DOE Solar Energy Technologies Program Peer Review

Technical Track: Crystalline Silicon & Related

Project Name: Wafer-Si

Principal Investigator: Qi Wang

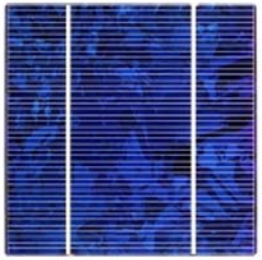
Denver, Colorado

March 9-10, 2009

Wafer Si Roadmap

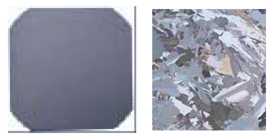
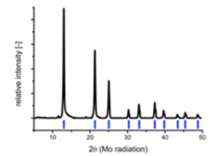
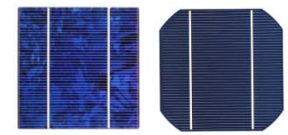
- High efficiency single c-Si

- Low cost mc-Si: casting and ribbon



- Common to both roadmaps
  - -- interconnect, packaging, reliability, process diagnostics and modeling, and reduced Si consumption

Wafer-Si Agreement Coverage

Si	Ingot	Wafer	Si analysis	Solar cell
				

NREL Wafer–Si Coverage

Si	Ingot	Wafer	Si analysis	Solar cell
Solar Si EG-Si Mixed-Si	3” CZ Grower	ID saw	Structure Defects Impurities Electronic	Diffused SHJ Back-interdigitated Passivation Contacts Light mgmt

Wafer-Si Agreement Tasks

Wafer Si	FY 2008 Budget ($K)	Lead	FTE	Note
CZ grower	194	Matt Page	0.7	
Silicon heterojunction solar cells	654	Qi Wang	1.7	continue work on small cell and prepare wafer size
Passivation of mc-Si	213	Qi Wang	0.6	wait for Si cluster tool
Interdigitated heterojunction solar cell	100	Scott Ward	0.3	
Black Si	151	Howard Branz	0.6	
TCO for HIT	200	John Perkins	N/A	move to TCO Agreement
Direct writing contact	200	Maikel Van-Hest	0.6	
18^{th} c-Si workshop	41	Bhushan Sopori	0.1	remove in FY09 task
Fire-through metal contacts	50	Bhushan Sopori	0.15	
Characterization	109	Pete Sheldon	N/A	move to M&C Agreement
Total	1912			

Highlights

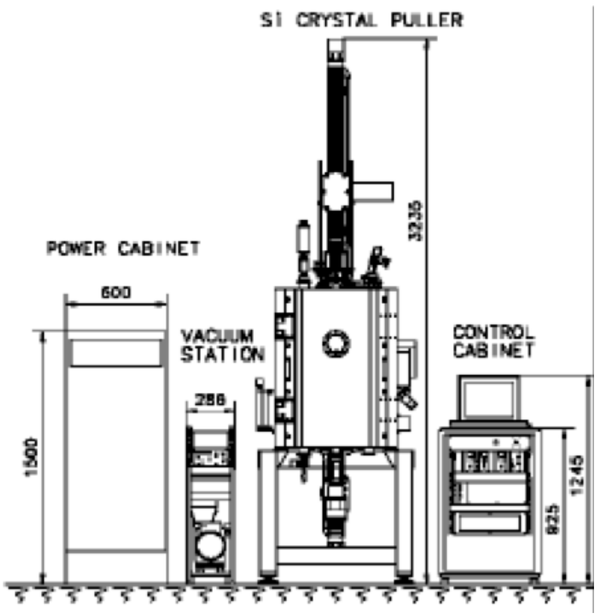
- Completed the purchase of CZ crystal grower
- Achieved 19.3% efficiency on FZ and 18.8% on CZ a-Si/c-Si heterojunction solar cells on *p*-type wafer
- Achieved over 700 mV on finished SHJ solar cell
- Completed the installation of Si cluster tool and ready for large area SHJ solar cells
- Achieved 17% (unofficial) and 16.7% (official) solar cell efficiency using black-Si process and exceeded milestones of FY08 and FY09.
- Achieved conductive narrower lines using ink-jet printing
- Successfully held 18^{th} c-Si workshop
- More than 10 conference and journal publications

CZ Puller

M. Page
M. Landry

Need a handy CZ puller to conduct Si feedstock study and support Si material companies

- **Specification**
  - 4” (100 mm) crystal
  - Max crystal length 10” (250 mm)
  - 6” crucible, 3” crystal, 2.7 kg
  - 8” crucible, 4” crystal, 4.9 kg
  - High-vacuum bake-out
    - Pfeiffer Turbo-molecular Drag Pump TMH/U-521P (270 L/s HI:10^{-6} Torr)
    - Edwards Dry Scroll Pump: XDS-10
  - 52 kW 480V 3PH @ Power Cabinet



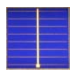
CZ Puller

M. Page

Status	Date
Request for proposal solicited to 3 selected companies	August 17, 2007
Awarded to one company	March 31, 2008
Current construction phase—vacuum station, power cabinet, control station are complete, delay in receiving CZ crystal puller chamber	November 6, 2008
Planed first acceptance test at company	March, 2009
Delivery and installation	March-June, 2009
Final acceptance test at NREL Growth of 64 mm +/- 2mm OD, dislocation free <100> single crystal, with [C], [O], [Metals]	Late May 2009 (1.5 months overdue)
Collaboration interest and other work; more than three companies have contacted us.	July, 2009

Si Heterojunction Solar Cells

- Scale up



1 x 1 cm^2

2007

2 x 2 cm^2

2008

5” solar wafer

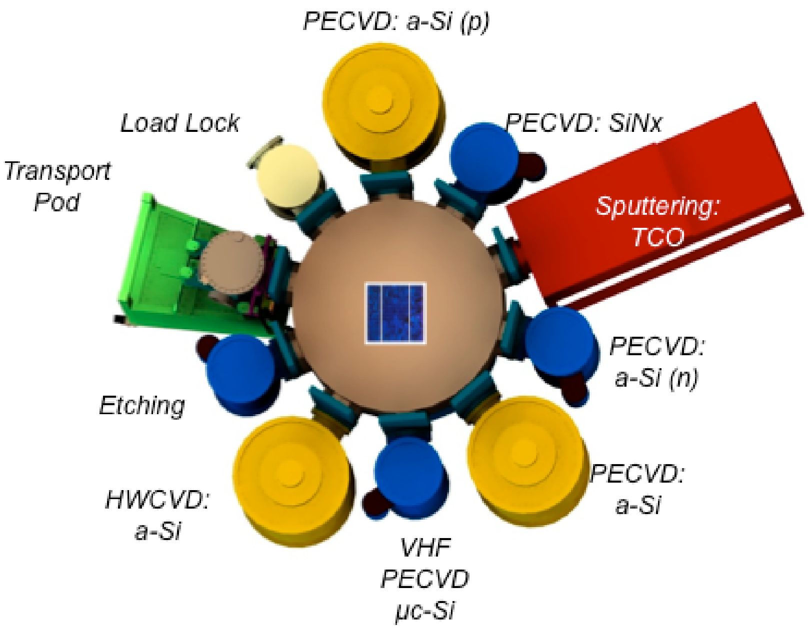
2009

- Increase current J_{sc}
  - improve surface texturing
  - enhance infrared response
  - reduce blue loss

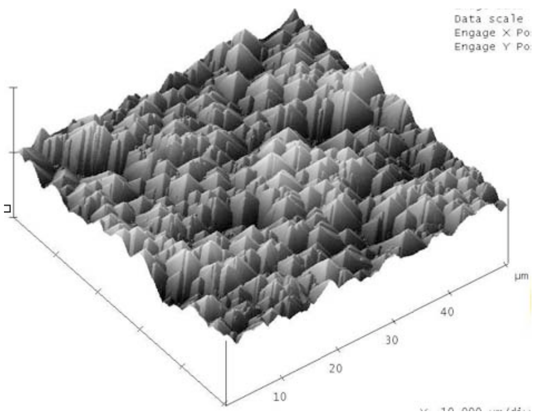
157 mm Si Cluster Tool

10/2007	7/2008	8/2008	9/2008		9/2009
System installation	ORR	Acceptance test	First films	Baseline films & devices	

8 deposition chambers

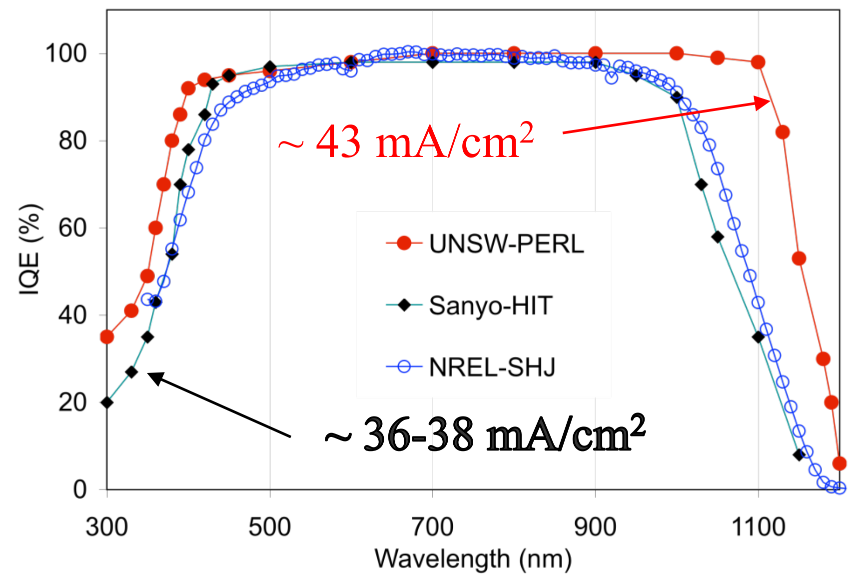


Si Heterojunction Solar Cells



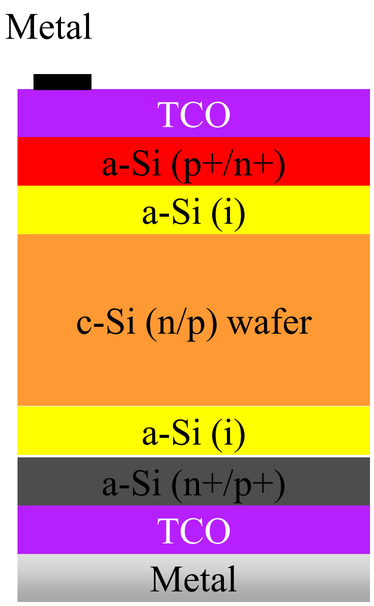
Achieve uniform < 10 µm size pyramids (KOH, H_2O, IPA)

- Better metal reflector
- More transparent ITO
- Wider bandgap a-Si:H



Si Heterojunction Solar Cells

SHJ cell structure



c-Si sandwich between thin Si layers

- **19.3% on *p*-type FZ c-Si meet FY07 19% milestone**
- **18.8% on *p*-type CZ c-Si**
- **700 mV on both *n*-type and *p*-type c-Si**

Black Si

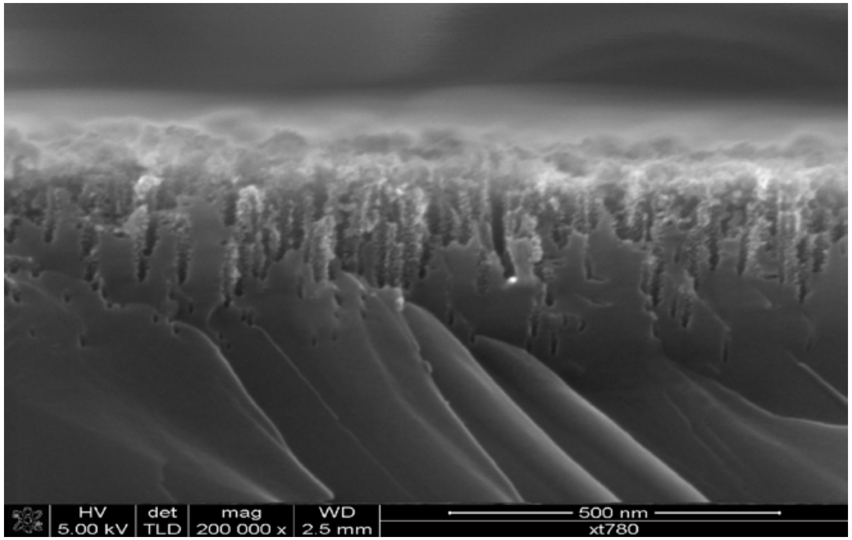
- A rapid process to create density-graded thin layer on the surface of c-Si and act as anti-reflection layer (black appearance)
- Apply the process to Si solar cell and improve the cell performance

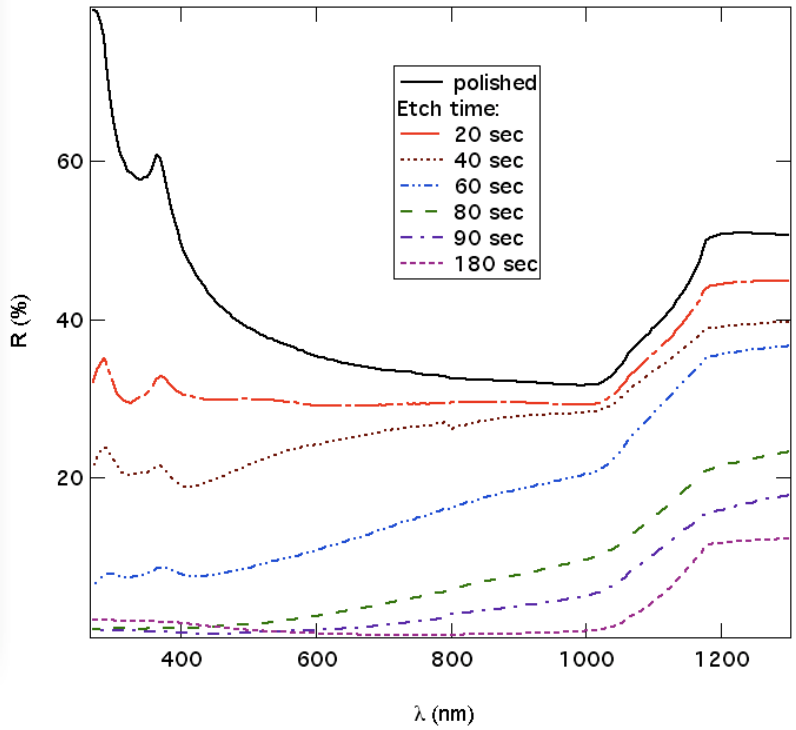
Black Si

Nanoporous 'black silicon' as anti-reflection

H.M. Branz
V. Yost
P. Stradins

- Nanoparticle-catalyzed liquid etch
  - Inexpensive precursors
  - $HAuCl_4 + HCl + HF$
- Density-graded nanoporous layer, 200-400 nm deep
- Reflectivity < 2% from 350-1000 nm
  - Wide angle anti-reflection better than conventional AR coatings



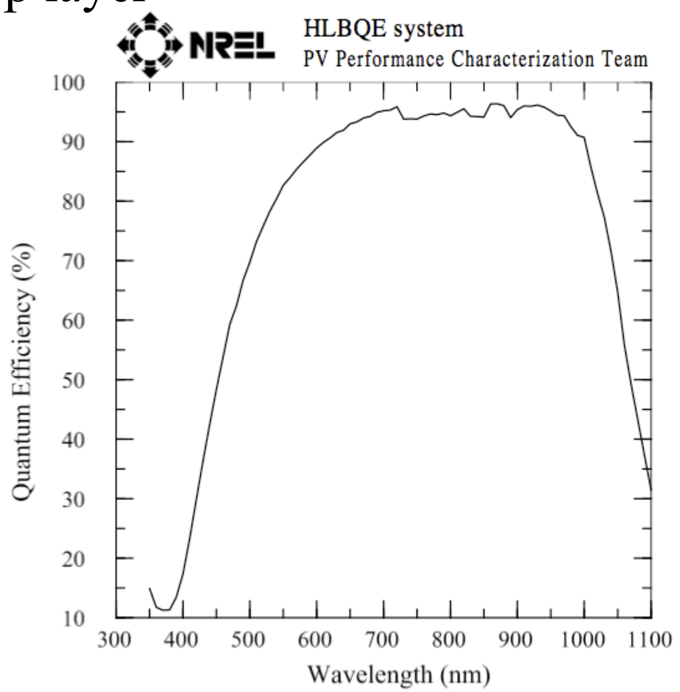


Black Si

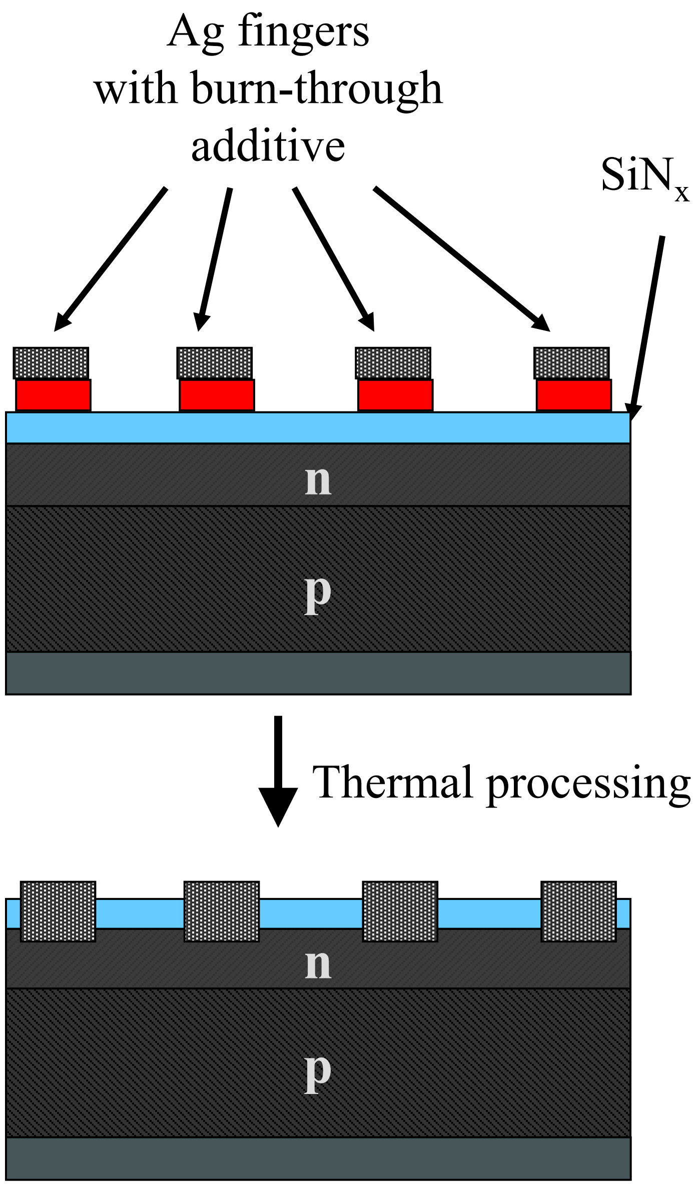
17%-efficient'black silicon' solar cells

H.-C. Yuan
V. Yost
M. Page
H.M. Branz

- 17.2% unconfirmed cell
  - Nanoporous black-etched p-wafer cleaned with KI
  - POCl-diffused emitter, Al-BSF, thermal oxidation
  - Wide light acceptance angle / no nitride or AR coating
  - Blue QE suffers due to high-recombination top layer
- 16.7% cell confirmed (1 cm^2)
  - J_{sc} = 34.57 mA/cm^2; 30% above bare Si
  - V_{oc} = 626 mV
  - FF = 78.2%
- Discussions with 3 U.S. companies
- Submit papers to 34th PVSC and journal



Inkjet Printed Contacts



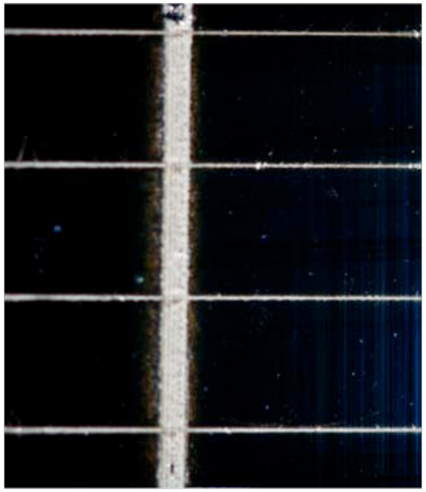
	Conventional	NREL
Deposition method	Screen printing	Inkjet printing
Material	Ag paste	Ag ink
Other materials	Al Paste	Cu, Ni, Al

NREL ink approach is unique:
- Conventional metal inks contain nanoparticles
- Nanoparticles agglomerate and clog inkjet nozzles
- NREL inks are proprietary true solution inks
    - No particles
    - No clogging of inkjet nozzles

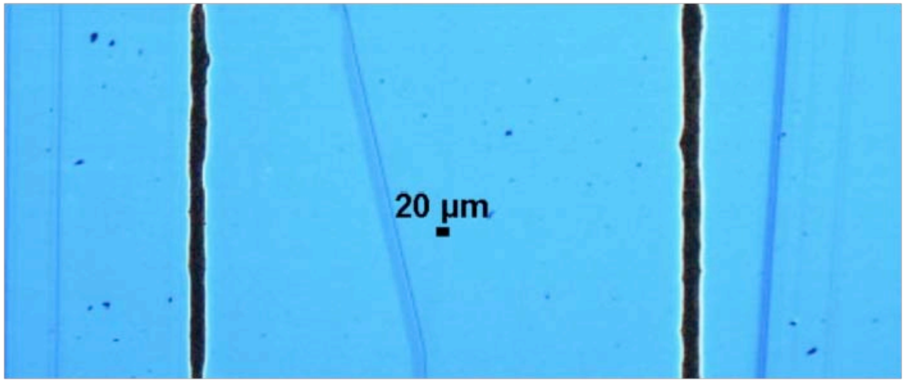
Conventional silicon PV contacts have to burn through SiN_x anti-reflection coating
- Screen printing pastes contain additive to facilitate burn through
- NREL has developed a proprietary inkjet-printable burn-through material which improves contact formation

Direct Write Contact

	Screen Printed Contacts	Inkjet Printed Contacts
Line width	>100 µm	30-40 µm (see below)
In-line resistivity	>10 µΩ/cm	2 µΩ/cm (1.2 x bulk silver)
Contact resistance	>10 mΩ/cm^2	3-4 mΩ/cm^2 with use of NREL burn through
Processing temperature	750ºC-850ºC	750ºC
Deposition method	Contact @ RT	Non-contact @ 200ºC
Waste	10-20%	<1%



Cell with 50-µm lines and busbar



Smaller lines → Reduction of shadow losses
→ Increased power output
Reduced resistivity → Less silver → Reduced cost
Non-contact → Reduction of wafer thickness
→ Reduced cost
Overall → Reduced $/W

Inkjet inks also developed for Ni, Cu, and Al

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Energy Efficiency and Renewable Energy
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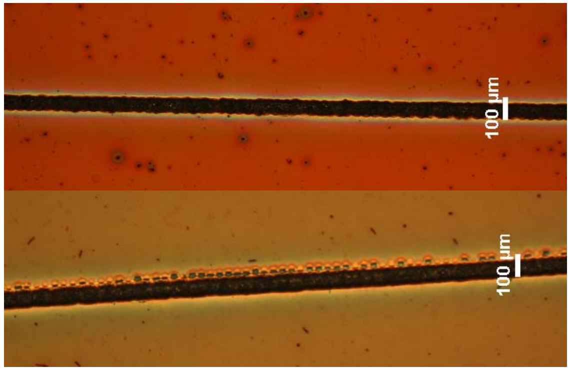
Inkjet Printed Contacts

Organic PV

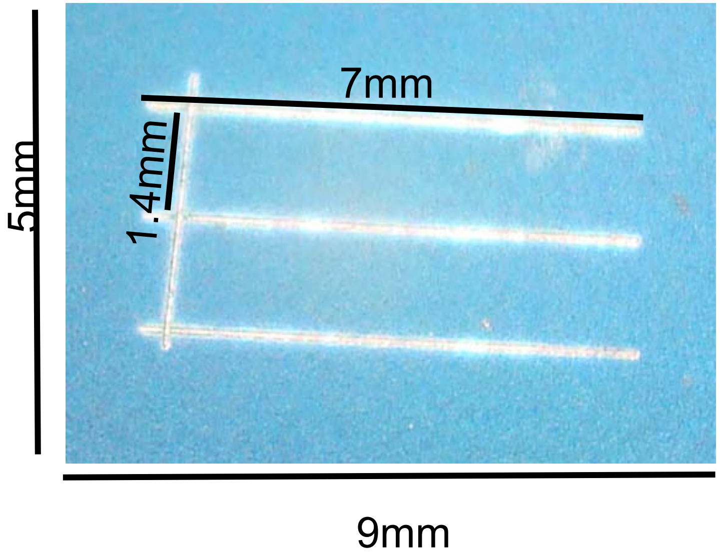
- Silver contacts printed at 140ºC to preserve organic material
- Resistivity silver 15x bulk due to lower processing temperature

CIGS

- Nickel silver contact on ZnO-coated CIGS devices
- Efficiency close to that of reference cell; difference due to difference in line width (printed 50µm vs. reference 25µm)



Printed contacts on OPV device



Bilayer of nickel and silver on CIGS
Maximum efficiency: 11.6%
Reference cell: 12.5%

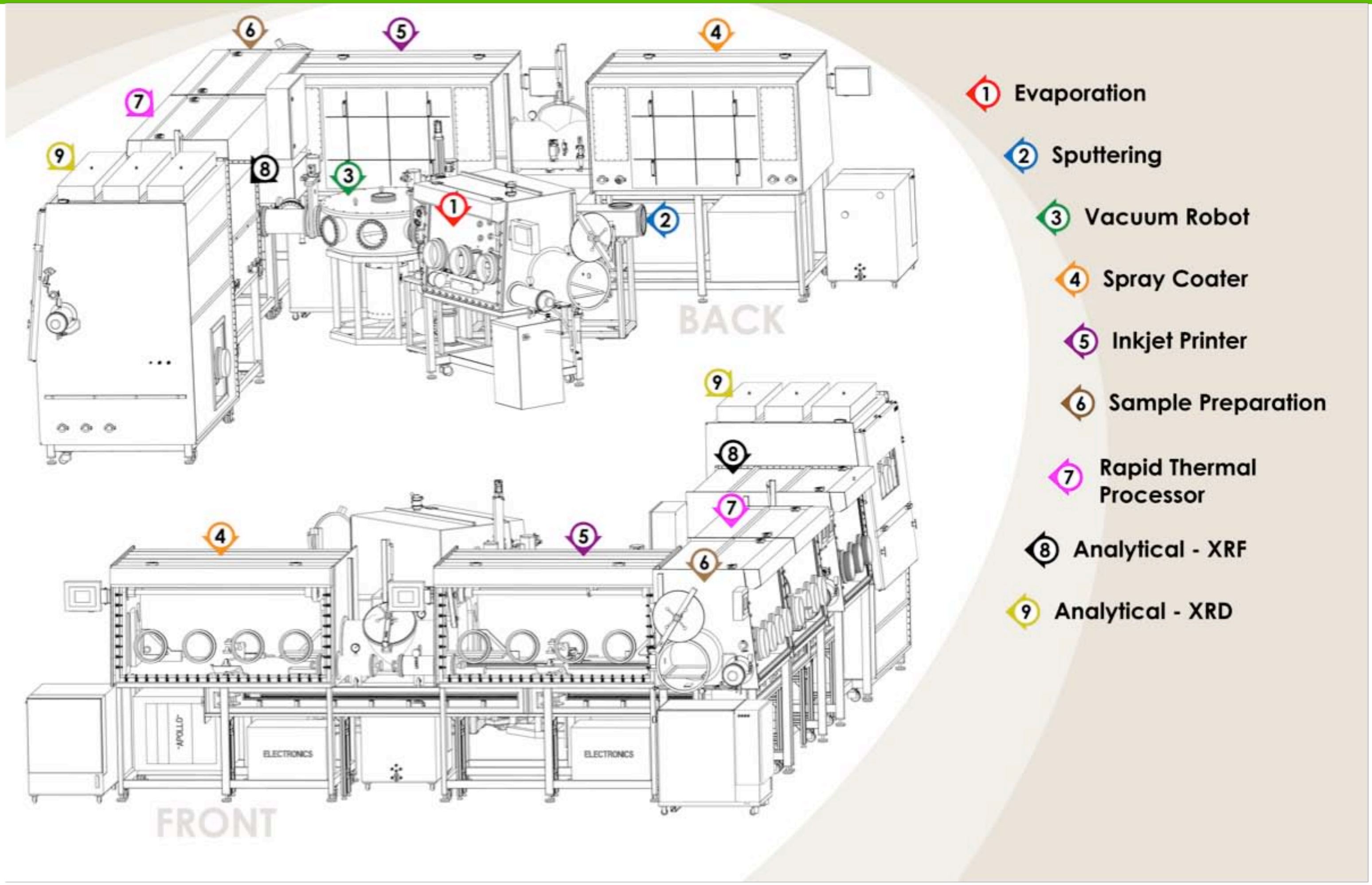
Non-Metal inks:

- Solution inks for deposition of CIGS, Cu-Se, In-Se, Ga-Se, Se; successfully used to produce large grain CIGS thin films
- Particle based inks for deposition of CdTe
- Solution based inks for deposition of transparent conductive oxides (In-Zn-O)

Goal:

Reduce cost by depositing complete or part of photovoltaic cell using inks and atmospheric processing

Direct Write Contact



PDIL Atmospheric Processing Platform:

Scaling sample size to 6" x 6" with atmospheric processing platform

-Multi-'color' inkjet printing and spray deposition

-High speed (1000 mm/s vs. current 25 mm/s)

-Large area thermal processing and analysis

-Multi-material evaporation and sputtering

18^{th} c-Si Workshop

Bhushan Sopori

Location and Participants: Vail, Colorado; workshop attended by representatives from photovoltaic (PV) and semiconductor industries and research institutions

Description/Extended Description: The 18th Workshop on Crystalline Silicon Solar Cells and Modules: Materials and Processes was held in Vail, Colorado, on August 3–6, 2008. Attendance included 179 scientists and engineers from 64 international PV and semiconductor companies and 24 research institutions from 14 different countries. The theme of the workshop, "New Directions for Rapidly Growing Silicon Technologies," reflects potential future changes in the PV industry that are expected to arise from synergism of a very rapid growth in PV energy production and a large infusion of investments into many new technologies.

Oral, poster, and discussion sessions addressed recent advances in crystal growth technologies, impurities and defects in semiconductors, solar cell processing, and module reliability issues. Each oral session was followed by an extended discussion session. Special sessions were devoted to:

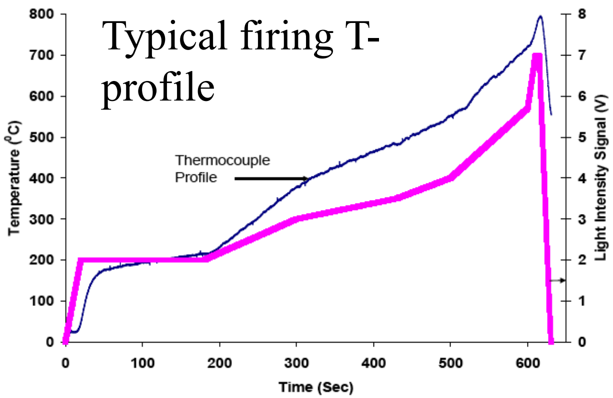
- Feedstock issues: monitoring and qualifying poly feedstock
- Progress in thin-film Si
- High-efficiency Si solar cells
- New metallization technologies.

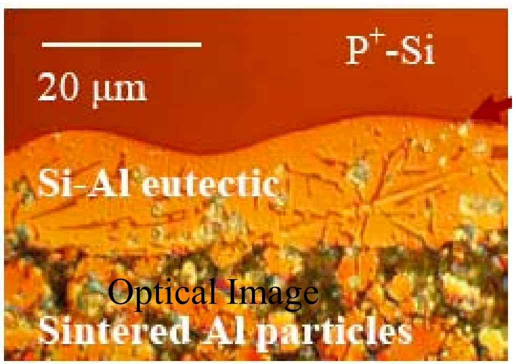
In addition, a rump session titled "R&D Strategies for a High-Growth Industry (Under Heavy Investment)" was held on Sunday evening, August 3.

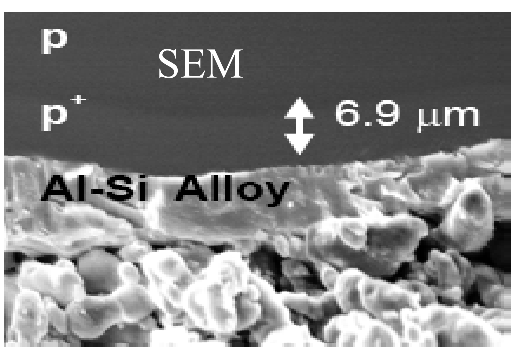
Seventeen students received graduate student awards from funds contributed by the PV industry.

Fire-Through Contacts

B. Sopori, et. al.







c-Si /Al back contact forms three regions at optimally fired condition:

1. P^+-Si (Al doped)
2. Si-Al eutectic
3. Agglomerated Al

Studies on Backside Al-Contact Formation in Si Solar Cells: Fundamental Mechanisms

Bhushan Sopori,[1] Vishal Mehta,[1] Przemyslaw Rupnowski,[1] Helio Moutinho,[1] Aziz Shaikh,[2] Chandra Khadilkar,[2] Murray Bennett,[3] and Dave Carlson[3]
[1]National Renewable Energy Laboratory, Golden, CO 80401, USA
[2]Ferro Electronic Materials, Vista, CA 92083, USA
[3]BP Solar, Frederick, MD 21703, USA

Presented at the MRS Fall Meeting 2008 Boston, Massachusetts December 1-5, 2008

Relevance/Impact

Wafer Si Tasks	Relevant & Impacts
CZ grower	Low cost solar Si feedstock
Silicon heterojunction solar cells	High efficiency and thinner Si
Passivation of mc-Si	Lead to high performance
Interdigitated heterojunction solar cell	High efficiency solar cell
Black Si	Rapid AR process and potential replacement of SiNx layer
Direct writing contact	Narrow line and potential replacement of screen printing process
18th c-Si workshop	Boost collaboration and education
Fire-through metal contacts	Understand the Si/Al back contact

Future Directions

- Install and operate CZ-crystal grower and establish quick evaluation of solar Si feedstock
- High efficiency SHJ solar cells on thin wafers (< 100 µm)
- Develop 5” wafer size heterojunction solar cells
- Study and develop novel materials and process for the surface and bulk passivation of mc-Si
- Develop high efficiency interdigitated solar cell using heterojunction a-Si:H layer
- Improve and deploy black Si solar cells process
- Direct writing contact on 5” wafer
- Efficient furnace and fire-through metal contact

Heterojunction Solar Cells

Team Members:

M. Page, E. Iwaniczko, YQ. Xu, F. Hasoon,
L. Roybal, H-C. Yuan, R. Bauer, Q. Wang,

Publications:

- Wang, Q.; Page, M. R.; Iwaniczko, E.; Xu, Y. Q.; Roybal, L.; Bauer, R.; To, B.; Yuan, H. C.; Duda, A.; Yan, Y (2008). “Crystal Silicon Heterojunction Solar Cells by Hot-Wire CVD: Preprint.” 8 pp.; 33rd PVSC

- Branz, H. M.; Teplin, C. W.; Young, D. L.; Page, M. R.; Iwaniczko, E.; Roybal, L.; Bauer, R.; Mahan, A. H.; Xu, Y.; Stradins, P.; Wang, T.; Wang, Q. “Recent Advances in Hot-Wire CVD R&D at NREL: From 18% Silicon Heterojunction Cells to Silicon Epitaxy at Glass-Compatible Temperatures.” *Thin Solid Films*. Vol. 516(5), 15 January 2008; pp. 743-746;

- Yuan, H.-C.; Page, M. R.; Iwaniczko, E.; Xu, Y.; Roybal, L.; Wang, Q.; Branz, H. M.; Meier, D. L. (2008). “Silicon Solar Cells with Front Hetero-Contact and Aluminum Alloy Back Junction: Preprint.” 7 pp.; 33rd PVSC

- Page, M. R.; Iwaniczko, E.; Xu, Y.; Roybal L.; Bauer, R.; Yan, H.-C.; Wang, Q.; Meier, D. L. (2008). “Photoconductive Decay Lifetime and Suns-Voc Diagnostics of Efficient Heterojunction Solar Cells: Preprint.” 7 pp.; 33rd PVSC

Direct Write Contact

Team Members:

Calvin Curtis: Senior Chemist
Alex Miedaner: Chemist
Jason Underwood: Post-doc (Physicist)
Jennifer Leisch: Post-doc (Material Scientist)
Maikel van Hest: Physicist/Material Scientist/Task Leader
David Ginley: Research Fellow/Group Manager/Chemist

Special recognition:

1) Federal Laboratory Consortium for Technology Transfer award for Hybrid CIGS.
2) Regular R&D 100 Award and Editors Choice award R&D 100 Award for Hybrid CIGS.

Publications

- M.F.A.M van Hest, C.J. Curtis, A. Miedaner, R.M. Pasquarelli, T. Kaydanova, P. Hersh, D.S. Ginley, "Direct-Write Contacts: Metalization and Contact Formation," *Photovoltaic Specialist Conference, 2008, Proceedings of the Thirty-third IEEE* (2008)
- C.J. Curtis, M.F.A.M. van Hest, A. Miedaner, J. Nekuda, P. Hersh, J. Leisch, D.S. Ginley, "Spray Deposition of High Quality $CuInSe_2$ and CdTe Films," *Photovoltaic Specialist Conference, 2008, Proceedings of the Thirty-third IEEE* (2008)
- B. Sang, F. Adurodija, M. Taylor, A. Lim, J. Taylor, S. McWilliams, R. Oswald, B.J. Stanbery, M.F.A.M. van Hest, J. Nekuda, A. Miedaner, C.J. Curtis, D.S. Ginley, "Low Cost Copper Indium Gallium Selenide by the FASST Process," *Photovoltaic Specialist Conference, 2008, Proceedings of the Thirty-third IEEE* (2008)
- M.F.A.M. van Hest and D.S. Ginley, "Future Directions for Solution-Based Processing of Inorganic Materials," book chapter in *Solution-Based Processing of Inorganic Films* edited by David Mitzi