Bridging scientific research and industry

Research progress on industrial crystalline silicon solar cells at SJTU

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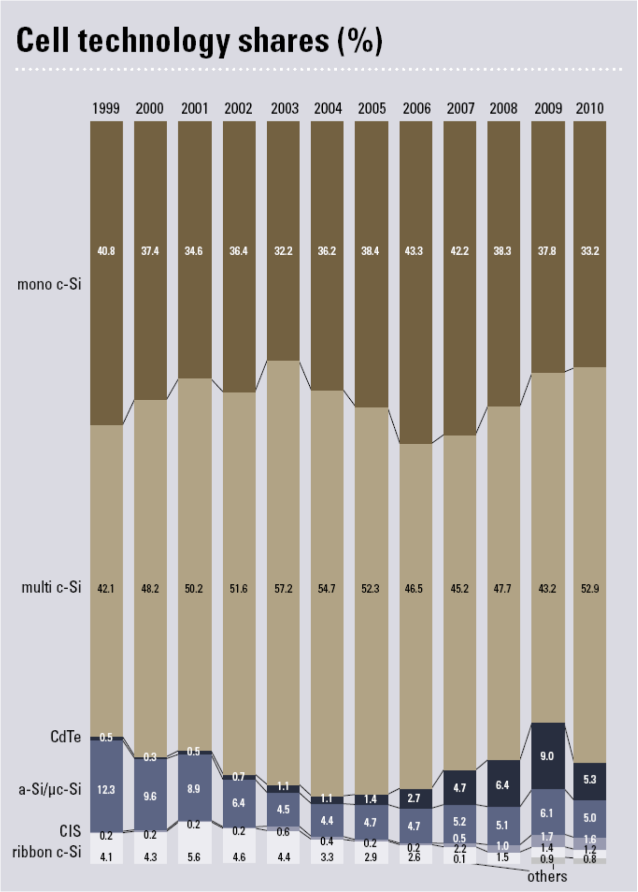
For PV application, who can compete with silicon?

- Cell efficiency > 20%
- Module cost < $0.4/Wp
- System stability > 25 years



Crystalline silicon solar cells have been the mainstream of PV market during the past decade (over 85-90%, 93.7% in 2016), and will continue to be next ten or even more years!

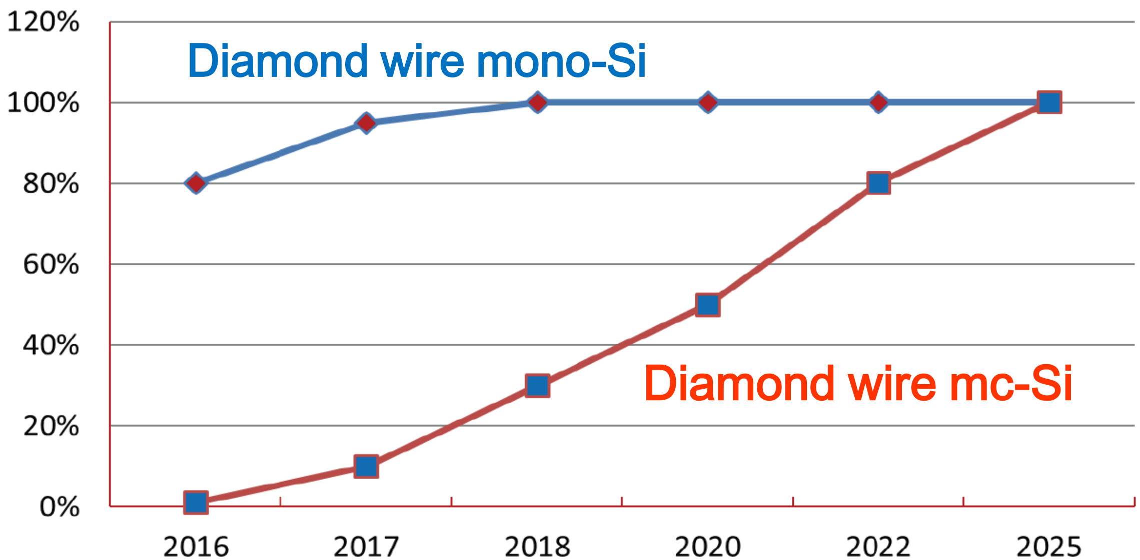
Outline

	Industrial Eff.
① Diamond wire sawn p-type mc-Si solar cells	19.0-20.5%
② p-type PERC (passivated emitter and rear contact) solar cells	21.0-22.5%
③ n-type PERT (passivated emitter, rear totally-diffused) bifacial c-Si solar cells	20.5-22.5% (f) 18.5-20.5% (r)
④ n-type BJBC (back-junction back-contact) solar cells	22.5-24.5%
⑤ a-Si/(n-type)c-Si heterojunction solar cells	22.5-24.5%
⑥ Ultrathin c-Si solar cells	>20.0%
⑦ Perovskite/c-Si tandem solar cells	>30.0%

① Diamond wire sawn p-type mc-Si cells → Module cost $0.3/Wp

Effective texturization:

- Reactive ion etching (RIE) – mature and high cost
- Metal-assisted chemical etching (MACE) – simple, cost-effective and compatible with current production lines



Source: CPIA-PV Roadmap 2016

Japan：

Diamond wire for mono-Si	100%
Diamond wire for mc-Si	70%
Cost reduction	30%

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Solar Energy Materials & Solar Cells 143 (2015) 302–310

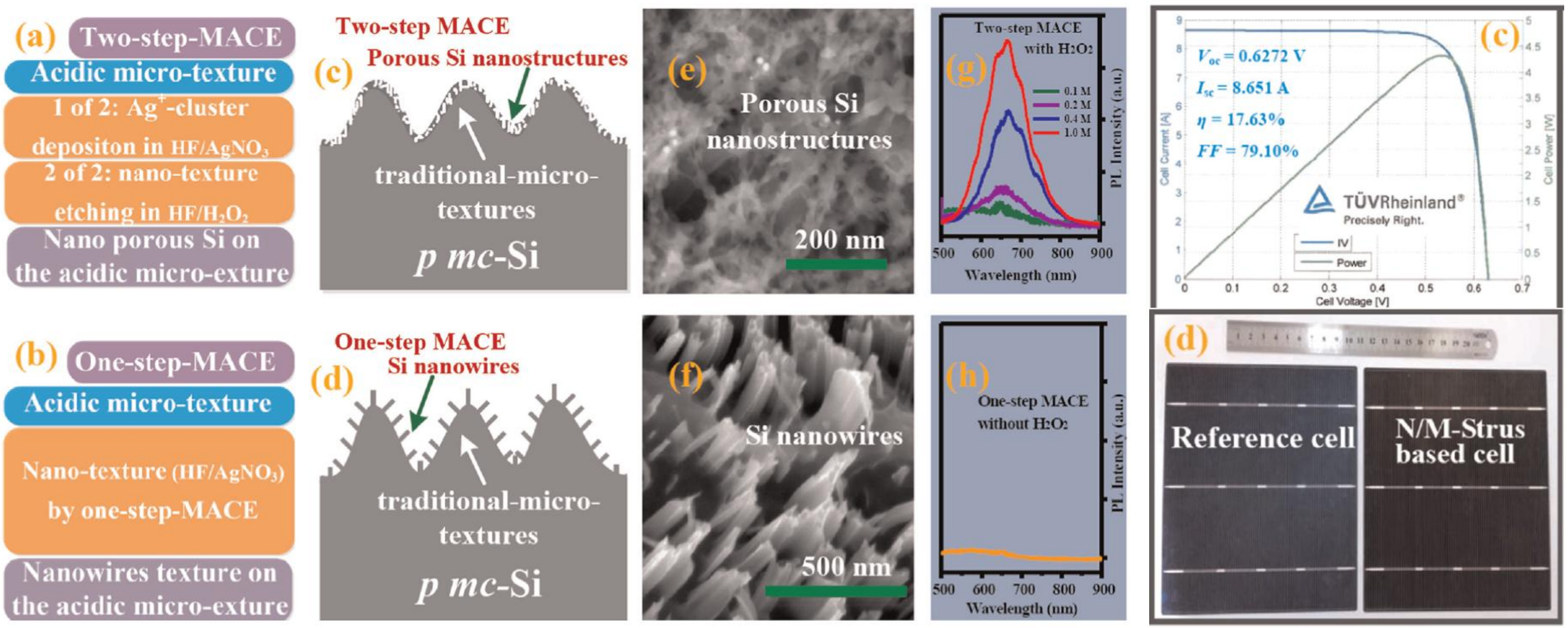
Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

One-step-MACE nano/microstructures for high-efficient large-size multicrystalline Si solar cells

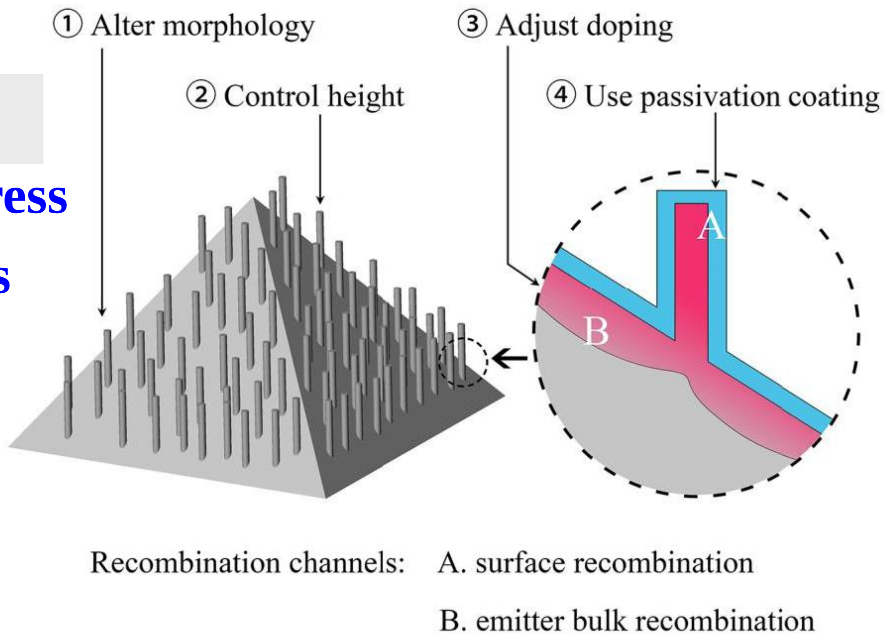
Z.G. Huang [a,b], X.X. Lin [a], Y. Zeng [a], S.H. Zhong [a], X.M. Song [b], C. Liu [c], X. Yuan [c], W.Z. Shen [a,*]



High-Efficiency Nanostructured Silicon Solar Cells on a Large Scale Realized Through the Suppression of Recombination Channels

*Sihua Zhong, Zengguang Huang, Xingxing Lin, Yang Zeng, Yechi Ma, and Wenzhong Shen**

Four countermeasures to suppress the two recombination channels

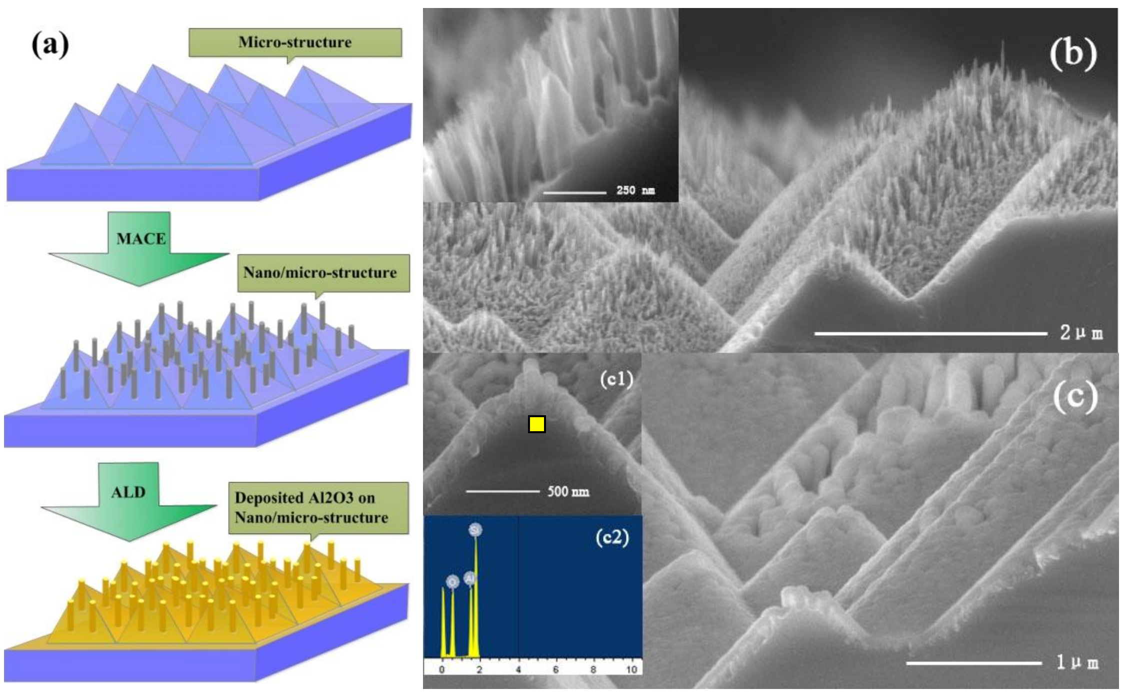


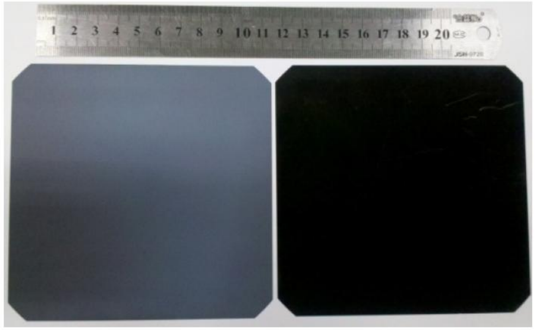
Advanced Materials **27**, 555-561 (2015)

Progress in PHOTOVOLTAICS
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2015; **23**:964–972
Published online 9 May 2014 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2506

An effective way to simultaneous realization of excellent optical and electrical performance in large-scale Si nano/microstructures

Zengguang Huang[1,2], Sihua Zhong[1], Xia Hua[1], Xingxing Lin[1], Xiangyang Kong[3], Ning Dai[4] and Wenzhong Shen[1]*



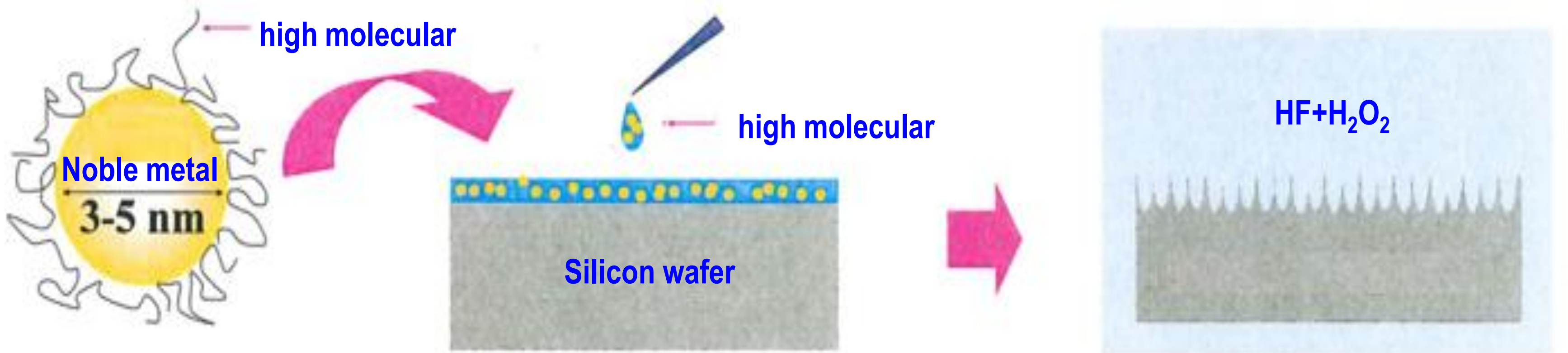


(c) Silicon nano/microstructure after depositing Al_2O_3 by ALD. Inset c1 is a larger image of nanowires with conformal thin film of Al_2O_3; Inset c2 is the energy dispersive X-ray spectroscopy (EDX) of the top part shown in inset c1.

(a) Schematic diagram of the process.

(b) As-prepared silicon nano/micro-structure. Inset is a larger image of nanowires on a facet of pyramid structure.

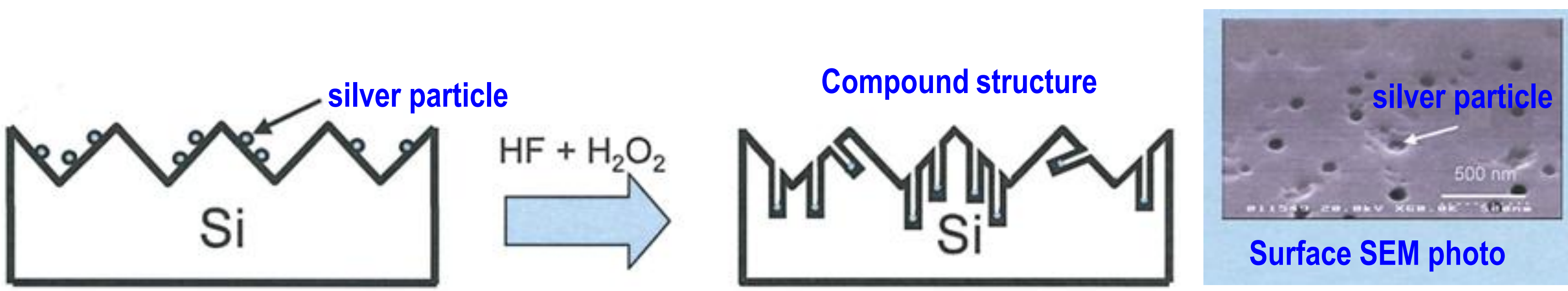
NANO TEXTURE



Single nanometer noble metal micro-particle

micro-particle liquid applied to silicon surface and dried

Anti-reflection structure is formed by soaking liquid only



碱修饰工艺倒金字塔制绒工艺金刚线切割多晶电池效率：+0.5% → +1.3% (PERC)

Solar Energy Materials & Solar Cells 153 (2016) 18–24

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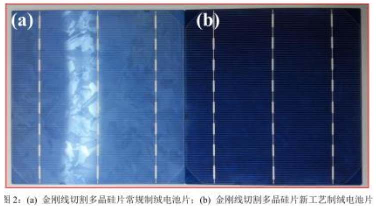
Solar Energy Materials & Solar Cells

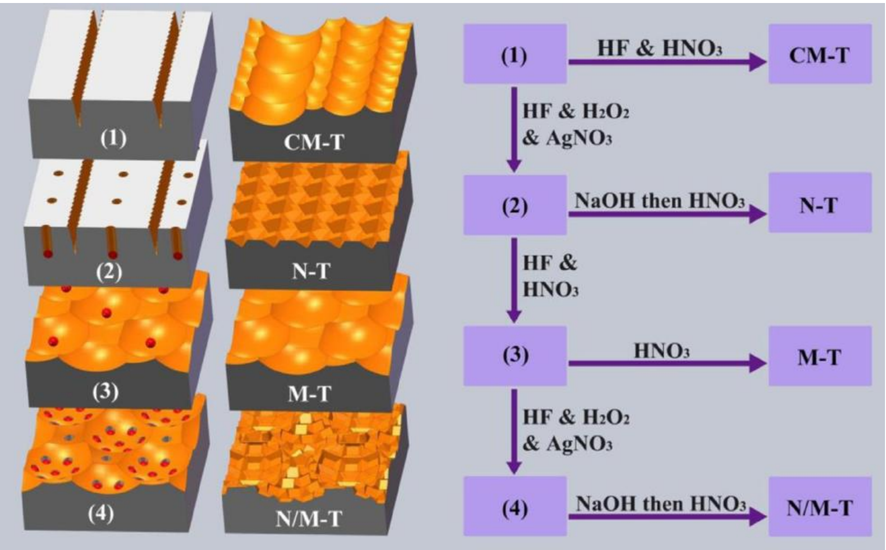
journal homepage: www.elsevier.com/locate/solmat

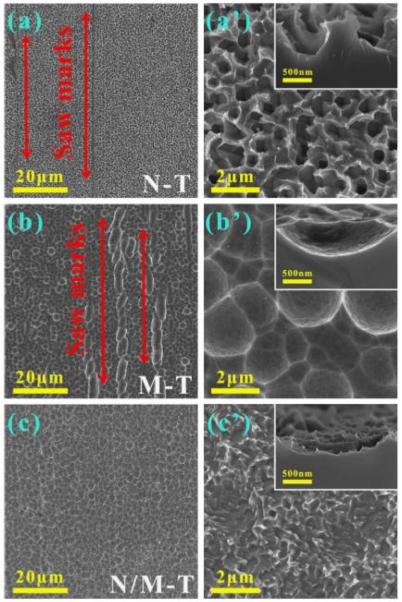
Versatile strategies for improving the performance of diamond wire sawn mc-Si solar cells

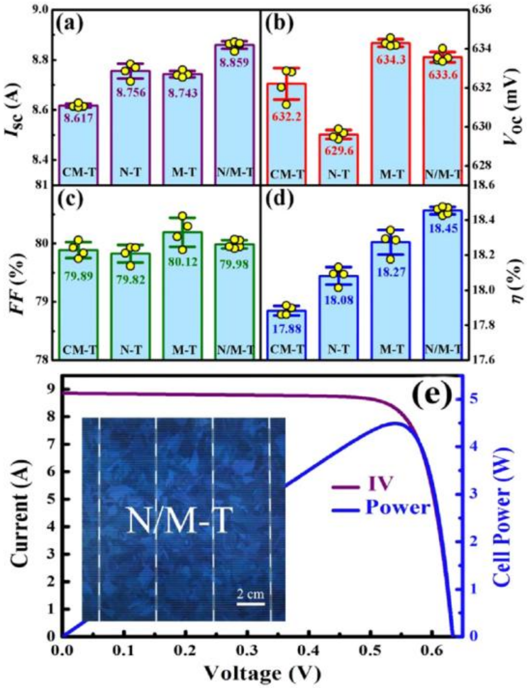


Y.F. Zhuang [a], S.H. Zhong [a], Z.G. Huang [a,b], W.Z. Shen [a,c,*]

[a] Institute of Solar Energy, and Key Laboratory of Artificial Structures and Quantum Control (Ministry of Education), Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[b] School of Science, Huaihai Institute of Technology, Lianyungang 222005, Jiangsu Province, People's Republic of China
[c] Collaborative Innovation Center of Advanced Microstructures, Nanjing 210093, People's Republic of China







mass production in 2016

Solar Cell Technologies

PV hypes: tops and flops

International Solar Energy Research Center Konstanz

flops

SoG-Si

quasi-mono

ion implantation

SiCx-passivarion

Al_2O_3-passivation

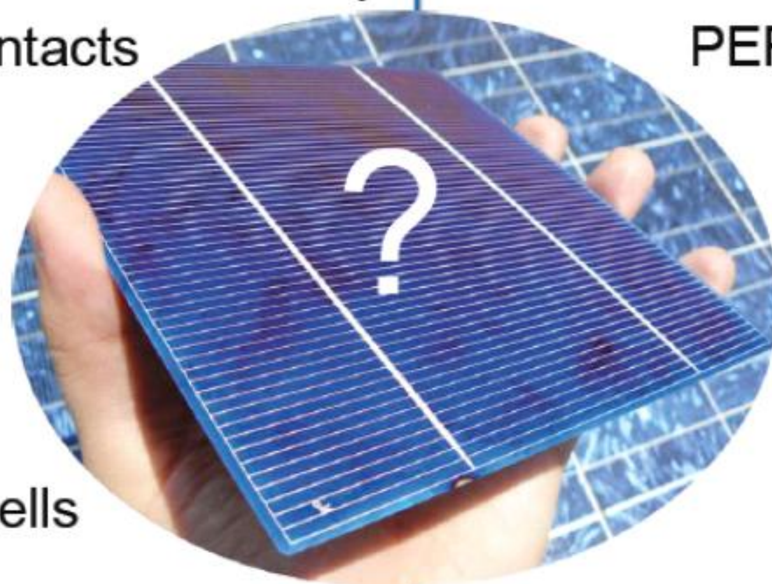
plated contacts

inline doping

sheet and ribbon cells

rear contact cells EWT

thin film cells



c-Si PV

tops

selective emitters

PERC

n-type cells

~21.5%

rear contact cells MWT

IBC

HIT cells

>23.0%

bifacial cells

conductive adhesives

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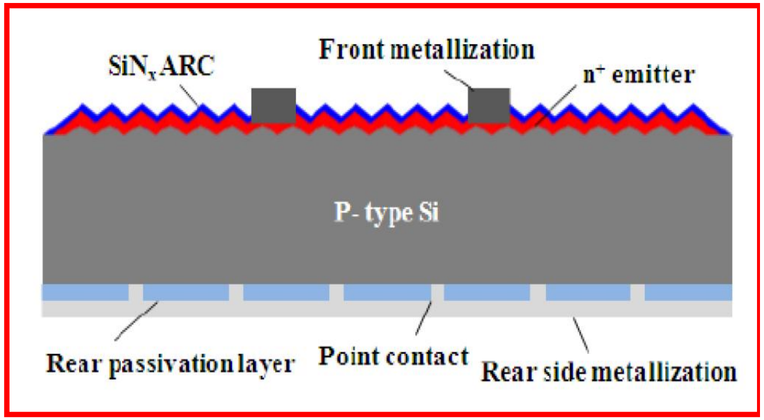
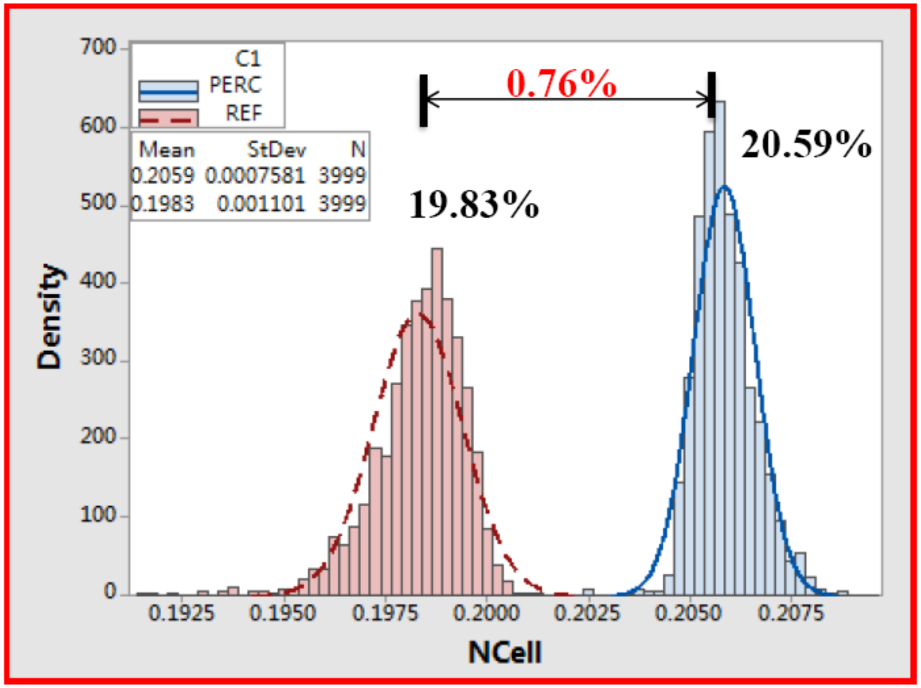
② Traditional Lines + Lasers Upgrades into PERC Lines

+0.8% (2015)→ +1.2% (2016)

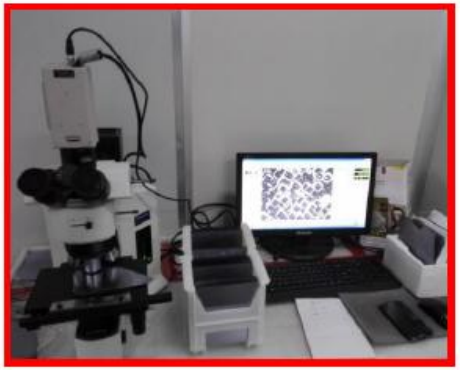




Group	Uoc/V	Isc/A	Rs/Ohm	Rsh/Ohm	FF/%	NCell	Irev2 @-12V	Quantity
REF	0.640	9.273	0.0019	123.3	80.12	0.1983	0.177	4000
PERC	0.655	9.591	0.0019	202.5	80.07	0.2059	0.102	4000

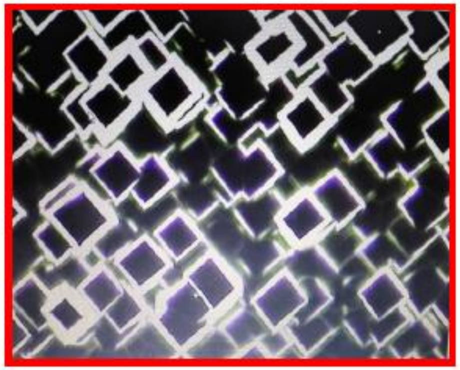
mass production in 2016

Improvement: Polish



光学显微镜

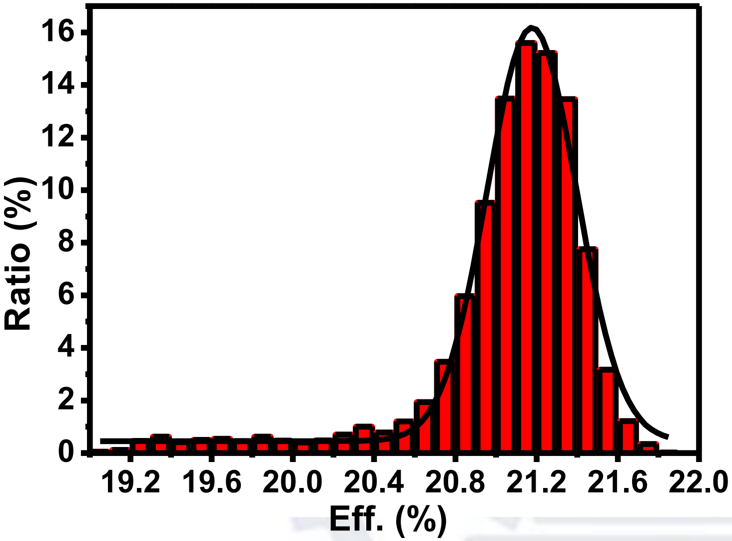
抛光（无添加剂）



抛光（有添加剂）

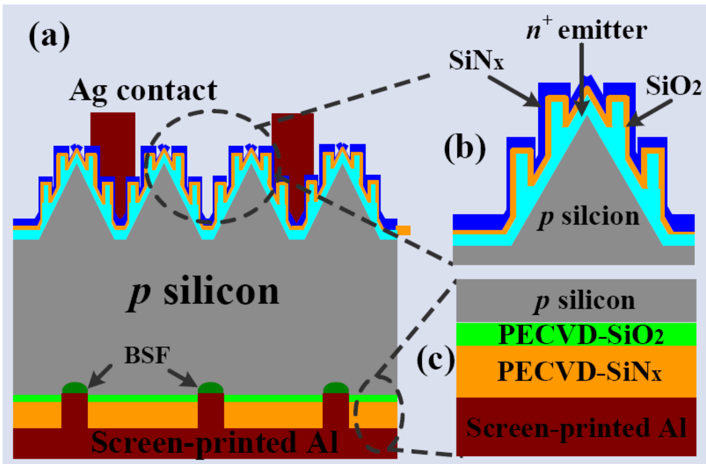
添加剂背面抛光工艺：

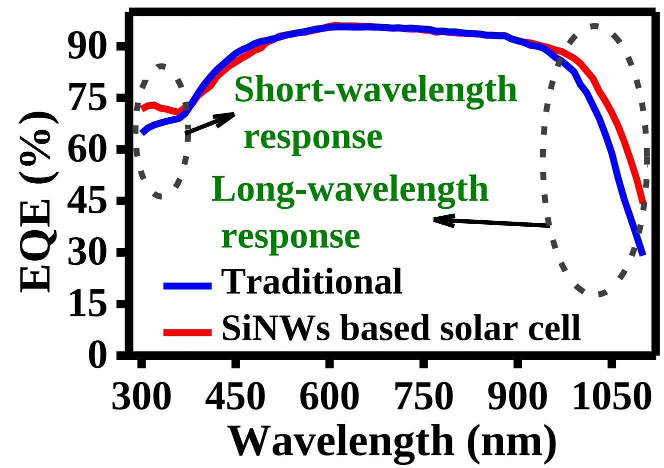
- 从微观层面，改善背面反射率；
- 提高工艺的稳定性与兼容性。

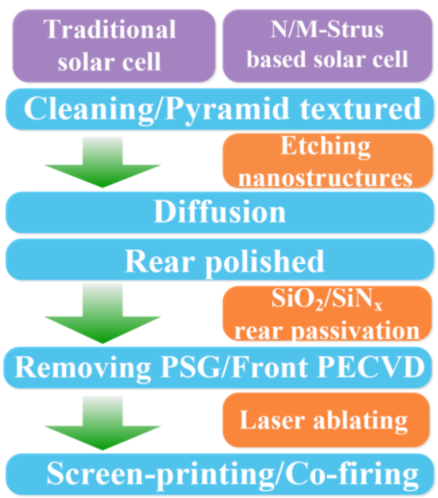


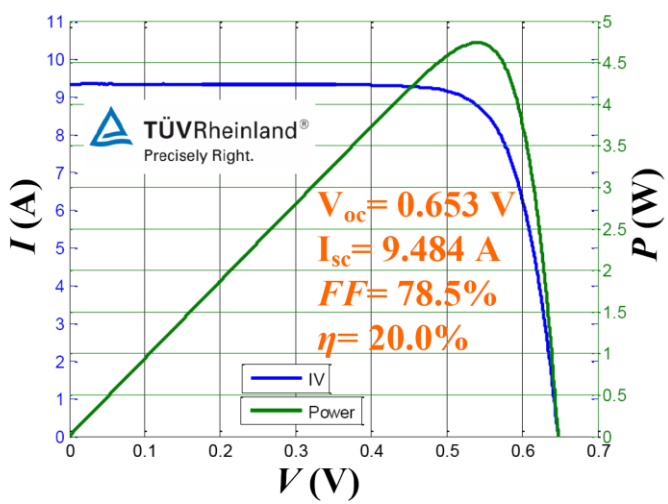
mass production in 2017

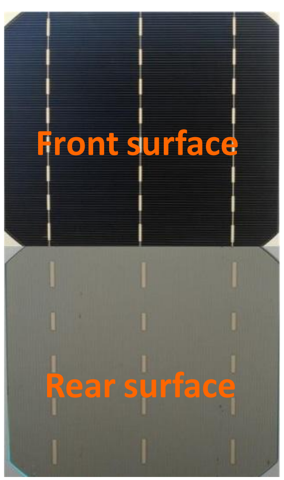
20.0%-efficient Si nano/microstructures based solar cells with excellent broadband spectral response











Adv. Funct. Mater. **26**, 1892-1898 (2016)

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Contents lists available at ScienceDirect

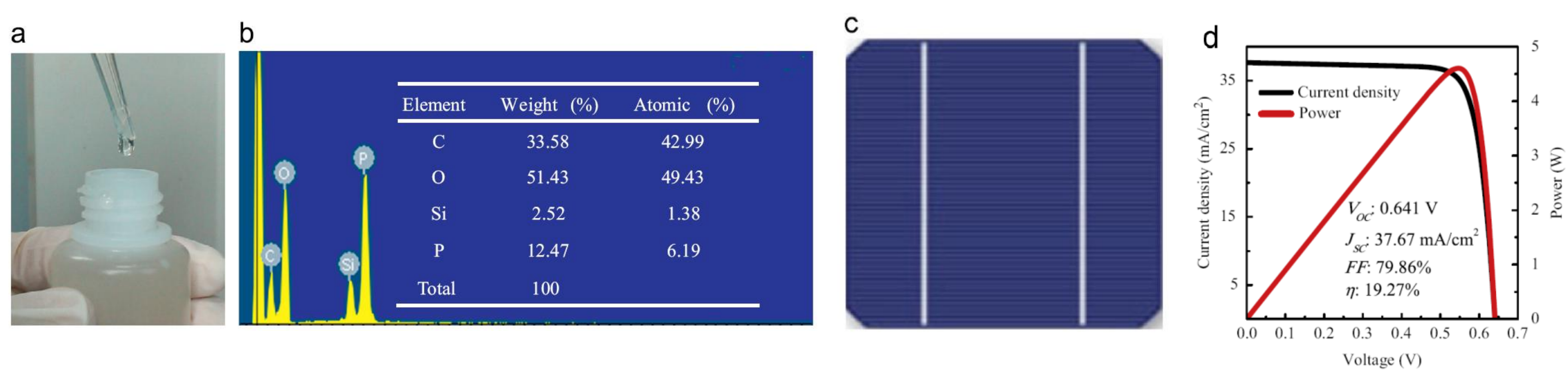
Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Mass production of high efficiency selective emitter crystalline silicon solar cells employing phosphorus ink technology

Sihua Zhong [a], Wenzhong Shen [a,*], Feng Liu [b], Xiang Li [b]

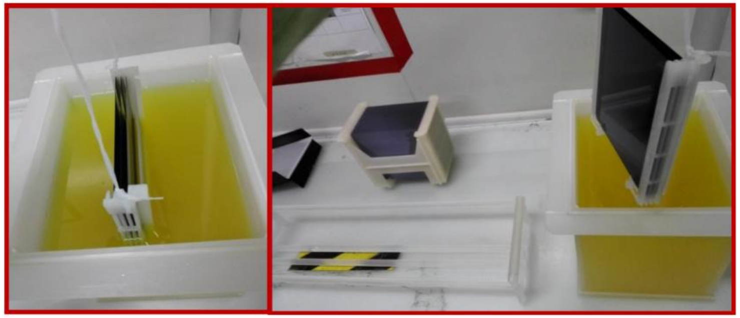
[a] Institute of Solar Energy, and Key Laboratory of Artificial Structures and Quantum Control (Ministry of Education), Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[b] Suzhou SolaRing Technology Co., Ltd., Suzhou 215200, Jiangsu Province, People's Republic of China



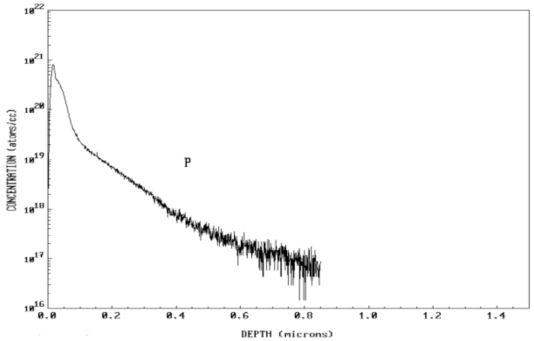
Element	Weight (%)	Atomic (%)
C	33.58	42.99
O	51.43	49.43
Si	2.52	1.38
P	12.47	6.19
Total	100	

P-ink PERC Cells

Coating



P concentration distribution



Nonuniformity of Sheet *R*

扩散温度 磷浓度	800℃	850℃	900℃
3%	\	\	3.50%
4%	\	\	2.60%
5%	\	1.15%	3.90%
6%	\	1.74%	5.23%
7%	\	3.28%	5.30%
8%	1.22%	3.49%	3.47%

P-ink PERC Cells

Traditional $POCl_3$ diffusion PERC Cells

方阻	Uoc(V)	Isc(A)	Rs(mΩ)	Rsh(Ω)	FF(%)	Ncell(%)
液态磷源扩散（100Ω/□）	0.654	9.73	2.19	105	79.18	20.62
液态磷源扩散（100Ω/□）	0.657	9.79	2.42	126	79.99	21.06
液态磷源扩散（100Ω/□）	0.661	9.77	2.96	161	80.01	21.14
液态磷源扩散（100Ω/□）	0.657	9.79	2.80	162	79.75	21.01
平均值（100Ω/□）	0.657	9.77	2.59	139	79.73	20.95
常规$POCl_3$扩散（95Ω/□）	0.657	9.77	2.42	130	79.94	20.99
常规$POCl_3$扩散（95Ω/□）	0.656	9.71	1.88	187	80.03	20.88
常规$POCl_3$扩散（95Ω/□）	0.655	9.77	2.46	204	80.23	21.01
常规$POCl_3$扩散（95Ω/□）	0.657	9.76	2.50	38	80.18	21.05
常规$POCl_3$扩散（95Ω/□）	0.657	9.77	2.09	225	80.41	21.12
常规$POCl_3$扩散（95Ω/□）	0.660	9.75	2.91	213	80.24	21.14
常规$POCl_3$扩散（95Ω/□）	0.651	9.76	2.71	162	79.52	20.67
常规$POCl_3$扩散（95Ω/□）	0.658	9.76	2.45	149	80.18	21.07
平均值（95Ω/□）	0.656	9.76	2.43	164	80.09	20.99

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③ Bifacial Solar Cells

Bifacial history

YINGLI SOLAR
PVG Solutions
bSolar The Bifacial PV Cell Company
LG Electronics

2016–2017
乐叶光伏 LERRI Solar
SolarWorld REAL VALUE
Trinasolar 天合光能
JA SOLAR
中来股份 JOLYWOOD

1974-2000 Russian space applications

2010+ first bifacial cell production

2015 in production
MISSION SOLAR ENERGY
MegaCell

1954 bifacial n-type IBC

Gerald Pearson, Darryl Chapin, and Calvin Fuller testing their silicon solar cell.

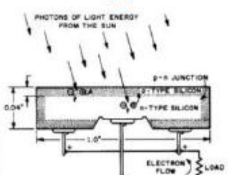


Fig. 2. Schematic of early silicon solar cell [8].
Cross section of the first cell:
- Arsenic-doped n-type base
- Boron-doped emitter

1998 bifacial installations Nordmann in Switzerland

2000+ bifacial concepts
UKN- POWER 2001
ISFH- OEKO 2003
ANU- SLIVER 2003
ECN- n-PASHA 2007
ISC- FOXY2007
and other

2013 large bifacial installations in Japan

Hokuto Solar Power Plant
(World largest bifacial plant)

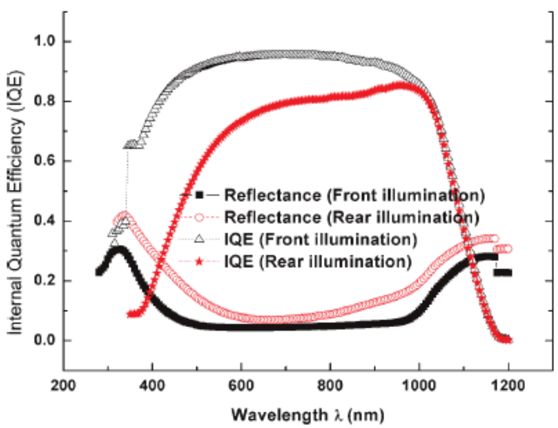
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2011; **19**:275–279

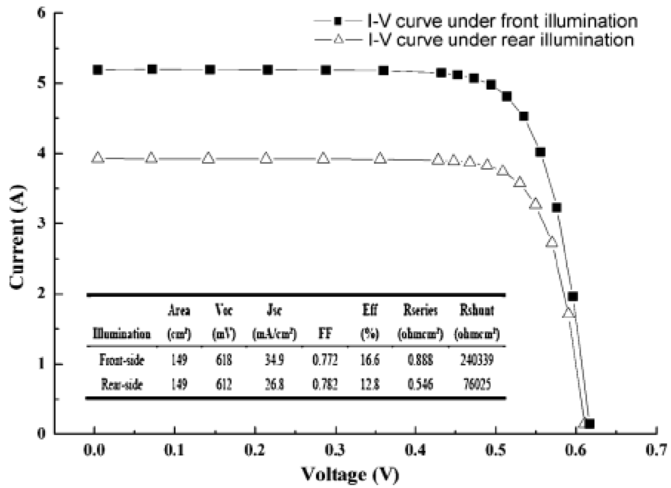
RESEARCH ARTICLE

High efficiency screen printed bifacial solar cells on monocrystalline CZ silicon

L. Yang[1]*, Q.H. Ye[1], A. Ebong[2], W.T. Song[3], G.J. Zhang[3], J.X. Wang[3] and Y. Ma[3]

[1] Solar Energy Institute of the Physics Department, Shanghai Jiao Tong University, Shanghai, PR China
[2] University Center of Excellence for Photovoltaic Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology, 777 Atlantic Drive, Atlanta, GA 30332-0250, USA
[3] Solarfun Co., Ltd, Linyang Road 666, Qidong, Jiangsu, China

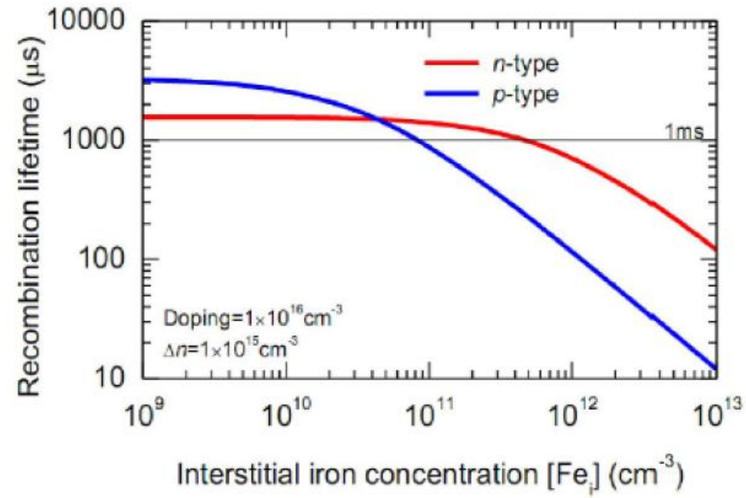


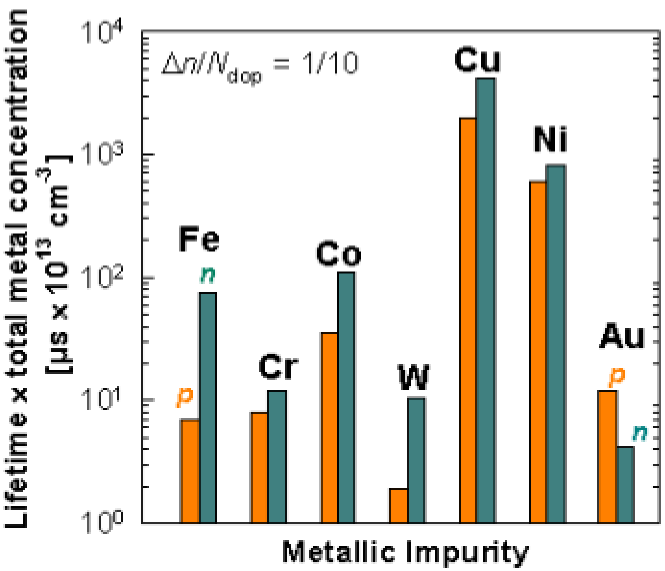


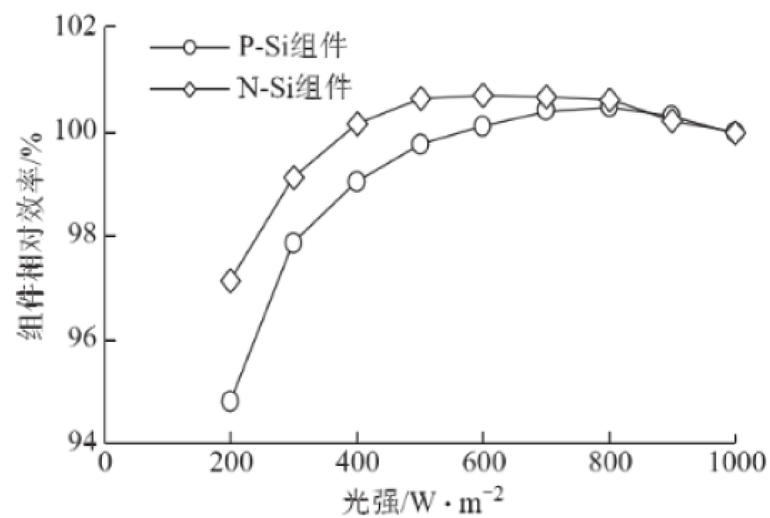
Illumination	Area (cm²)	Voc (mV)	Jsc (mA/cm²)	FF	Eff (%)	Rseries (ohmcm²)	Rshunt (ohmcm²)
Front-side	149	618	34.9	0.772	16.6	0.888	240339
Rear-side	149	612	26.8	0.782	12.8	0.546	76025

Advantages of n-type Si

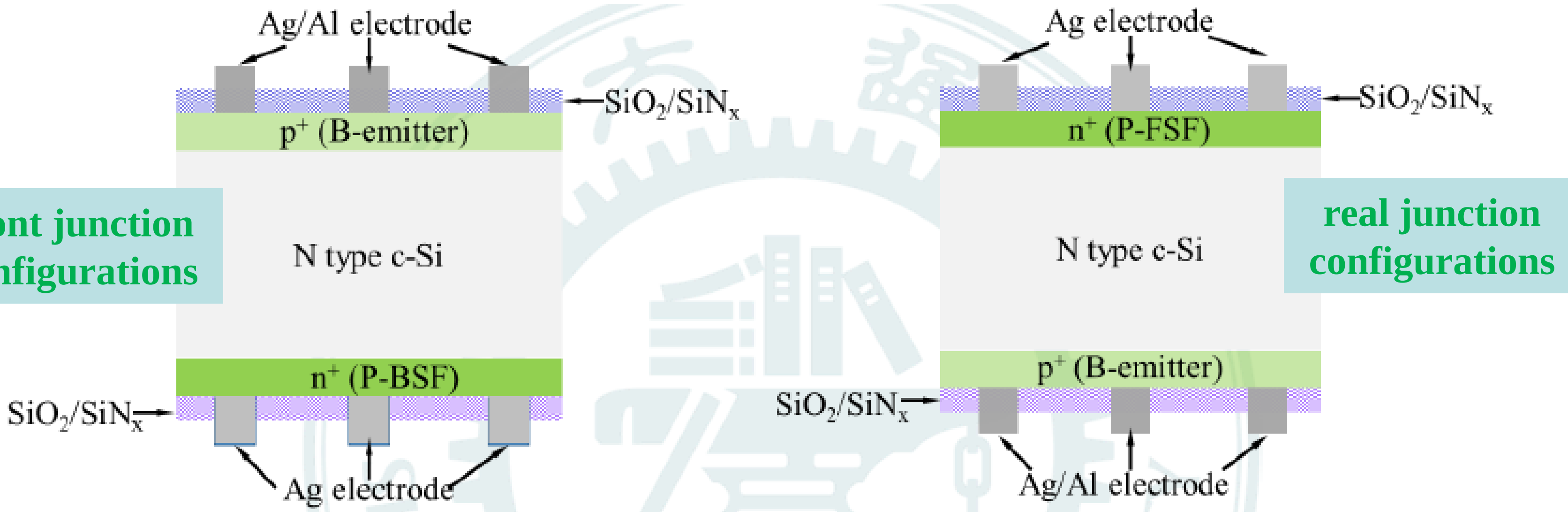
- Higher minority carrier lifetime
- More tolerable to metal impurities
- No LID
- Better weak light performance







Main technologies



结的制备方式	优点	缺点
BBr_3+$POCl_3$	现有设备利用率高	工艺复杂，有绕镀现象
BBr_3+P implantation	工艺简单，选择性掺杂	需设备投入
B-Spin On+$POCl_3$	现有设备利用率高	浆料成本高，均匀性难
BSG APCVD	可共扩散，均一性好	APCVD维护周期短，量产化需进一步改进

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Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
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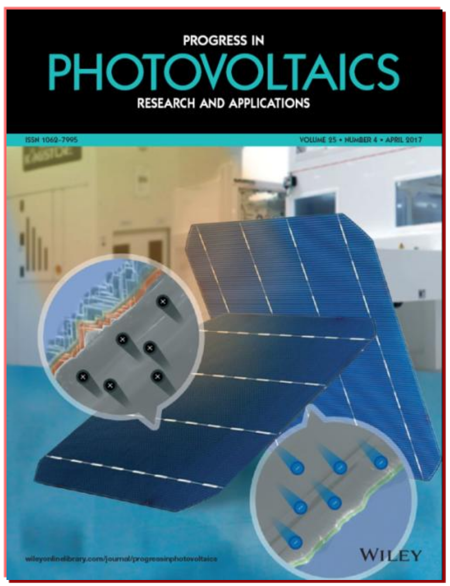
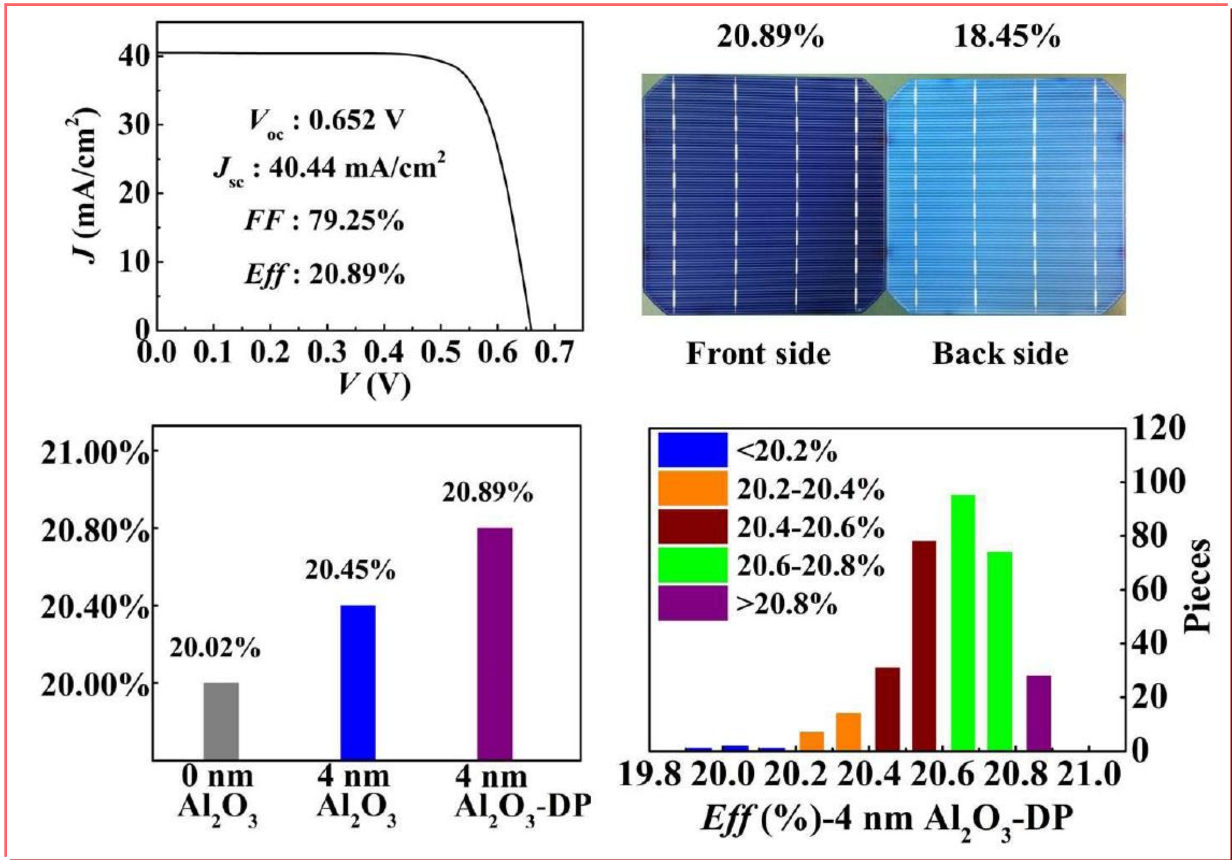
- **BBr_3 diffusion + P ion-implantation**

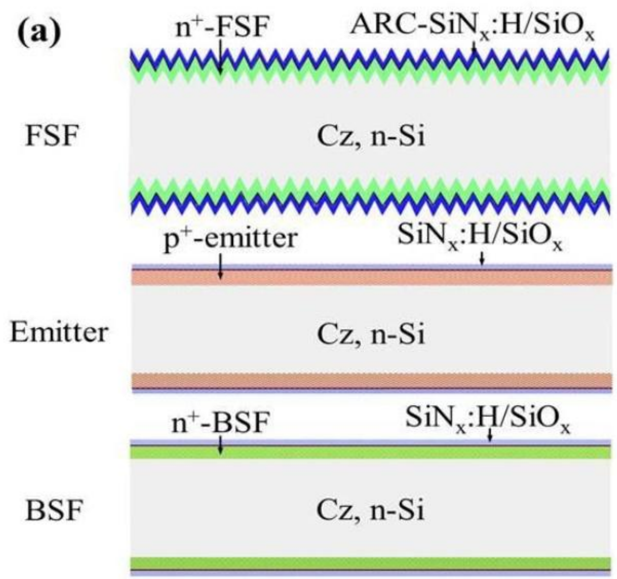
  (simplify the process flow and mass production in 2015)

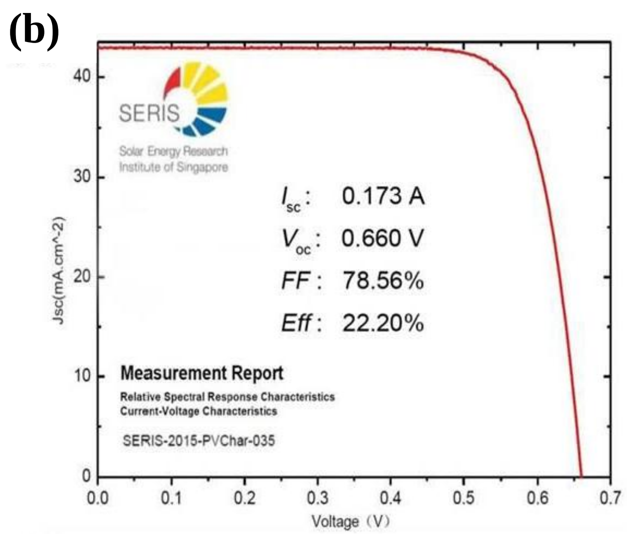
- **ALD Al_2O_3 + PECVD SiN_x:H FSF passivation** （2015）

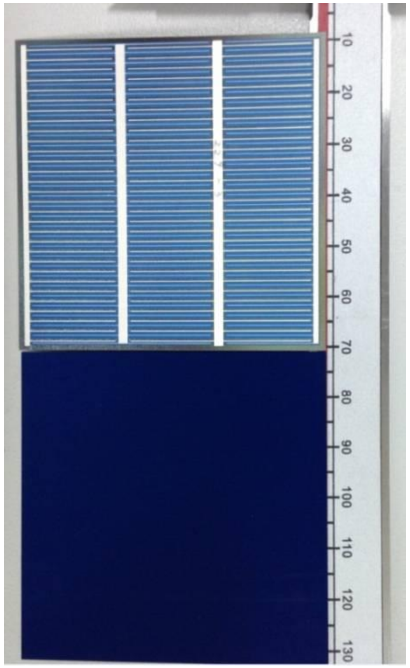


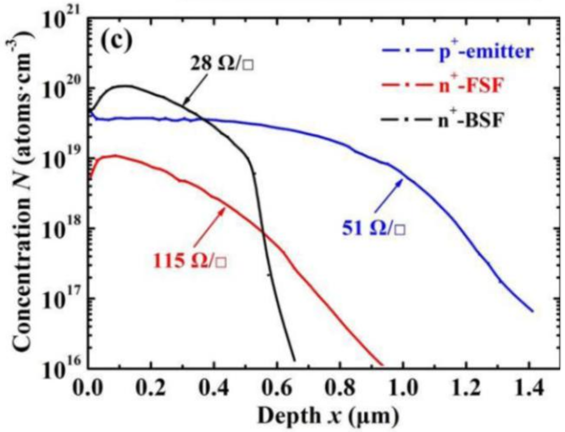


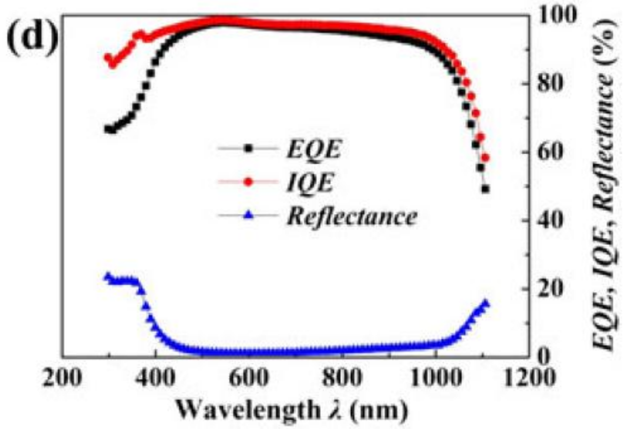
④ BJBC: P ion-implantation + BBr_3 diffusion with *Eff* > 22%

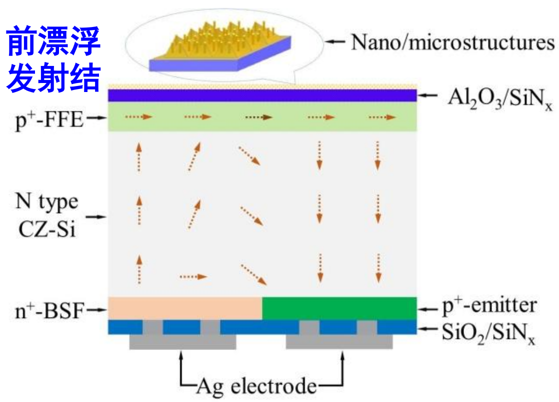






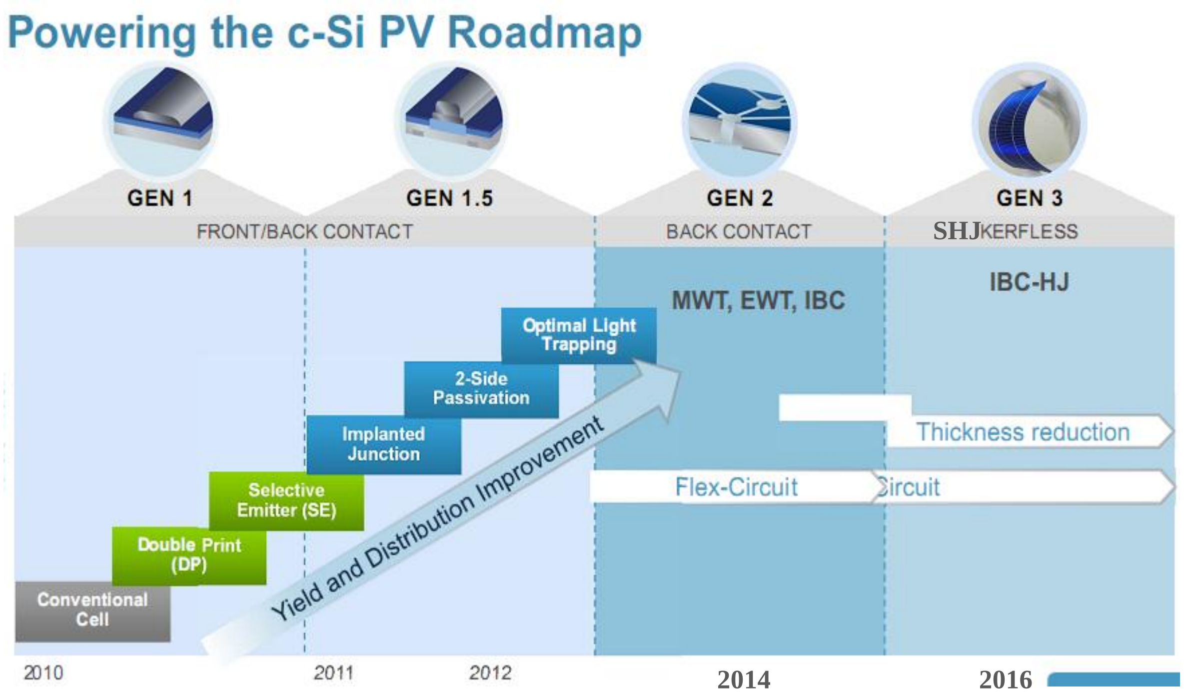






Prog. Photovolt.: Res. Appl. **25**, 441-451 (2017)

⑤ Silicon Heterojunction Solar Cells for Efficiency over 22%



Wenzhong Shen and Zhengping Li, *Physics and devices of silicon heterojunction solar cells*, Scientific Press, 2014, Beijing, ISBN: 978-7-03-041514-1.

科学出版社，2014年度国家科学技术学术著作出版基金资助

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

GCL

Complete Pilot Line of Heterojunction Solar Cells

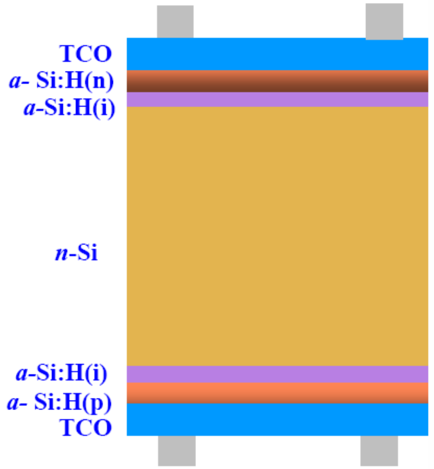
Texture

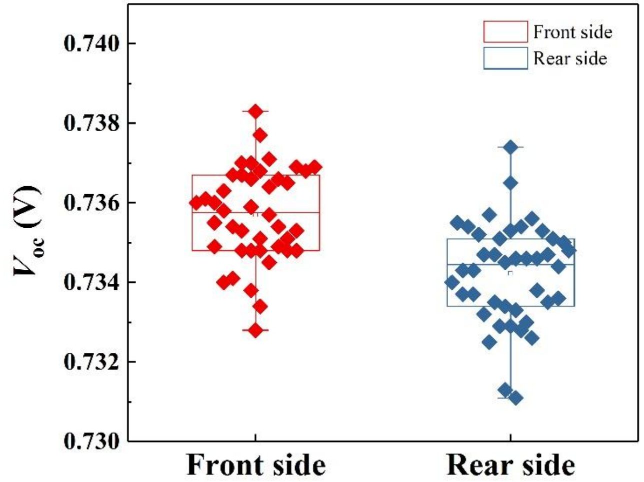
PECVD

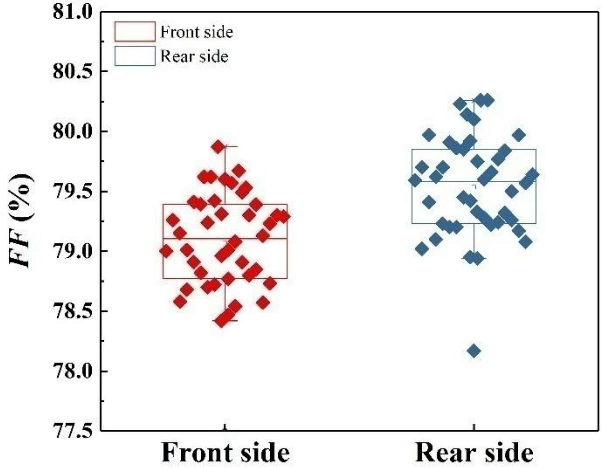
RPD

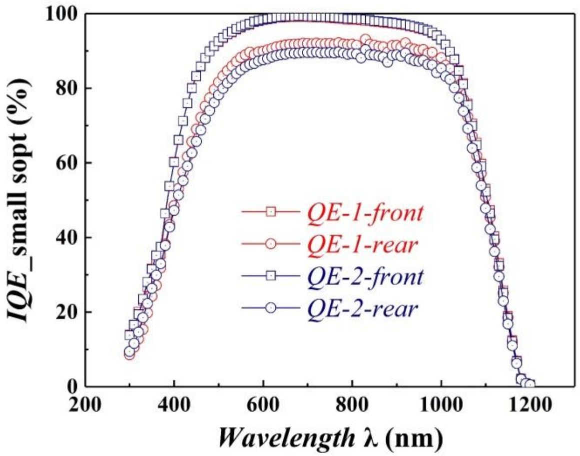
Screen Printing

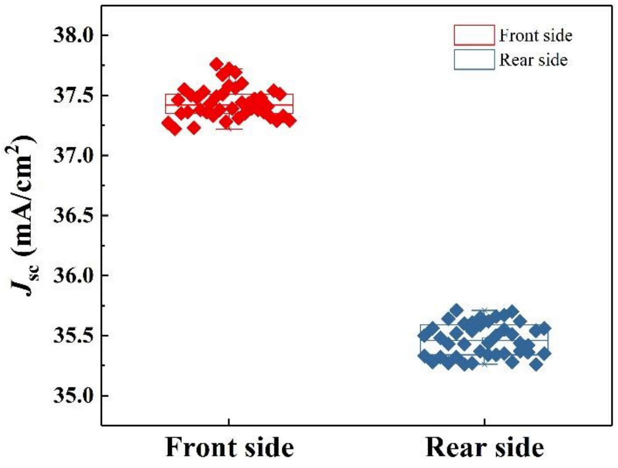
n-SHJ双面电池技术 (Bifaciality 95%+)

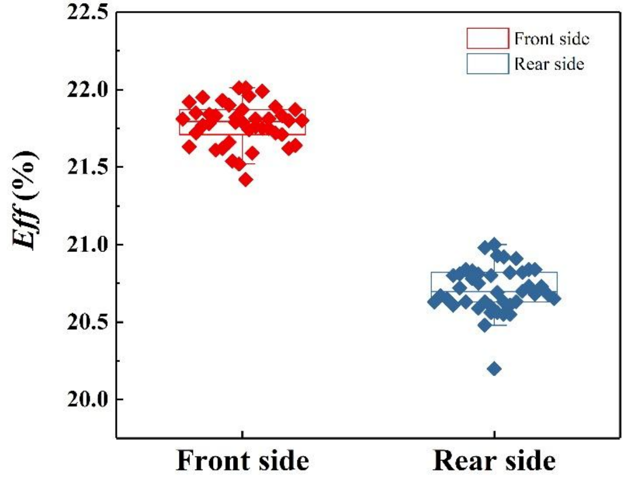








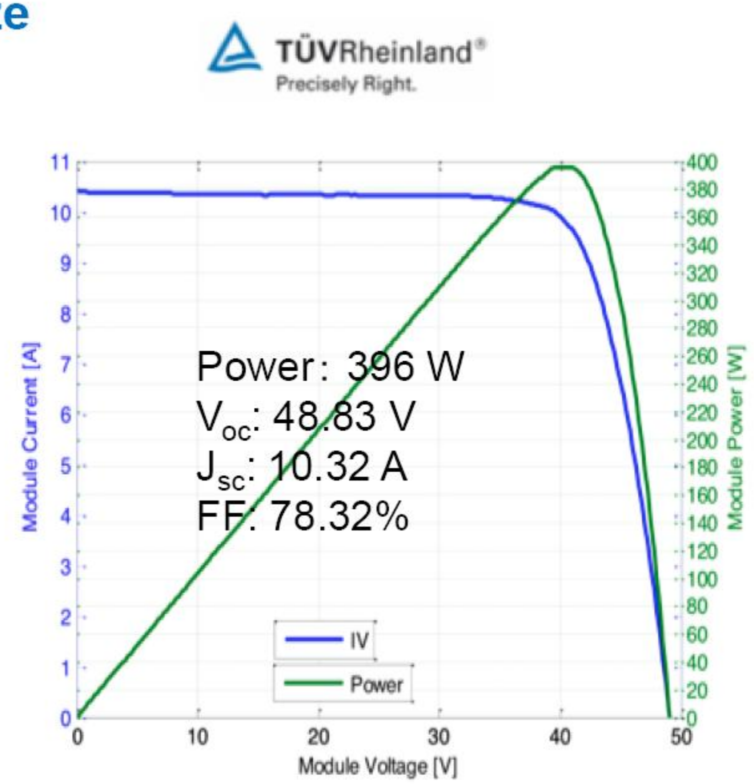




High density high power module

Normal 72 cell size

HD Module



reduce electrical loss

160MWp mass production under way (2017)

⑥ Ultrathin c-Si solar cells (<50μm)

Advantages:

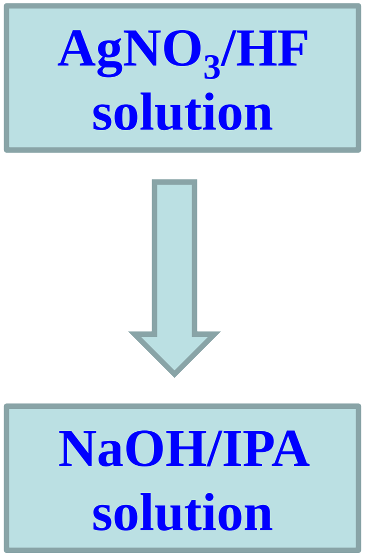
- ✓ Lower consumption of c-Si materials, thus lower cost;
- ✓ Have a potential to higher Voc;
- ✓ Lower requirement for Si quality;
- ✓ Flexible.

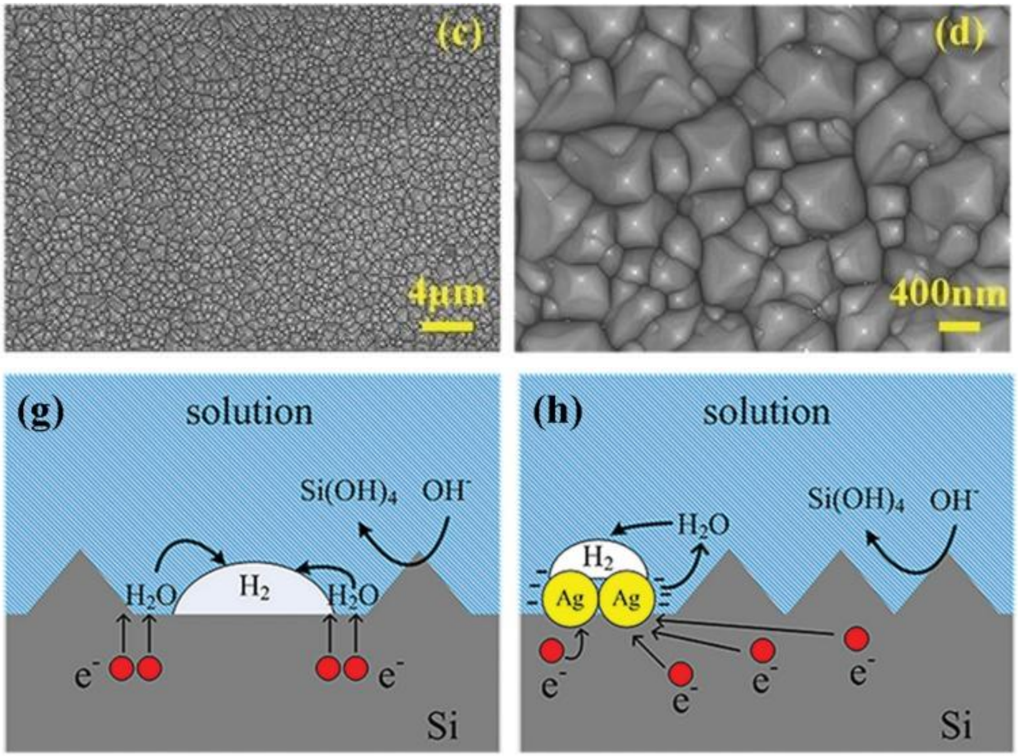
Disadvantage:

- ✓ As an indirect band gap material, ultrathin c-Si solar cells may easily suffer from poor light absorption, which results in low photocurrent.

Light management is extremely important in ultrathin c-Si solar cells!

All-solution-processed nanopyramids for ultrathin c-Si





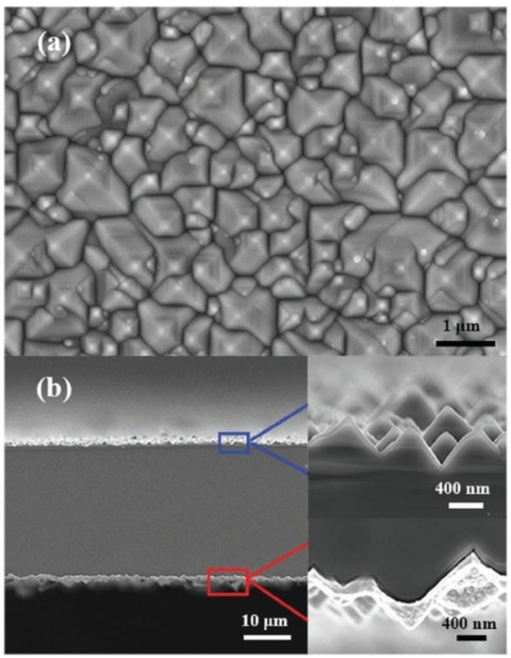
- Two steps: (1) depositing Ag nanoparticles in $AgNO_3$ solution; (2) etched in alkaline solution.
- Free of lithography or ion etching process, it is an all-solution process. The technique to form Si nanopyramids is very easy and cheap.
- The success of forming Si nanopyramids lies in the transferred generation site of H_2 bubbles.

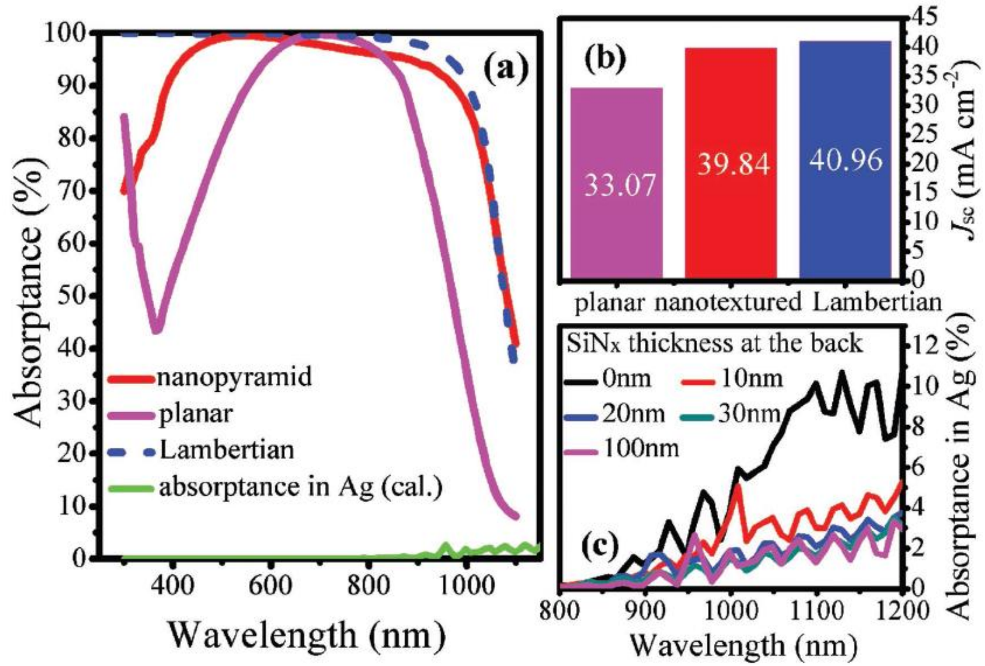
S. Zhong, *et al.*, Adv. Funct. Mater. **26**, 4768 (2016)

Materials Views
www.MaterialsViews.com
ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

All-Solution-Processed Random Si Nanopyramids for Excellent Light Trapping in Ultrathin Solar Cells

*Sihua Zhong, Wenjie Wang, Yufeng Zhuang, Zengguang Huang, and Wenzhong Shen**

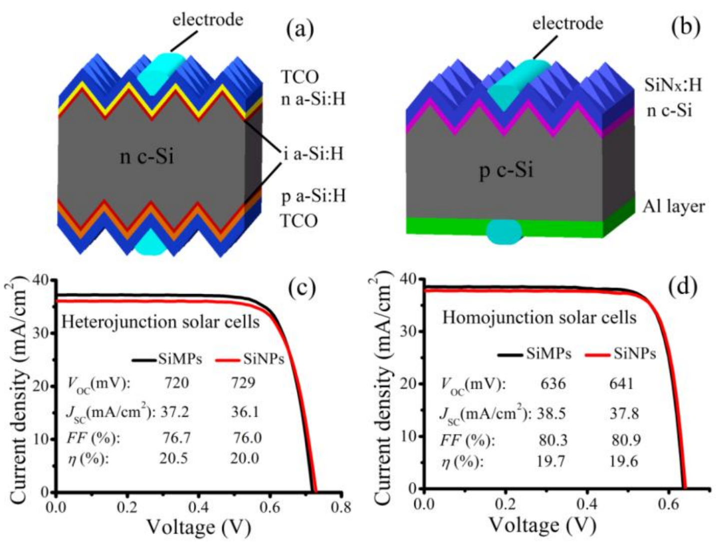


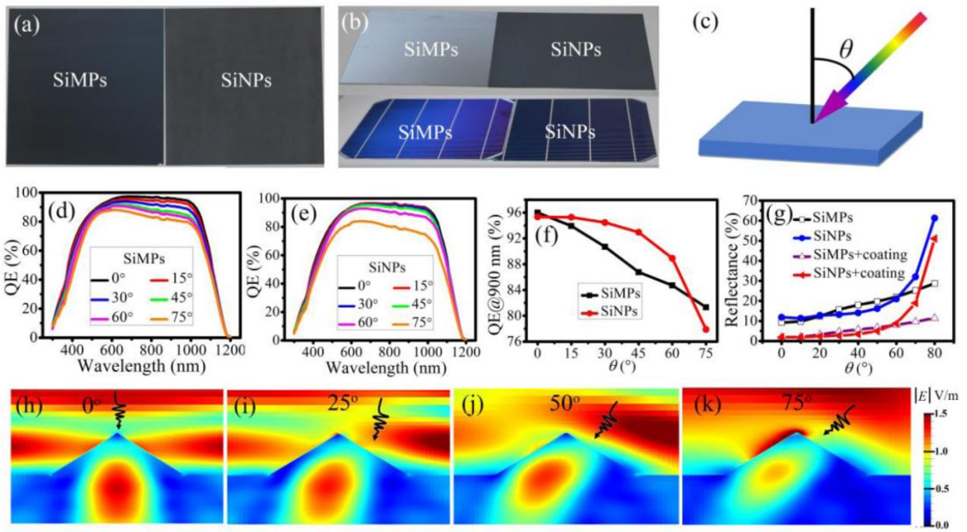


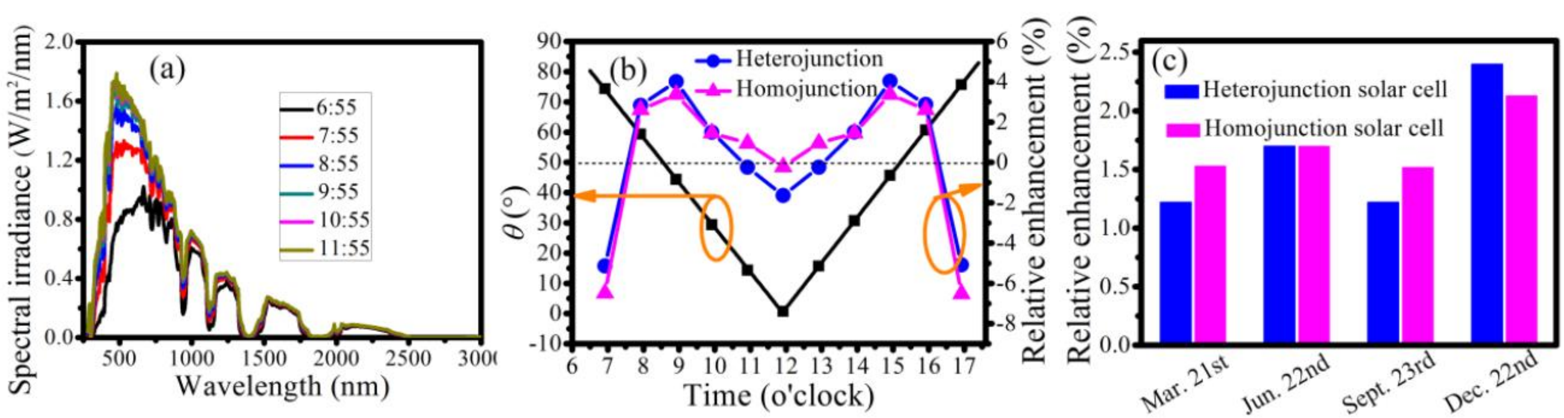
Applying the all-solution-processed nanopyramids to ultrathin c-Si (30μm), near-Lambertian light trapping effect is achieved, the calculated J_{sc} is far higher than that of the planar c-Si.

ADVANCED SCIENCE

Realization of quasi-omnidirectional solar cells with superior electrical performance by all-solution-processed Si nanopyramids







DOI: 10.1002/advs.201700200

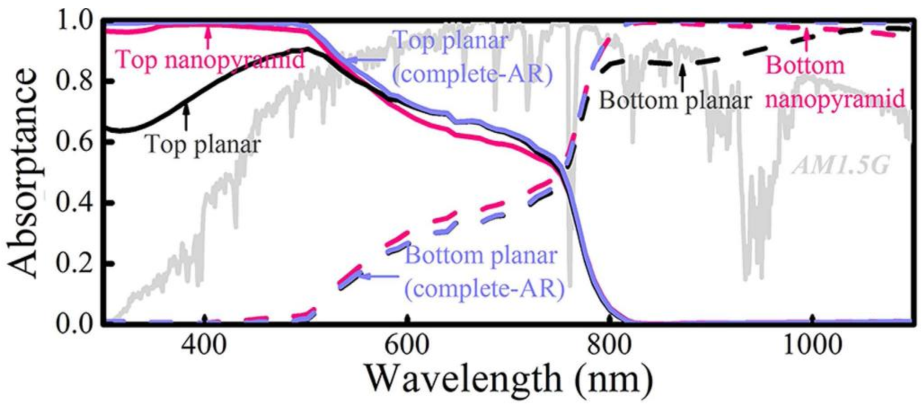
⑦ Perovskite/c-Si tandem solar cells (TSC)

Advantages:

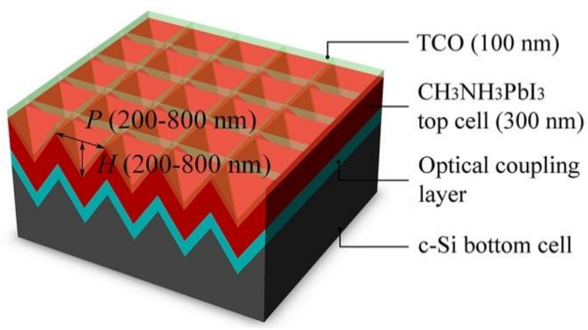
- Potentially surpass the 29.4% S-Q one junction limit
- Effectively harvest entire solar spectrum
- Tunable bandgap energies

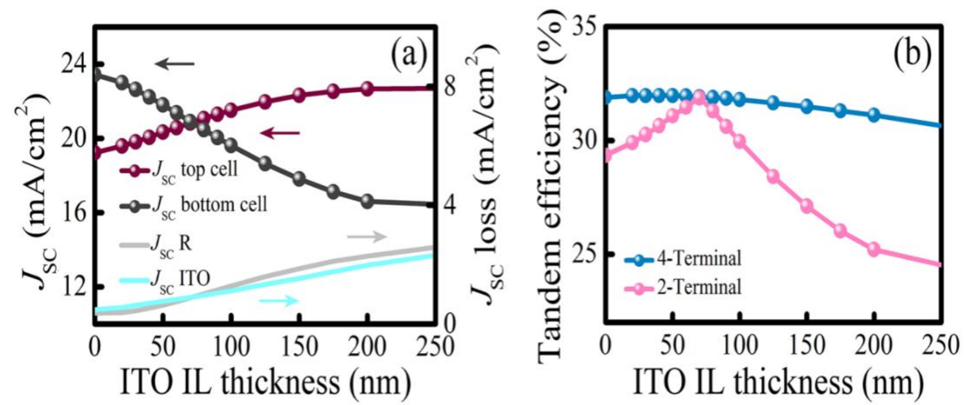
Challenges :

- Light management
- Current matching

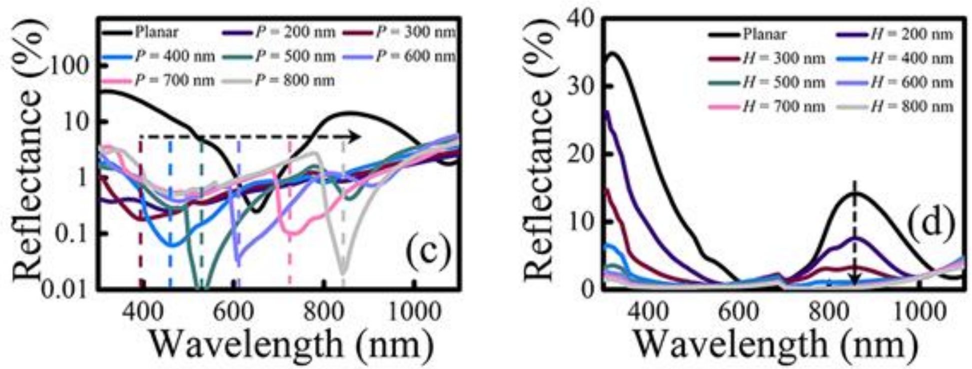


>30% Perovskite/c-Si TSC with varying inverted nanopyramid dimensions



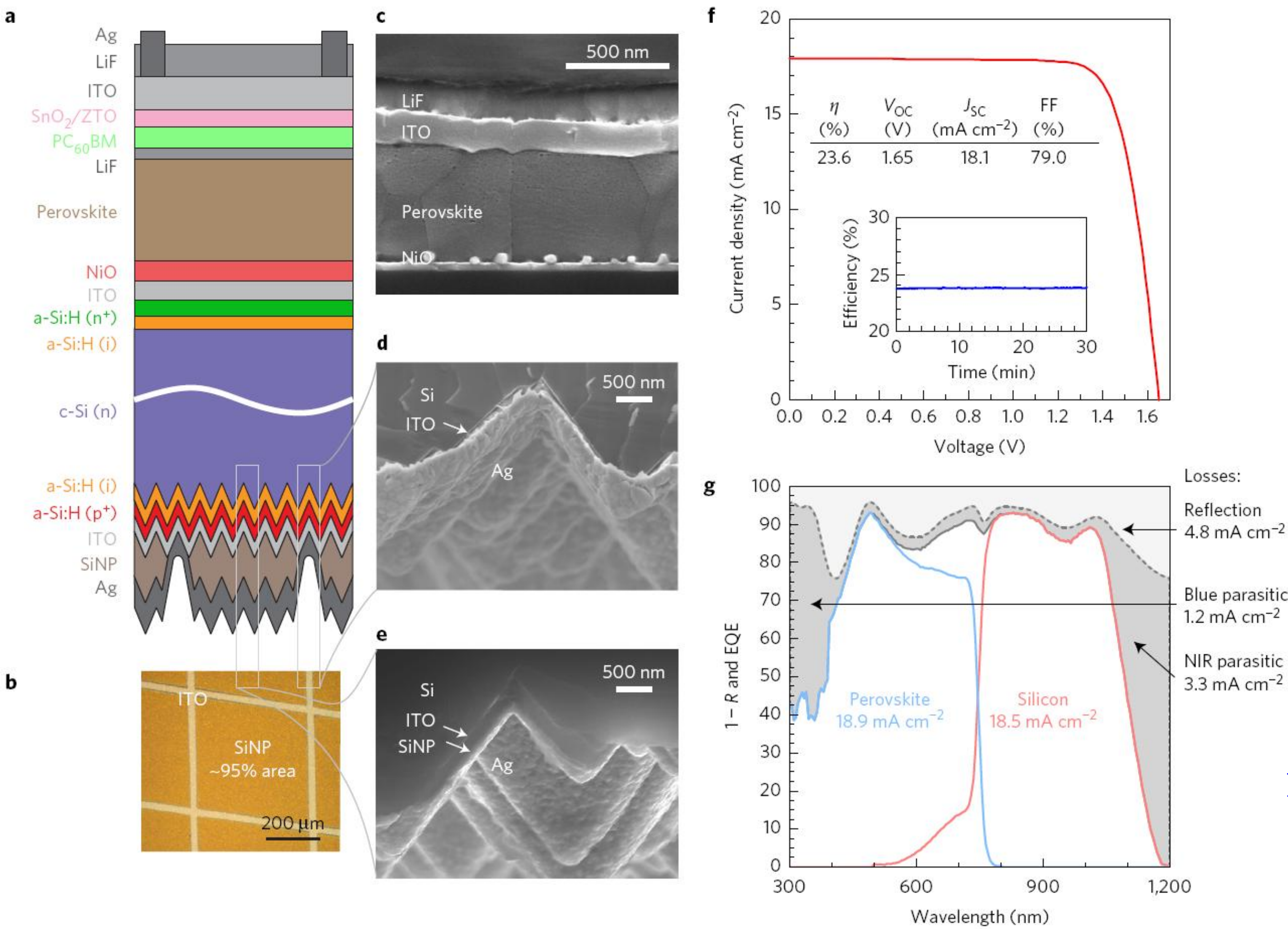


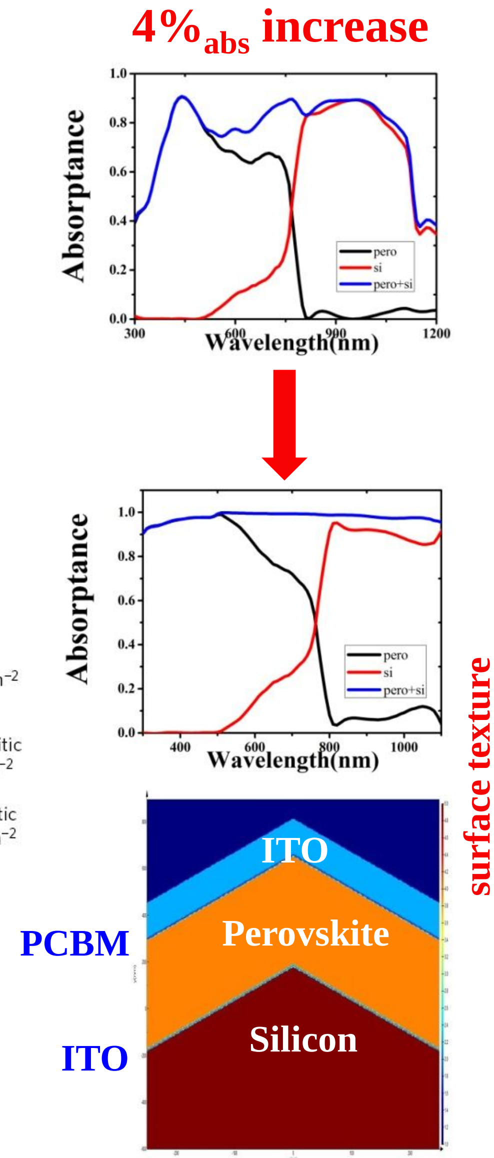
- Ultra-low surface reflectance (<2%) achieved by applying nanopyramid structure
- Optimal current-matching at an ITO thickness of 70nm



D. Shi, *et al.*, Scientific Reports **5**, 16504 (2015)

Best 2-T experimental results so far: 23.6%





K. A. Bush, *et al.*, Nature Energy **2**, 17009 (2017)

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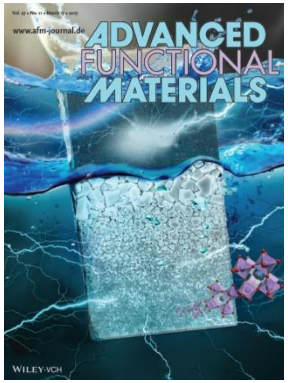
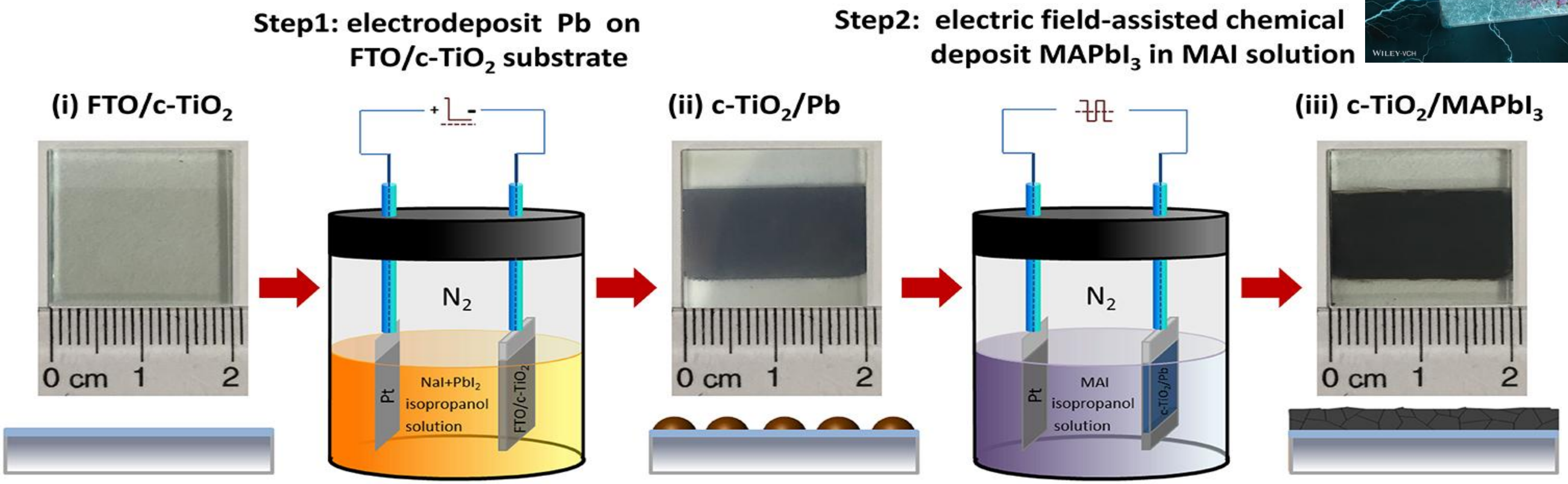
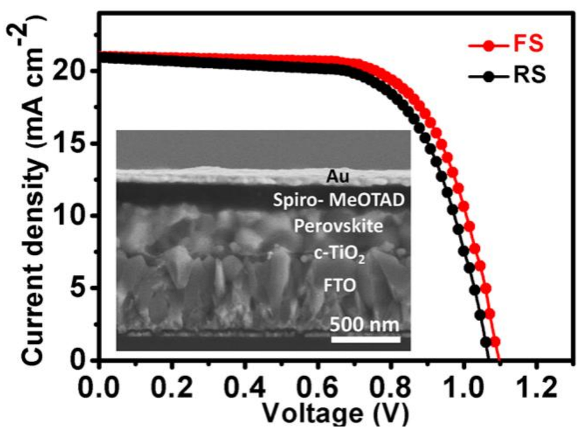
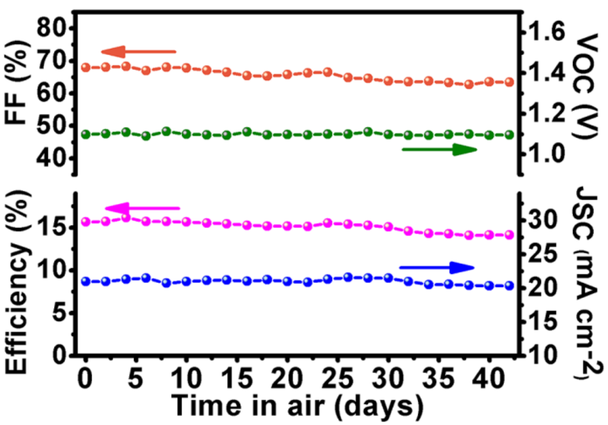


Electric-field-assisted reactive deposition of endurable self-annealing perovskite towards high performance solar cells







- Power conversion efficiency of 15.65%, little hysteresis and *long-time stability* have been achieved.
- Perovskite films *need no additional thermal annealing*, significantly reducing fabrication time.

Adv. Funct. Mater. **27**, 1606156-(1-14) (2017)

大会特色专题 (16 Special Topics in 13th CSPV):

GCL
晶硅材料技术与装备
Silicon Material Technology

LONGi 隆基 乐叶光伏
PERC 技术与应用
PERC Cell Technology and Application

中来股份 JOLYWOOD
N 型电池技术及双面组件应用
N-type Cell Technology and Bifacial Module Application

UNSW THE UNIVERSITY OF NEW SOUTH WALES
Towards 25% Industrial Silicon Solar Cells

ECN
PERC+, n-PERT and Beyond: From Solar Cells to Systems

Trinasolar 天合光能
双面双玻组件技术与应用
Double Glass Bifacial Module Technology and Application

SERAPHIM
先进组件技术与应用
Advanced Module Technology and Application

2017年中国太阳级硅及光伏发电研讨会

13th CSPV

2017年11月16–18日 中国 · 徐州

领跑+长跑—光伏关键辅材技术与应用
PV Auxiliary Material Technology and Application

高可靠封装材料
Highly Reliable Module Encapsulating Materials

分布式户用光伏发电系统
Distributed PV Generation System

跟踪系统技术与应用
Tracking System Technology and Application

储能+能源互联网应用
Energy Storage + Internet Application

屋顶分布式专题暨第六届蓝天实验者光伏高能会
Roof Distributed PV Application

光伏绿色智能制造
PV Intelligent Manufacturing

户外实证检测与认证
Outdoor Testing and Certification

新一代太阳电池技术和计量
New Generation Solar Cell Technology and Metrology

上海交通大學
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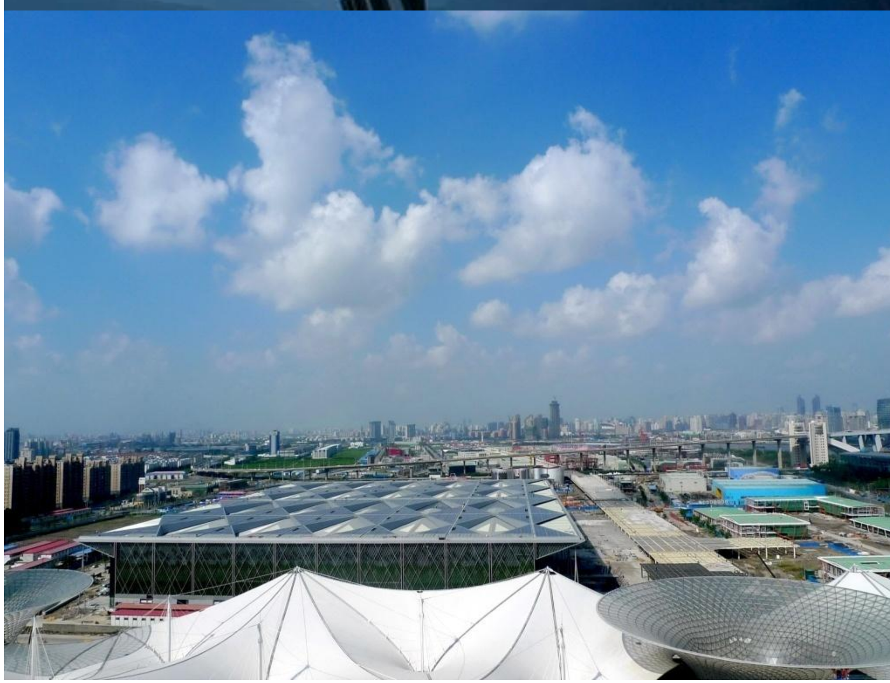

Let Sunlight Chang Life！

Thank you！