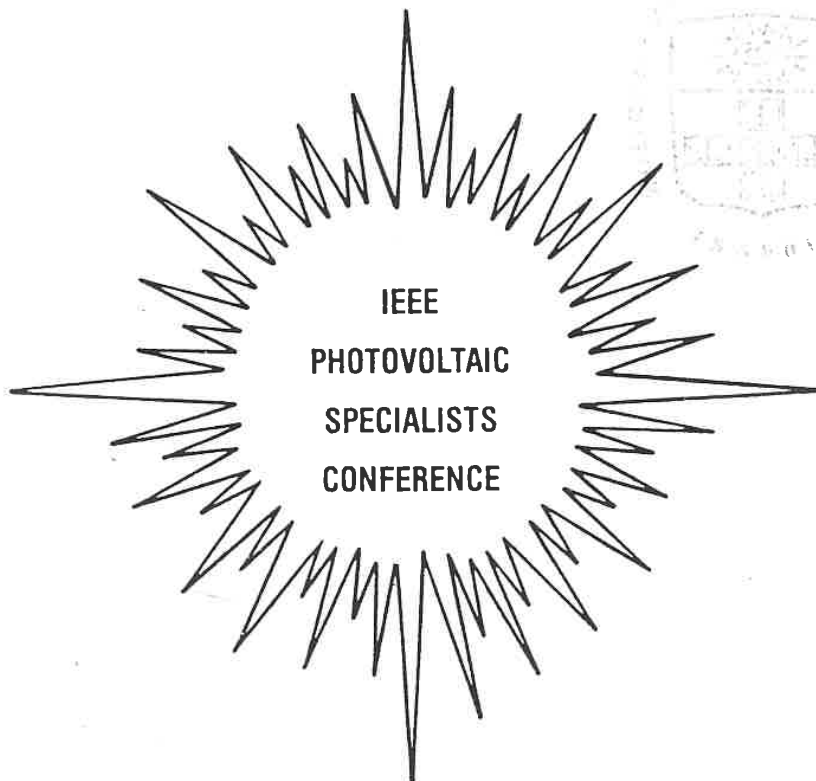


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TABLE OF CONTENTS

VOLUME I

William Cherry Award

Chairpersons:

J.D. Meakin

E.L. Ralph

Photovoltaics: Coming of Age

M.A. Green

High Efficiency Crystalline Cells and Materials

Overview of Recent Photovoltaic Developments

Chairperson:

J.D. Meakin

Organizer:

R.J. Schwartz

Photovoltaics: Meeting the Environmental Imperatives of Clean Air and Climate Change

W. Moomaw

Solar Photovoltaic Power: A U.S. Electric Utility R&D Perspective

E.A. DeMeo, F.R. Goodman, Jr., T.M. Peterson and J.C. Schaefer

Recent Advances in High Efficiency GaInP₂/GaAs Tandem Solar Cells

J.M. Olson, S.R. Kurtz, A. E. Kibbler and P. Faine

Photovoltaic Power for Space Station Freedom

C.R. Baraona

Advances in a-Si:H Alloys for High Efficiency Devices

A. Catalano

III-V Single and Multijunction Cells

Chairpersons:

S.P. Tobin

M. Yamaguchi

Organizer:

J.M. Gee

The Potential Performance of GaAs-Based Mechanically Stacked, Multijunction Solar Concentrator Cells

J.M. Gee and C.J. Chiang

Mechanically Stacked Two-Tandem Concentrator Solar Cell Concept

B. Beaumont, P. Garabedian, G. Nataf, J.C. Guillaume, P. Gibart and C. Verie

High-Efficiency GaAs/CuInSe₂ and AlGaAs/CuInSe₂ Thin-Film Tandem Solar Cells

R.P. Gale, R.W. McClelland, B.D. Dingle, J.V. Gormley, R.M. Burgess, N.P. Kim, R.A. Mickelsen and B.J. Stanbery

AlGaAs Top Solar Cell for Mechanical Attachment in a Multi-Junction Tandem Concentrator Solar Cell Stack

L.C. DiNetta, G.H. Negley, M.H. Hannon, J.R. Cummings, J.B. McNeely and A.M. Barnett

Monolithic Tandem Solar Cell Based on GaAlAs-GaAs System

L. Mayet, M. Gavand, B. Montégu, J.P. Boyeaux and A. Laugier

Graded-Band-Gap AlGaAs Solar Cells for AlGaAs/Ge Cascade Cells

M.L. Timmons, R. Venkatasubramanian, T.S. Colpitts, J.S. Hills, J.A. Hutchby, P.A. Iles and C.L. Chu

Development of Low Bandgap Ge and Si_{0.07}Ge_{0.93} Solar Cells for Monolithic and Mechanically-Stacked Cascade Applications

R. Venkatasubramanian, M.L. Timmons, R.T. Pickett, T.S. Colpitts, J.S. Hills, J.A. Hutchby, P.A. Iles and C.L. Chu

Large Scale, High Efficiency GaAs/Ge Cell Production

Y.C.M. Yeh, C. Cheng, F. Ho and H. Yoo

Large Area Shunt Defect Free GaAs Solar Cells

L.C. Kilmer and A.M. Barnett

A GaAs-ON-Si Solar Cell for Space Use

Y. Ohmachi, T. Ohara and Y. Kadota

New Results in Hetero-Epitaxy of GaAs/Ge/Si for High Efficiency in III-V Solar Cells on Low Cost Substrates

A. Leycuras, M.F. Vilela, J.C. Grenet, M. Leroux, G. Strobl, G. Neu and C. Verie

Back Contacted Emitter GaAs Solar Cells

G.L. Araujo, A. Marti and C. Algora

Application of InAlAs/GaAs Superlattice Alloys to GaAs Solar Cells

T.L. Drummond, J.M. Gee, F.L. Terry and R. Weng

Peeled Film GaAs Solar Cell Development

D.M. Wilt, R.D. Thomas, S.G. Bailey, G.A. Landis, D.J. Brinker, F.L. DeAngelo and N.S. Fatemi

An Evaporated Aluminum Metallization for High Efficiency GaAs Solar Cells

M. Ladle Ristow, M.S. Kuryla, H.F. MacMillan, N.R. Kaminar, G.F. Virshup, H.C. Hamaker, J.G. Werthen and K.A. Bertness

An Analysis of the Contact Sintering Process in III-V Solar Cells	119
V.G. Weizer and N.S. Fatemi	
Photovoltaic Characteristics of n⁺pp⁺ InP Solar Cells by OMVPE	125
S. Tyagi, K. Singh, H. Bhimnathwala, S.K. Ghandhi and J.M. Borrego	
Study of Surface Passivation as a Function of InP Closed Ampoule Solar Cell Fabrication Processing Variables	130
Maria Faur, Mircea Faur, M. Goradia, C. Goradia, P. Jenkins, D. Jayne, S. Bailey and I. Weinberg	
High Efficiency GaAs Solar Cells Using GaInP₂ Window Layers	138
S.R. Kurtz, J.M. Olson and A.E. Kibbler	

LATE NEWS

Emitter Structures in MOCVD InP Solar Cells	141
C.J. Keavney, V.E. Haven and S.M. Vernon	
High Efficiency Thin Film GaAs Bifacial Solar Cells	145
R.W. McClelland, J.C.C. Fan, R.P. Gale and B.D. Dingle	
High Efficiency 1.0-eV GaInAs Bottom Solar Cell for 3-Junction Monolithic Stack	148
J.C. Schultz, M.E. Klausmeier-Brown, M.L. Ristow and M.M. Al-Jassim	

High Efficiency III-V Cells

Chairpersons:

J. Benner
C. Verie

Organizer:

J.M. Borrego

Buried Homojunction Solar Cells Formed in p-InP During Sputter Deposition and Hydrogen Plasma Processing	153
T.A. Gessert, X. Li, M.W. Wanlass and T.J. Coutts	
Advances in High-Efficiency GaAs Solar Cells	158
S.P. Tobin, S.M. Vernon, S.J. Wojtczuk, C. Bajgar, M.M. Sanfalcon and T.M. Dixon	
High Efficiency GaAs and AlGaAs Solar Cells Grown by Molecular Beam Epitaxy	163
M.R. Melloch, S.P. Tobin, C. Bajgar T.B. Stellwag, A. Keshavarzi, M.S. Lundstrom and K. Emery	
High Voltage, Monolithically Interconnected GaAs Thin Film Solar Submodules	168
R.W. McClelland, B.D. Dingle, R.P. Gale and J.C.C. Fan	
Development of High-Performance GaInAsP Solar Cells for Tandem Solar Cell Applications	172
M.W. Wanlass, J.S. Ward, G.S. Horner, T.A. Gessert, K.A. Emery, T.J. Coutts, G.F. Virshup and M.L. Ristow	

27.6% (1-Sun, Air Mass 1.5 G) Monolithic Two-Junction AlGaAs/GaAs Solar Cell and 25% Three-Junction AlGaAs/GaAs/InGaAs Cascade Solar Cell	179
B.C. Chung, G.F. Virshup and J.C. Schultz	
Progress Toward a 30% Efficient, Monolithic, Three-Junction, Two-Terminal Concentrator Solar Cell for Space Applications	184
L.D. Partain, B.C. Chung, G.F. Virshup, J.C. Schultz, H.F. MacMillan, M. Ladle Ristow, M.S. Kuryla, K.A. Bertness, M.E. Klausmeyer-Brown, M.W. Wanlass and T.J. Coutts	
Over 35% Efficient GaAs/GaSb Stacked Concentrator Cell Assemblies for Terrestrial Applications	190
L.M. Fraas, J.E. Avery, V. Sundaram, V.T. Dinh, T.M. Davenport, J.W. Yerkes, J.M. Gee and K.A. Emery	

High Efficiency Solar Cells

Chairperson:

R.M. Swanson

Organizer:

P.A. Basore

A Review of Indium Phosphide Space Solar Cell Fabrication Technology	196
M.B. Spitzer, B. Dingle, J. Dingle and R. Morrison	
Recent Improvements in Silicon Solar Cell and Module Efficiency	207
M.A. Green, S.R. Wenham, J. Zhao, J. Zolper and A.W. Blakers	
Experimental Study of Solar Cell Performance Versus Dislocation Density	211
S.M. Vernon, S.P. Tobin, M. M. Al-Jassim, R.K. Ahrenkiel, K.M. Jones and B.M. Keyes	

Silicon Solar Cells

Chairpersons:

R. Mertens
D.R. Lillington

Organizer:

R.M. Swanson

Crystalline Photovoltaic Cell Research, Status and Future Direction	217
D.E. Hasti, D.L. King and J.D. McBrayer	
Cost Effectiveness of High Efficiency Cell Processes as Applied to Cast Polycrystalline Silicon	221
J.H. Wohlgemuth, S. Narayanan and R. Brenneman	
Passivated Emitters in Silicon Solar Cells	227
R.R. King, P.E. Gruenbaum, R.A. Sinton and R.M. Swanson	
Surface Passivation of High Efficiency Silicon Solar Cells	233
A. Aberle, W. Warta, J. Knobloch and B. Voss	

UV Radiation Hardness of Silicon Inversion Layer Solar Cells	239	The Effects of Different Diffusion Sources on Silicon Solar Cell Recombination Properties	311
R. Hezel		D.S. Ruby and J.D. McBrayer	
Polysilicon Emitters for Silicon Concentrator Solar Cells	245	Stable Passivations for High-Efficiency Silicon Solar Cells	317
J.-Y. Gan and R.M. Swanson		P.E. Gruenbaum, J.Y. Gan, R.R. King and R.M. Swanson	
Deeply-Grooved Silicon Concentrator Solar Cells for use with Prismatic Covers	251	Advancements in Silicon Buried Contact Solar Cells	323
J.S. Culik, E.L. Jackson and A.M. Barnett		S.R. Wenham, F. Zhang, C.M. Chong and M.A. Green	
Super Self-Aligned Technology for Backside Contact Solar Cells: A Route to Low Cost and High Efficiency	257	Point- and Planar-Junction PIN Silicon Solar Cells for Concentration Applications, Fabrication, Performance and Stability	327
P. Verlinden, B. Lafontaine, P. Jacquemin, E. Goutain and A. Crahay		A. Cuevas, R.A. Sinton and R.M. Swanson	
Light Trapping in Thin Crystalline Silicon Solar Cells	263	24% Efficient PERL Structure Silicon Solar Cells	333
J.A. Rand, R.B. Hall and A.M. Barnett		J. Zhao, A. Wang and M.A. Green	
Fermi Degeneracy and Quantum Collection Efficiency in Heavily Doped Silicon Solar Cells	269		
A. Morales-Acevedo			
Silane Glow Discharge Based Double Antireflection Coatings for cr-Si Solar Cells	275		
G. Willeke, E. Demesmaeker, J. Nijs and R. Mertens			
Development of a Multi-Purpose, Pulsed-Laser System for Solar Cell Processing Applications	278		
D.L. King, B.R. Hansen and W.M. Lehrner			
Electrical Parameter Changes in Silicon Solar Cells Induced by Thermal Donor Formation	284		
J.M. Ruiz and M. Cid			
Series Resistance Calculations in Silicon Solar Cells at Very High Concentration	289		
I. Tobias and A. Luque			
Annealing and Temperature Effects on Minority Carriers in Ion Implanted Silicon Solar Cells	295		
P. Nubile, A.F. Beloto, N. Veissid, B. Waldman, I. Pereyra and A.M. Andrade			
LATE NEWS			
Characterization of Very-Thin High-Efficiency Corrugated Silicon Solar Cells	299		
T. Uematsu, K. Kanda, S. Kokunai, T. Warabisako, S. Iida and T. Saitoh			
Developments in Module Ready Si Backside-Contact Solar Cells	302		
R.A. Sinton, R.A. Crane, S. Beckwith, A. Cuevas, P.E. Gruenbaum, D.E. Kane, J.Y. Gan, R.R. King, N. Midkiff and R.M. Swanson			
High Efficiency Silicon Solar Cells			
Chairpersons:			
A. Luque			
R.A. Sinton			
Organizer:			
R.M. Swanson			
Electro-Epitaxial Growth of Thin Film Silicon	307		
D.W. Cunningham, M.G. Mauk, J.P. Curran and A.M. Barnett			
		Modeling and Characterization of Single Crystal Solar Cells	
		Chairpersons:	
		A. Cuevas	
		G.F. Virshup	
		Organizer:	
		J.L. Gray	
		Temperature Coefficients of Multijunction Solar Cells	336
		G.F. Virshup, B.C. Chung, M. Ladle Ristow, M.S. Kuryla and D. Brinker	
		Modeling of Two-Junction, Series-Connected Tandem Solar Cells Using Top-Cell and Coating Thicknesses as Adjustable Parameters	339
		P. Faine, S.R. Kurtz and J.M. Olson	
		Numerical Model for Tunnel Junctions with Application to Cascade Solar Cells	345
		J.L. Gray	
		OBIC Studies: Classification of Structural Defects and Their Influence on the Performance of MOCVD Grown GaAs Solar Cells	348
		X. Tang, P.J.M. Boots and L.J. Giling	
		Intensity Effects in Minority Carrier Lifetime Measurements	353
		D.C. Marvin and L.F. Halle	
		Transient Photoluminescence Decay Investigations of LPE GaAs Heteroface Solar Cells	357
		W. Wetling, A. Ehrhardt, A. Bett and F. Lutz	
		Characterization of Antireflection Films for Surface-Passivated Crystalline Silicon Solar Cells Using Spectroscopic Ellipsometry	363
		O. Kamataki, T. Saitoh, S. Iida and T. Uematsu	
		Detailed Analysis of the Factors Affecting Emitter Recombination in Solar Cells Through the Small-Signal Voltage Decay Method	368
		K. Joardar, D.K. Schroder and C.E. Backus	
		Microwave-Detected Photoconductance Decay	374
		P.A. Basore and B.R. Hansen	

Experimental Measurement of the Intrinsic Carrier Concentration of Silicon	380
A.B. Sproul and M.A. Green	
Key Factors Limiting the Open Circuit Voltage of n⁺pp⁺⁺ Indium Phosphide Solar Cells	386
C. Goradia, W. Thesling and I. Weinberg	
Lifetime Measurements by Open Circuit Voltage Decay in GaAs and InP Diodes	394
H. Bhimnathwala, S.Bothra, S. Tyagi, S.K. Ghandhi and J.M. Borrego	
Measurement of Surface Recombination Velocity on Heavily Doped InP	399
P. Jenkins, S.G. Bailey, Mircea Faur, M. Ghalla-Goradia and Maria Faur	
Surface Recombination Velocity and Lifetime in InP Measured by Transient Microwave Reflectance	404
S. Bothra, S. Tyagi, S.K. Ghandhi and J.M. Borrego	
Energy and Free Energy Analyses of Photovoltaic Energy Conversion	409
J.E. Parrott	
PC-ID Modeling of Depletion Layer Recombination in GaAs Solar Cells	415
L.C. Olsen, D.A. Huber, G. Dunham and F.W. Addis	
Non-Solar Photovoltaic Cells	420
P.A. Iles	

Modeling and Characterization of Single Crystal Solar Cells

Chairpersons:

P.A. Basore
J.L. Gray

Organizer:

R.A. Sinton

Texture: A Ray Tracing Program for the Photovoltaic Community	426
A.W. Smith, A. Rohatgi and S.C. Neel	
Design of High Efficiency GaAs Solar Cells by Photoluminescence Studies	432
R.K. Ahrenkiel, D.J. Dunlavy, B. Keyes, S.M. Vernon, S.P. Tobin and T.M. Dixon	
Physical Parameters of Highly Injected Silicon in the Modelling of Concentrator Solar Cells	437
D.E. Kane, R.A. Sinton, J.Y. Gan and R.M. Swanson	
Effects of Perimeter Recombination on GaAs-Gated Solar Cells	442
T.B. Stellwag, P.E. Dodd, M.S. Carpenter, M.S. Lundstrom, R.F. Pierret, M.R. Melloch, E. Yablonovitch and T.J. Gmitter	
Reverse I-V Characteristics of GaAs Cells	448
P.A. Iles, H. Yoo, C. Chu, J. Kroger and K.I. Chang	
Effects of Heavy Impurity Doping on the np Product in p-GaAs	455
M.E. Klausmeier-Brown, M.R. Melloch and M.S. Lundstrom	

Polycrystalline Solar Cells

Thin Film Compound Semiconductors

Chairpersons:

J.E. Phillips
K.W. Mitchell

Organizer:

C. Eberspacher

Polycrystalline Thin Film Photovoltaics	458
K. Zweibel, H.S. Ullal and R.L. Mitchell	
Key Issues and Cost Estimates for the Fabrication of CuInSe₂ (CIS) PV Modules by the Two-Stage Process	467
V.K. Kapur and B.M. Basol	
A Novel Electrochemical Technique for Insitu Deposition of Photoactive CuInSe₂ Thin Films for Solar Cells	471
P. Garg, J.C. Garg and A.C. Rastogi	
A Low Cost Method for Large Area Production of CuInSe₂/(CdZn)S Devices	477
H. Oumous, A. Knowles, M.H. Badawi, M.J. Carter and R. Hill	
Improvement of Cu(Ga,In)Se₂ Based Solar Cells by Etching the Absorber	481
R. Klenk, R. Menner, D. Cahen and H.W. Schock	
Photovoltaic Performance of p-AgGaSe₂/n-CdS Thin Film Heterojunction	487
Y.S. Murthy, O.M. Hussain, B.S. Naidu and P.J. Reddy	
Junctions Mode Using p-CdTe Films with Ion-Assisted Doping	493
P. Sharps, A.L. Fahrenbruch, A. Lopez-Otero, M. Schöfthaler and R.H. Bube	
CdS/CdTe Solar Cells by the Screen-Printing-Sintering Technique	498
N. Suyama, T. Arita, Y. Nishiyama, N. Ueno, S. Kitamura and M. Murozono	
Effects of Preheat Treatment of CdS on MOCVD CdTe/Cds Solar Cell Performance	504
R. Sudharsanan and A. Rohatgi	
Cd_{1-x}Zn_xTe Films Obtained by the Solid-State Reaction of Elemental Layers	509
B.M. Basol, V.K. Kapur and R.L. Mitchell	
Polycrystalline Thin Films of Mercury Zinc Telluride for Use in Multijunction Solar Cells	514
S. Arshed, R.W. Miles and R. Hill	
Improvement of ZnO/WSe₂ Solar Cells by Doping?	519
M. Vogt, M.Ch. Lux-Steiner, P. Dolatzoglou, W. Reetz, B. Bumuller and E. Bucher	
Ionized Cluster Beam Deposition of GaAs Thin Films for Solar Cells	525
D. Bonnet and S. Oelting	

LATE NEWS

- Reactor Analysis of Copper Indium Selenization** 529
R.D. Varrin, Jr., S. Verma, R.W. Birkmire, B.E. McCandless and T.W.F. Russell

- 4-CM² CuInGaSe₂ Based Solar Cells** 535
W.E. Devaney, J.M. Stewart and W.S. Chen

- Correlations of Single-Crystal CuInSe₂ Surface Processing with Defect Levels and Cell Performance** 541
F.A. Abou-Elfotouh, L.L. Kazmerski, A.A.J. Al-Douri and A.M. Bakry

Thin Film Compound Semiconductors

Chairpersons:

R. Noufi
R. Hill

Organizer:

B. Basol

- CuInSe₂ Thin Films and High-Efficiency Solar Cells Obtained By Selenization of Metallic Layers** 546
B.M. Basol and V.K. Kapur

- Options for Fabrication and Design of CuInSe₂ Based Solar Cells** 550
R.W. Birkmire, W.N. Shafarman and R.D. Varrin

- Individual Losses in Thin-Film CdTe Solar Cells** 556
H. Tavakolian and J.R. Sites

- A Study on the Optical and Microstructural Characteristics of Quaternary Cu(In,Ga)Se₂ Polycrystalline Thin Films** 562

D. Albin, J. Tuttle, G.D. Mooney, J.J. Carapella, A. Duda, A. Mason and R. Noufi

- The Use of CuIn_{1-x}Ga_xSe₂ Layers to Improve the Performance of CuInSe₂ Cells** 570
R.J. Schwartz and J.L. Gray

- Towards High Efficiency Electrodeposited CdS/CdTe Thin Film Cells** 575
G.C. Morris, P.G. Tanner and A. Tottszer

Polycrystalline Solar Cells

Chairpersons:

T.J. Coutts
C. Eberspacher

Organizer:

T.J. Coutts

- Doping and Oxygen Dependence of Efficiency of EFG Silicon Solar Cells** 581

A. Rohatgi, W.A. Doolittle, A.W. Smith, F.V. Wald, R.O. Bell and C.E. Dube

- Thin Film CdTe Solar Cells—A Review** 588
B. Basol

- Advances in Large Area CuInSe₂ Thin Film Modules** 595

J.H. Ermer, J. Hummel, C.L. Jensen, C.V. Fredric, D. Pier, D. Tarrant and K. Mitchell

Polycrystalline Silicon

Chairpersons:

D.K. Schroder
A.M. Barnett

Organizer:

R. Hall

- Status of the Direct Solidification of Silicon Wafers by RAFT** 600

A. Beck, J. Geibler and D. Helmreich

- 10 % Efficient Commercial-Scale Silicon-Film Solar Cells** 604
C.L. Kendall, J.C. Checchi, M.L. Rock, R.B. Hall and A.M. Barnett

- Improvements in Direct-Cast Semicrystalline Silicon Solar Cells** 608

H. Somberg

- Development of the E.P.R. Technology for an Oriented Crystal Growth of Semiconductor Wafers** 610

A. Chibani, S. Sof, M. Hamoud, R. Gauthier, P. Pinard and K. Marsh

- Recent Results in Optical Processing of Silicon Sheet** 615
J.M. Serra and A.M. Valleria

- Effects of Encapsulation on the Performance of Silicon Solar Cells** 618

B.L. Sopori

- Improved Contact Metallization for High Efficiency EFG Polycrystalline Silicon Solar Cells** 624

C.E. Dubé and R.C. Gonsiorawski

- Rapid Thermal Processing Effect on the Intragrain and Grain Boundaries Properties of Multicrystalline Silicon Solar Cells** 629

J.P. Boyeaux, K. Masri, G. Chaussemy, L. Mayet and A. Laugier

- Process Induced Improvements in Polycrystalline Silicon-Film Solar Cells** 634

M.L. Rock, D.W. Cunningham, C.L. Kendall, R.B. Hall and A.M. Barnett

- Hydrogen Passivation of Polycrystalline Silicon Solar Cells by Plasma Deposition of Silicon Nitride** 638

P.P. Michiels, L.A. Verhoef, J.C. Stroom, R.J.C. van Zolingen, C.M.M. Denisse, M. Hendriks and W.C. Sinke

- Defect Generation/Passivation by Low Energy Hydrogen Implant for Silicon Solar Cells** 644

B.L. Sopori, T.Q. Zhou and G.A. Rozgonyi

- Improved Backside Hydrogenation on Semicrystalline Silicon Solar Cells by RF Plasma** 650

M.A.G. Soler, I. Pereyra, F.J. Fonseca and A.M. Andrade

- One Sun Crystalline Silicon Materials Research: Current Direction and Future Needs** 653

B.L. Sopori, J. Benner and J.D. McBrayer

Formation of PN Junction with Hydrogenated Microcrystalline Silicon 659

K. Kawabata, H. Morikawa, T. Ishihara, K. Sato, H. Sasaki, T. Itagaki, M. Deguchi, S. Hamamoto and M. Aiga

LATE NEWS

Cast Polycrystalline Silicon Solar Cell with Grooved Surface 664

T. Nunoi, S. Okamoto, K. Nakajima, S. Tanaka, N. Shibuya, K. Okamoto, T. Nammori and H. Itoh

Ink Jet Printing for Metallization on Very Thin Solar Cells 666

H. Somberg

Large Area High Efficiency Multicrystalline Silicon Solar Cell 668

K. Shirasawa, H. Yamashita, K. Fuku, M. Takayama, K. Okada, K. Masuri and H. Watanabe

Cold Crucible Induction Casting of Semi-Conductor Silicon for Solar Cell 674

K. Kaneko, T. Misawa and K. Tabata

Polycrystalline Silicon

Chairpersons:

R.B. Hal

A. Goetzberger

Organizer:

T. Gessert

18% Efficient Polycrystalline Silicon Solar Cells 678

S. Narayanan, J. Zolper, F. Yun, S.R. Wenham, A.B. Sproul, C.M. Chong and M.A. Green

Correlation Between Impurities, Defects and Cell Performance in Semicrystalline Silicon 681

W.A. Doolittle, A. Rohatgi and R. Brennenman

The Effects of Chromium on Edge-Defined Film-Fed Growth (EFG) Polycrystalline Silicon Solar Cells 687

B. Bathey, C.E. Dubé, J.P. Kalajs and F.V. Wald

Hydrogen Passivation of Polycrystalline Silicon Solar Cells by Means of Catalytic Reactions 691

M. Kaiser and R. Schindler

Manufacture of SI Ribbons by the S-Web Technique 695

R. Falckenberg, J.G. Grabmaier, K.H. Eisenrith, B. Freienstein, A. Lerchenberger, R. Schindler and F. Lutz

Mass-Production of High Quality Polycrystalline Silicon Sheets by the New Spin Cast Process 700

M. Suzuki, I. Hide, T. Matsuyama, H. Yamashita, T. Suzuki, T. Moritani and Y. Maeda

Polycrystalline Materials and Device Characterization

Chairperson:

B.J. Stanbery

Organizer:

C. Eberspacher

Lateral Distribution of Metallic Impurities in Silicon Bicrystals Investigated by Scanning MCTS 705

T. Heiser, A. Mesli and P. Siffert

Physical and Electrical Investigation of Silicide Precipitates in EFG Polycrystalline Silicon Intentionally Contaminated with Chromium 711

J.B. Mohr, S.H. Park, S.N. Schauer, D.K. Schroder and J. Kalejs

Influence of Oxygen on Polycrystalline Silicon Sheet 717

I. Hide, T. Matsuyama, M. Suzuki, H. Yamashita, T. Suzuki, T. Moritani and Y. Maeda

DLTS Study of EFG Solar Cells 721

S. Mil'shtein, J.T. Borenstein, J.I. Hanoka and Y. Yang

Automated Defect, Inclusion and Morphological Analysis of Solarex Polycrystalline Silicon 726

R. Brennenman, D. Ramsey and D. Angell

Modeling of the Grain Boundary Potential for Poly-Si 731

Z. Chen and L.C. Burton

Investigation of Conventional and Pregettered Multicrystalline Silicon Cells in Terms of Lifetime, Diffusion Length and Defects 737

I. Perichaud, G. Mathian, S. Martinuzzi, M. Pasquinelli and J. Gervais

Effect of Oxidation-Reduction Heat Treatments on CuInSe₂/CdS Device Behavior 743

M. Roy and J.E. Phillips

Secondary and Polymorphic Phase Behavior of Thin Film CuInSe₂: Ramifications on the Device Performance 748

J.R. Tuttle, D.S. Albin, J. Goral and R. Noufi

Nomarski Contrast Microscopy of CuBSe₂/Mo (B = In, Ga) Films 755

L. Margulis, A. Jakubowicz, G. Hodes and D. Cahen

Raman Scattering Study of CuInSe₂ Films Prepared by Three-Source RF-Sputtering and by Selenization of Cu/In/Se Stacked Layers 758

S. Yamanaka, M. Tanda, K. Horino, K. Ito, A. Yamada, M. Konagai and K. Takahashi

Deposition of CuInSe₂ by the Hybrid Sputtering and Evaporation Method 764

A. Rockett, C.J. Kiely, G. Kenshole, L. Chung Yang, H. Talieh, L.C. Yang, E. Banda and A. Agarwal

Preparation of Nonstoichiometric CuInSe₂ Crystals by the Bridgman Method 768

L.S. Yip, W.S. Weng, I. Shih and C.H. Champness

LATE NEWS

Shunt Effects in Polycrystalline GaAs Solar Cells	772
C. Honsberg and A.M. Barnett	
Thin Film CdTe Homojunctions by MOCVD	777
T.L. Chu, S.S. Chu, C. Ferekides, J. Britt and C.W. Wu	

Polycrystalline Materials and Device Characterization

Chairpersons:

B.L. Sopori

G.C. Morris

Organizer:

T. Coutts

Determination of Diffusion Length with Bi-Facial Spectral Response	782
J.E. Phillips	
Advanced X-Ray Analysis of Polycrystalline CuInSe₂ Thin Films	787
H. Dittrich, R. Menner and H.W. Schock	
In-Depth Characterization of Si Solar Cells	793
L.A. Verhoef, F.J. Bisschop, J.C. Stroom and W. Sinke	
Hot Spots and Heavily Dislocated Regions in Multi-crystalline Silicon Cells	800
A. Simo and S. Martinuzzi	

VOLUME II

Terrestrial Systems and Technology

Utility PV Systems and Concentration Technology

Chairpersons:

A.B. Maish
D.L. King

Organizers:

S. Hester
R. McConnell

Analysis of the Value of Photovoltaics for Demand Side Management	809
S. Rahman, J. Jockell and S. Lahouar	
A Utility Strategy for Photovoltaics	815
C. Herig, G. Atmaram and B. Marion	
Performance of a 15 kWp Amorphous Silicon Photovoltaic System	821
G.H. Atmaram, B. Marion and C. Herig	
Effect of Central Station Photovoltaic Plants on Power System Security	831
B.H. Chowdhury	
Photovoltaics in the Utility Distribution System: The Evaluation of System and Distributed Benefits	836
D.S. Shugar	
Carrisa Plains PV Power Plant Performance	844
H. Wenger, C. Jennings and J. Iannucci	
Problems and Countermeasures on Safety of Utility Grid with a Number of Small Scale PV Systems	850
H. Kobayashi, K. Takigawa, E. Hashimoto, A. Kitamura and H. Matsuda	
Early Applications of Photovoltaics in the Electric Utility Industry	856
J.E. Bigger and E.C. Kern, Jr.	
A Twenty Percent Efficient Photovoltaic Concentrator Module	861
C. Chiang and E. Richards	
Performance of a Self-Aligning Solar Array Tracking Controller	864
A.B. Maish	
The Photovoltaic Concentrator Initiative	870
J.L. Chamberlin and D.L. King	
Design and Construction of an Extruded, Curved, Linear Focus, Fresnel Lens	876
N.R. Kaminar and D. Curchod	
Performance Testing and Qualification of Sandia's Third Baseline Photovoltaic Concentrator Module	881
E. Richards, C. Chang and M. Quintana	

LATE NEWS

Sandia's Concept-90 Photovoltaic Concentrator Module	887
C. Chiang and M. Quintana	

Utility Applications and Testing

Chairpersons:

A.D. Krantz
R. McConnell

Organizers:

S. Hester
R. DeBlasio

Maximizing the Benefit Derived from PV Plants: Selecting the Best Plant Design and Plant Location	892
T. Hoff and J.J. Iannucci	
Lessons Learned with Residential Photovoltaic Systems	898
M.C. Russell and E.C. Kern, Jr.	
Results from Arizona Public Service Company's Star Center	903
T.L. Lepley	
Lessons Learned from Testing Utility Connected PV Systems	909
S.J. Durand, D.R. Bowling and V.V. Risser	
PG&E'S Cost-Effective Photovoltaic Installations	914
C. Jennings	
Photovoltaic Power Conditioning: Status and Needs	919
P. Steitz, T.S. Key and F.R. Goodman, Jr.	
Optimizing the Component Mix of a Mini-Utility	926
T. Hoff and J.J. Iannucci	
Utility Use of PV System Ratings	932
K. Firor, C.M. Whitaker and C. Jennings	

Terrestrial Systems & Array Technology

Chairperson:

L. Herwig

Organizer:

A.D. Krantz

PVUSA: Lessons Learned from Startup and Early Operation	937
S.L. Hester, T.U. Townsend, W.J. Stolte and W.T. Clements	

Photovoltaic Concentrator Technology Development	944	PV Module Performance and Testing	
E.C. Boes		Chairpersons:	
Objectives and Results of the PEP '87 Round-Robin Calibration of Reference Solar Cells and Modules	952	C.E. Backus	
J. Metzdorf, T. Wittchen, K. Heidler, K. Denhe, R. Shimokawa, F. Nagamine, H. Ossenbrink, L. Fornarini, C. Goodbody, M. Davies, K. Emery and R. DeBlasio		P. Garvison	
Terrestrial Systems, Applications and Technology		Organizers:	
Chairpersons:		R. DeBlasio	
K. Emery		R. McConnell	
C.J. Chiang		A New Approach for the Performance Evaluation of Solar Cells Under Realistic Reporting Conditions	1017
Organizers:		K. Heidler, A. Raicu and H.R. Wilson	
P. Garvison		PV Module Performance Outdoors at PG&E	1023
A.D. Krantz		C. Jennings and C. Whitaker	
Synthesis of Worldwide Solar Isolation Data for Photovoltaic System Sizing	960	Seasonal Performance of Three Grid-Connected PV Systems	1030
P.A. Hutchinson, D.E. Andersen and V.V. Risser		B. Marion and G. Atmaram	
The Synthesis of Solar Radiation Data for Sizing Stand-Alone Photovoltaic Systems	965	Outdoor Stability Performance of CIS and CdTe Photovoltaic Modules at SERI	1038
R.N. Chapman		L.C. Mrig and S. Rummel	
Optimum Switching Points for Array Reconfiguration Controller	971	Health and Safety Issues Related to the Production, Use and Disposal of Cadmium-Based Photovoltaic Modules	1040
Z. Salameh and C. Liang		P.D. Moskowitz, V.M. Fthenakis and K. Zweibel	
Photovoltaic Applications for Electric Vehicles	977	Long-Term Photothermal/Humidity Testing of Photovoltaic Module Polymer Insulations and Cover Films	1043
R.J. King		G. Mon., C. Gonzalez, P. Willis, E. Jetter, R. Sugimura and R. Ross, Jr.	
The ANCIPA Project—PV Plant to Power Four Sliding Gates and Trash-Rack Rake	982	PV System Performance and Measurement	
A. Previ, A. Illiceto, S. Righi and S. Guastella		Chairperson:	
Lessons Learned from Testing Photovoltaic Vaccine Refrigerators	985	M.J. O'Neill	
D. Kilfoyle, B. Marion and G.G. Ventre		Organizers:	
Photovoltaic Powered Lights for Indian Villages	991	R. DeBlasio	
N.P. Singh and B. Bhargava		A. Maish	
Two Examples of Photovoltaic Generators on a High-Voltage Overhead Line	994	Case Study of a Central-Station Grid-Intertie Photovoltaic System with V-Trough Concentration	1051
J. Alzieu, Y. Le Cunff, J. Maire and Y. Moller		J. Freilich and J.M. Gordon	
A Simple Way to Implement the Direct Coupling of PV Generator and Battery in Energy Simulation Models	999	Comparative Short Term/Long Term Field Test Performance and Stability of Tandem and Single Junction a-Si Modules	1057
A.P. van Dijk, E.A. Alsema, K. Blok and W.C. Turkenburg		M.J. Hahn, W.B. Berry and L. Mrig	
Analysis of Photovoltaic Modules with Protection Diodes in Presence of Mismatching	1005	Primary Reference Cell Calibrations at SERI: History and Methods	1062
A. Abete, E. Barbisio, F. Cane and P. Demartini		C.R. Osterwald, K.A. Emery, D.R. Myers and R.E. Hart	
Development of Photovoltaic in China: Status and Future	1011	PV Performance Measurement Algorithms, Procedures and Equipment	1068
C.R. Qiang, Y.J. Huan, Z.F. Xin, L. W. Zhe and W.S. Chen		K.A. Emery and C.R. Osterwald	
Photovoltaic Environmental, Health and Safety Electronic Bulletin Board Service	1014	Reliability of Photovoltaic Concentrator Modules	1074
A.F. Meinhold and P.D. Moskowitz		E. Richards and C. Chiang	

Study of the Long Run Field Degradation of Flat Plate Photovoltaic Module	1080
P.K. Koner and J.C. Joshi	
What is an Air Mass 1.5 Spectrum?	1085
C. Riordan and R. Hulstrom	
A Simple Method to Analyze and Present Performance Data of the 300 kW Delphos PV PLant	1089
A. Sarno, S. LiCausi, F. Apicella and M. Guerra	
Toward the Photovoltaic Farm	1095
D. Coiante	
Comparison Between Pyranometers and Encapsulated Solar Cells as Reference PV Sensors. Outdoor Measurements in Real Conditions	1099
F. Chenlo, N. Vela and J. Olivares	
A Versatile Microprocessor Based Controller for Solar Tracking	1105
A.K. Saxena and V. Dutta	

LATE NEWS

Solar Spectral Irradiance Under Overcast Skies	1110
S. Nann and C. Riordan	
Mixing Optical Beams for Solar Simulation—A New Approach	1116
B.L. Sopori, C. Marshall and K. Emery	

Stand Alone Systems and Concentrator Modules/Arrays

Chairpersons:

M. Prince
K. Collier

Organizers:

P. Garvison
A. Maish

Performance of Battery Charge Controllers: An Interim Test Report	1122
W.L. Bower, J.P. Dunlop and C.W. Maytrott	
Terrestrial Photovoltaics Systems for U.S. Military Applications	1130
R. Ducey, G. Smith, L. Humble, L. Strother, K. Agi, A. Seiss and J.F. Hoelscher	
Production of the Alpha Solarco Proof-of-Concept Array	1136
D. Carroll, E. Schmidt and B. Bailor	
22.7% Efficient 1000X GaAs Concentrator Module	1142
M.S. Kuryla, N.R. Kaminar, H.F. MacMillan, M. Ladle Ristow, G.F. Virshup, M.R. Klausmeier-Brown and L.D. Partain	
Fabrication, Installation & Initial Operation of the 2,000 SQ.M. Linear Fresnel Lens Photovoltaic Concentrator System at 3M/Austin (Texas)	1147
M.J. O'Neill, R.R. Walters, J.L. Perry, A.J. McDanal, M.C. Jackson and W.J. Hesse	

Space Systems and Technology

Flight Experiments and Results

Chairperson:

R.D. Williams

Organizer:

D.J. Brinker

Multijunction Component Cells on LIPS III	1153
J.G. Werthen, G.F. Virshup, M.E. Klausmeier-Brown, B.C. Chong, M. Ladle Ristow and N.R. Kaminar	
Results of the MBB LIPS III Experiment	1159
H. Kulms, G.J. LaRoche and B. Czup	
An Analysis of Spaceflight Performance of Several Types of Silicon Solar Cells on the LIPS III Satellite	1164
D. Warfield and J. Silver	
Recent Results from the InP Homo Junction Cell Module on the LIPS III Spacecraft	1167
D.J. Brinker and I. Weinberg	
Radiation and Flight Testing of ITO/InP Solar Cells	1172
N.M. Pearsall, C. Goodbody, N. Robson, I. Forbes and R. Hill	
Forward-Biased Current Annealing of Radiation Degraded Indium Phosphide and Gallium Arsenide Solar Cells	1178
S. Michael, C. Cypranowski and B. Anspaugh	
The Solar Cell Experiment of the First Brazilian Complete Space Mission Satellite	1184
N. Veissid, P. Nubile, A.F. Beloto and A.M. Andrade	
The Design and Performance of the Hughes HS 393C Satellite Solar Arrays Featuring Large Area Solar Cells	1188
J.S. Fodor, S.W. Gelb, L.J. Goldhammer and D.W. Moffett	
Electrical Design and Performance of the British Satellite Broadcast Spacecraft	1193
D.W. Moffett, S.W. Gelb, L.J. Goldhammer and B.D. Edwards	

LATE NEWS

First Space Flight of InP Solar Cells	1198
M. Yamaguchi, T. Hayashi, A. Ushirokawa, Y. Takahashi, M. Koukata, M. Hashimoto, H. Okazaki, T. Takamoto, M. Ura, M. Ohmori, S. Ikegami, H. Arai and T. Orii	
High Altitude AMO Testing of PV Concentrator Lens Elements	1203
M.F. Piszczor, D.J. Brinker, E.O. Boyer, R.C. McKnight, R.J. Ranado, M.J. O'Neill and A.J. McDanal	

Space Environmental Effects

Chairperson:

J.W. Koch

Organizer:

R.W. Francis

- Systematic Anomalies in Experiment Data from LIPS III** 1208
J.G. Severns, T.G. Stern, D.K. Conway, R.M. Hobbs and R.W. Conway
- Preliminary Results from the Advanced Photovoltaic Experiment Flight Test** 1213
D.J. Brinker, R.E. Hart, Jr. and J.R. Hickey
- Space Proven GaAs Solar Cells—Main Power Generation for CS-3** 1219
N. Takata, H. Kurakata, S. Matsuda, T. Okuno, S. Yoshida, H. Matsumoto, M. Goto, M. Ohkubo and M. Ohmura
- In-Flight Performance of the SBS-1A Solar Array, Featuring Ultrathin High Efficiency Solar Cells** 1226
R.D. Williams, S.W. Gelb and J.S. Fodor
- 16%-Efficient GaAs Solar Cell After 10^{15} cm⁻², 1-MeV Radiation** 1231
K.A. Bertness, M. Ladle Ristow, M.E. Klausmeier-Brown, M. Grounner, M.R. Kurlya and J.G. Werthen
- Effects of Radiation on InP Cells Epitaxially Grown on Si and GaAs Substrates** 1235
I. Weinberg, C.K. Swartz, D.J. Brinker and D.M. Wilt

Space Systems and Technology

Chairpersons:

D.Flood

L.M. Fraas

Organizer:

B. Anspaugh

- Recent Solar Flare Activity and Its Effect on In-Orbit Solar Arrays** 1241
L.J. Goldhammer
- Measurement Techniques for Multijunction Solar Cells** 1249
G.F. Virshup

Space Solar Arrays and Components

Chairpersons:

D.J. Brinker

P.A. White

Organizer:

L. Goldhammer

- Design Considerations for Lunar Base Photovoltaic Power Systems** 1256
J.M. Hickman, H. Curtis and G.A. Landis
- Design Considerations for Mars Photovoltaic Power Systems** 1263
G.A. Landis and J. Appelbaum
- The Mini-Dome Fresnel Lens Photovoltaic Concentrator Array: Current Status of Component & Prototype Panel Testing** 1271
M.F. Piszczor, C.K. Swartz, M.J. O'Neill, A.J. McDanal and L.M. Fraas
- Lightweight Concentrator Module with 30% AMO Efficient GaAs/GaSb Tandem Cells** 1277
J.E. Avery, L.M. Fraas, V. Sundaram, N. Mansori, J.W. Yerkes, D.J. Brinker, H.B. Curtis and M.J. O'Neill
- Investigation of the Reverse Biasing of Solar Cells in a Space Array** 1282
R. Kimber, R. Hill and N.M. Pearsall
- The Bypass Diode Assembly: Solar Cell Protection for Space Station Freedom** 1288
T.W. Woike, S.C. Stotlar and L.M. Woods
- Direct Glassing of Silicon Space Solar Cells: Approach and Manufacturing Experiences** 1294
J.W. Koch and P.A. White
- A Coverglass for Gallium Arsenide Solar Cells** 1300
P.A. White
- A Light Trapping Solar Cell Coverglass** 1304
G.A. Landis
- HST Solar Generator Design for a Decade in Orbit** 1308
L. Gerlach, A. Fournier-Sicre, A. Fromberg and S. Korehnert
- Stability of GaAs/Ge Solar Cells with Standard Front Contacts After Long-Term, High-Temperature Exposure** 1314
S. Gasner, G. Pack, M. Gates and R. Given
- Application of the GaSb Solar Cell to Isotope-Heated Power Systems** 1320
A.C. Day, W.E. Horne and M.D. Morgan
- Reappraisal of Solid Selective Emitters** 1326
D.L. Chubb

LATE NEWS

Electrical and Thermal Behavior of GSPG Type Solar Array	1334
J.P. David, J. Duveau, J. Guerin, A. Michel, E. Rapp, M. Roussel and L. Pelenc	
Performance Evaluation of CLEFT GaAs/CuInSe₂ Tandem Cell Circuits Through Solar Simulator Testing and Computer Modeling	1340
R. Burgess, C. Flora and M. Schneider	
23.5% Thin-Film Space Concentrator Cells	1346
B.D. Dingle, R.P. Gale, R.W. McClelland, M.B. Spitzer, H.B. Curtis and D.J. Brinker	
Effect of Emitter Parameter Variation on the Performance of Heteroepitaxial Indium Phosphide Solar Cells	1350
R.K. Jain and D.J. Flood	

Advanced Array Technology

Chairpersons:

M. Kruer
K.P. Bogus

Organizer:

R. Patterson

Photovoltaic Superiority for Space Station Freedom Power in the 21st Century	1356
S.G. Bailey, G.A. Landis and M.A. Perino	
Mission Applications for Advanced Photovoltaic Solar Arrays	1362
P.M. Stella, J.L. West, R.G. Chave, D.P. McGee and A.S. Yen	
Retractable Planar Space Photovoltaic Array	1369
E.L. Ralph, M. A. Chung and K.C. Reinhardt	
Large Area Space Solar Cells—Si or GaAs	1374
S. Khemthong, H. Yoo, N. Hansen, C. Chu, P. Iles and J. Krogen	
Development of 2.7 Mil BSF and BSFR Silicon Wrapthrough Solar Cells	1378
A.V. Mason, J.R. Kukulka, S.M. Bunyan and L.M. Woods	
High Efficiency, Rugged, Lightweight GaAs Solar Cells	1383
F.H. Ho, P.A. Iles, C. Chu, Y.C.M. Yeh, J. Krogen, W. Patterson and B. Reed	

Amorphous Silicon Based Solar Cells

Amorphous Silicon Cells and Modules

Chairpersons:

D. Morel
H. Sakai

Organizer:

M. Prince

The Density of States (DOS) of I-Layers in a-Si:H Based pin Cells Determined by CPM Measurements	1389
H. Rübel, R. Geyer, B. Scheppat, P. Lechner, M. Gorn, and N. Kniffler	
New Type Structures on A-Si Solar Cell Submodules Fabricated by Microscopic Hole Spacing Technique	1394
M. Ohnishi, H. Shibuya, N. Okuda, H. Inoue, Y. Kishi, S. Kiyama, H. Kawata, S. Tsuda, S. Nakano, Y. Kuwano and S. Okamoto	
High Effective Area Amorphous Silicon Solar Cell Using Eximer Laser Process	1400
M. Abe, H. Shinohara, Y. Arai, N. Ishida, A. Satake, K. Nishi, S. Kugawa, S. Nakajima, Y. Uehara, M. Ishii and S. Yamazaki	
Outdoor Performance Studies of a-Si Alloy Multi-Junction Solar Cells Using Simulated Solar Illumination	1403
J. Burdick and T. Glatfelter	
Status of the DOE/SERI Amorphous Silicon Research Project: Recent Advances and Future Directions	1409
B.L. Stafford, W. Luft, B. von Rodern and W.L. Wallace	
Hydrogen-Plasma Reactive Flushing for a-Si:H and A-SiGe:H Solar Cell Fabrication	1416
Y.S. Tsuo, Y. Xu, R.S. Crandall, D. Han, C. Qiu and J.I. Pankove	
a-Si/poly-Si Two- and Four-Terminal Tandem Type Solar Cells	1420
Y. Matsumoto, K. Miyagi, H. Takakura, H. Okamoto and Y. Hamakawa	
A Three Dimensional Design Approach for a-Si:h Multijunction Solar Cells	1426
M.M. Alkaisi and A.Z. Sadik	
Power Optimization for Large-Area a-Si:H Solar Modules	1432
F. Willing, S. Wiedeman, J. Newton, J. O'Dowd and K. Jansen	
Two Source Simulator for Improved Solar Simulation	1438
M. Bennett and R. Podlesny	
Advances in Large Area Si:H Thin Film Modules	1443
D.R. Willett, S.A. Vasquez and D.P. Tanner	
High Reliability Three-Stacked Amorphous-Silicon Solar Cell	1449
S. Moriuchi, Y. Inoue, H. Sannomiya, A. Yokota, M. Itoh, Y. Nakata and H. Itoh	

Amorphous Silicon Based Cells

Chairpersons:

S. Wagner
G.H. Bauer

Organizer:

R. Arga

High Performance Interconnected Amorphous Silicon Based Modules 1455

J. Morris, R.R. Arya, C. Poplawski, A. Catalano, R. Podlesny, J.L. Newton, A. Wilczynski and T. Lommason

Role of Film Thickness in Amorphous Silicon Solar Cell Cell Characterization 1459

P. McElheny, S. Nag, S.J. Fonash, C.R. Wronski, M. Bennett and R. Arya

Sub-Bandgap Photocurrent in Reverse Based p-i-n a-Si:H Solar Cells 1465

A. Mittiga, P. Fiorini, S. Korepanov, M. Sebastiani and F. Evangelisti

High Efficiency A-Si/a-Si Tandem Solar Cells 1471

D.S. Shen, R.E. Schropp, H. Chatham, R.E. Hollingsworth, J. Xi and P.K. Bhat

A Stable 10% Solar Cell with a-Si/a-Si Double-Junction Structure 1475

Y. Ichikawa, S. Fujikake, T. Yoshida, T. Hama and H. Sakai

41.5 Watt, 10.5% Si:H/CuInSe₂ Tandem Thin Film Modules 1481

K.W. Mitchell, D.R. Willett, C. Eberspacher, J.H. Ermer, D.N. Pier and K.L. Pauls

Amorphous Silicon

Chairpersons:

B. Baron
M. Konagai

Organizer:

S. Fonash

Instabilities In A-Si:H Solar Cells: Materials and Device Issues 1487

C.R. Wronski

a-SiGe:H Alloy Material Limitations and Device Considerations 1493

C.M. Fortmann

A 10 MWp A-Si:H Module Processing Line 1501

J. Macnall, A.E. Delahoy, F. Kampas, F. Ellis, E. Eser and A. Varvar

Modeling and Stability of Amorphous Silicon Alloys

Chairpersons:

V.L. Dalai
S.S. Hegedus

Organizer:

C. Wronski

Evaluation of Degradation in Amorphous Silicon Solar Cells 1506

D. Redfield and R.H. Bube

1.00 MEV Proton Radiation Resistance Studies of Single-Junction and Single Gap Dual-Junction Amorphous-Silicon Alloy Solar Cells 1510

S. Abdulaziz, Y. Li, J.S. Payson, Y. Li and J.R. Woodyard

A Technique for Determining Urbach Edge, Midgap States and Electric Field in a-Si:H and A-(Si,Ge):H Devices 1516

V.L. Dalai, R.D. Knox and B. Moradi

An Extended "Collection Length Model" for the Description of the keV-Electron Induced Degradation and Thermal Recovery of p-i-n Solar Cells 1521

U. Schneider and B. Schroder

Optimum Band Gap for Amorphous Silicon Based Solar Cells 1526

P. Fiorini, A. Mittiga, I. Chamboueyron and F. Evangelisti

Optical Losses in Multi-Junction a-Si:H Based Solar Cells and Modules 1529

S. Wiedeman, J. Morris and L. Yang

Computer Modeling of a-SiC:H/a-Si:H Heterojunction Solar Cell Performance as a Function of the Apportionment of the Bandgap Discontinuity 1535

J.Y. Hou, J.K. Arch and S.J. Fonash

Sensitivity of the Spectral Response of a-Si:H Schottky Barriers to the Density of States Profile: A Computer Simulation 1540

P.J. McElheny and S.J. Fonash

Capacitance Studies of a-SiGe:H p-i-n Solar Cells 1544

S.S. Hegedus

Modelling of Transport and Recombination of Photoexcited Carriers in a-Si:H and a-SiGe:H 1550

C.D. Abel and G.H. Bauer

Superlattice Contact Layers for High Open Circuit Voltage A-Si:h Solar Cells 1555

A. Rothwarf and A. Varonides

Measurement of Ambipolar Mobility-Lifetime Product and its Significance for Amorphous Silicon Solar Cells 1560

E. Sauvain, A. Shah and J. Hubin

LATE NEWS

- Staebler-Wronski Effect in a-Ge:H Films** 1564
C.F. de O. Graeff, P.V. Santos, G. Marcand and I. Chambouleyron
- Performance of Large Area Thin Film Si:H Modules: A Link Between Shunting and Stability** 1569
R.D. Wieting, M. Boeligen, J.A. Anderson and D.R. Willett

Amorphous Silicon: Materials and Processing

Chairpersons:

R. Arya
B.L. Stafford

Organizer:

L. Kazmerski

- Silicon Carbon Alloy Thin Film Depositions Using Electron Cyclotron Resonance Microwave Plasmas** 1574
Y.H. Shing and F.S. Pool
- Bulk Photoconductivity of a-Ge:H Films from Spectral Measurements** 1579
H. Pfeleiderer, F. Schmeling, W. Kusian, F.H. Karg and W. Kruhler
- Effect of Hydrogen Plasma Treatment on SnO₂:F Films for Use in a-Si Solar Cells** 1584
K. Sato, Y. Gotoh, Y. Hayashi and H. Nishimura
- Effect of the Deposition Parameters on the Electro-optical Properties and Morphology of Microcrystalline Hydrogenated Silicon Alloys** 1588
E.T. Dirani, I. Pereyra, A.M. Andrade, A.M. Soler and R. Martins
- Ion-Beam Hydrogenation of Sputter-Deposited Amorphous Silicon and Amorphous Silicon-Germanium Alloys** 1591
X.J. Deng, Y.S. Tsuo and J.U. Trefny
- Studies of Substrate Induced Disorder in Amorphous Silicon by In-Situ-Raman Backscattering During Film Growth** 1595
M.B. Schubert and G.H. Bauer
- Tin Oxide Electrode for A-Si:H Solar Cells Deposited by a Spray Pyrolysis Technique** 1601
A. Antonaia, S. Aprea and P.T. Menna
- Ambipolar Diffusion Length in a-Si:H(F) and a-Si,Ge:H,F Measured with the Steady-State Photocurrent Grating Technique** 1606
J.Z. Liu, X. Li, P. Roca i Cabarrocas, J.P. Conde, A. Maruyama, H. Park, S. Wagner and A.E. Delahoy
- Improving Tin Oxide/Hydrogenated Amorphous Silicon Interfaces for Solar Cell Applications** 1610
P. Roca i Cabarrocas, S. Ramprashad, J.Z. Liu, V. Chu, A. Maruyama and S. Wagner

LATE NEWS

- Intrinsic Microcrystalline Silicon Deposited by Remote PECVD: A New Thin-Film Photovoltaic Material** 1614
C. Wang and G. Lucovsky
- A-(Si,Ge):H Alloys: Status and Issues** 1619
B. Stafford, B.N. Baron, V. Dalal and M. Silver

Modeling and Stability of Amorphous Silicon

Chairpersons:

R.S. Crandall
S. Guha

Organizer:

S. Fonash

- The Mobility Gaps in a-Si:H and its Effect on Solar Cell Performance** 1624
S. Lee, J.K. Arch, S.J. Fonash and C.R. Wronski
- Band Bending Due to Charged Dangling Bonds in Amorphous Silicon P-i-N Solar Cells** 1630
R.S. Crandall and H.M. Branz
- First Principles Computer Model Showing the Effect of p-Layer Thickness and Front Contact Barrier Height on the Performance of a-Si:H p-i-n Solar Cells** 1636
J.K. Arch, F.A. Rubinelli, J. Hou and S.J. Fonash
- Saturation Behavior of the Light-Induced Defect Density in Hydrogenated Amorphous Silicon** 1642
H.R. Park, J.Z. Liu, P. Roca i Cabarrocas, A. Maruyama, M. Isomura and S. Wagner
- Deposition Conditions, Hydrogen Content, and the Staebler-Wronski Effects in Amorphous Silicon** 1648
C.M. Fortmann, T. Zhou, C. Malone, M. Gunes and C.R. Wronski
- Improved Stability in Amorphous Silicon Germanium Solar Cells Made from Hydrogen-Diluted Silane and Germane** 1653
M.S. Bennett, A. Catalano, K. Rajan and R.R. Arya

Amorphous Silicon: Materials and Processing

Chairpersons:

C. Scherring
H. Aulich

Organizer:

C. Fortmann

High Absorption-Coefficient and Stable a-Si for High Efficiency Solar Cells 1656

S. Nakano, S. Okamoto, T. Takahama, M. Nishikuni,
K. Ninomiya, N. Nakamura, S. Tsuda, M. Ohnishi, Y.
Kishi and Y. Kuwano

Electrical and Structural Properties of a-Ge:H Alloys 1662

J.L. Newton and K. Kritikson

Production of 20 A/Sec⁻¹ a-Si Alloys for Use in Solar Cells 1667

P. Nath, K. Hoffman, J. Call, G. DiDio and S.R.
Ovshinsky

Large Area Deposition of a-Si PV Modules 1670

L. Boman, A. Bubenzer, J. Meot, J.P.M. Schmitt and
J.M.Siefert

POLYSILICON EMITTERS FOR SILICON CONCENTRATOR SOLAR CELLS

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ABSTRACT

Polysilicon emitters with a thermally grown interfacial oxide are examined in great detail. Both J_o and ρ_c are measured for the polysilicon emitter (contact) which is annealed under various conditions. $J_o \leq 5 \times 10^{-14}$ A/cm² and $\rho_c \sim 1 \times 10^{-5}$ Ω -cm² are obtained for both n- and p-type polysilicon emitters. The results also indicate that the interfacial oxide is only broken by a very small fraction in order to have $\rho_c \sim 1 \times 10^{-5}$ Ω -cm². Under such a condition, J_o is primarily dominated by the recombination at the oxide interface.

INTRODUCTION

Polysilicon emitters, because of their important applications in high speed bipolar transistors, have been widely studied. It was found that, between the polysilicon and the substrate, there always exists a very thin oxide (interfacial oxide), which can be as a by-product of the cleaning process or is grown intentionally [1,2,3,4,5,6,7]. In either case, the oxide is not thermally stable; i.e., it tends to break up during high temperature anneals [1,2,3,4,5,6,7]. The breakup of the interfacial oxide has direct impact on both majority and minority carrier transport in the polysilicon emitter. This can be seen from the dependence of the specific contact resistivity (ρ_c) [6] and the emitter saturation current density (J_o) [1,2,3,4,5,6,7] upon either the anneal condition or the oxide integrity. When the effect of the interfacial oxide is negligible, such as when the interfacial oxide loses its integrity in high temperature anneals, the ρ_c is low ($\sim 2 \times 10^{-7}$ Ω -cm²) [6] and the J_o is high ($\sim 1 \times 10^{-12}$) [1,3]. Conversely, when both carriers are mostly blocked by the interfacial oxide, like for an intact chemical oxide (~ 15 Å), the ρ_c is high and the J_o is low. Typically, $\rho_c \geq 1 \times 10^{-4}$ Ω -cm², and the corresponding $J_o \sim 1 \times 10^{-14}$

A/cm² have been observed on the n-type polysilicon emitter [1,5,6].

With the extent of the oxide breakup between these two extremes, various combinations of ρ_c and J_o can be obtained. It is of particular interest to know the ρ_c and the corresponding J_o when only a small fraction of the interfacial oxide is broken. For silicon solar cells operated under high concentrated sunlight, the emitter recombination is one of the main recombination that limit the solar cell performance [8]. This is because the diffused-emitter, which is formed with dopant diffusion into the base (substrate), has high J_o ($= 4.5 \times 10^{-13}$ A/cm²). Consequently, the cell performance can be improved if the diffused-emitter is replaced with the polysilicon emitter, of which the J_o is less than 4.5×10^{-13} A/cm² and the ρ_c is low enough.

In this paper, detailed calibrations for the polysilicon emitter with a thermally grown interfacial oxide is presented. Compared with the the chemical oxide, the thermal oxide appears to be more robust to the high temperature anneal. Consequently, this lends more controllability on the oxide breakup process. In addition, two separate anneal steps were used in order to avoid any possible interference from the dopant diffusion. It has been reported that the interfacial oxide tends to break up more rapidly with the existence of dopant [3,5]. Moreover, J_o also depends on the surface dopant concentration and the emitter depth [9]. In order to see the effect of the oxide breakup on J_o and ρ_c alone, it is therefore desirable to separate these two processes. The first-step anneal, which serves to break the oxide, was performed at higher temperature than that for the second-step anneal which aims for the dopant drive-in.

EXPERIMENTAL

Procedures

In this work, the J_0 and ρ_c were measured independently for each type of polysilicon emitter (or contact). J_0 was measured with photoconductivity decay method which has been reported elsewhere [10]. Because high bulk lifetime is needed for such a measurement, the samples were prepared with high resistivity ($>100 \Omega\text{-cm}$) FZ wafers. In contrast, ρ_c was measured on devices made on CZ wafers of which resistivity is 0.28 and $0.5 \Omega\text{-cm}$ for p- and n- type respectively. The device for ρ_c -measurement is shown in Fig. 1 schematically. Except for the pattern-definition steps which were not required for J_0 -measurement samples, the two sets of wafers were always processed together. The process sequence is shown as followings:

1. Field oxidation ($2000 \text{ \AA}$)*.
2. Polysilicon-substrate contact opening*.
3. Thin thermal oxide growth at 800°C *. (10-minute oxygen flow)
4. Polysilicon deposition ($6000 \text{ \AA}$) and first-step anneal (1050°C)*.
5. First-step anneal*.
6. Polysilicon finger definition.
7. Undoped glass deposition ($2000 \text{ \AA}$).
8. Metal-polysilicon and metal-substrate contact opening.
9. Doped glass deposition on both sides of the wafer*.
10. Drive-in; $900\text{-}1000^\circ\text{C}$ *.
11. Doped glass stripping and Al-1% Si alloy deposition.
12. Metal finger definition.

Note that the steps marked with “*” are the steps for J_0 -measurement samples. In addition, the J_0 -samples are divided into two sets; one set of samples had an additional 400°C -30 min forming gas anneal (FGA), the other did not. The growth of thin oxide was carried out with 200 sccm oxygen and 5 slm argon mixture. Typically, oxide thickness less than $20 \text{ \AA}$ was measured with ellipsometer. In step 2, a series of square contacts of size between 1 and $64 \mu\text{m}$ are opened for polysilicon-substrate contacts.

ρ_c Measurement

As shown in Fig. 1, the voltage difference, V_{ab} , between probe A and B is caused by several components of the series resistance along the current loop. They are the resistance imposed by the bulk of the polysilicon and the wafer, the metal-polysilicon contact resistance, and the polysilicon-substrate contact resistance. The potential drop across the polysilicon film is conceivably negligible because the film is heavily doped and very thin. The metal-polysilicon contact resistance is actually measured on the similar device (four-terminal resistor [11]) next to the device shown in the figure. Typi-

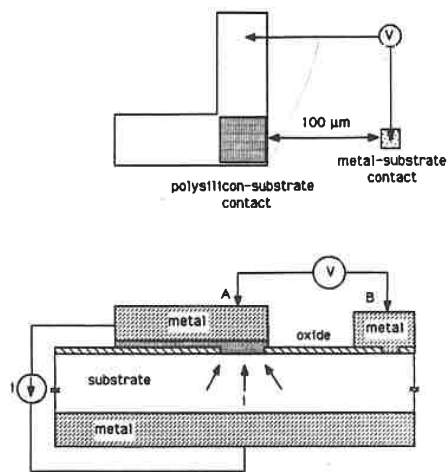


Figure 1: The device structure for the specific contact resistivity measurement.

cally, the ρ_c of the metal-polysilicon contact is less than $1 \times 10^{-6} \Omega\text{-cm}^2$. With such low ρ_c and large contact area between the metal and the polysilicon, the metal-polysilicon contact resistance can be ignored as well. As a result, the series resistance derived from V_{ab}/I is essentially determined by two terms; the bulk resistance of the silicon substrate and the polysilicon-substrate contact resistance. Such a series resistance can be expressed as a function of the size of the polysilicon-substrate square contact.

$$R = C \frac{\rho}{d} + \frac{\rho_c}{d^2}, \quad (1)$$

or

$$R_c = R \times d^2 = \rho_c + C \rho d; \quad (2)$$

where C is a constant that accounts for the contact geometry factor, ρ is the substrate resistivity, d is the width of the square contact, and ρ_c is the specific contact resistivity of the polysilicon-substrate contact. The contact size dependence of the last term in Eqn. (2) results from the crowding effect as the current flows toward the polysilicon-substrate contact. It is obvious that, from Eqn. (2), the ρ_c can be derived from the plot of R_c versus d which is obtained by measuring the series resistance of contacts of different sizes.

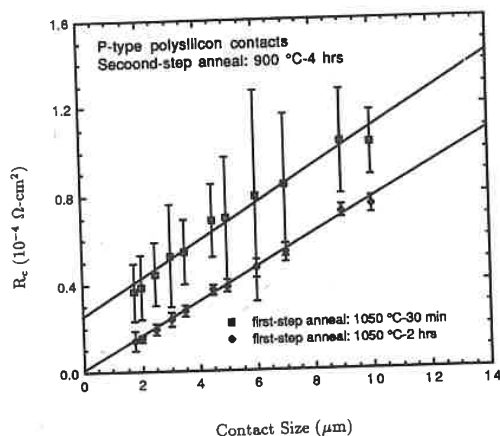


Figure 2: The R_c versus the contact size for p-type polysilicon contacts of different first-step anneals.

RESULTS AND DISCUSSIONS

Fig. 2 shows two R_c -plots for the p-type polysilicon contacts. One has the first-step anneal at 1050 °C for 30 minutes, the other has 1050 °C for 2 hours. Each data point is the average of 16 measurements across the wafer and the error bar is drawn with 4 standard deviations. Since devices were made on the wafers of about the same resistivity, the slopes of the linear-fit lines are almost identical. Note that, the devices that received a 30-minute first-step anneal have higher intercepts than those that received a 2-hour first-step anneal. This indicates that more oxide breakup occurs when the anneal time increases. Another characteristic of the interfacial oxide breakup can also be seen from the spread in the data (the length of the error bar). The magnitude of the error bar is not due to the measurement uncertainty; instead, it results from the random distribution of the oxide breakup. When only a very small fraction of the interfacial oxide is broken, it is possible that the interfacial oxide on each contact may not be broken equally. Consequently, this gives rise to the fluctuation of the resistance measured. On the other hand, the fluctuation will be subdued when more oxide is broken. This explains the different appearance of error bars observed between these two sets of data.

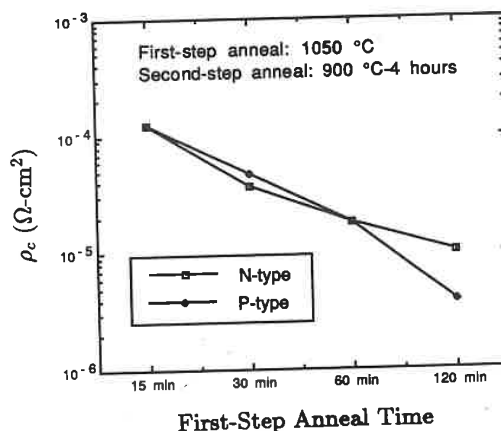


Figure 3: ρ_c of both n- and p- type polysilicon-substrate contacts is shown as a function of the time of the first-step anneal.

To see how the J_o and the ρ_c is affected by the first-step anneal, one set of samples (and device wafers) were first annealed at 1050 °C for various lengths of time (first-step anneal). After the doped-glass deposition, they were all annealed at 900 °C for 4 hours. The ρ_c measured from the device and the J_o measured from the photoconductivity decay are presented in the following figures.

In Fig. 3, ρ_c is plotted against the time of the first-step anneal for both types. Note that the ρ_c decreases as the anneal time increases. In addition, ρ_c measured from both n- and p- type devices are more or less the same, except those annealed with 120 minutes. The similarity of ρ_c between the n- and the p- type contact also indicates that the interaction between the dopant and the interfacial oxide is negligible; since such an interaction, if exists, would cause the ρ_c of the p-type to be lower [6].

The effects of the first-step anneal on J_o are presented in Fig. 4 and 5 for the n-type and the p-type polysilicon emitters respectively. In each figure, two sets of data are shown: the one with an FGA, and the one without. For the samples with an FGA, the J_o is significantly less than that without FGA for the same anneal condition. This indicates that the recombination

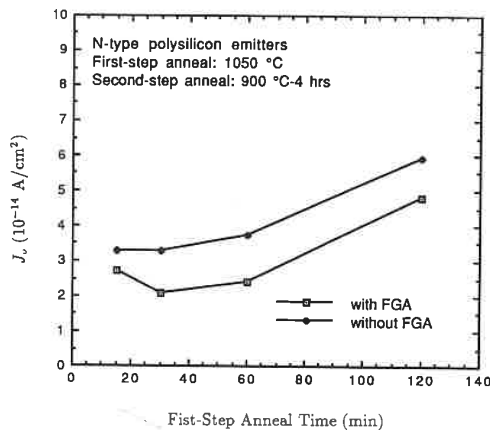


Figure 4: The J_o versus the first-step anneal time for n-type polysilicon emitters.

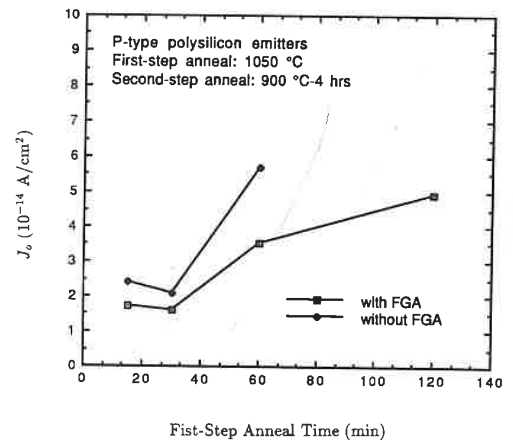


Figure 5: The J_o versus the first-step anneal time for p-type polysilicon emitters.

at the oxide interface is, at least, one of the dominant mechanisms for the emitter recombination. It is also important to note that the J_o of the p-type polysilicon emitter (Fig 5) appears to be much lower than what has been previously reported [1]. This may have to do to the use of thermal oxide as the interfacial layer in our samples. Either the thermal oxide is most robust during the high temperature anneal or the thermal oxide has lower interface defect state density (D_{it}) compared to the chemical oxide. Another interesting thing in these figures is that the J_o of the sample that received a 15-minute anneal is higher than the sample that received a 30-minute anneal. Moreover, such a behavior occurs in both the n- and the p- type samples. The possible explanation is that the interfacial oxide quality is improved by the high temperature anneal. This is not too surprising because the oxide was grown around 800 °C, in which higher D_{it} is expected [12,13]. Other than that, the J_o of both types appears to increase slowly with the anneal time. In addition, because the dominant recombination is likely at the oxide interface, it implies that the oxide must only be broken by very a small fraction, which is in consistent with what was observed in Fig. 2.

The effect of the second-step anneal (dopant drive-in) on both the J_o and the ρ_c were also investigated. All samples (and devices) received a first-step anneal at 1050 °C for one hour, followed with various treatments in the second-step anneal. The results are summarized in Table 1. The label on the right most column represents the second-step anneal condition of that sample. As shown in the table, the J_o increases with the temperature and time of the second-step anneal. In the meantime, the ρ_c decreases as the drive-in temperature increases. Considering the significant increase of J_o caused by increasing the drive-in temperature from 900 to 1000 °C, it is beneficial to use the two-step anneal to optimize J_o .

In Fig. 3, the decrease of ρ_c with the anneal time is what would be expected from the gradual breakup of the interfacial oxide. This is in consistent with the increase of J_o shown in Fig. 4 and Fig. 5, since J_o depends on the oxide integrity in the opposite way. This is especially clear when both ρ_c and J_o are plotted together. Fig. 6 is the ρ_c versus J_o plot for all the results obtained in this experiment. The inset is the list of the label

Table 1: The effect of the second-step anneal on J_o and ρ_c .

	N-type		P-type	
	$J_{o,e}$ ($\times 10^{-14}$ A/cm ²)	ρ_c ($\mu\Omega\text{-cm}^2$)	$J_{o,e}$ ($\times 10^{-14}$ A/cm ²)	ρ_c ($\mu\Omega\text{-cm}^2$)
900 °C-4 hour	2.4	18	3.5	18
1000 °C-30 min	4.5	~ 6	8.2	3.8
1000 °C-60 min	7.9		10.5	

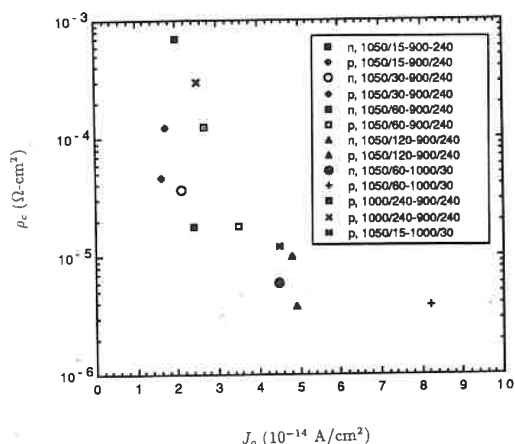


Figure 6: ρ_c - J_o of this work.

for each point. It specifies the type of polysilicon emitter, the first-step anneal (temperature/minute), and the second-step anneal (temperature/minute). As shown in the figure, the data runs from the upper-left corner to the lower-right corner which is similar to that reported by Crabbé [6] and is the typical trend when both ρ_c and J_o are regulated by the extent of oxide breakup. Nevertheless, from left to right, two distinct regimes are shown in the figure. In one regime, J_o is almost constant while ρ_c drops drastically. In the other regime, ρ_c decreases very slowly and J_o increases in much faster pace. In the first regime, that the J_o is inert to the oxide breakup is because the extent of the oxide breakup is very small such that the J_o is still dominated by the recombinations at the oxide interface and in the singly-crystal outdiffusion. On the other hand, the drastic change of the ρ_c can be attributed to the transition of the majority carrier transport from the tunneling to the channel resistance. When the interfacial oxide is intact, tunneling is the only process available for the majority carriers to pass through the interfacial oxide. This usually results in a high contact resistance because of low tunneling probability. As the oxide starts to break up, additional highly conductive channels are created due to the intimate contacts formed between the polysilicon and the substrate in the broken regions [3,4,5]. A drastic change of ρ_c is observed when more currents flow through those channels. In the other regime, J_o starts to increase because the recombination in the polysilicon becomes comparable to the recombination mentioned

previously. On the other hand, the slow decrease of the ρ_c in this regime is because the majority carrier transport is completely dominated by the channel resistance. The increase of the oxide breakup can be thought as more parallel resistors added together; consequently, a significant change of ρ_c will not be observed.

The data shown in Fig. 6 are quite useful for silicon solar cells. First, most of J_o are below 5×10^{-14} A/cm² which is about one order magnitude lower than that of diffused-emitters. Second, most of ρ_c are also lower than 5×10^{-5} Ω-cm². This means that the potential drop across the contact is negligible as long as the current density is less than 100 A/cm². It is interesting to see how much of the cell efficiency can be improved with polysilicon emitters of characteristics given here. With the cell modeling, which is similar to the one reported by Sinton [8], more than one absolute percent of the cell efficiency is obtained for a backside contact solar cell with polysilicon emitters with characteristics shown here ($J_o=2 \times 10^{-14}$ A/cm² for the n-type, $J_o=3.5 \times 10^{-14}$ A/cm² for the p-type, and $\rho_c=1 \times 10^{-5}$ Ω-cm² for both types).

CONCLUSIONS

To conclude, we showed that polysilicon emitters with low J_o and ρ_c can be obtained with a very small fraction of interfacial oxide breakup. Typically, $\rho_c \sim 1 \times 10^{-5}$ Ω-cm² and $J_o \leq 5 \times 10^{-14}$ A/cm² are obtained for both n- and p- type polysilicon emitters. From the cell modeling, polysilicon emitters with these qualities can be quite useful for silicon concentrator solar cells. Because only small fraction of interfacial oxide is broken, the J_o is primarily dominated by the recombination at the oxide interface and in the single-crystal diffusion region. Consequently, an interfacial oxide of good quality is important to obtain low J_o . Our results also indicates that ρ_c drops drastically when the oxide starts to breakup. This is explained by the transition of the dominant majority-carrier transport from the tunneling to the channel resistance.

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