Architectures for high-efficiency crystalline silicon solar cells

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Photovoltaic Materials and Devices group

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PVMD Delft University of Technology

TU Delft

Outline

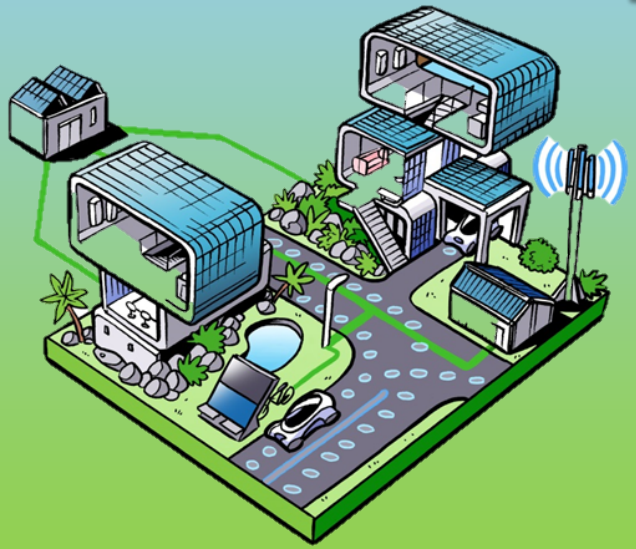
- Introduction
  - Photovoltaic Materials and Devices group
  - c-Si wafer-based PV technology
- c-Si solar cells @PVMD
  - Structures for minimizing recombination
  - Performance optimization using modelling
  - Poly-c-Si(O_x) carrier-selective contacts
- Summary

Photovoltaic Materials and Devices

group

PVMD leading strategy

Photovoltaics everywhere



PVMD group: People

- **3 Full professors** (Miro Zeman, Arno Smets, Arthur Weeber)
- **2 Associate professors** (Rene van Swaaij, Olindo Isabella)
- **2 Technical staff** (Martijn Tijssen, Stefaan Heirman)
- **1 Secretary** (Ilona van der Wenden)
- **4 PostDoc**
- **14 PhD students**
- **25-35 MSc diploma students**
- **1 visitor / trainee**

Total: ~ 50-60 members

PVMD
Delft University of Technology


Miro Zeman


Arno Smets


Arthur Weeber


Rene van Swaaij


Olindo Isabella


Martijn Tijssen

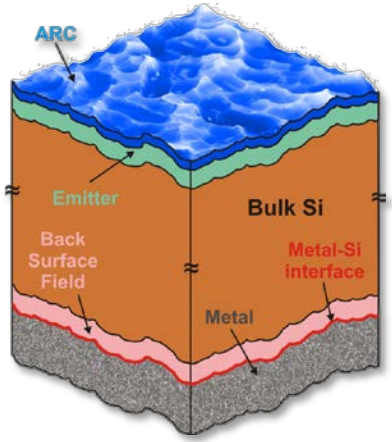

Stefaan Heirman


Ilona vd Wenden

PVMD group: Research areas

c-Si solar cells

Large-scale cost-effective electricity generation



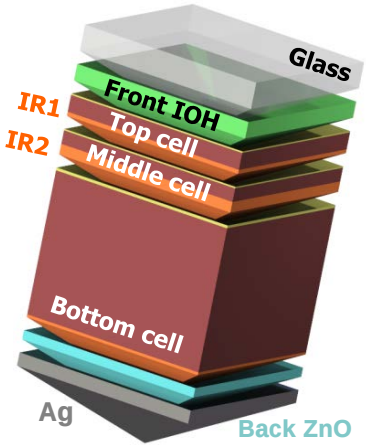
PV systems

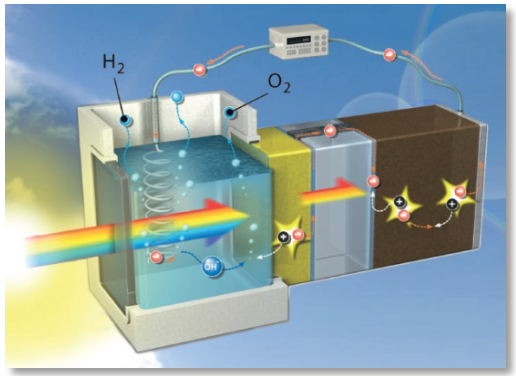
New applications for increased penetration of PV

TF solar cells

(TF-Si, CIGS, Hybrid)

Testbed for innovation & new applications





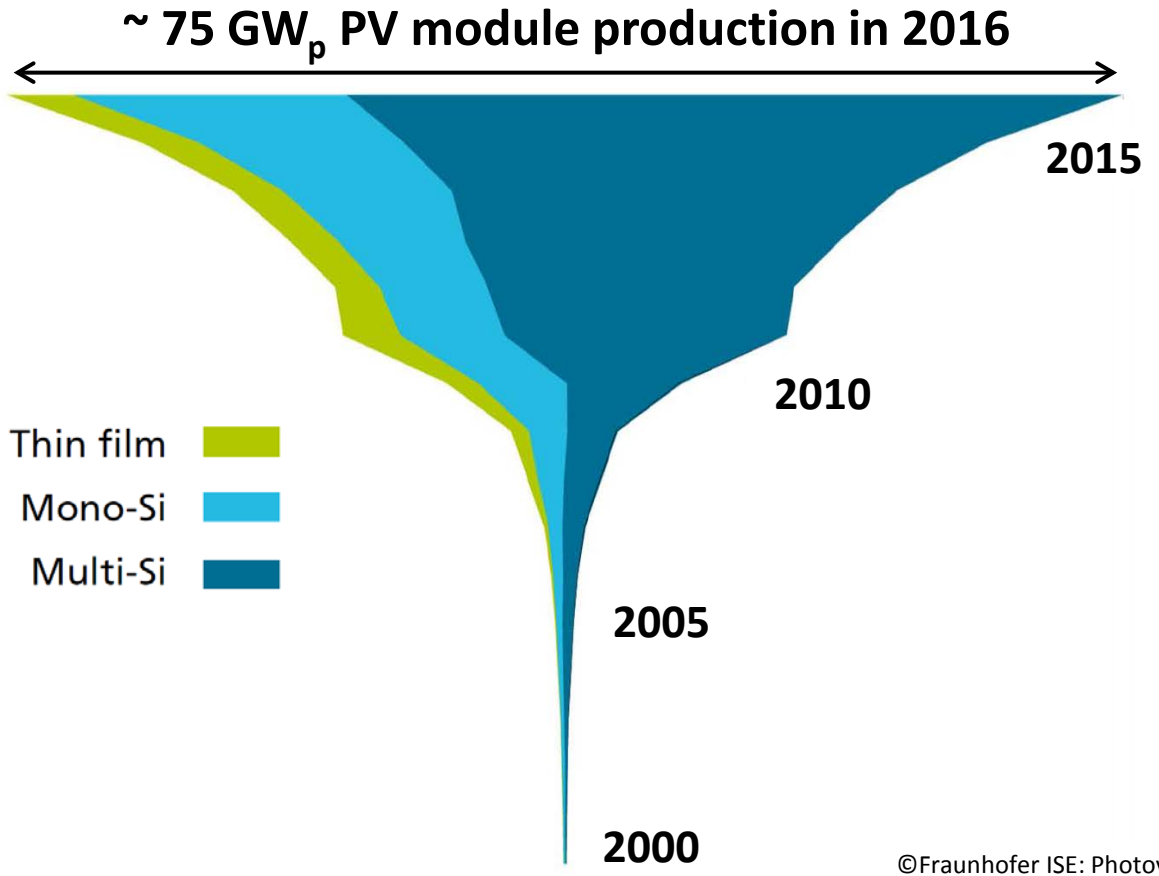
Solar fuels

Storage for abundant solar electricity

Solar water cleaning

c-Si wafer-based PV technology

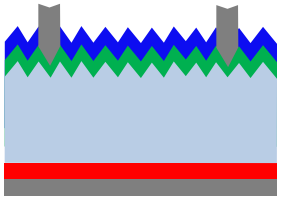
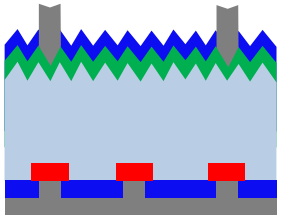
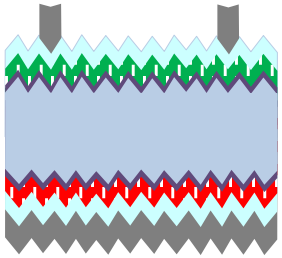
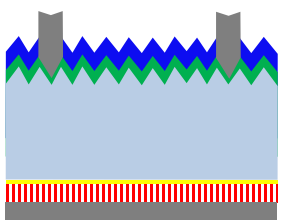
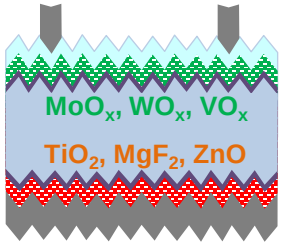
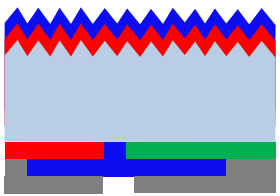
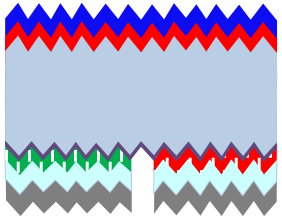
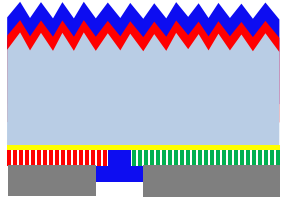
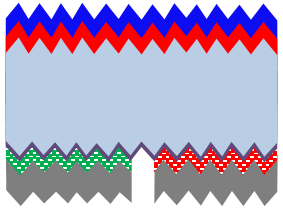
Commercial PV technologies



c-Si wafer-based PV technology

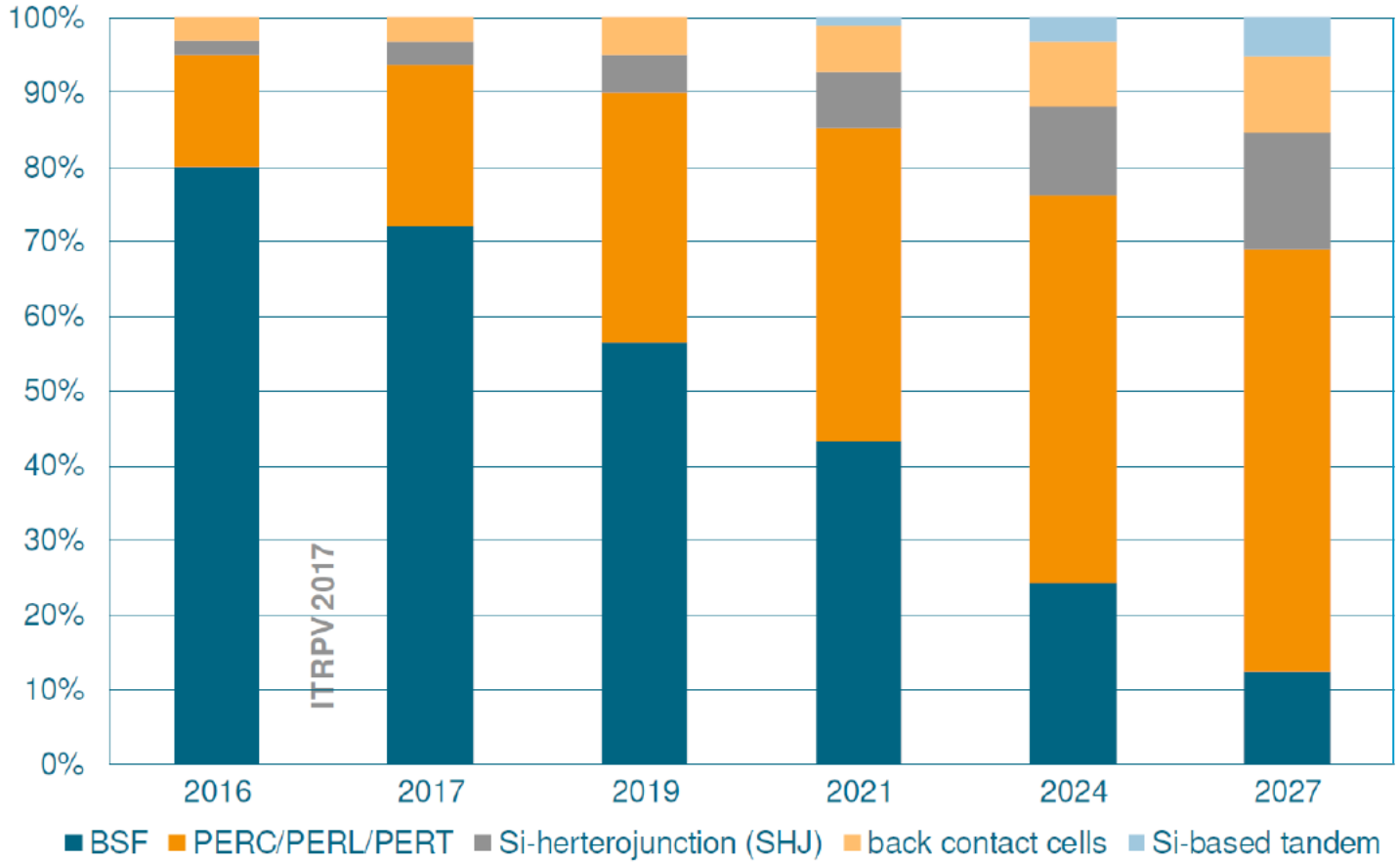
http://es.memegenerator.net/instance/59530172/good-news-everyone-good-news-everyone-im-still-alive-and-kicking

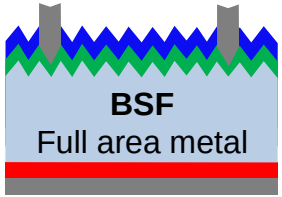
c-Si wafer-based solar cells

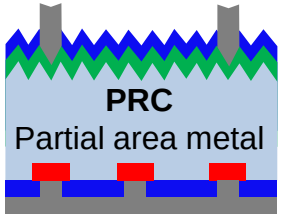
Contacts	HOMO-junction		HETERO-junction / carrier-selective contacts		
			Si Heterojunction	Poly c-Si(O_x)	Doping free
Front and Back Contacted Fully or partially metal covered back-side	 Full-area M/S	 Partial-area M/S			
Interdigitated Back Contacted					

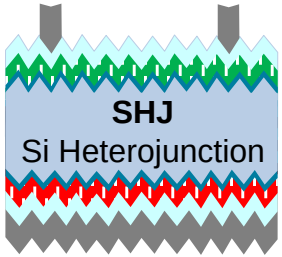
c-Si surface field
a-Si:H surface field
poly-Si(O_x) surface field
c-Si emitter
a-Si:H emitter
poly-Si(O_x) emitter
Doping free hole collector
Doping free electron collector
Tunneling oxide
i-aSi:H
Passivation layer
TCO
Metal

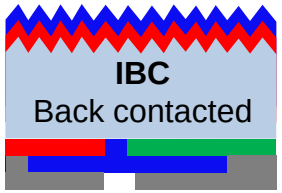
Trend in c-Si PV technology









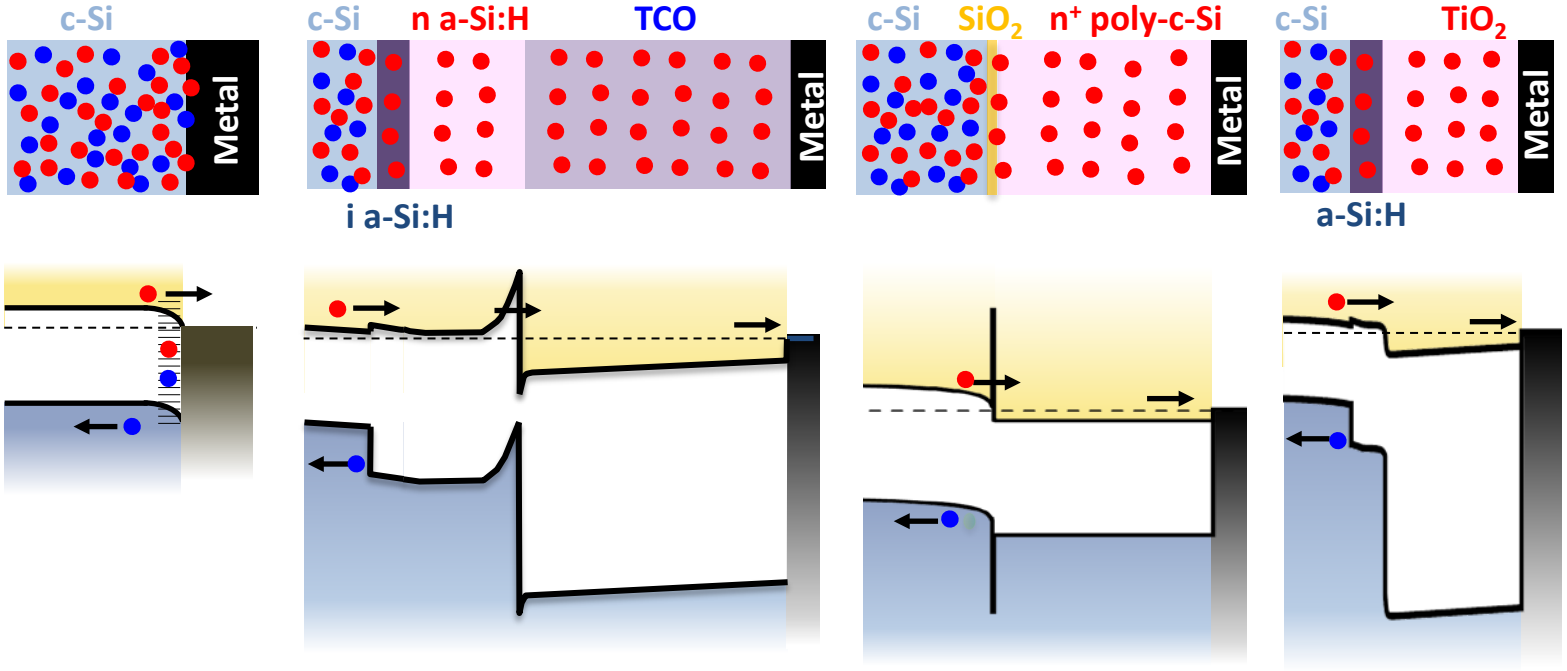


International Technology Roadmap for Photovoltaics, Eight Edition (2016)

c-Si solar cells @PVMD

Minimizing recombination

c-Si wafer-based solar cells



$J_{0,contact}$	High → low V_{oc}	Low → High V_{oc}	Low → High V_{oc}	Low → High V_{oc}
$\rho_{contact}$	Low → High FF	Low → High FF	Low → High FF	Low → High FF
Parasitic absorption	High free Carrier	Absorption	Low absorption	Low/no absorption
Thermal stability	High	Low	High	Low

c-Si wafer-based solar cells @PVMD: Supporting films

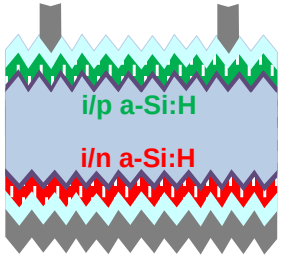
Thermal budget	low		high
Category	**Metal oxides / Organics**	**Si:H alloys**	**Poly c-Si alloys**
Electron selective	TiO_2, LiF_x Cs_2CO_3, PCBM	n^+ a/µc-Si(O_x) :H n^+ a/µc-Si(C_x) :H	n^+ poly-c-Si n^+ poly-c-SiO_x n^+ poly-c-SiC_x
Hole selective	MoO_x, WO_x, VO_x P3HT, PEDOT:PSS	p^+ a/µc-Si(O_x) :H p^+ a/µc-Si(C_x) :H	p^+ poly-c-Si p^+ poly-c-SiO_x p^+ poly-c-SiC_x
Interface layer	a-Si:H, a-SiC:H, a-SiO:H; high band-gap dielectrics (SiO_2, HfO_x, AlO_x,…)		

PVMD.TUDelft.nl	MoO_x, TiO_2	HTJ	doped poly-c-Si doped poly-c-SiO_x

c-Si wafer-based solar cells @PVMD

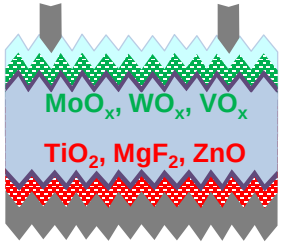
FBC

Si heterojuncton

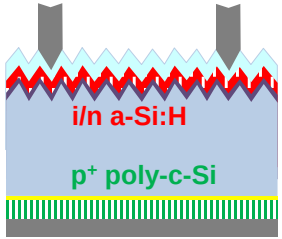


η = 20.8%

Doping free collector

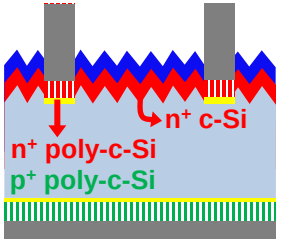


Hybrid
HJ/poly-c-SiOx



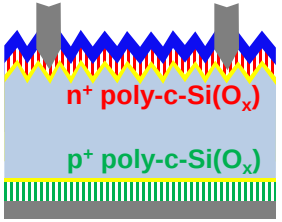
η = 21.0%

PERFECT
Homo/poly-c-Si(Ox)



η = 20.1%

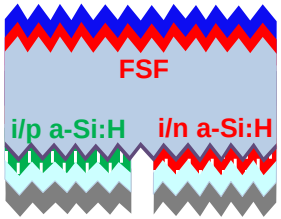
Poly-c-Si(Ox)



η = 19.5%

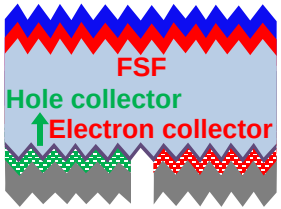
Temperature

Si heterojuncton

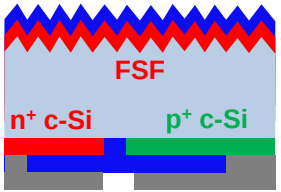


η = 15.5%

Doping free collector

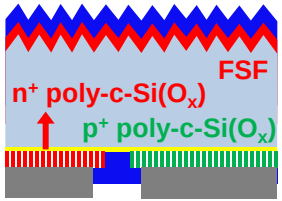


Homo-junction



η = 20.2%

Poly-c-Si(O)x



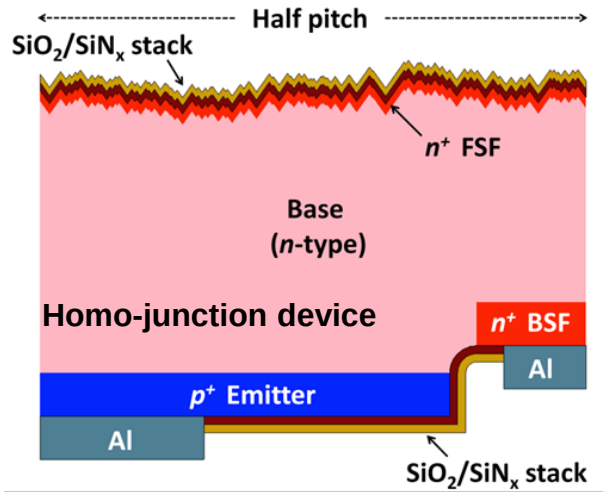
η = 23.0% (2cm²)

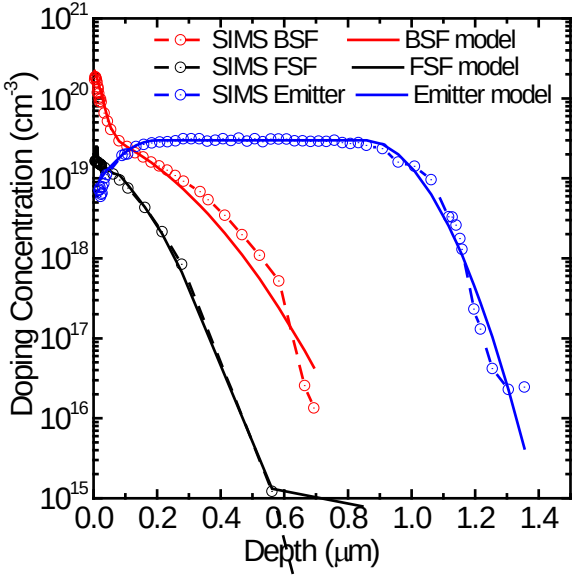
c-Si solar cells @PVMD

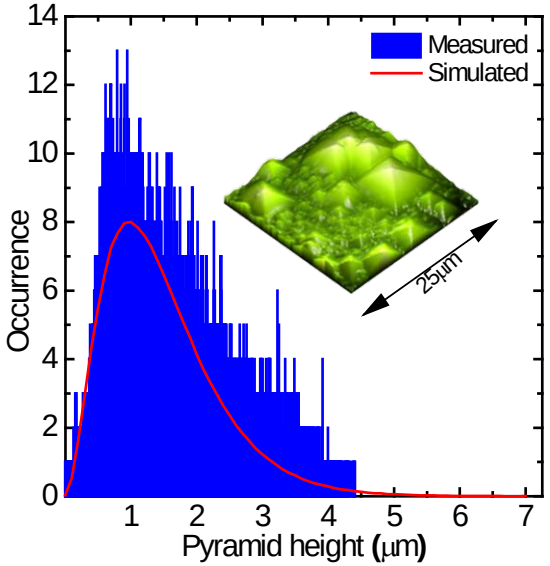
Modelling

Advanced opto-electrical modelling [1]

Device structure + input parameters



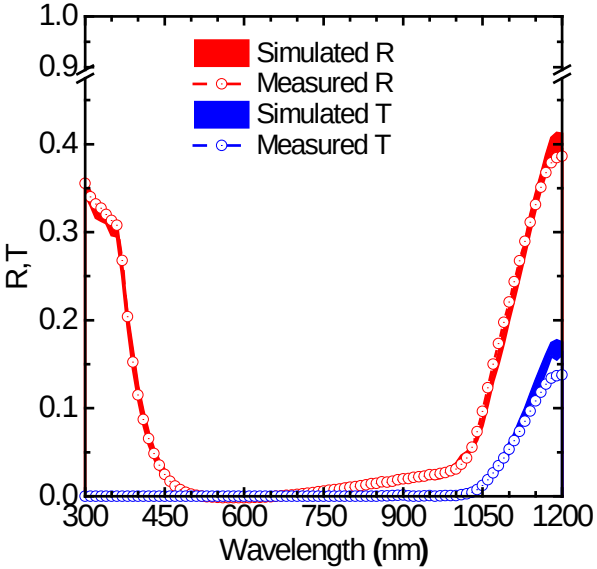


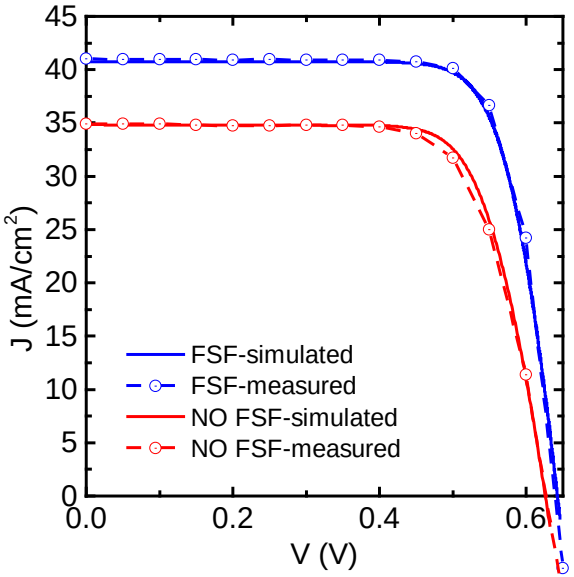


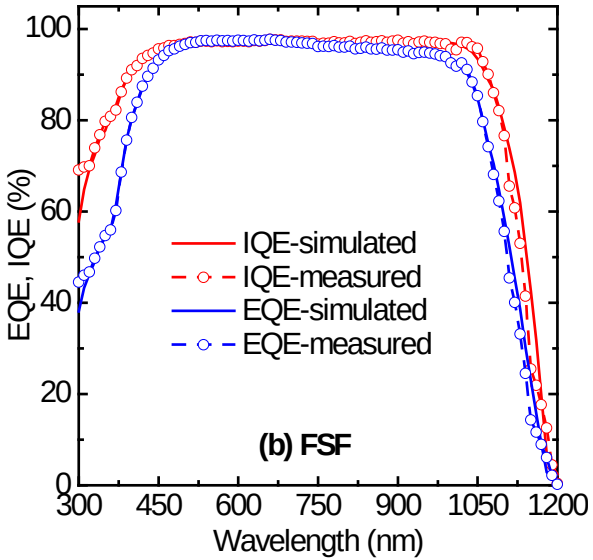
[1] P. Procel, et al., PiP 10.1002/pip.2874 (2017)

Advanced opto-electrical modelling [1]

Model validation



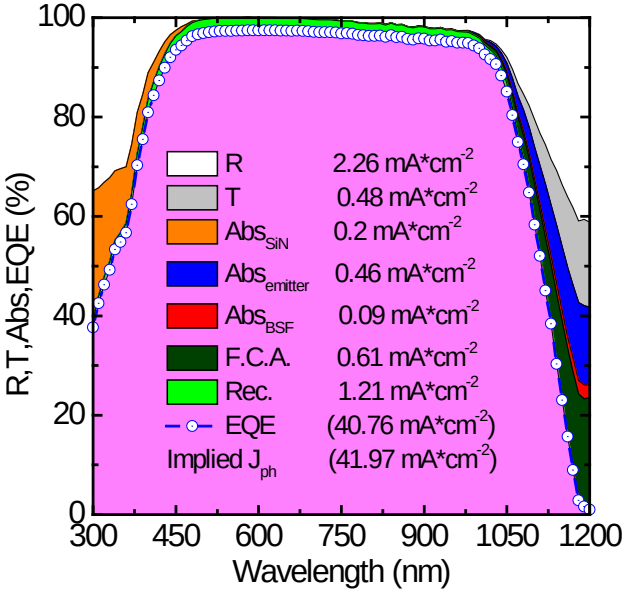




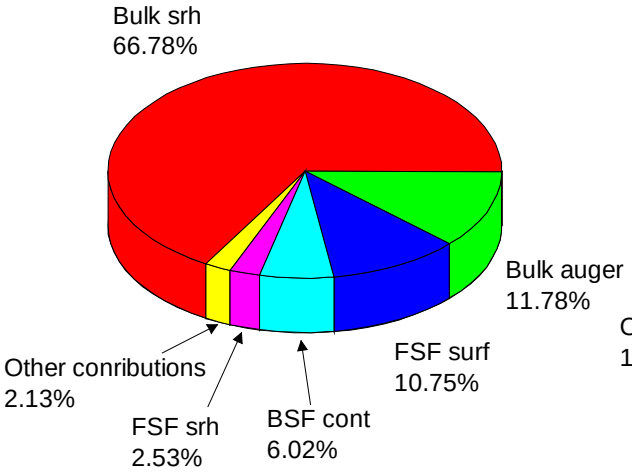
[1] P. Procel, et al., PiP 10.1002/pip.2874 (2017)

Advanced opto-electrical modelling [1]

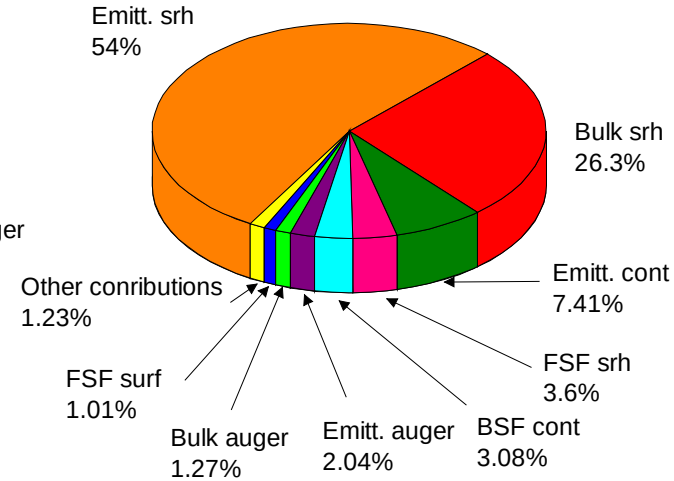
Performance analysis



J_{rec}=1.21 mA/cm^2



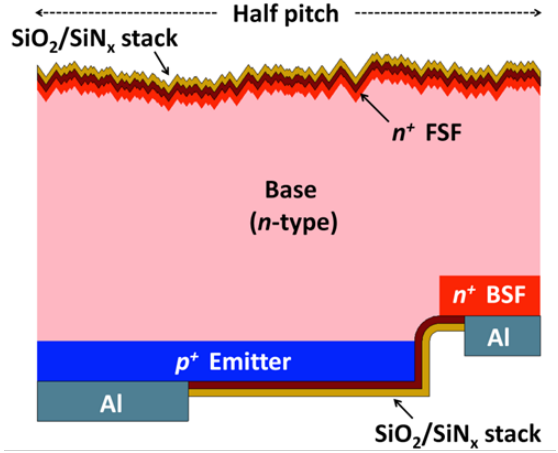
J_o=743 fA/cm^2



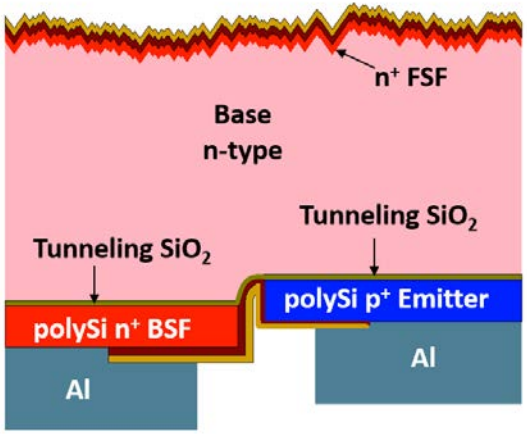
[1] P. Procel, et al., PiP 10.1002/pip.2874 (2017)

Advanced opto-electrical modelling [1]

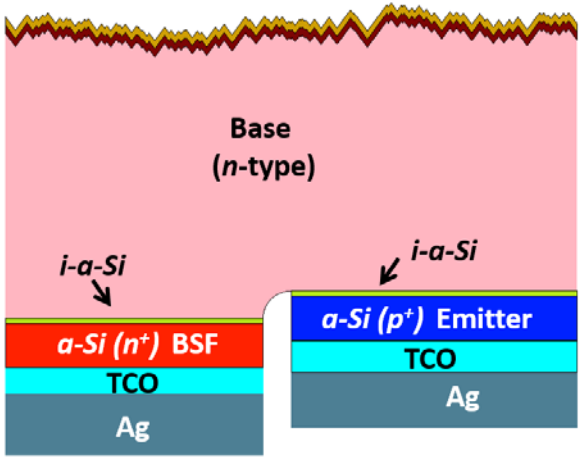
Performance optimization



Homo-junction
optimized design
η=23%



Passivated poly-c-Si
optimized design[2]
η=27.1%



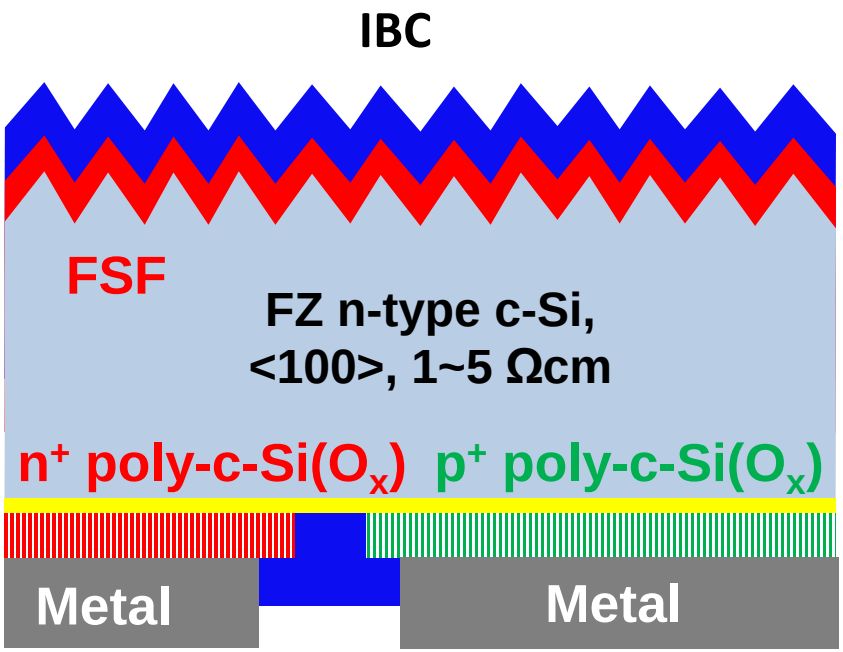
Silicon Hetero-junction
optimized design[3]
η=27.1%

[1] P. Procel, et al., PiP 10.1002/pip.2874 (2017)
[2] P. Procel, presented at SiliconPV (2017)
[3] P. Procel, presented at EUPVSEC (2017)

c-Si solar cells @PVMD

High temperature poly-c-Si(O_x) carrier-selective contacts

c-Si solar cells: High temperature poly-c-Si(O_x) carrier-selective contacts



Objectives for IBC poly-c-Si cell:

1. Quench back-side recombination losses

   → Deploying **poly-c-Si** CSCs

2. Quench front-side recombination losses

   → **FSF passivation**

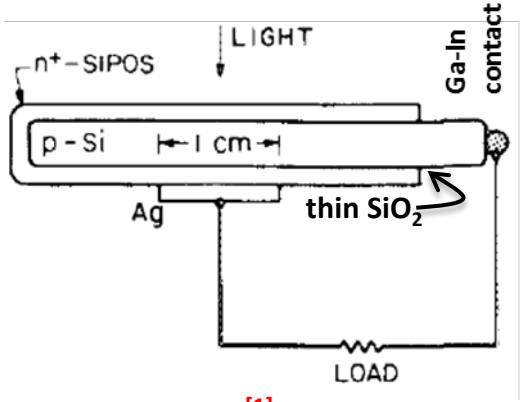
3. Quench back-side parasitic absorption

   → **poly-SiO_x alloys**

c-Si solar cells: High temperature poly-c-Si(O_x) carrier-selective contacts

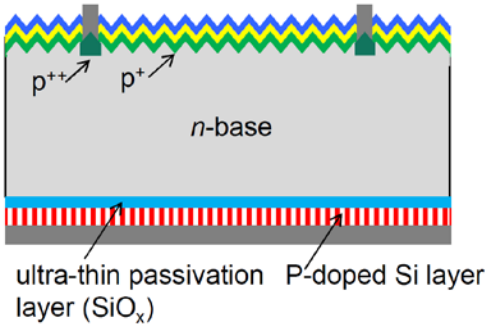
Development:

Semi-insulating poly-c-Si (SIPOS)



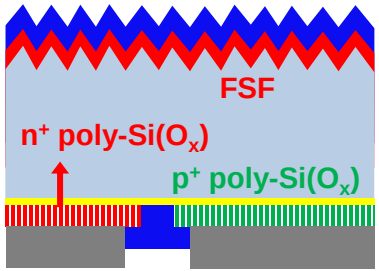
V_{oc} = 720 mV [1]

Tunneling Oxide Passivating Contact [2] (TOPCON) @ISE



25.1% [3] **25.7%** [4]

Ion-implanted poly-c-Si (poly-Si) @TUDelft



19.2% [5] **22.1%** [6]

23.9% [7] **25%** [8]

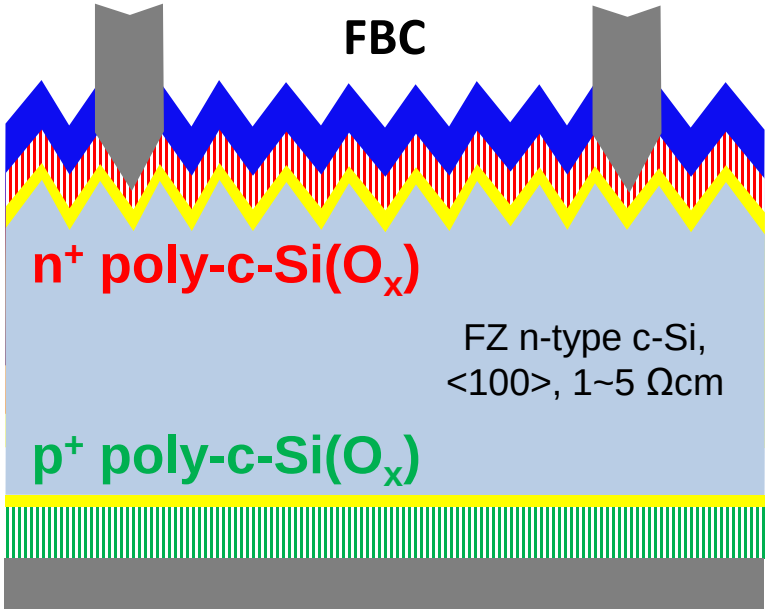
1. E. Yablonovitch, APL, 47, (1985) 1211.

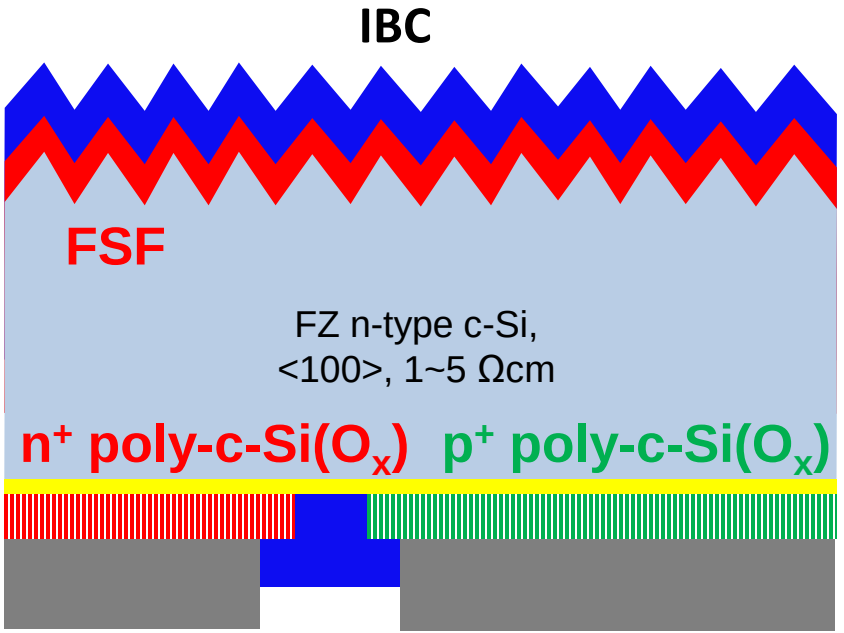
[2] F. Feldmann, et al., SOLMAT, 120, (2014) 270.
[3] S. W, Glunz, et al. EUPVSEC-31, (2016) Hamburg
[4] A. Richter, et al. SOMAT, (2017)

[5] G. Yang, et al., APL, 118, (2016) 033903.
[6] G. Yang, et al. SOMAT, 158 (2016) 84.
[7] M. Rienacker, et al., energy procedia, 92 (2016) 412.
[8] F. Haase, et al. PVSEC-26, (2016) Singapore.

c-Si solar cells: High temperature poly-c-Si(O_x) carrier-selective contacts

Tunneling oxide/poly-c-Si @TUDelft



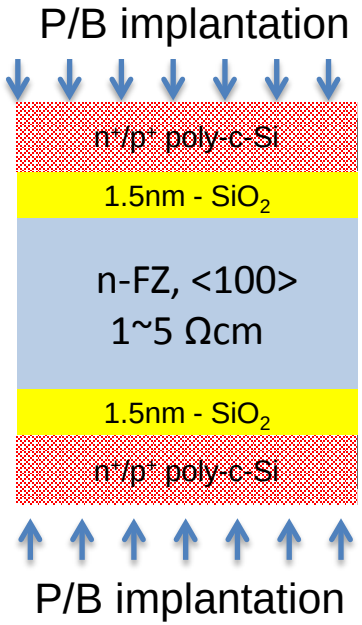


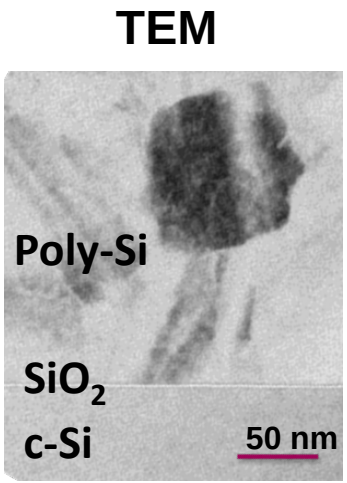
c-Si surface field
poly-c-Si(O_x) emitter
poly-c-Si(O_x) surface field
Tunneling oxide
Passivation layer
Metal

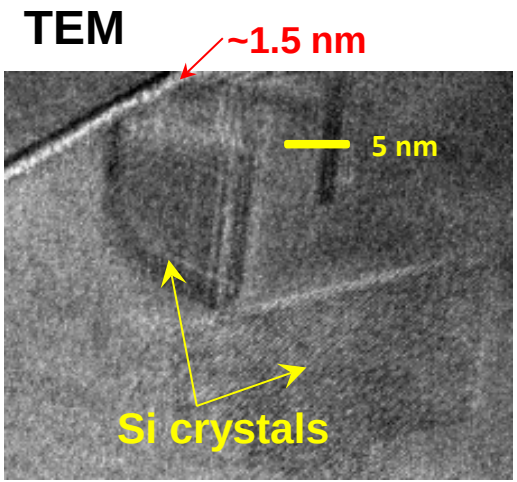
c-Si solar cells: High temperature poly-c-Si carrier-selective contacts

Ion-implanted poly-c-Si passivated carrier-selective contacts

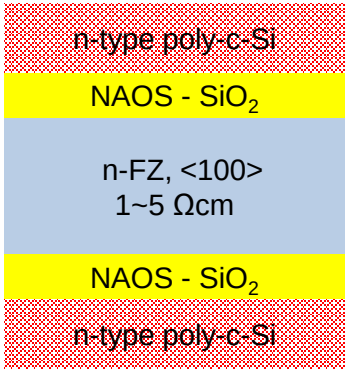
(poly-Si) @TUDelft

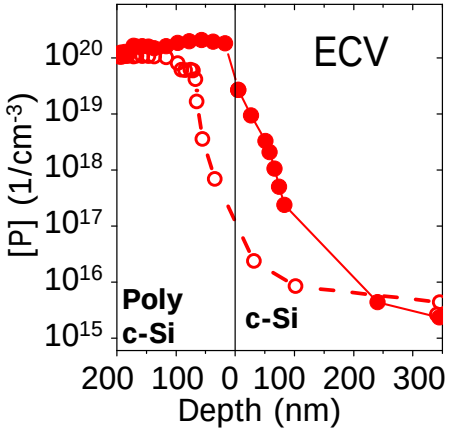


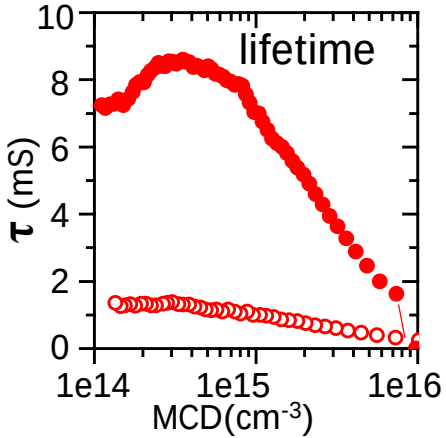


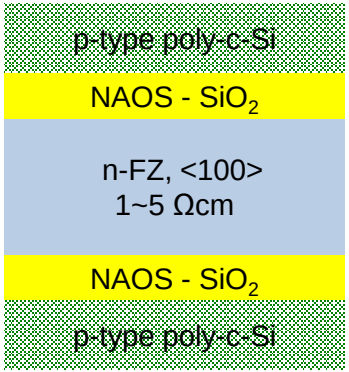


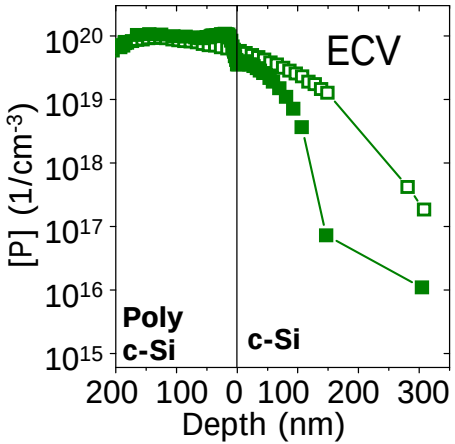
c-Si solar cells: High temperature poly-c-Si carrier-selective contacts

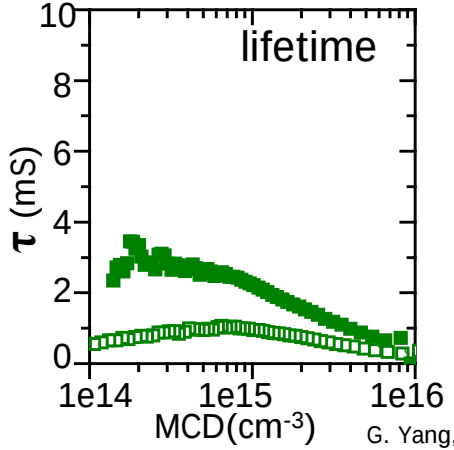






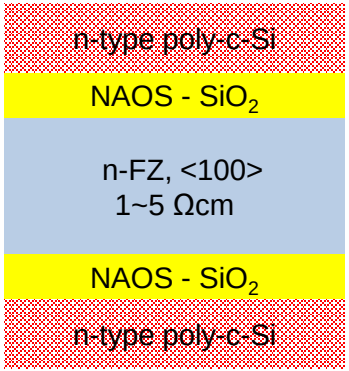






G. Yang, et al., *Appl. Phys. Lett.* **108**, 033903 (2016)

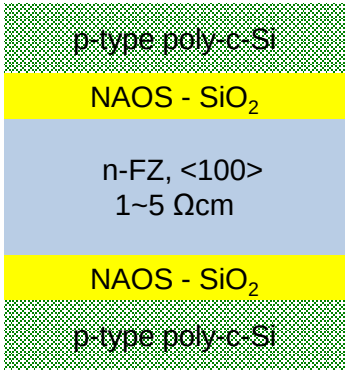
c-Si solar cells: High temperature poly-c-Si carrier-selective contacts



+ SiN_x:H capping

τ_{eff} [ms]	R_{sh} [Ω/□]	J_0 [fA/cm²]	iV_{oc} [mV]
18	85	4.5	735

Annealing: 950˚C, 5 min



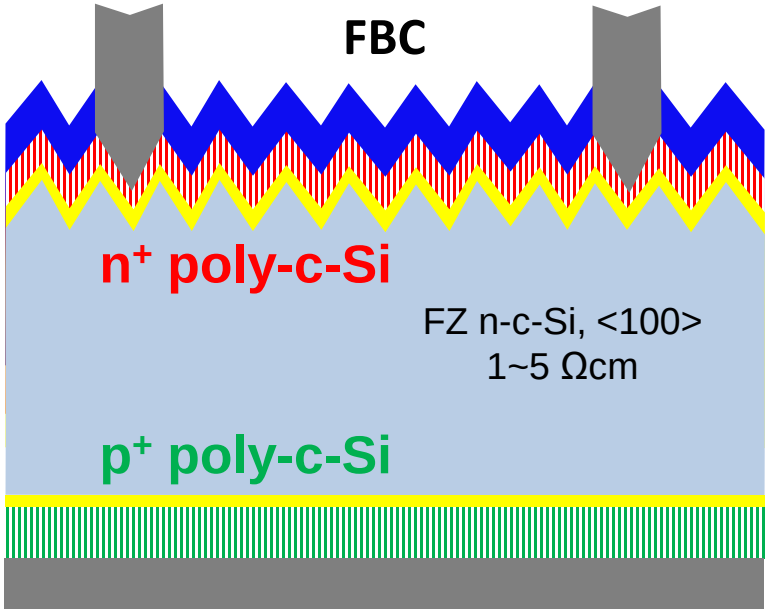
+ SiN_x:H capping

τ_{eff} [ms]	R_{sh} [Ω/□]	J_0 [fA/cm²]	iV_{oc} [mV]
4.5	150	11	716

G. Yang, et al., *Appl. Phys. Lett.* **108**, 033903 (2016)

c-Si solar cells: High temperature poly-c-Si carrier-selective contacts

Tunneling oxide/poly-c-Si



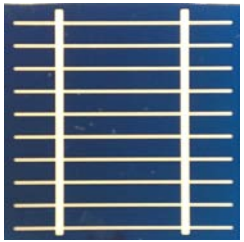
n+ poly-Si FSF:
(35-nm, textured)

J_0 = 14 fA/cm²
iV_{OC} = 708 mV

p+ poly-Si emitter:
J_0 = 11 fA/cm²
iV_{OC} = 716 mV

Solar cell:

V_{OC} = 703 mV
J_{SC} = 38.4 mA/cm²
FF = 70.0%
η = 18.9%
η = 19.5%



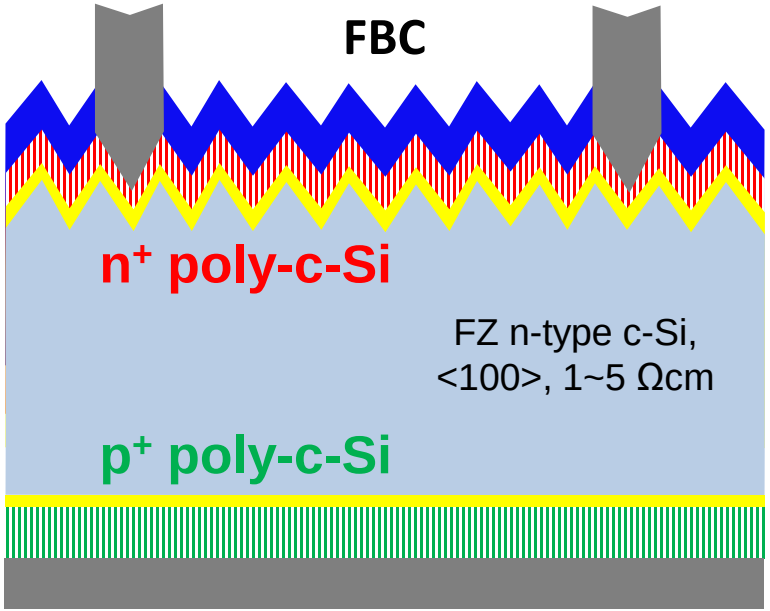
7.8 cm²
5.0% shading

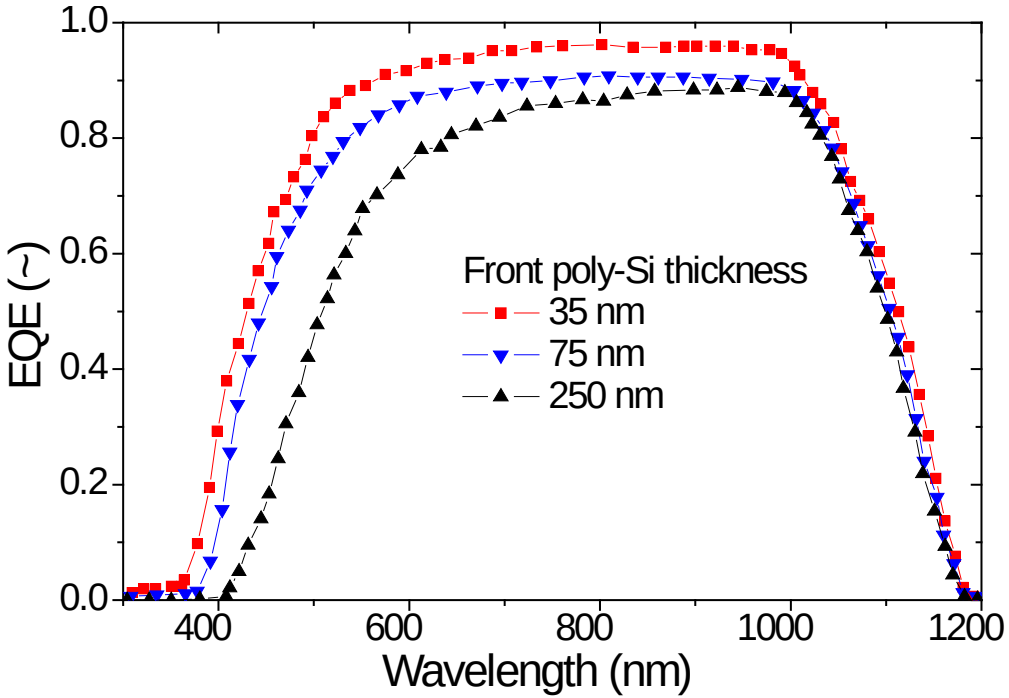
c-Si surface field
poly-c-Si(O_x) emitter
poly-c-Si(O_x) surface field
Tunneling oxide
Passivation layer
Metal

G. Limodio, G. Yang, H. Ge, O. Isabella, M. Zeman, SiliconPV, (2017), Freiburg.

c-Si solar cells: High temperature poly-c-Si carrier-selective contacts

Tunneling oxide/poly-c-Si

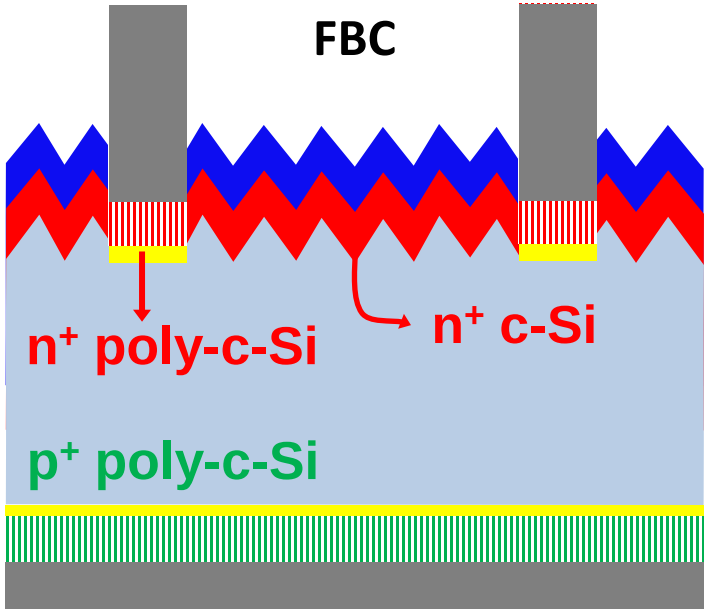


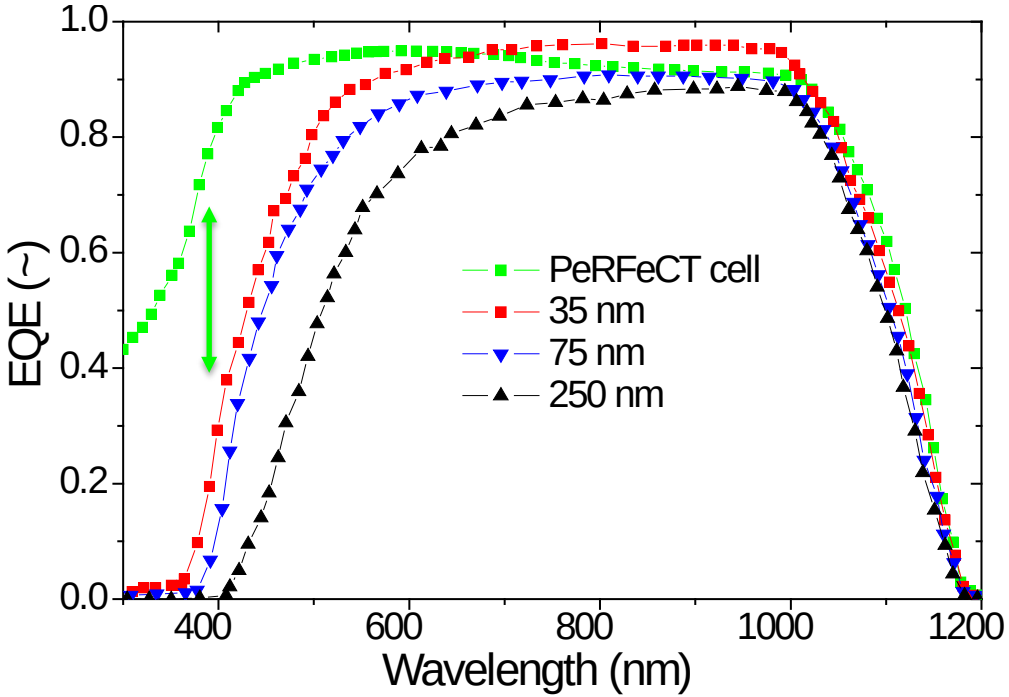


c-Si surface field
poly-c-Si(O_x) emitter
poly-c-Si(O_x) surface field
Tunneling oxide
Passivation layer
Metal

c-Si solar cells: High temperature poly-c-Si carrier-selective contacts

PeRFeCT (Passivated Rear and Front ConTacts**) solar cell**



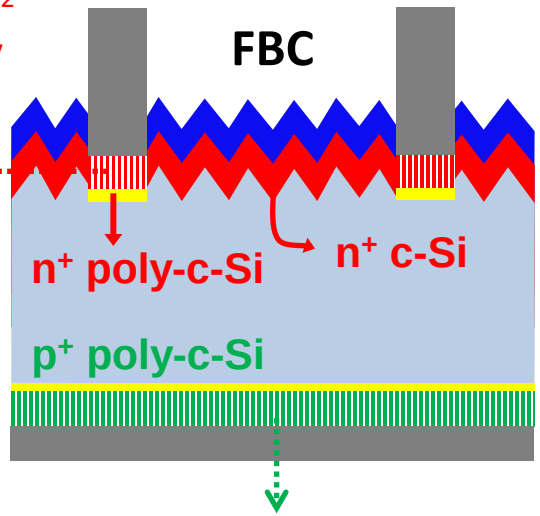


c-Si surface field
poly-c-Si(O_x) emitter
poly-c-Si(O_x) surface field
Tunneling oxide
Passivation layer
Metal

c-Si solar cells: High temperature poly-c-Si carrier-selective contacts

PeRFeCT (Passivated Rear and Front ConTacts**) solar cell**

n+ poly-c-Si contact:
(flat, 4% area fraction)
J_0 = 4.5 fA/cm^2
iV_{OC} = 735 mV



p⁺ poly-Si emitter:
J_0 = 11 fA/cm^2
iV_{OC} = 716 mV

n+ c-Si FSF:
(textured, 96% area fraction)
J_0 = **31** fA/cm^2
iV_{OC} = 680 mV

n+ c-Si FSF:
(optimized, textured)
J_0 = **6.5** fA/cm^2
iV_{OC} = 708 mV

Work in progress
Estimated V_{OC} > 710 mV

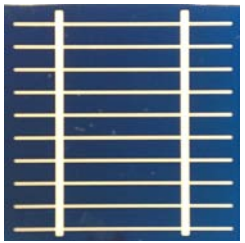
Solar cell:

V_{OC} = 656 mV

J_{SC} = 40.7 mA/cm^2

FF = 75.2%

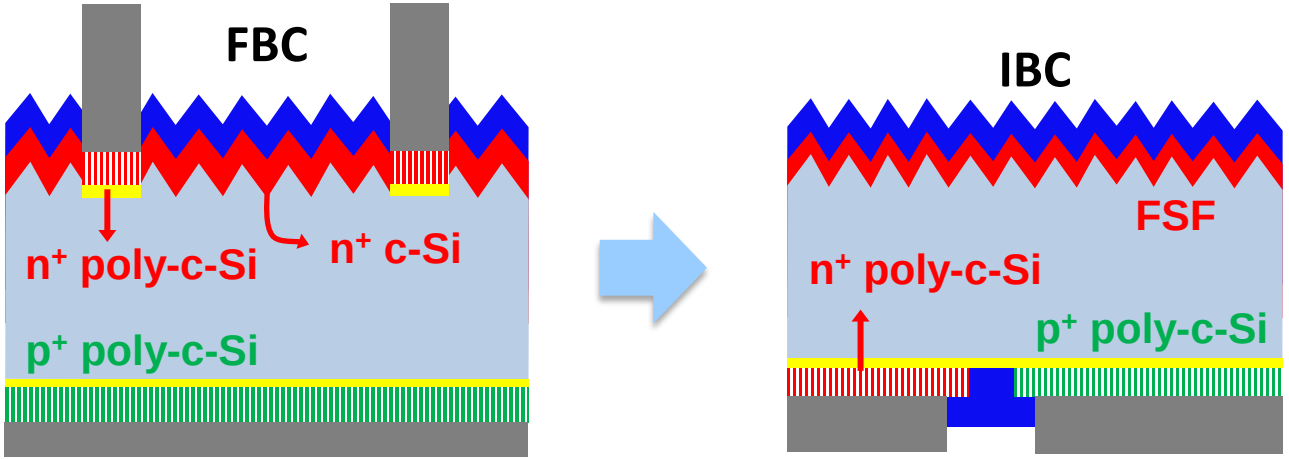
η = 20.0%



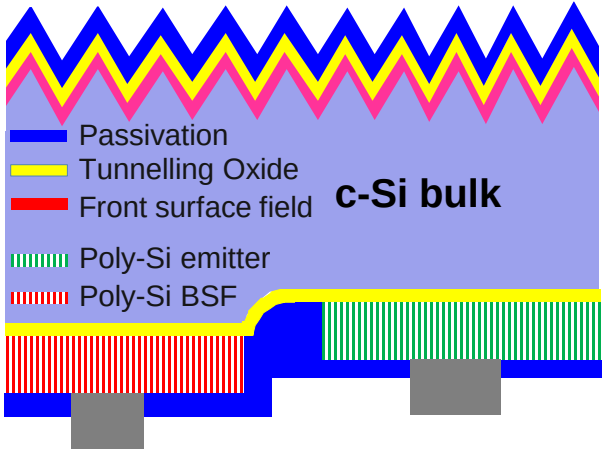
3x3 cm^2

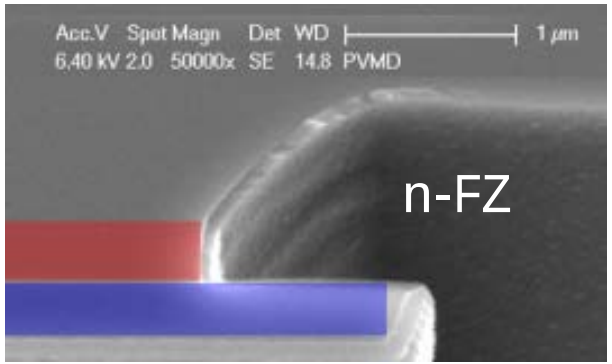
c-Si solar cells: High temperature poly-c-Si carrier-selective contacts

PeRFeCT (Passivated Rear and Front ConTacts**) solar cell**

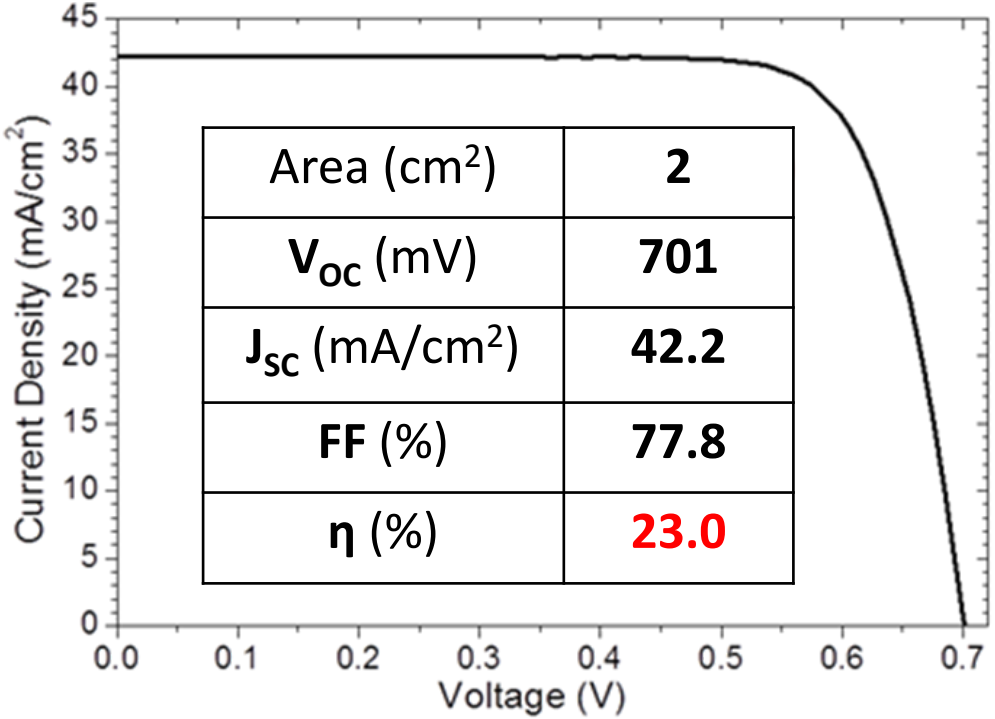


Interdigitated Back Contact (IBC) c-Si solar cell





Self-aligned process developed at TU Delft



Area (cm^2)	**2**
V_{oc} (mV)	**701**
J_{sc} (mA/cm^2)	**42.2**
FF (%)	**77.8**
η (%)	**23.0**

Best c-Si solar cell fully fabricated in the Netherlands

Summary

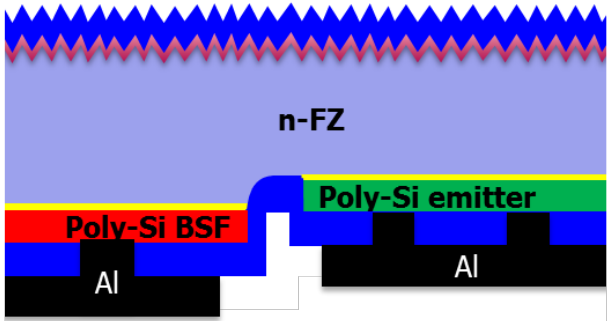
c-Si wafer-based solar cells

- Architectures for minimizing recombination
- Thermal budget
- **Opto-electrical modeling** important tool for optimization
- High T poly-c-Si selective-carrier contact cells

Good passivation

CSC	doping	J_0 (fA/cm²)	iV_{OC} (mV)	$\rho_{C,TLM}$ (Ω·cm²)
poly-SiO_x	n-type	3.0	740	0.7
	p-type	23.0	700	0.5
poly-Si	n-type	4.5	735	0.9
	p-type	11.0	711	0.3

IBC solar cell 22.5%



Acknowldgements

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Thank you for your attention!

TU Delft

PVMD