a thick layer of diffusion glass on the surface [10], and thus provides a supply of phosphorus which exceeds the solid solubility. In this case the surface concentration is dictated by the solid solubility of P in Si, and thus the only degrees of control is the diffusion temperature and time. But by fabricating solid doping sources in the limited source regime we now have a third degree of control in addition to temperature and time; the *source concentration*.

The situation for boron sources fabricated from a boron SOD film is analogous to phosphorus: The Boron-A film used in these experiments is a proprietary boron-based polymer dissolved in cyclohexane and diluted with toluene, which converts directly to B_2O_3 at about 450 °C [11]. It is likely that B_2O_3 is directly transported from the source to sample wafer, although HBO_2 which has a much higher vapor pressure than B_2O_3 is known to form in the presence of even trace amounts of moisture [12]. For the case of limited boron diffusions, the reactions on the sample surface proceed as in the case of phosphorus:



resulting in a thin SiO_2 -rich glass layer and a boron concentration below the solid solubility.

To test the above hypothesis; that the emitter surface concentration depends on the starting thickness of P_2O_5 on the sample wafers, diffusions were carried out using planar and textured sample wafers which face opposite sides of the same phosphorus source. By etching [111] oriented pyramids in the [100] sample surface, the surface area is increased by a factor of $1/\cos\phi=1.73$ over a planar surface. Thus for a *limited* dose of H_3PO_4 , the resulting thickness of P_2O_5 on the textured sample will be less than the planar sample since the available quantity of P_2O_5 is spread out over a larger surface area. According to the proposed model this should result in a lower surface concentration on the textured wafers or equivalently a higher sheet resistance. As shown in figure 4 this is indeed the case.

Figure 4 shows that for low concentrations of P_2O_5 in the SOD films used to fabricate the sources, the textured wafers have a higher sheet resistance than the planar wafers by a factor of about 2 when facing the same sources. As the % P_2O_5 in the SOD film is increased, the difference in ρ_s is reduced until the ρ_s 's for the textured

and planer wafers approach the same value for the "infinite" P_2O_5 case, which corresponds to that of conventional solid sources.

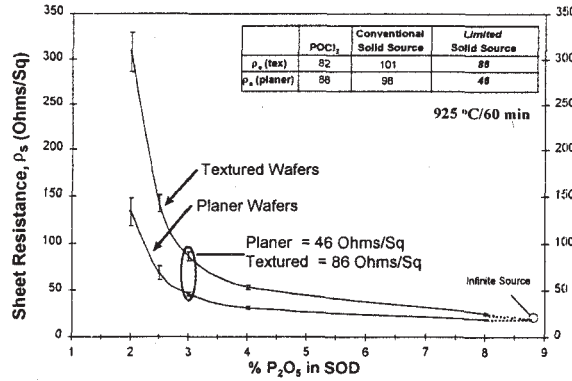


Figure 4. Dependence of sample sheet resistance on source concentration for textured and planer wafers.

For comparison, diffusions were carried out using $POCl_3$ and conventional SiP_2O_7 - based solid sources, with textured and planer wafers diffused simultaneously. As shown in the inset table of figure 4, the values of ρ_s for textured and planer wafers is nearly identical when using $POCl_3$ and conventional solid sources. However, in the case of *limited* solid sources used in the DOSS technique, the same source can produce an 86 $\Omega/\square$ textured emitter and a 46 $\Omega/\square$ planer emitter. This feature can be used to obtain an *in-situ* selective emitter for screen-printed contacts: By selectively texturing the field region of an emitter using a SiN texture mask, one can simultaneously diffuse a flat grid region of 46 $\Omega/\square$, and a textured field region of 86 $\Omega/\square$, taking full advantage of the *in-situ* oxide passivation found in the DOSS technique.

III-D. In-Situ Oxide Surface Passivation

Table 1 shows the results of emitter saturation current density (J_0) measurements at 25 °C [13], made on heavy and light boron and phosphorus diffusions, with *in-situ* oxide passivation. As shown in table 1, a heavy (25 $\Omega/\square$) boron BSF typically used in high efficiency cell designs results in a J_0 value of 417 fA/cm². By forming a lighter boron diffusion of 110 $\Omega/\square$, coupled with *in-situ* oxide passivation this J_0 value can be reduced to 92 fA/cm². This value for J_0 is a factor of two higher than reported by King [14] for 126 $\Omega/\square$ boron diffusions formed using CVD doped oxides, but is still capable of producing low values of effective recombination velocity at the high-low (pp⁺) junction. For a 2 Ω -cm (p-type) material, the effective surface recombination velocity at the pp⁺ junction can be expressed as:

$$S_{pp^+} = \frac{N_A}{qn_i^2} \left(1 + \frac{\Delta n}{N_A}\right) J_0 \quad (4)$$

which corresponds to an S_{pp^+} = 56 cm/s under low level injection ($\Delta n \ll N_A$). In practice the true value of S_{pp^+} will be higher due to additional recombination at the ohmic contacts to the (full) p⁺ BSF. But, by reducing the metal coverage by forming point contacts or screen-printing an

Dopant	Sheet Resistance	J_0
Boron	25 $\Omega/\square$	417 fA/cm ²
Boron	110 $\Omega/\square$	92 fA/cm ²
Phos. (with Ox.)	90 $\Omega/\square$	67 fA/cm ²
Phos. (w/o Ox.)	90 $\Omega/\square$	809 fA/cm ²
Phos. (with Ox.)	43 $\Omega/\square$	130 fA/cm ²

Table 1. J_0 measurements for heavy and light boron and phosphorus diffusions.

Al/Ag grid, the effects of contact recombination can be reduced.

The benefits of *in-situ* oxide passivation of phosphorus diffused emitters formed using SOD-coated source wafers are shown in Table 1. As shown in Table 1, for a 90 $\Omega/\square$ n⁺ diffusion with *in-situ* oxide passivation, the resulting J_0 value is low, resulting in J_0 = 67 fA/cm². By removing the *in-situ* oxide, the J_0 value increases to 809 fA/cm², demonstrating the superb passivating qualities of the *in-situ* oxide provided by the DOSS technique. By forming a heavier n⁺ diffusion (~43 $\Omega/\square$) which is appropriate for screen printed contacts, we have found that the J_0 value shows only a moderate increase to 130 fA/cm², which is still capable of producing high open circuit voltages. That we can obtain a low J_0 of 130 fA/cm² for a (semi-opaque) 43 $\Omega/\square$ phosphorus diffusion is most likely due to the fact that the diffusions are carried out well below the solid solubility. This reduces the probability of introducing significant surface damage, commonly referred to as a "dead layer" [15], allowing the device to take advantage of the high-quality *in-situ* oxide passivation.

Work is currently under way to introduce screen-printed contacts to the cell fabrication process using the 43 $\Omega/\square$ phosphorus emitter and 110 $\Omega/\square$ boron BSF shown in Table 1. Measurements of the specific contact resistance (ρ_c) by the transmission line method have resulted in average ρ_c values of 2.9 m Ω -cm² for 46 $\Omega/\square$ phosphorus diffusions and 4.3 m Ω -cm² for 85 $\Omega/\square$ boron diffusions using Ag/P and Ag/Al pastes respectively. Computer modeling indicates that greater than 18% Cz screen-printed cells should be feasible if effective surface passivation can be maintained and the metal area coverage kept to a minimum ($\leq 10\%$).

III-C. Impurity filtering and Gettering Using DOSS Technique

Historically it has been difficult to obtain high minority carrier lifetimes when using a boron SOD film as a dopant source, when spun directly onto a wafer. The impurity levels of contaminants such as Fe, Cr, Cu and Ni are typically present in the 10 ppb range for the SOD films used in this work [11], which can lead to significant bulk lifetime degradation. In the present work it was discovered that by fabricating separate boron sources using a relatively impure boron SOD film, one could filter out much of the contaminants present in the film, liberating a relatively "pure" flux of B_2O_3 from the film-coated source wafer.

The effectiveness of this impurity filtering action is seen in figure 5, in which the boron-diffused bulk lifetime, τ_b , is shown as a function of injection level, n . Two sets of source/sample wafers were used in these experiments, in which a 100% Boron-A film was applied to a p-type 2.3 Ω -cm float zone silicon wafer which was then used as a source for an adjacent 2.3 Ω -cm sample wafer. Special care was taken in these experiments to insure cleanliness of the spin-on process. The first set of wafers, labeled **Sample 1** and **Source 1** respectively in figure 5 were diffused at 1000 °C for 60 min in N_2 , with no *in-situ* oxide grown. The second set of source/sample wafers were subjected to an additional 66 min *in-situ* oxidation at 1000 °C to grow a thick thermal oxide and are labeled **Sample 2** and **Source 2**. As shown in figure 5, the difference in bulk lifetime between the source and sample wafers is large for the cases with and without the thick *in-situ* oxide. In both cases the impurity filtering action resulted in high bulk lifetimes in excess of 1 ms for the sample wafers, but degraded the source wafers to a lifetime of 227 μ s and 5.9 μ s for the non-oxidized (case 1) and oxidized cases (case 2) respectively. We have observed this behavior numerous times using 5 different lots of boron SOD film manufactured over the past 2 years. By indirectly doping the samples via film-coated source wafers, impurities in the boron SOD film are diffused into the sources but are not transported to the samples, resulting in lifetimes in excess of 1 ms for these high-quality Fz-Si wafers. Thus the sources act to filter out impurities from the boron SOD film, allowing a relatively pure layer of B_2O_3 to deposit on the sample surface.

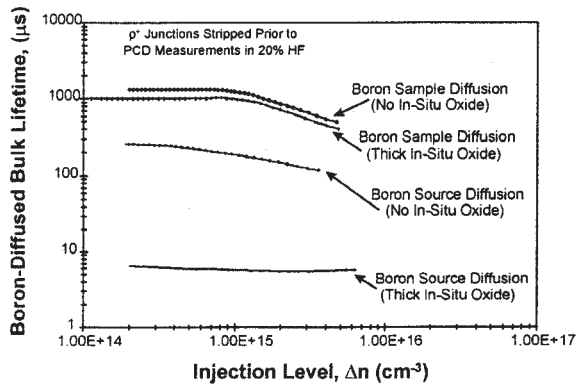


Figure 5. Impact of impurity filtering action on bulk minority carrier lifetime for oxidized and un-oxidized boron diffusions.

It is interesting to note that the lifetime of the oxidized Source 2 wafer (5.9 μ s) was significantly lower than the non-oxidized Source 1 wafer (227 μ s) in figure 5. We attribute this to a reduction in the *gettering effectiveness* of the boron BSF as a result of dopant redistribution during the 66 minute *in-situ* oxidation. During the *in-situ* oxidation, boron preferentially segregates into the growing oxide layer so that the surface concentration is reduced. Similar results have been reported in the use of boron nitride solid sources [16], in which it was proposed that further oxidation after diffusion in N_2 leads to re-injection of impurities from the

BSF to the bulk region as the surface concentration is reduced. In addition, workers at Bell Laboratories [17] have recently shown that the ability to getter impurities which form metal-acceptor complexes (e.g. Fe, Mn and Cr) from a p^- to p^+ region strongly depends on the difference in boron concentration between the two regions, expressed as

$$\frac{[X_i^+]_{p^+}}{[X_i^+]_{p^-}} = e^{\frac{\Delta E_f}{kT}} \quad (5)$$

where X_i^+ is the ionized interstitial metal concentrations and ΔE_f is the fermi-level offset between the p^- and p^+ regions.

While we have not attempted to identify the lifetime limiting impurities in this work, our results are consistent with those reported in the literature for boron gettering of the metallic impurities present in the Boron-A SOD film. These results suggest that clean boron diffusions resulting from the impurity filtering mechanism in the DOSS technique, coupled with effective boron gettering can be used to significantly enhance the minority carrier lifetime of solar grade materials. The simplicity and flexibility of the DOSS diffusion technique makes this an ideal approach to study boron and phosphorus (co)gettering phenomena while maintaining the ability to produce high efficiency solar cells in one furnace step.

III-D. High Efficiency Solar Cell Fabrication

The ability of the DOSS technique to produce optimal emitter and BSF profiles, *in-situ* oxide surface passivation and maintain high bulk lifetimes is demonstrated by high efficiency solar cell fabrication. The cell structure used is referred to as a Simultaneously diffused, Textured, *in-situ* oxide AR-coated solar cell (STAR cell). Figure 6 shows the light IV, IQE and reflectance measurements confirmed by Sandia National Laboratories of two STAR cells made on (boron) source and sample wafers, in order to illustrate the power of impurity filtering in this technology. The 4 cm^2 random textured cells were fabricated on 2.3 Ω -cm float zone silicon, in a 60 min simultaneous diffusion process at 1000 °C in N_2 followed by a 66 min *in-situ* oxidation to grow a ~1070 Å SiO_2 single layer antireflection coating. Photolithography was used for the front and back contacts, with point contacts made to a full boron BSF in order to use the (back) *in-situ* oxide as a dielectric for a back side reflector. This type of structure has recently produced (confirmed) efficiencies as high as 20.1% in one furnace step [18] using the DOSS diffusion technique.

Figure 6 illustrates the merit of using separate boron source wafers, which resulted in an efficiency of 19.4% for the cell adjacent in the diffusion furnace to the 15.2% cell to which the boron SOD film was applied. Both cells were fabricated out of the same float zone silicon material and had the same emitter and BSF sheet resistances. The 4.2% boost in absolute efficiency by using a separate boron source is attributed to the filtering of impurities present in the boron SOD film, a process

which according to figure 5 results in bulk minority carrier lifetimes in the vicinity of 1 ms for this material.

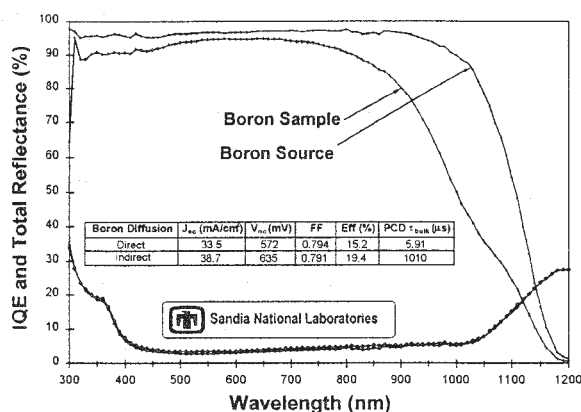


Figure 6. Impact of impurity filtering action on solar cell efficiency, showing a 4.2% increase in (absolute) efficiency for the sample device as compared to the corresponding source device.

In order to reduce the processing temperature from 1000 °C and improve the surface passivation and AR coating properties, a second generation (STAR-II) process is currently under development. In the STAR-II design, the diffusion temperature is reduced to 925 °C and the oxidation time reduced to 10 min. These process changes produce a lighter boron BSF (~100 $\Omega/\square$) and a thinner oxide so that a ZnS/MgF₂ DLAR-coating can be used with the textured emitter. PECVD SiO₂ is deposited on the back *in-situ* oxide as a dielectric for a back side reflector, and point contacts made to the (full) transparent boron BSF. Preliminary STAR-II results are encouraging, giving efficiencies of 20.3% on 4 cm² Fz (2.3 Ω -cm) cells and 19.1% on 200 μ m thick Cz (10 Ω -cm) cells. Internal quantum efficiency measurements are shown in figure 7 for the 19.1 % Cz STAR-II cell. The high long wavelength quantum efficiency demonstrates that in addition to good surface passivation and bulk lifetime, effective light trapping is achieved in this 200 μ m thick device, due to the Si/SiO₂/Al back side reflector. In comparing STAR-I and STAR-II Fz cells, a 10 mV increase in V_{oc} is obtained which can be largely attributed to the transparent, oxide passivated boron BSF. Further improvements are expected through optimization of the surface passivation and AR coating properties, in order to reach the goal of producing 20% Cz cells in one furnace step using the STAR-II process. Research is also underway to integrate screen printing with the STAR technology to produce manufacturable, high efficiency solar cells.

IV. CONCLUSION

In conclusion, we have made significant advances in the DOSS simultaneous boron and phosphorus diffusion technique. It is shown that the boron and phosphorus source wafers can be fabricated from SOD films, which provide a high degree of flexibility in process design and eliminate the need for separate POCl₃ and BBr₃ diffusion furnaces. Several efficiency-

enhancing features of the DOSS technique, such as *in-situ* oxide surface passivation, impurity filtering and boron gettering are presented and quantified. These efficiency enhancement techniques are combined to produce 19-20% efficient Fz and Cz solar cells in a single thermal cycle, using sources and equipment which are completely compatible with the current PV technology base of conventional diffusion furnaces.

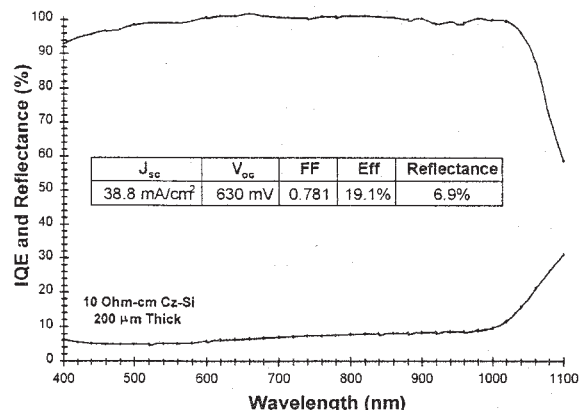


Figure 7. IQE of 19.1% STAR-II cell on 200 μ m thick Cz-Si.

V. REFERENCES

- [1] P. Basore, J. Gee, E. Buck, K. Schubert, D. Ruby, *Solar En. Mat. and Solar Cells*, V34 pg 91 (1994).
- [2] B. Hartiti, S. Sivoththaman, R. Schindler, J. Nijs, J.C. Muller, P. Siffert, *IEEE 1st World Conf. On PV Energy* (1994).
- [3] A. U. Ebong, C. B. Honsberg, *Solar En. Mat. And Solar Cells*, V 44, pg 271 (1996).
- [4] T. Krygowski, A. Rohatgi, *J. Electrochem. Soc.*, Vol 144, pg 346 (1997).
- [5] T. Krygowski, P. Sana, G. Crotty, A. Rohatgi, *Proc. 25th IEEE Photovoltaic Spec. Conf.* (1996).
- [6] K. Fujino, Y. Nishimoto, N. Tokumasu, K. Maeda, *J. Electrochem. Soc.*, Vol 137, pg 2883 (1990).
- [7] B. Gelernt, *Semiconductor International*, March 1990.
- [8] N. Nagasima et. al., *J. Electrochem. Soc.*, Vol 121, pg 434 (1974).
- [9] T. Koval, US Patent 4360393 (1982).
- [10] J. R. Flemish, R. E. Tressler, J. Ruzyllo, *J. Electrochem. Soc.*, Vol 138, pg 233 (1991).
- [11] Tim Selzer, Filmtronics (Private Communication).
- [12] A. Yeckel, S. Middleman, *AIChE Spring National Meeting*, pg35 (1987).
- [13] D. E. Kane, R. M. Swanson, *Proc. 18th IEEE Photovoltaics Spec. Conf.*, pg 578 (1985).
- [14] R. King, Ph.D. Thesis, Stanford University (1990).
- [15] S. R. Wenham, M. A. Green, *Prog. In Photovolt.*, Vol4 pg 3 (1996).
- [16] T. Saitoh, T. Warabisako, *Tech. Digest for 9th Workshop on Crystalline Silicon Solar Cells* pg 29 (1996).
- [17] J. L. Benton, et. al. *J. Appl. Phys.*, Vol 80, pg 3275 (1996).
- [18] T. Krygowski, A. Rohatgi, *IEEE Transac. Elec. Dev.*, Jan 89 To be published.

ACKNOWLEDGMENTS This work was supported by Sandia National Laboratories under contract AO-6162.