TAIYANGNEWS

Webinar

Potential and Recent Developments of High Efficiency N-type Passivated Contact (TOPCon) Solar Cell Technologies

Presentations and Panel Discussion

June 9, 2020 at 14:00 – 15:00 CET

The webinar looks into the latest developments of n-type passivated contact (TOPCon) solar cell technology, a promising candidate to upgrade today's PERC standard cells to the next efficiency level. While TaiyangNews will provide an overview on the latest in high efficiency solar cells; the leading commercial cell/module manufacturer in the field of n-type passivated contact technology, Jolywood, will present an update on its work and projects; and German Institute for Solar Energy Research Hamelin (ISFH) will discuss the potential of passivated contact cells.

Michael Schmela,

Managing Director
TaiyangNews

Introduction

Shravan Chunduri,

Head of Technology,
TaiyangNews

Presentation:
Overview of recent developments in high-efficiency cell technologies

Dr. Chen Jia,

R&D Director,
Jolywood

Presentation:
How n-type TOPCon technology maximize module power gains

Dr. Felix Haase,

Project Manager,
Institute for Solar Energy Research Hamelin (ISFH)

Presentation:
What's behind the high potential of passivated contact solar cells

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Webinar

High Efficiency Cell Technologies Report 2019

TaiyangNews First Report on High Efficiency Cell Technologies Provides an overview on the well-known advanced cell technologies with an emphasis on passivated contacts, HJT and the new incumbent PERC.

All TaiyangNews PV technology reports and market surveys are available for free at:

www.taiyangnews.info/reports

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Report: Metallization Pastes Market Survey 2019-2020

TaiyangNews Metallization Pastes Market Survey 2019 - 2020 was published in early 2020 and is available for download.

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Overview on Passivated Contacts Technology

Shravan K. Chunduri,

Head of Technology,

TaiyangNews

Two companies, two platforms:

TAIYANGNEWS
ALL ABOUT SOLAR POWER

Open solar news platform

All information can be accessed for free online

Daily updates of solar market & technology news

Technology reports

Market surveys on production equipment & processing consumables

MISCHCO

- Consulting & Communications
- Communication Strategy Development
- Technical Research & Consulting:
  - Status & Trends in wafer, cell & module technologies
  - Trends in production equipment & process consumables
  - Market intelligence on advanced cell architectures

High Efficiency Cell Technologies Report 2019

The TaiyangNews Report on High Efficiency Cell Technologies 2019 is essentially our famous PERC Cell Technology Report. Since PERC is fully established, in this new report we look at the technologies that are likely to come after PERC. With more emphasis on passivated contacts, this report also summarizes the recent developments in the areas of PERC and heterojunction technologies.

All TaiyangNews PV technology reports and market surveys are available for free at:

www.taiyangnews.info/reports

This presentation summarizes the Passivated contacts part of the report

Several questions about industrialization of passivated contacts

Several questions about passivated contacts (similar to PERC in its early days)					
	Substrate	**Thin oxide**	**Poly silicon**	**Metallization**	**Others**
Passivated contacts	● P-type? ● N-type?	● Wet-chemical? ● UV? ● Thermal?	● PECVD? ● LPCVD? ● in-situ doping? ● Ex-situ doping? ● Annealing?	● Evaporation? ● Screen printing? ● TCO?	● Cell structure? ● Process flow? ● Industrial maturity? ● Yield? ● Cost?
PERC	**Substrate**	**Passivation**	**AlO_x**	**Metallization**	**Others**
PERC in 2014	● P-type? ● LID?	● AlO_x:H? ● Thermal SiO_2? ● SiO_xN_y:H? ● SiN_x:H capping?	● ALD? ● PECVD? ● PVD?	● LFC? ● Laser/chem. opening? ● Evaporation? ● Screen printing?	● Cell structure? ● Process flow? ● Industrial maturity? ● Yield? ● Cost?

Source: Trina Solar; graphic: © TaiyangNews 2019

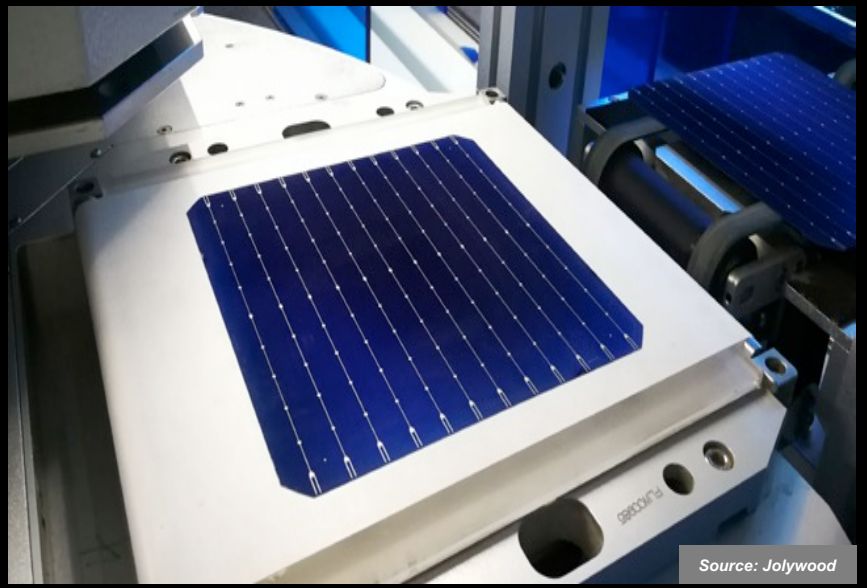
Passivated contacts could be the next big thing in cell making

Current practice

- Today's industrial passivated contacts are implemented on n-type and on rear side
- Many believe that passivated contacts is a line of extension to PERC
- Processing wise passivated contacts is very close to current mainstream, which is PERC
- The key for passivated contacts processing is:

  - Applying ultrathin silicon oxide film

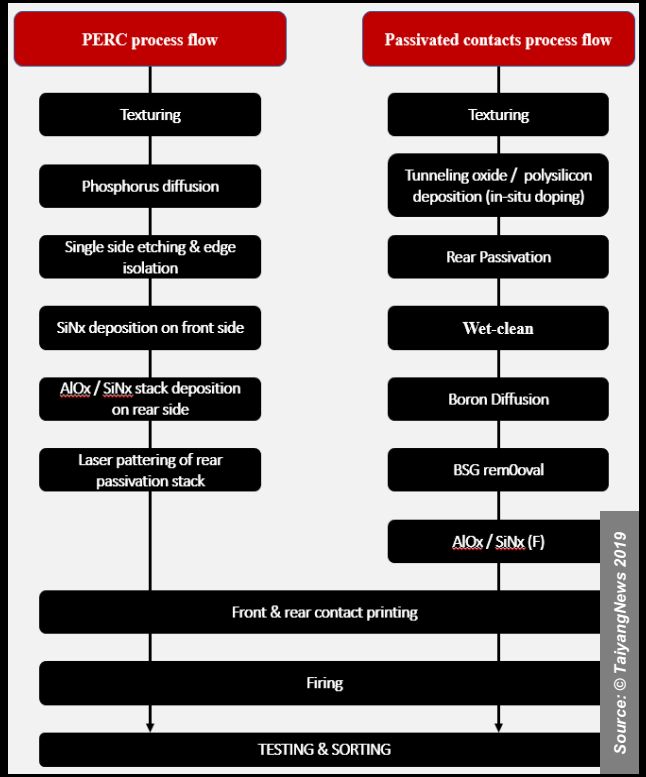
  - On top a polysilicon layer, which is doped subsequently



Passivated contacts process is not easy as it appears

Process flow of passivated contacts

- There are several variants of the passivated contacts process flow
- One way is to start with formation of the boron emitter, the most followed method
- It is also possible to start the flow by accomplishing rear surface engineering first, followed by front side processing
- Depending on the process flow equipment used, the process requires masking and wet-chemical treatment steps
- Annealing and removing wrap-around are also part of typical industrial process
- Emitter formation with boron is often more complex than using phosphorus



LPCVD is currently the only technology in mass production

Deposition technology is the key

- As during early days of PERC, every known deposition technology is promoted for passivated contacts
- We identified 5 technologies that are in the race from various vendors – LPCVD, APCVD, PECVD, PVD and PEALD. These technologies are at different stages of commercialization – from development to experience in mass production
- LPCVD is most-widely used method as of now
- APCVD has been available commercially
- PECVD and PEALD are in final stages of testing
- PVD is still under development

Characteristics of LPCVD Systems

- Several companies including international and domestic equipment makers are offering LPCVD tools
- The tools accomplish all processes – tunneling oxide growth, deposition and doping of polysilicon – in one tool
- LPCVD comes with wrap around deposition
- Tools from all vendors have same throughput and processing capabilities

Company	Centrotherm	S.C. New Energy	SEMCO	Tempress
Model	SPECTRUM LPCVD		HORTUS	SPECTRUM LPCVD
Applications	Tunneling oxide + polysilicon	Tunneling oxide + polysilicon	Tunneling oxide + polysilicon	Tunneling oxide + polysilicon
Suitable fab configuration	New / upgrade (PERC / PERT)	New / upgrade (PERC / PERT)	New / upgrade (PERC / PERT)	New / upgrade (PERC / PERT)
Wafer orientation	Vertical	Vertical	Horizontal	Vertical
Equipment configuration	5-stack tube	5-stack tube	5-stack tube	5-stack tube
Wrap-around	Yes	Yes	Minimal	Yes
In-situ doping	Optional	Yes	Yes	Yes
Wafers per tube	-	-	1,400	1,200
Growth rate	-	-	-	4 - 5 nm/min
Oxide layer thickness	1.3 - 2.4 nm	1.4 - 1.6 nm	1.4 - 1.6 nm	1.2 - 1.6 nm
Polysilicon layer thickness	100 - 200 nm	100 - 200 nm	100 - 160 nm	150
Throughput (WPH)	4000**	3,000*	4000*	3,000*; 4,000**
Film uniformity	3% batch-batch; 5% wafer to wafer & within wafer	-	3.7% wafer to wafer	3% batch-batch; 5% wafer to wafer & within wafer
Footprint	9.35 x 5.6 x 3.62 m	-	-	-
Uptime (%)	95%	95%	95%	95%
Commercial status	Ready	Ready	Ready	Ready
Already in mass production	Finished testing	Finished testing	Yes	Yes

*in-situ doping; ** Ex-situ doping

Source: Datasheets from companies; graphic: © TaiyangNews 2019

There is no clear winner in the race of deposition tools

Comparison of Different Deposition Technologies

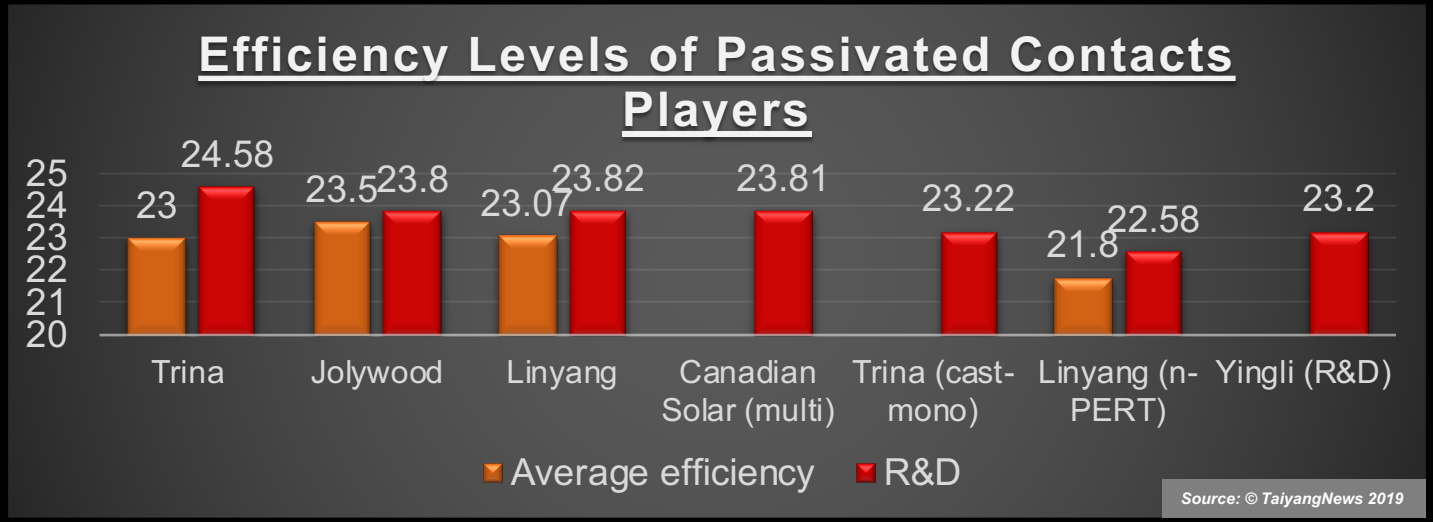
Technology	No of suppliers	Commercial availability	Mass production	Avoiding wrap-around	Ability for in-situ doping	Passivation quality	Throughput
LPCVD	✓✓✓	✓✓✓	✓✓✓	✖	✓✓✓	✓✓✓	✓
PECVD	✓	✓	✖	✓✓✓	✓✓✓	✓✓✓	✓✓
PEALD	✓	✓	✖	✓✓✓	✓	✓✓✓	✓✓
PVD	✓	✖	✖	✓✓✓	✓	✓✓	✓✓✓
APCVD	✓	✓✓	✓	✓✓✓	✓✓	✓	✓✓

Legend: ✓✓✓High; ✓✓ Medium; ✓ Low; ✖ No

Metallization pastes for passivated contacts

- Passivated contacts structure requires a special pastes system
- The rear paste should have a controlled etching attribute so that it can establish a contact with the doped polysilicon layer, while not hurting the underlying tunneling oxide film
- The requisite for front contact pastes - it must be compatible with rear pastes, especially supporting low temperature processing
- Leading paste makers are developing specific pastes for passivated contacts cells and one company is also developing an aluminum-based paste solution
- While work is in progress, there is room for further optimization

Only few companies have mastered the technology so far



Limitations of passivated contacts

- **Application method** for applying tunneling oxide and polysilicon layer is not yet clear
- Like with any other n-type structure, it requires **silver paste on both sides**
- Due to the absorption in doped polysilicon film, passivated contacts suffers from **low bifaciality**
- **Low compatibility with p-type**; though doable then benefits are not paying off the effort
- Due to the **high development pace in the PERC** field, it is becoming a standing block for any new technology - and passivated contacts is no exception
- Backed by the rapid introduction of larger and **larger wafer formats**, PERC is becoming an even bigger threat to any new and advanced cell technology

Conclusions

- Passivated contacts is currently viewed as an extension to PERC, and the technology is indeed at the same level as PERC was during its inception
- There is no clear winner for deposition technologies, while LPCVD is the current state of the art
- Fully compatible pastes that would help to reap complete benefit of the structure are under development
- Issues with deposition methods and metallization pastes are expected to be addressed soon, while low bifaciality and more importantly competition from PERC would be persistent threats to passivated contacts

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Questions?

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Progress of Jolywood NTOPCon Technology

Taiyang News Webinar

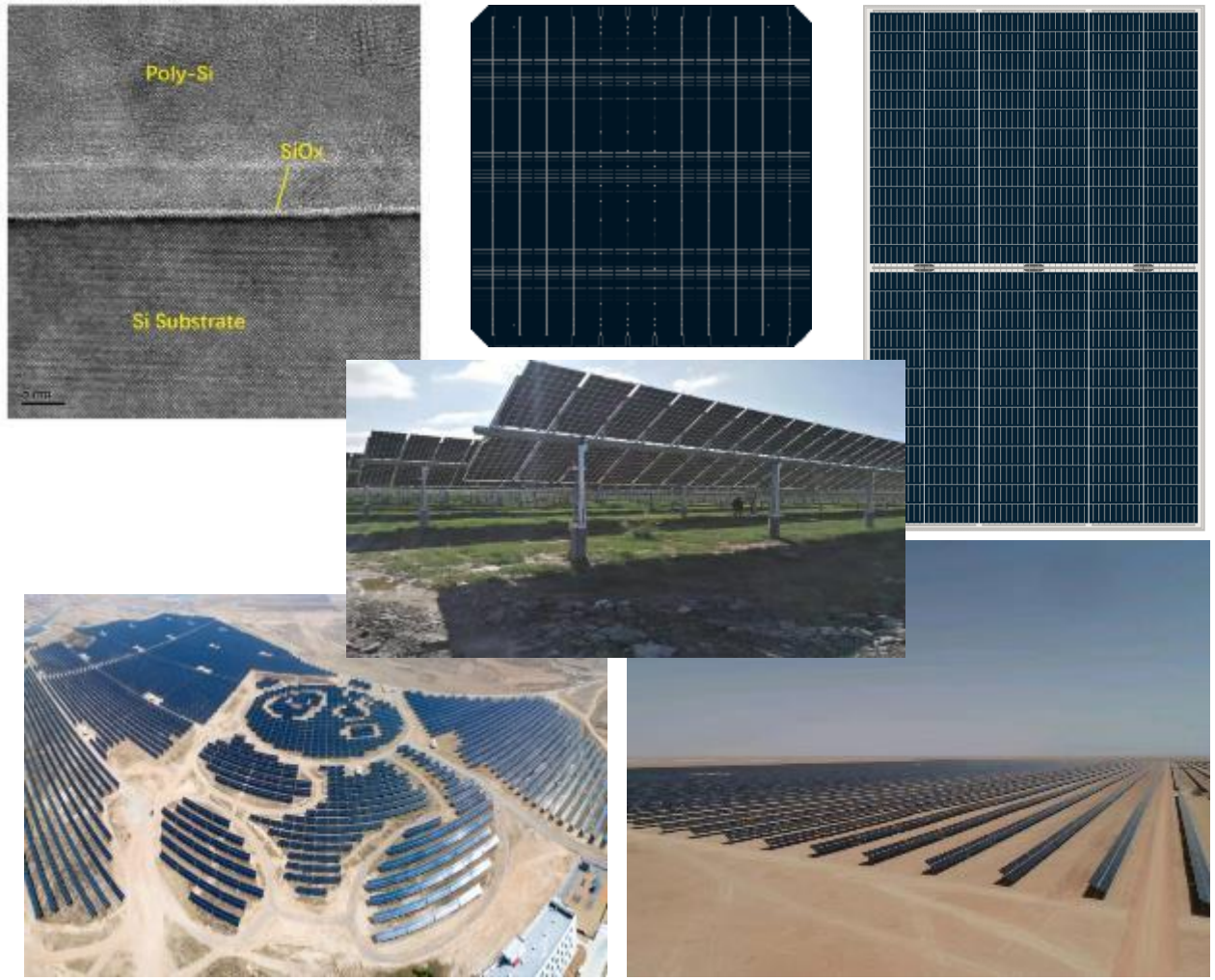
Dr. Chen Jia

Jolywood Solar Taizhou

2020.06.09

Content

- Company Introduction
- Jolywood NTOPCon progress
- Application of Jolywood NTOPCon Technology
- Outlook and Conclusions



Part 01

Jolywood Group

About Jolywood

- Established in 2008
- Listed 2014, Shenzhen stock exchange (300393)
- Four business sectors: New Material, High efficiency solar cell and module, System development, and Renewable plus creative solar deployment
- Over 2700 employees globally

Jolywood Group

- Jolywood (Suzhou) Sunwatt Co., Ltd
- Jolywood (Taizhou) Solar Technology Co.,Ltd.
- Zoomlight (Suzhou)Solar Power Co.,Ltd.
- Jolywood (Suzhou) New Energy Co.,Ltd.

About Jolywood

- Founded in 2016 under Jolywood Group(SZ 300393)
- Registered capital $328M
- World largest n-type bifacial cell and module manufacturer
- 101 patents applied related to N-type cell and module technology (58 patents granted)
- Average efficiency up to **23.5%** in mass production, **80%-85%** bifaciality, **provides the lowest LCOE solution**

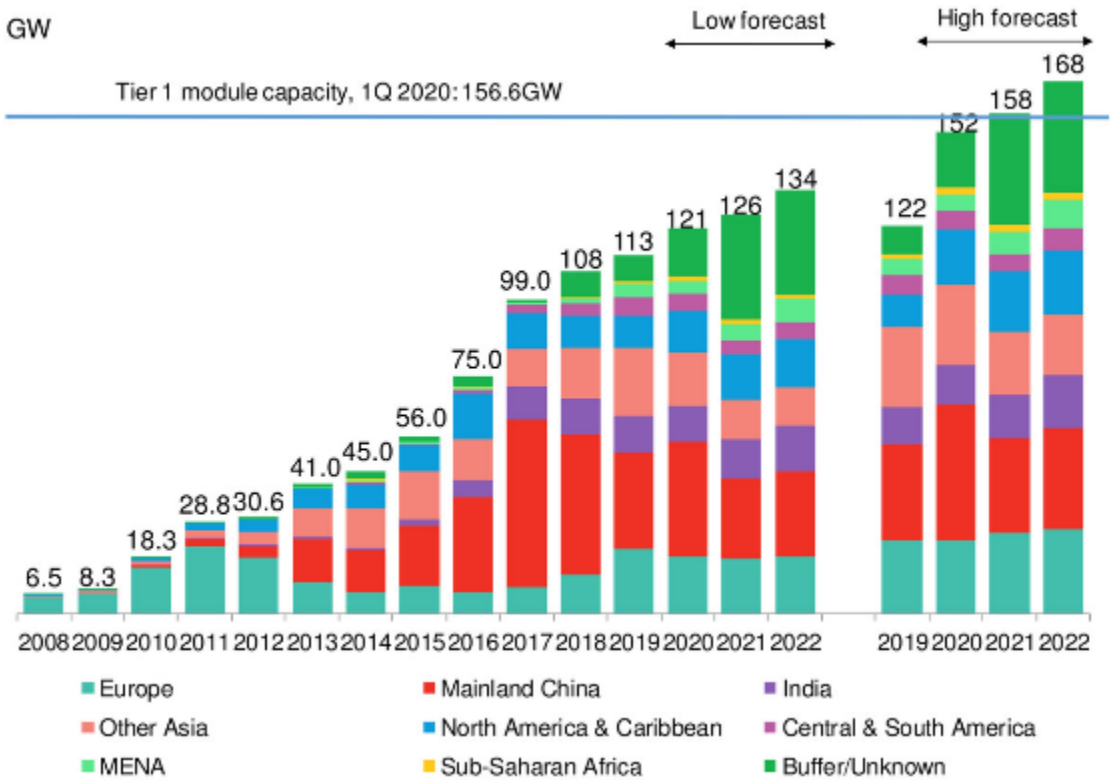
14
N-type bifacial solar cell production lines

>2 GW
2.4 GW N-type bifacial cell capicity

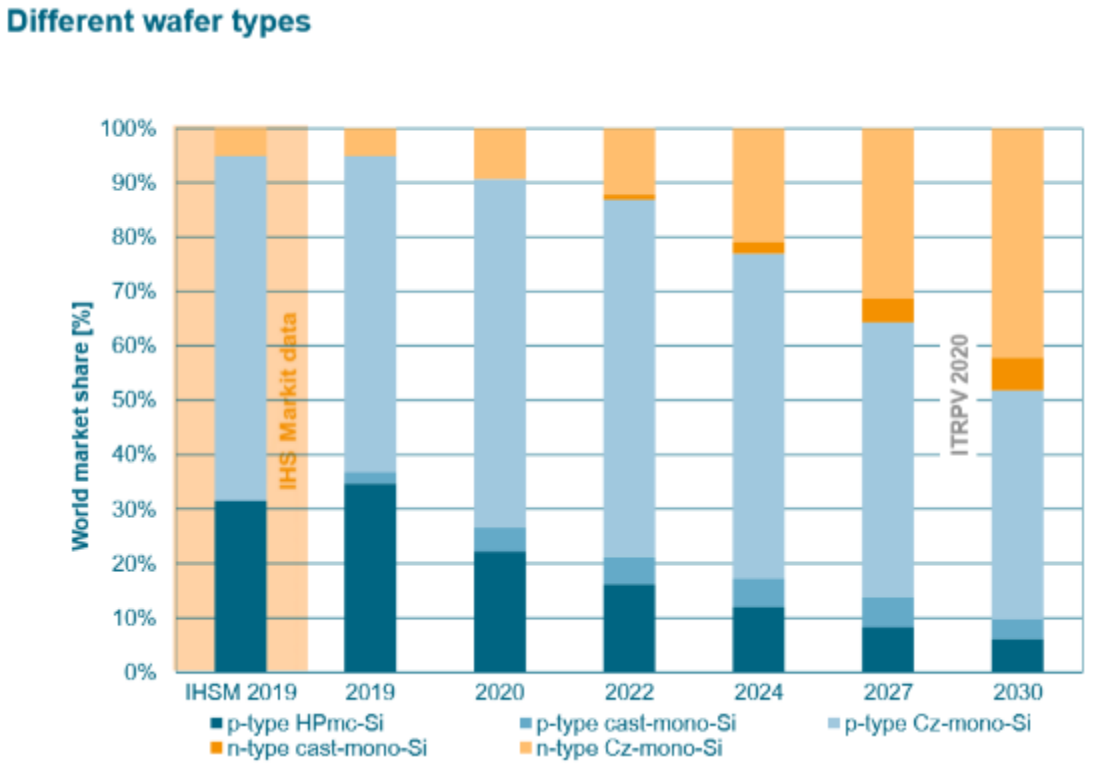
>3 GW
N-type bifacial module capacity

TIER 1 Bloomberg NEW ENERGY FINANCE

Why N-type Technology



* Data from Bloomberg forcast Q1.2020



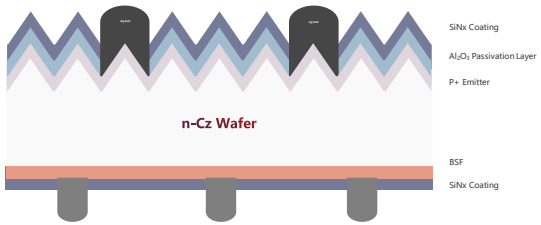
* Data from ITRPV Forcast 2020

Higher efficiency n-type modules growing fast with annual rate of 33.8%

Jolywood n-type Technology

1st Generation ⟹ *2nd Generation* ⟹ *Future Generation*

n-PERT: Eta> 22%

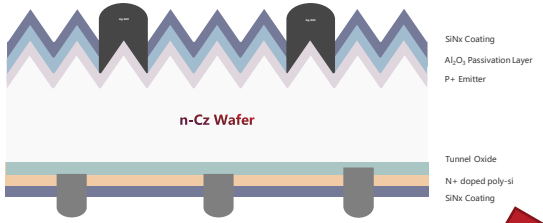


Previous production

Rear passivation improvement

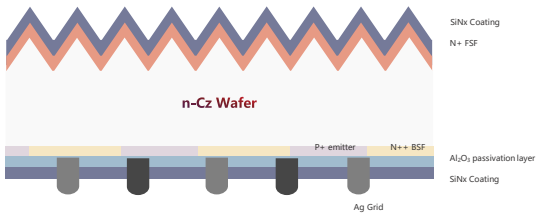
Front shading reduction

NTOPCon: Eta>23.5%



2.4 GW

n-IBC: Eta>23.5%

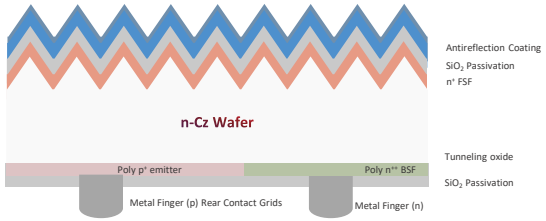


150MW

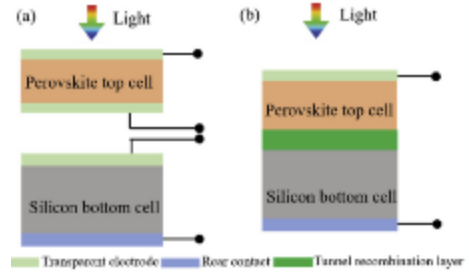
High Voc

High Jsc

n-TBC: Eta>25%



Tandem: Eta>26%

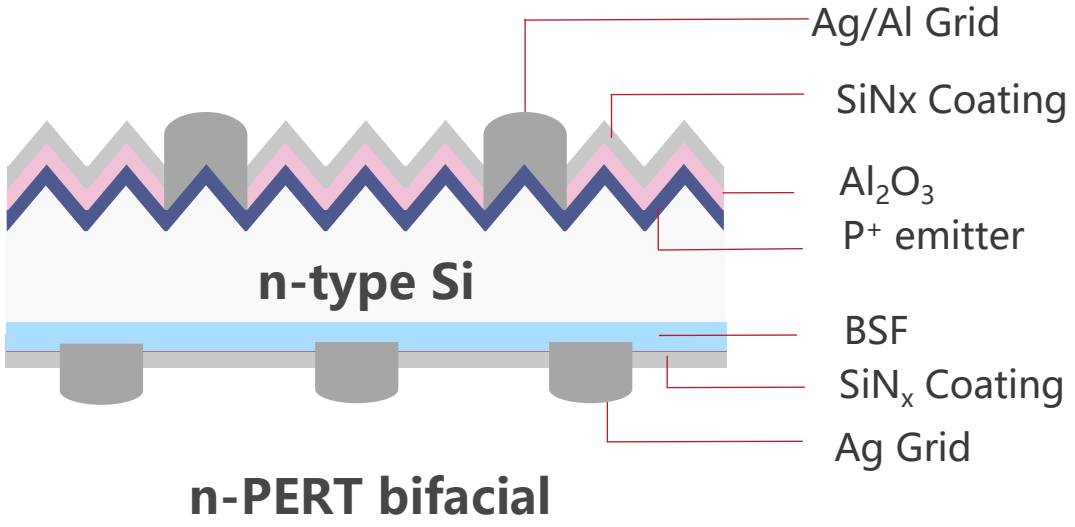


RD

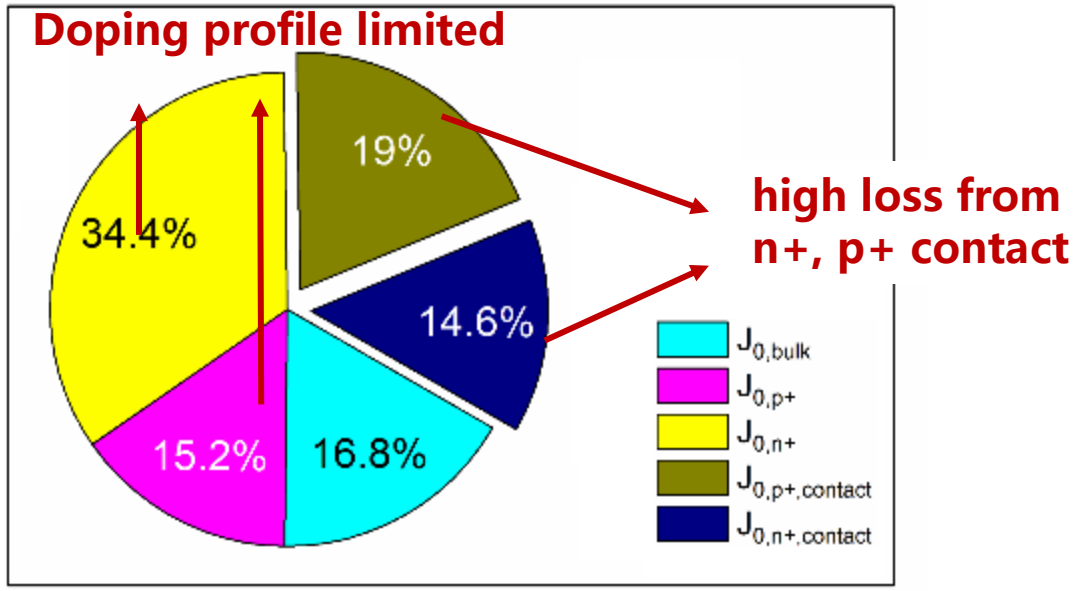
Part 02

Jolywood NTOPCon Progress

Why Passivating Contact?



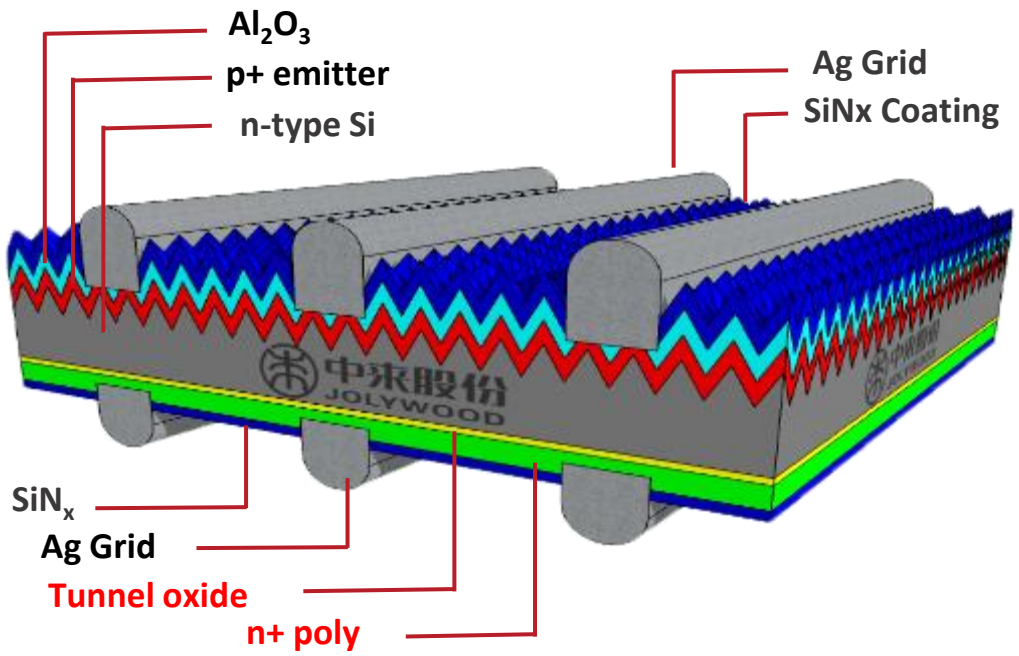
n-PERT bifacial



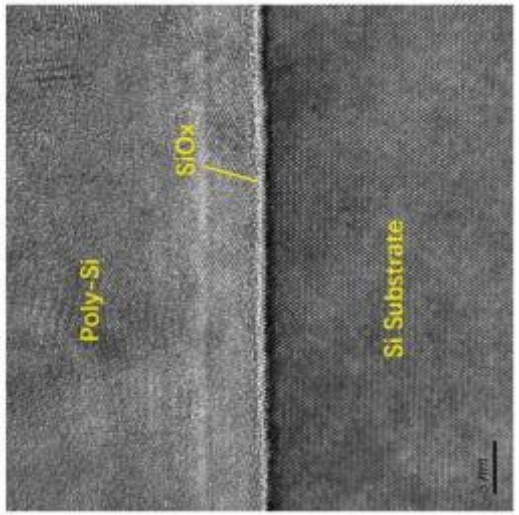
I-V	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Eff. (%)	Area (cm^2)
n-PERT	669.8	40.44	81.38	**22.03**	246.21

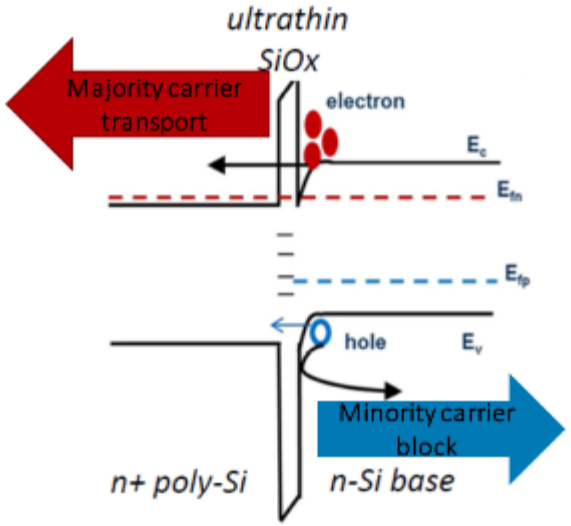
- Passivating-contact is required for significant reduction of $J_{0,met}$
- The room for improvement for non-contact area is limited due to requirement of doping conc. & depth for direct contacting of fire-through pastes and exhausted methods for conventional passivation

Jolywood NTOPCon Bifacial Cell Technology



Hermle et al, *EUPVSEC*, 2017



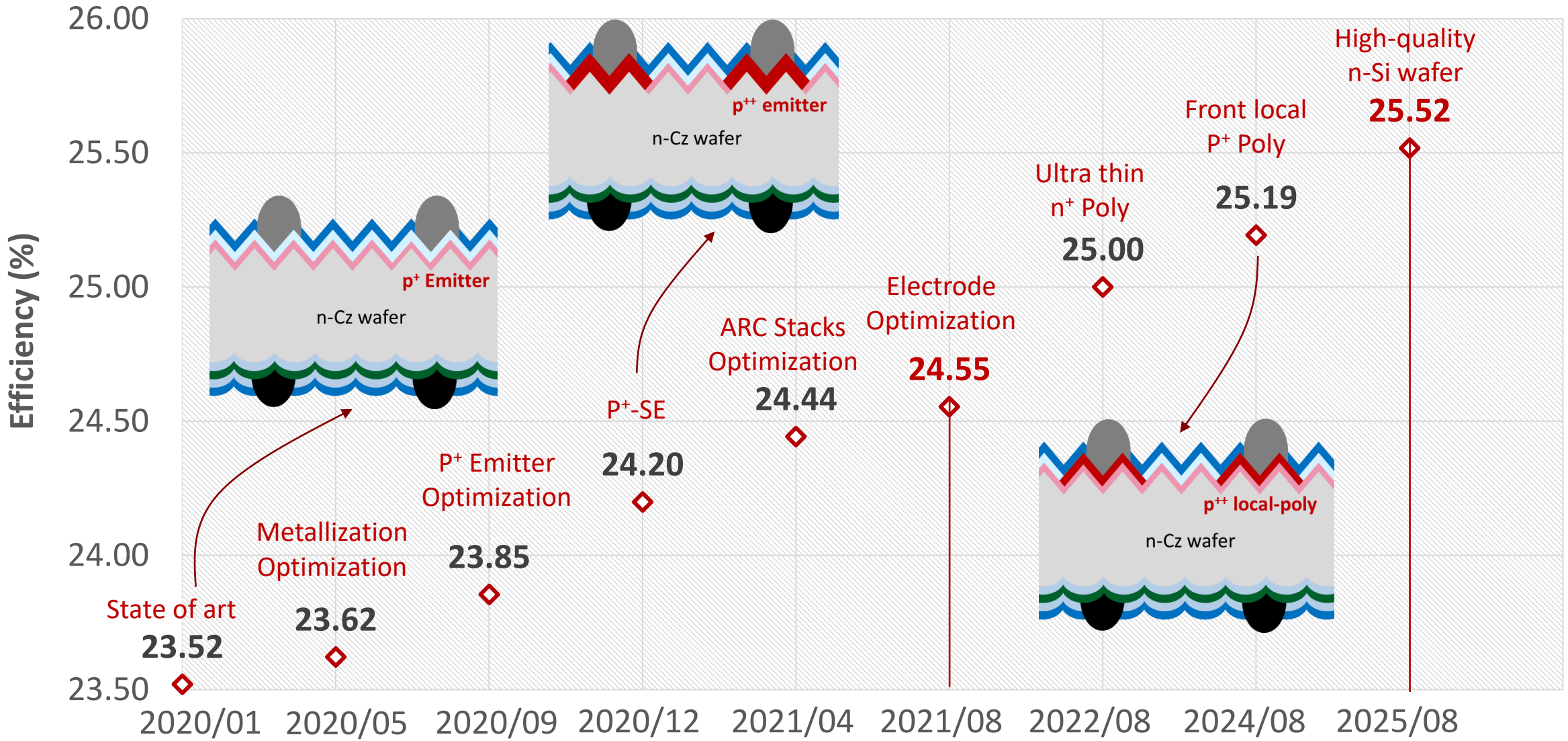


Advantages of passivated contact structure:

1) Excellent chemical passivation & field-effect passivation

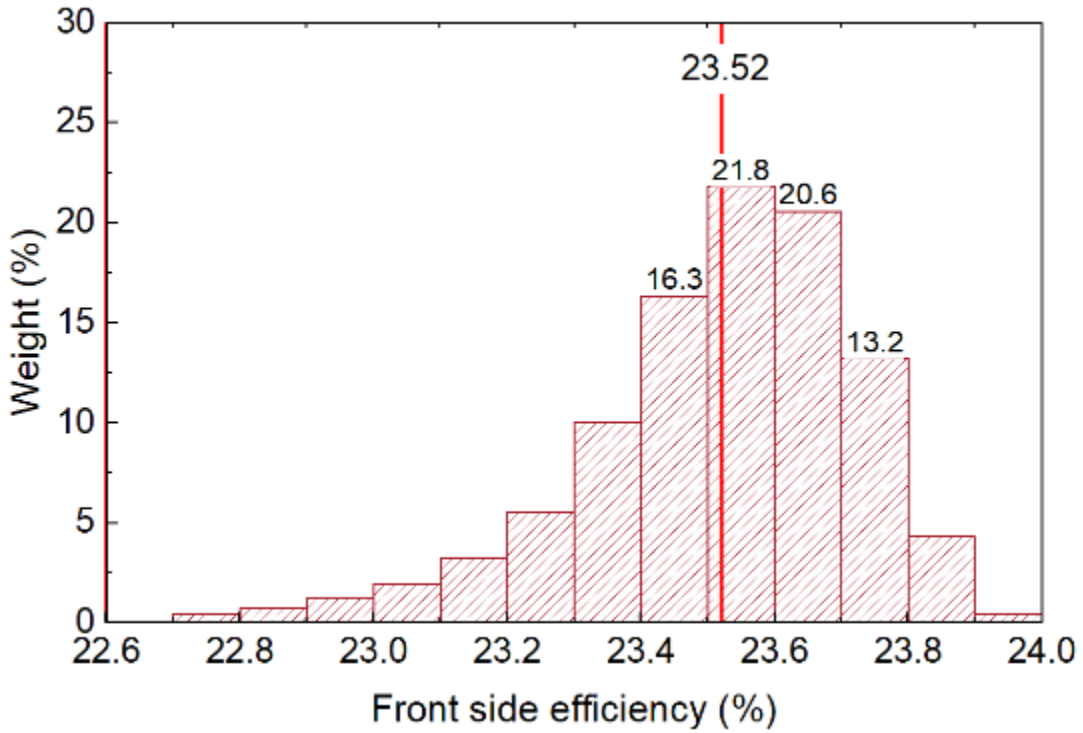
2) Good majority carrier selectivity, rapid carriers transport between absorption and doped layer

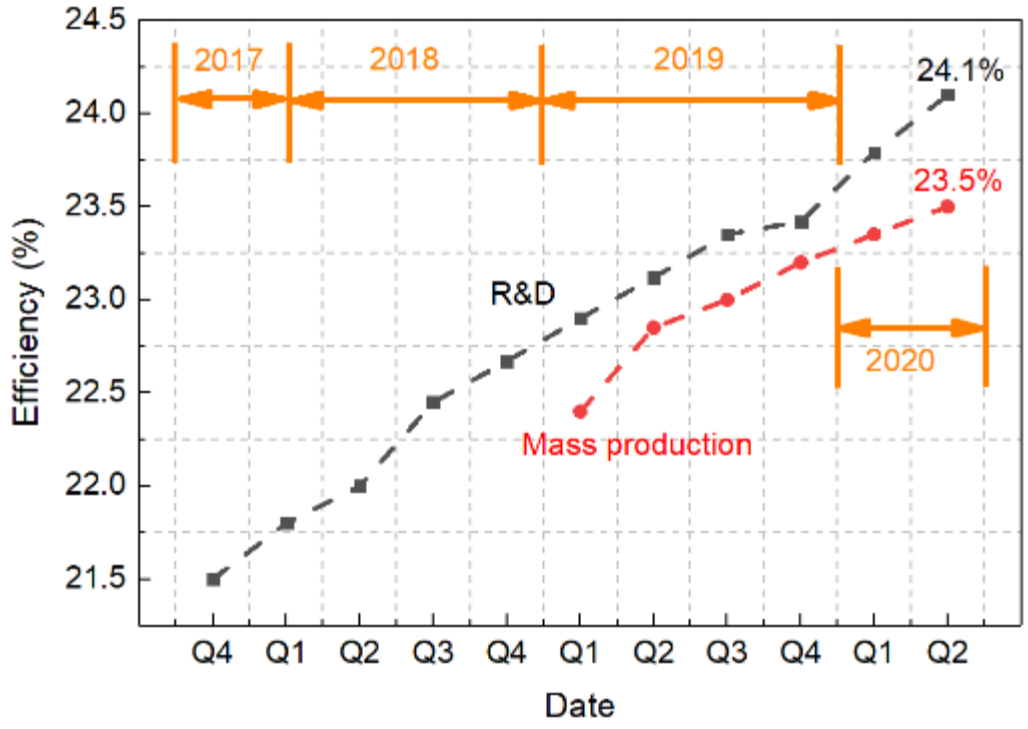
Jolywood NTOPCon Bifacial Cell Technology



Jolywood NTOPCon Bifacial Cell Eff in Mass Production

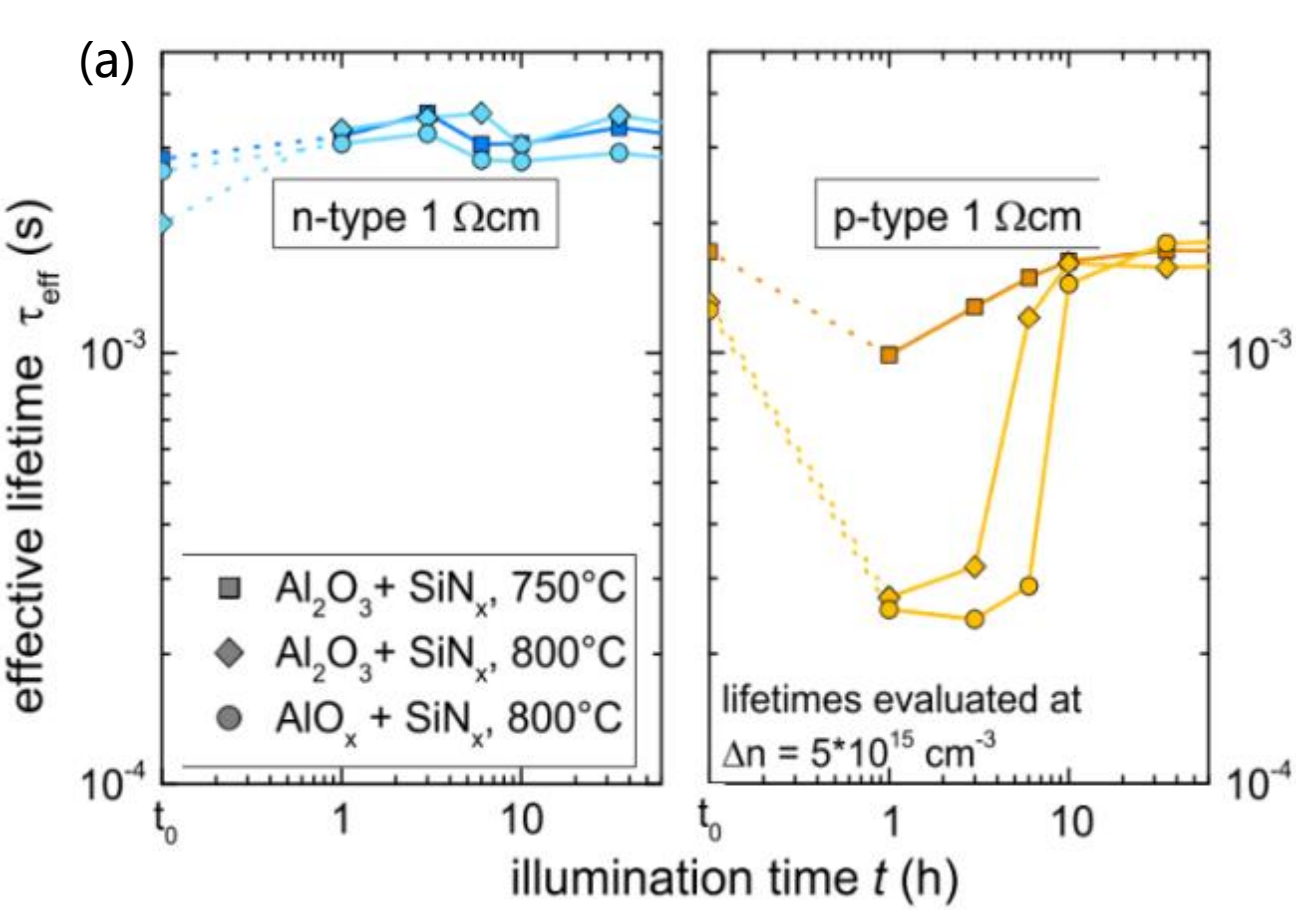
Cell	V_{oc} (mV)	J_{sc} (mA/cm^2)	I_{sc} (A)	FF (%)	Eff. (%)	Area (cm^2)
Ave.	702.7	40.83	10.29	81.99	**23.52**	251.99

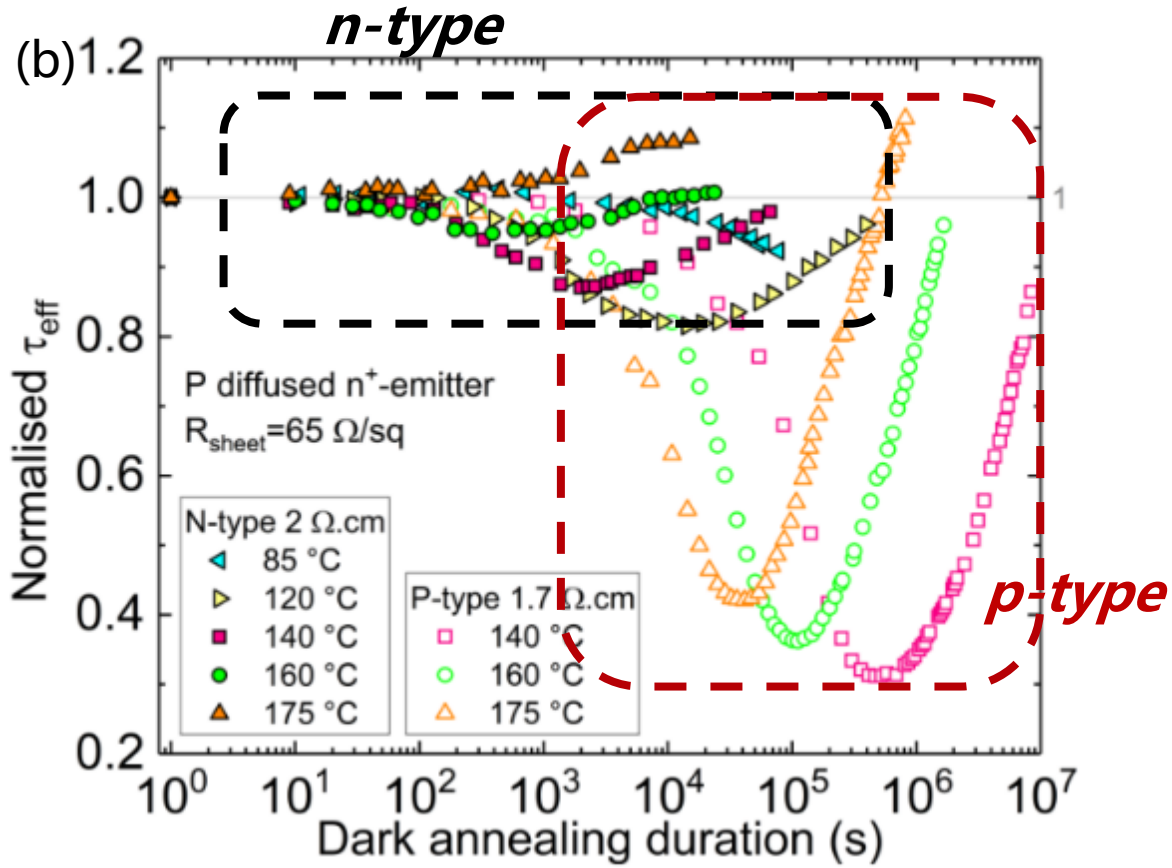




- Average efficiency up to 23.52% with an excellent V_{oc} of 702.7 mV are obtained in the mass production.

LID and LeTID



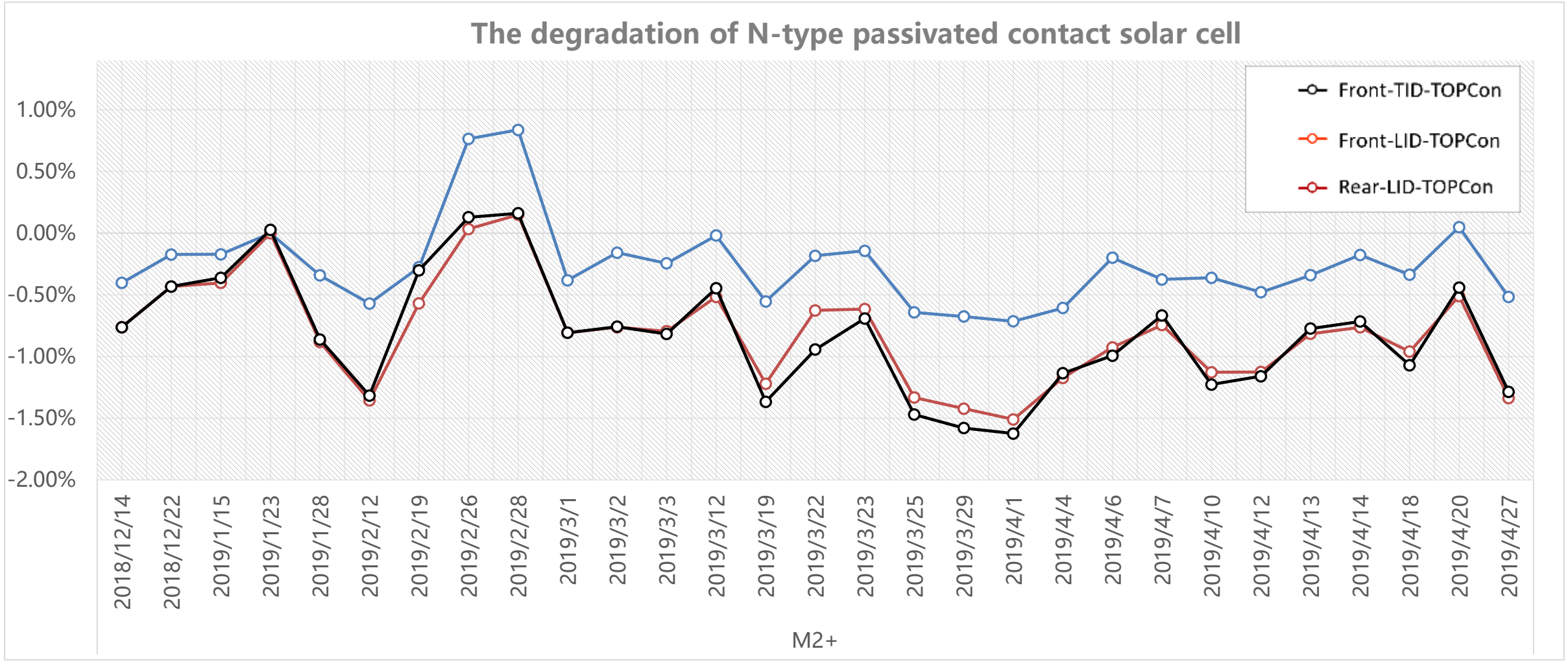


- No B-O defect that leads to no degradation for n-type material (Fig.a)
- The effect of LeTID also exists in n-type material, but it is significantly less prominent than p-type material

[1] Niewelt T et al, *Journal of Applied Physics*, 2017

[2] Chen D et al, *Solar Energy Materials and Solar*, 2018

Jolywood NTOPCon Bifacial Cell with No LID



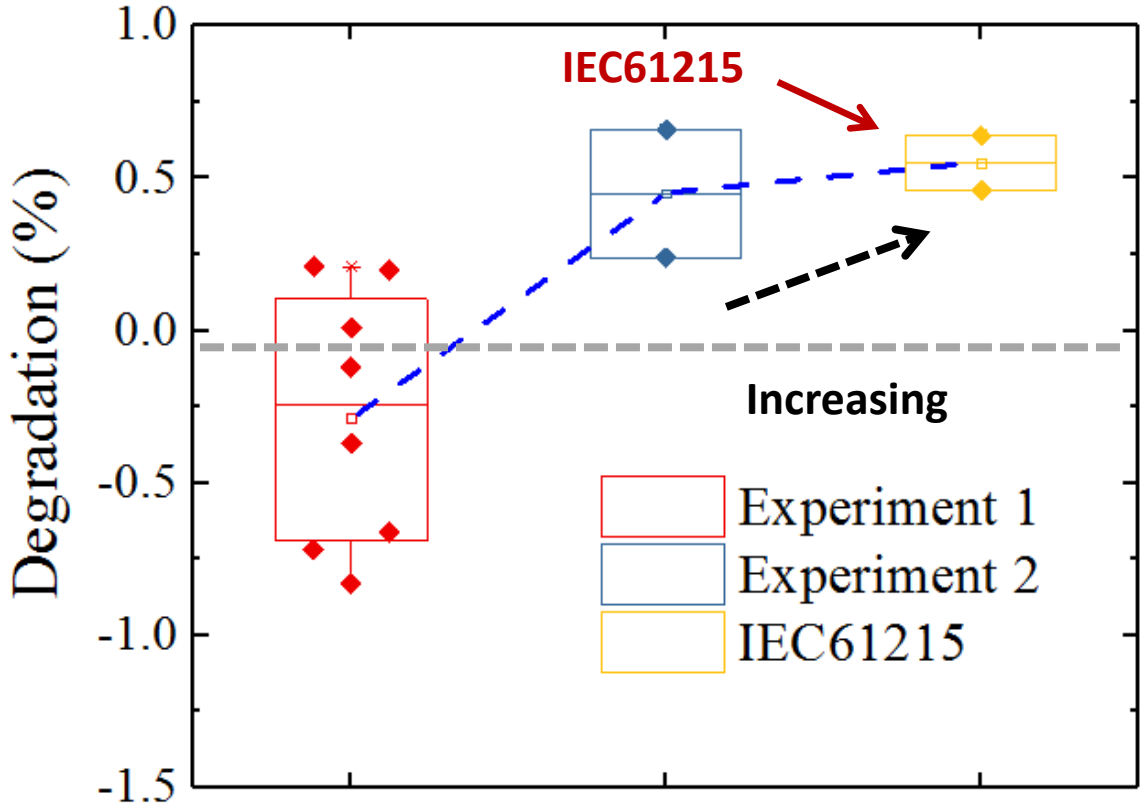
- Long-term LID and TID results show that the degradation of NTOPCon cells is negative, which indicates no degradation will occur in n-type solar cell

Jolywood NTOPCon Bifacial Module with Low LeTID

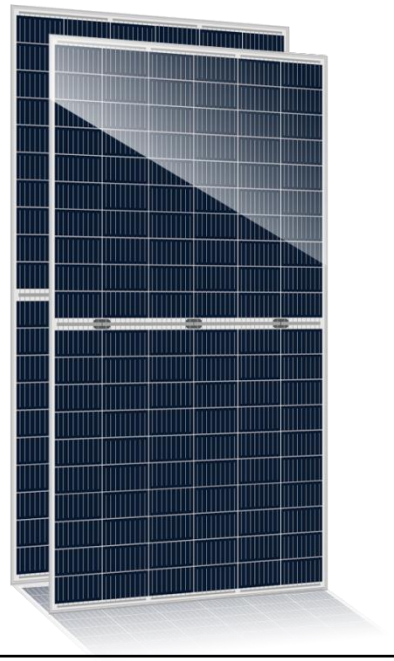
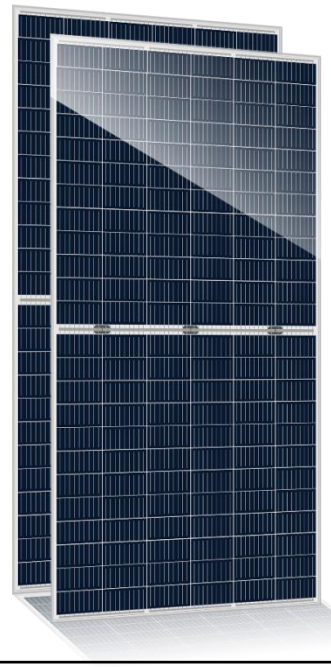
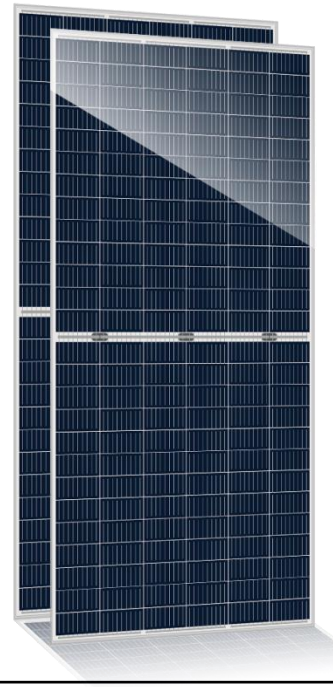
Strict LeTID Test Condition

- **Experiment 1 (Current injection)：75℃ ,1 A, 690 H**
- **Experiment 2 (Light and Current injection): pre-process (1 Sun, 10 kw/h) + 75℃, 1 A, 690 H**
- **IEC61215: pre-process (25 ℃, 9 A , 168 H) + 75℃, 1 A, 690 H**

ID	*Before (W)*	*After (W)*	*degradation%*	*Experiment*
JW242219040007000252	385.1	381.9	-0.83%	Experiment 1
JW242219040007000448	389.2	387.7	-0.37%	
JW242119040006900089	374.4	371.9	-0.66%	
JW242119040006900091	374.8	372.1	-0.72%	
JW142119070004400871	317.6	318.2	0.20%	
JW142119070004400872	318.0	318.0	0.01%	
JW142119070004400874	319.7	320.3	0.21%	
JW142119070004400875	318.9	318.6	-0.12%	
JW242219040007000886	392.2	394.8	0.66%	Experiment 2
JW242219040007004311	394.3	395.2	0.24%	
JW242219040007000754	**392.5**	**394.3**	**0.46%**	**IEC61215**
JW242219040007004676	**393.3**	**395.8**	**0.64%**	



Jolywood NTOPCon Bifacial Module Technology

NTOPCon half-cut cell 9 busbar/120cell-G1	NTOPCon half-cut cell 9 busbar/144cell-G1	NTOPCon half-cut cell 9 busbar/156cell-G1
- 350W - 20.79%	- 415W - 20.67%	- 450W - 20.73%
		

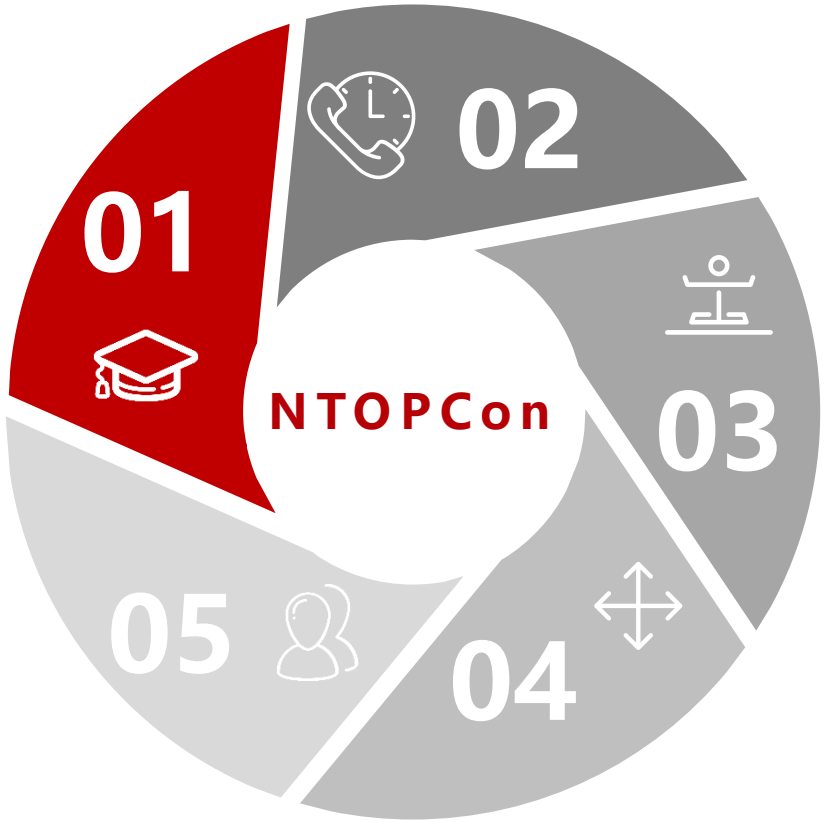
Jolywood NTOPCon Bifacial Module Technology

Higher Bifaciality

80%-85%

Better Low Illumination Response

Wide spextral response, higher power output even under low light settings like smog or cloudy days.



Low Degradation

1st year ≤ 1%
30th year ≤ 12.6%
(annually ≤ 0.4%)

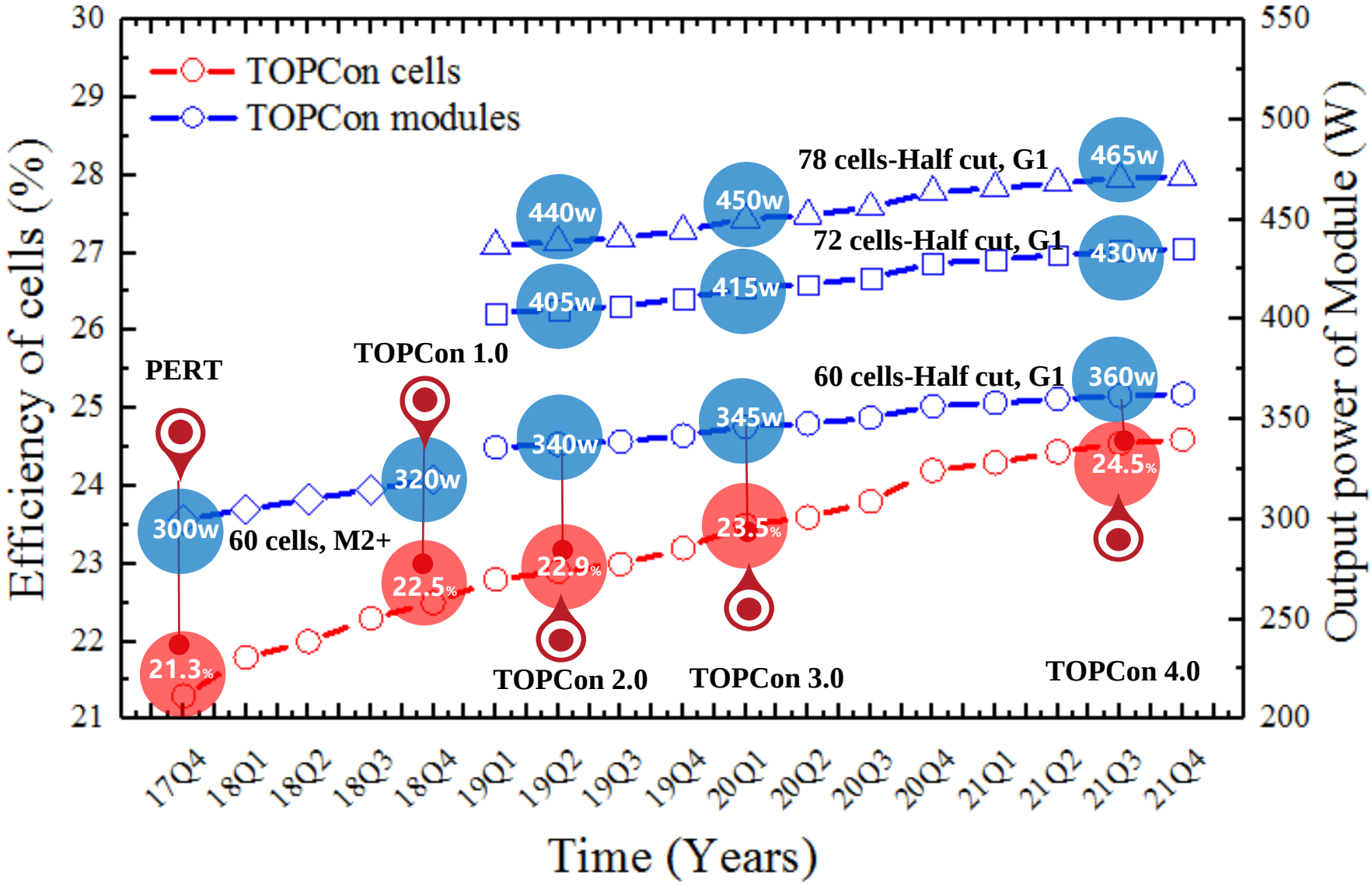
Low Temperature Coefficient

-0.32%/K

Higher Reliability

30 years warranty for all Jolywood products

Jolywood NTOPCon Bifacial Module Technology



Part 03

Application of Jolywood NTOPCon Technology

Panda Solar Project

Owner: Panda Green

UN Development Programme renewable energy project

Jolywood offered 29MW n-type bifacial modules, 310Wp

Tested energy gain: 13% more than p-type monofacial modules

China Top-runner: Sihong Fish-farming Project

Owner: SPIC & GCN

-World largest n-type solar farm (Total 1GW)

-World largest fish-farming project

-Top-runner Project

-Phase one, COD September 2018.

Phase II Jolywood as solely n-type module supplier for GCN, 100MWp, COD June 2020

Netherland Zonnepark Rilland

- Largest n-type bifacial project in Europe: 100% suppplied by Jolywood
- 8%-12% more power gain compared p-type monofacial projects in same region

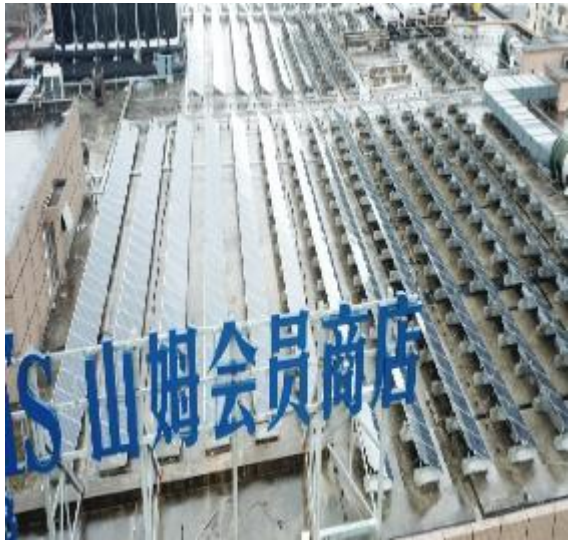
Ukraine Fruzynvka/Stara Synyava Projects

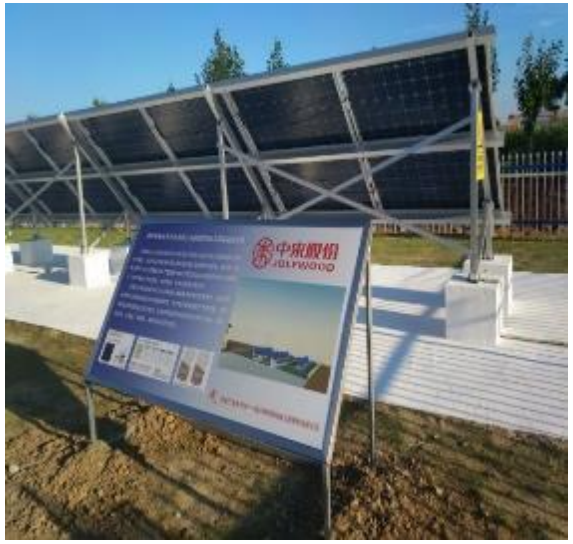
- Ukraine 1st n-type bifacial solar park : 100% suppplied by Jolywood
- “Best innovative project" awarded by SEF 2019

Oman Amin Marubeni Solar Project

- Project size 125MW, invested by Marubeni, modules 100% supplied by Jolywood
- Largest n-type bifacial solar farm worldwide

Industrial & Commercial Rooftop Projects





Part 04

Outlook and Conclusions

Outlook and Conclusion

Ion implantation + LPCVD	P diffusion + LPCVD
Texturing	Texturing
Boron diffusion	Boron diffusion
Single side etch	Single side etch
LPCVD	Polishing / Texturing
Implantation	LPCVD
RCA	PCl3 diffusion
Anneal	Single side etch
Rear PECVD	Wrap-around poly removal
Wrap-around poly removal	AlOx
AlOx	Front PECVD
Front PECVD	Rear PECVD
Metallization	Metallization

Challenges:

1) High-temperature, long processing-time boron diffusion process

2) Poly-silicon deposition process with wrap-around

3) Under-developed metallization pastes

Outlook and Conclusion

- Jolywood has 2.4GW NTOPCon cell and 3GW module capacity

- Progress in NTOPCon bifacial solar cells in Jolywood:
  - Average efficiency of 23.5% achieved in production using ion-implantation and screen-printing
  - Average efficiency of 23.8% and best efficiency of 24.2% achieved in R&D

- The roadmap of industrial bifacial passivating-contact solar cells exceeding 24% defined

- NTOPCon bifacial modules showed no LID degradation (< 0.1%) and the lowest outdoor power degradation

中来股份 JOLYWOOD

THANK YOU

Jolywood (Taizhou) Solar Technology Co., Ltd.

What's behind the high potential of passivated contact solar cells?

F. Haase, R. Peibst

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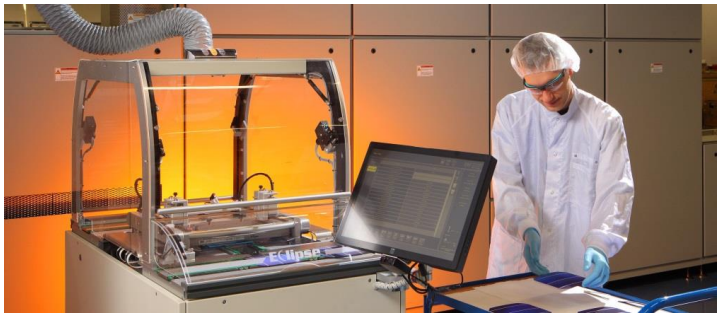
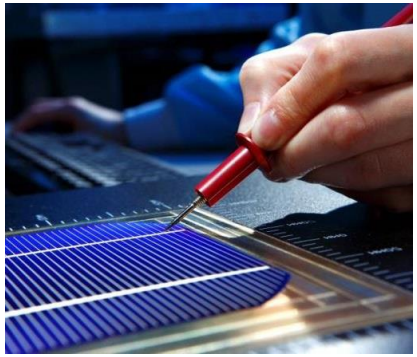
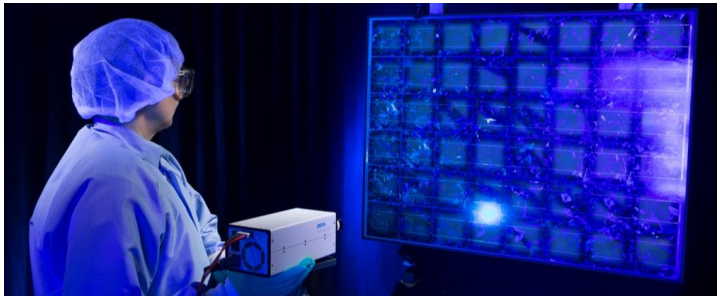
www.isfh.de

ISFH

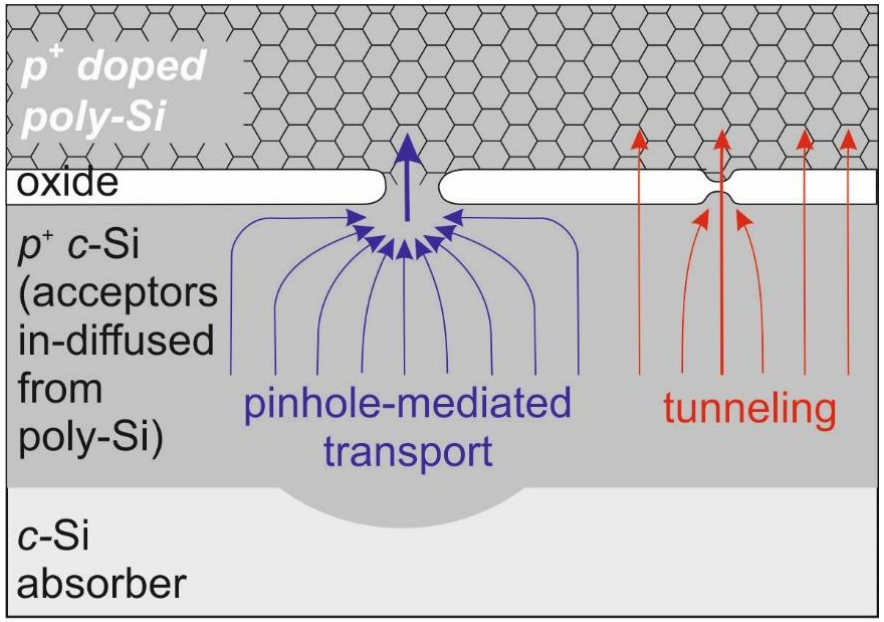






- Founded in 1987
- 12.1 Mio € turnover (2018)
- 155 employees
- R&D in photovoltaics and solar systems
- R&D in cooperation with industrial partners
- Focus in PV on applied research in c-Si PV, tandems, modules
- Independent calibration and test laboratory (ISFH CalTeC)

What is TOPCon or POLO?



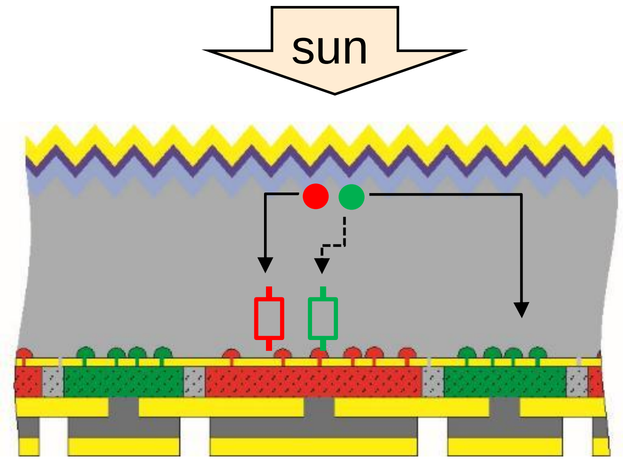
N. Folchert et al., Temperature-dependent contact resistance of carrier selective Poly-Si on oxide junctions. Solar Energy Materials and Solar Cells. 185. 10.1016/j.solmat.2018.05.046.

Tunnel **O**xide **P**assivated **Con**tact (TOPCon) or
Poly-Si on **o**xide (POLO) technology consists of:

- a 1 to 4 nm thin silicon oxide layer
- a doped polycrystalline silicon layer
- and a subsequent annealing

Carrier transport by tunneling and pinholes

Selectivity
A measure of the quality of the contact



$$S_{10} \equiv \log_{10}\left(\frac{[\text{green resistor}]}{[\text{red resistor}]}\right) = \log_{10}\left(\frac{V_{th}}{J_0 \rho_c}\right)$$

- Different proposals for definition and quantification of selectivity[1-5]
- Idea of R. Brendel *et al*.: ratio of resistivities for minority carriers (to be blocked) and majority carriers (to be collected)[1]
- Required input parameters easily accessible experimentally:
  J_0 - QSSPC + Kane & Swanson[6]
  ρ_c - TLM + Quokka3[7] or Eidelloth[8]
- Efficiency limit implied by contact can be calculated from S_{10} (1 diode eq.)[1]
- Different passivating contact schemes and their combination[9] can be compared on equal footing

Black = ISFH works, grey = works from other groups
[1] R. Brendel *et al*., IEEE Journal of Photovoltaics **6**, 1413 (2016)
[2] P. Koswatta, thesis Arizona State University (2016)
[3] C. Onno *et al*., Proc. of the 46th IEEE PVSC Conference - Chicago, IL, (2019)
[4] C. D. Weber *et al*., J. Phys. Chem. C 120 (36), 19951 (2016)
[5] U. Rau *et al*., Adv. Mater. Interfaces 1900252 (2019)
[6] D. E. Kane *et al*., Proc. of the 18th IEEE PVSC, 578 (1985)
[7] G. Kökbudak *et al*., Proc. of the 33rd EUPVSEC, 242 (2017)
[8] S. Eidelloth *et al*., IEEE Elec. Dev. Lett. **35**, 9 (2014)
[9] J. Schmidt *et al.,* Sol. En. Mat. Sol. Cells **187**, 39 (2018).

Promising electron & hole contact combinations

	η_{max} [%] $S_{e\&h}$	Electron-selective contacts						
		P-diffused n^+	a-Si:H(i) /a-Si:H(n)	th-SiO_x/ poly-Si(n^+) PECVD	th-SiO_x/ poly-Si(n^+) LPCVD	chem-SiO_x/ poly-Si(n^+) LPCVD	SiO_x/TiO_y	MgO_x
	Al-p^+	**24.5 (PERC)** **11.7**	26.8 12.8	26.9 12.8	27.1 12.9	27.1 13.0	26.3 12.5	24.9 11.9
Hole-selective contacts	a-Si:H(i/p)	24.7 11.8	**27.5 (HIT)** **13.2**	27.7 13.3	27.9 13.5	28.0 13.5	26.8 12.8	25.1 12.0
	SiO_x/ poly-Si(p^+)	24.9 11.9	28.1 13.6	28.3 13.8	28.7 14.2	28.7 14.2	27.3 13.1	25.4 12.1
	SiO_x/Si:C (p^+)	24.9 11.9	28.0 13.5	28.2 13.7	28.5 14.0	28.6 14.1	27.2 13.0	25.3 12.1
	a-Si:H(i)/MoO_x	24.4 11.7	26.5 12.6	26.6 12.7	26.8 12.8	26.8 12.8	26.0 12.4	24.7 11.8
	MoO_x	24.1 11.6	25.9 12.3	26.0 12.4	26.1 12.4	26.1 12.4	25.5 12.2	24.4 11.7
	PEDOT:PSS	24.1 11.6	26.0 12.4	26.1 12.4	26.2 12.5	26.2 12.5	25.6 12.2	24.5 11.7

J. Schmidt, R. Peibst, and R. Brendel, Sol. En. Mat. Sol. Cells **187**, 39 (2018)

- PERC limited to 24.5% by contacts only (according to J_0, ρ_c input data)

J_0, ρ_c data from different groups, table and derivation of combined selectivity from
J. Schmidt, R. Peibst, and R. Brendel, Sol. En. Mat. Sol. Cells **187**, 39 (2018).

Promising electron & hole contact combinations

	η_{max} [%] $S_{e\&h}$	Electron-selective contacts						
		P-diffused n^+	a-Si:H(*i*) /a-Si:H(*n*)	th-SiO_x/ poly-Si(n^+) PECVD	th-SiO_x/ poly-Si(n^+) LPCVD	chem-SiO_x/ poly-Si(n^+) LPCVD	SiO_x/TiO_y	MgO_x
Hole-selective contacts	Al-p^+	**24.5 (PERC)** **11.7**	26.8 12.8	26.9 12.8	27.1 12.9	27.1 13.0	26.3 12.5	24.9 11.9
	a-Si:H(*i*/*p*)	24.7 11.8	**27.5 (HIT)** **13.2**	27.7 13.3	27.9 13.5	28.0 13.5	26.8 12.8	25.1 12.0
	SiO_x/ poly-Si(p^+)	24.9 11.9	28.1 13.6	28.3 13.8	28.7 14.2	28.7 14.2	27.3 13.1	25.4 12.1
	SiO_x/Si:C (p^+)	24.9 11.9	28.0 13.5	28.2 13.7	28.5 14.0	28.6 14.1	27.2 13.0	25.3 12.1
	a-Si:H(*i*)/MoO_x	24.4 11.7	26.5 12.6	26.6 12.7	26.8 12.8	26.8 12.8	26.0 12.4	24.7 11.8
	MoO_x	24.1 11.6	25.9 12.3	26.0 12.4	26.1 12.4	26.1 12.4	25.5 12.2	24.4 11.7
	PEDOT:PSS	24.1 11.6	26.0 12.4	26.1 12.4	26.2 12.5	26.2 12.5	25.6 12.2	24.5 11.7

J. Schmidt, R. Peibst, and R. Brendel, Sol. En. Mat. Sol. Cells **187**, 39 (2018)

- Combination of a-Si:H(i/n) and a-Si:H(i/p) enables 27.5%
- This is the combination used in the current 26.7% world record cell from Kaneka

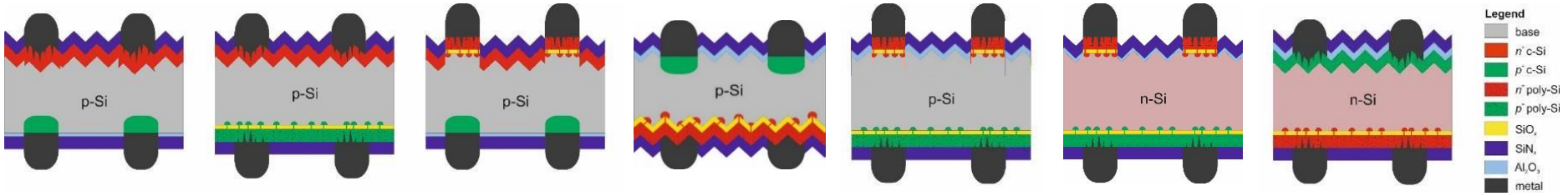
Promising electron & hole contact combinations

	η_{max} [%] $S_{e\&h}$	Electron-selective contacts						
		P-diffused n^+	a-Si:H(*i*) /a-Si:H(*n*)	th-SiO_x/ poly-Si(n^+) PECVD	th-SiO_x/ poly-Si(n^+) LPCVD	chem-SiO_x/ poly-Si(n^+) LPCVD	SiO_x/TiO_y	MgO_x
Hole-selective contacts	Al-p^+	**24.5 (PERC)**	26.8	26.9	27.1	27.1	26.3	24.9
		11.7	12.8	12.8	12.9	13.0	12.5	11.9
	a-Si:H(*i*/*p*)	24.7	**27.5 (HIT)**	27.7	27.9	28.0	26.8	25.1
		11.8	**13.2**	13.3	13.5	13.5	12.8	12.0
	SiO_x/ poly-Si(p^+)	24.9	28.1	28.3	28.7	28.7	27.3	25.4
		11.9	13.6	13.8	14.2	14.2	13.1	12.1
	SiO_x/Si:C (p^+)	24.9	28.0	28.2	28.5	28.6	27.2	25.3
		11.9	13.5	13.7	14.0	14.1	13.0	12.1
	a-Si:H(*i*)/MoO_x	24.4	26.5	26.6	26.8	26.8	26.0	24.7
		11.7	12.6	12.7	12.8	12.8	12.4	11.8
	MoO_x	24.1	25.9	26.0	26.1	26.1	25.5	24.4
		11.6	12.3	12.4	12.4	12.4	12.2	11.7
	PEDOT:PSS	24.1	26.0	26.1	26.2	26.2	25.6	24.5
		11.6	12.4	12.4	12.5	12.5	12.2	11.7

J. Schmidt, R. Peibst, and R. Brendel, Sol. En. Mat. Sol. Cells **187**, 39 (2018)

- All combinations including poly-Si or Si:C on SiO_x show even higher selectivities and higher efficiency potentials > 28%
- This is the combination used in the current 26.1% vice-world record cell from ISFH

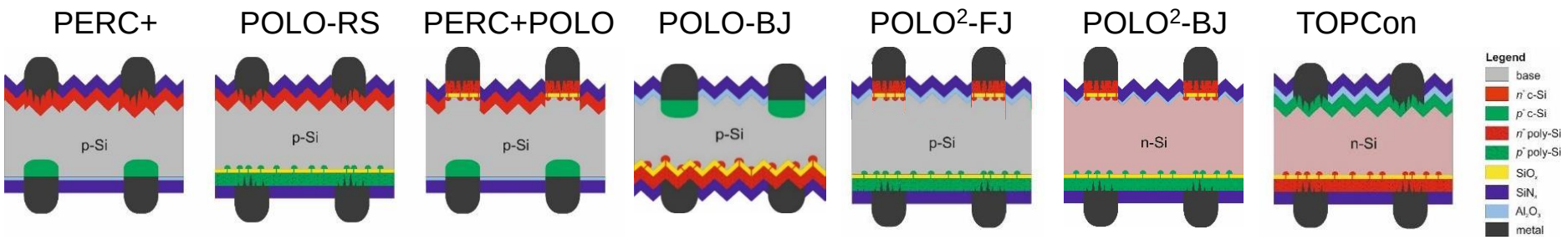
POLO – double side contacted industrial solar cell concepts



- **Various cell concepts** / process sequences / poly-Si depositions **under investigation**[1]
- Benefit of POLO: stable under high-temperature, compatible with high-temperature screen-printing
  → Possible "add-on" for PERC mainstream

[1] R. Peibst et al. For none, one, or two polarities—How do POLO junctions fit best into industrial Si solar cells?. *Prog Photovolt Res Appl*. 2020; 28: 503– 516. https://doi.org/10.1002/pip.3201

POLO – double side contacted industrial solar cell concepts

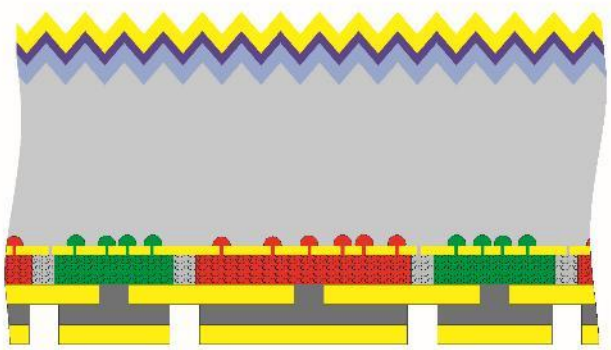


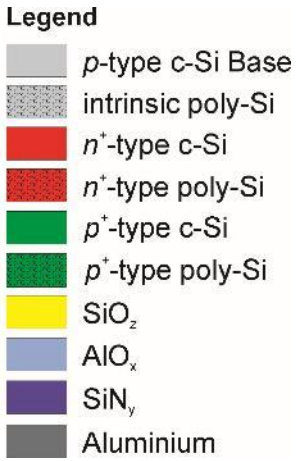
- Efficiency gain over PERC (simulated with measured input parameter):

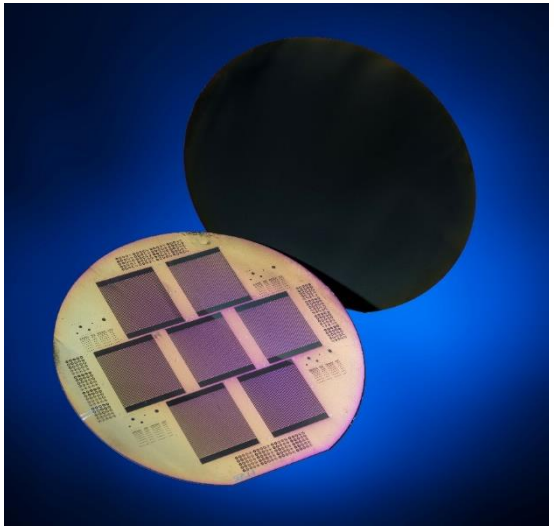
  +0.2-0.4% +0.2-0.4% +0.6-1.0% +1.0-1.4% +1.1-1.5% +0.6-0.9%

- **Costs** depend on **number of process steps** (can be more or less than PERC)
- High efficiency for n-type and p-type wafers
- High quality industrial p-type wafers available (e.g. Ga- doped)

p+ and n+ POLO junctions: POLO²-IBC cell







- Most efficient cell with passivating contacts
- P-type Si world record
- **η = 26.1%[1]** independently confirmed at ISO17025-accredited Calibration and Test Center, ISFH-CalTeC
- Realistic potential of 27% evaluated

[1] F. Haase *et al*., Solar Energy Materials and Solar Cells **186**,184 (2018)

Promising electron & hole contact combinations

η_{max} [%] / $S_{e\&h}$		Electron-selective contacts: P-diffused n^+	a-Si:H(*i*)/a-Si:H(*n*)	th-SiO_x/poly-Si(n^+) PECVD	th-SiO_x/poly-Si(n^+) LPCVD	chem-SiO_x/poly-Si(n^+) LPCVD	SiO_x/TiO_y	MgO_x
Hole-selective contacts	Al-p^+	**24.5 (PERC)**	26.8	26.9	27.1	27.1	26.3	24.9
		11.7	12.8	12.8	12.9	13.0	12.5	11.9
	a-Si:H(*i*/*p*)	24.7	**27.5 (HIT)**	27.7	27.9	28.0	26.8	25.1
		11.8	**13.2**	13.3	13.5	13.5	12.8	12.0
	SiO_x/ poly-Si(p^+)	24.9	28.1	28.3	28.7	28.7	27.3	25.4
		11.9	13.6	13.8	14.2	14.2	13.1	12.1
	SiO_x/Si:C (p^+)	24.9	28.0	28.2	28.5	28.6	27.2	25.3
		11.9	13.5	13.7	14.0	14.1	13.0	12.1
	a-Si:H(*i*)/MoO_x	24.4	26.5	26.6	26.8	26.8	26.0	24.7
		11.7	12.6	12.7	12.8	12.8	12.4	11.8
	MoO_x	24.1	25.9	26.0	26.1	26.1	25.5	24.4
		11.6	12.3	12.4	12.4	12.4	12.2	11.7
	PEDOT:PSS	24.1	26.0	26.1	26.2	26.2	25.6	24.5
		11.6	12.4	12.4	12.5	12.5	12.2	11.7

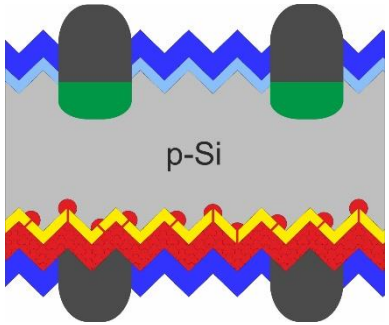
J. Schmidt, R. Peibst, and R. Brendel, Sol. En. Mat. Sol. Cells **187**, 39 (2018)

- P-diffused contact limits cell, no improvement for substituting Al-p+
- Replacing P-diffused contact increases efficiency limit to 27%

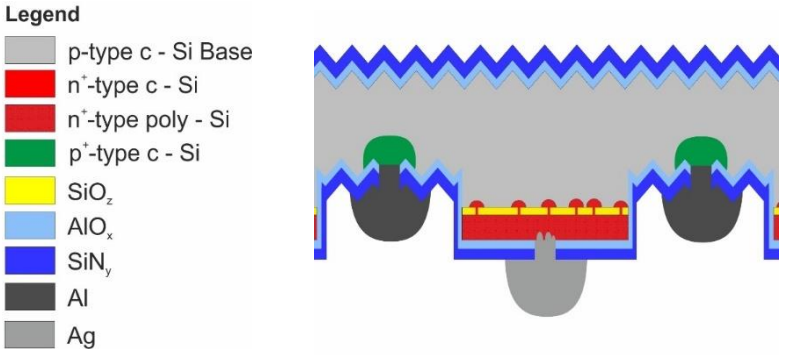
Industrial POLO-BJ[1] and POLO-IBC cell[2]

- Same process equipment as PERC+ except poly-Si deposition tool
- Low silver consumption
- Only one high temperature step

- POLO-BJ: η = 24.3% simulated

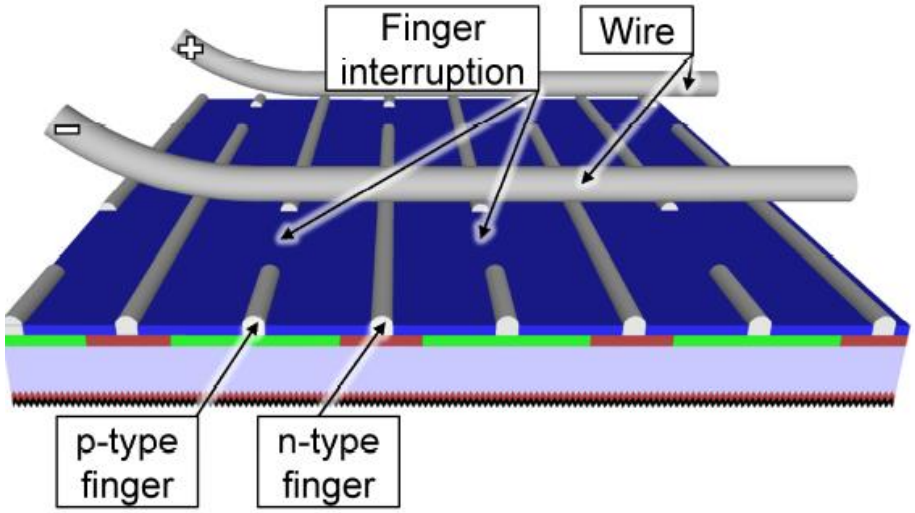


- POLO-IBC: η = 25%simulated
- η = 22.6% and V_{OC} = 711 mV demonstrated[3]



[1] R. Brendel et al., Screening Carrier Selective Contact Combinations for Novel Crystalline Si Cell Structures, Proc. of the 35th European Photovoltaic Solar Energy Conference and Exhibition, 39–46 (2018).
[2] F. Haase *et al*., Transferring the record p-type Si POLO-IBC cell technology towards an industrial level, Proc. of the 46th IEEE Photovoltaic Specialist Conference (PVSC) Chicago, IL, USA, 20.06.2019.
[3] F. Haase *et al*., accepted at 37th EUPVSEC 2020.

Modules with passivating contacts



Wire cell interconnection without busbars[1]

- Ribbon or Multiwire cell interconnection possible
- Similar process equipment for module manufacturing as PERC+
- High robustness against efficiency losses by cell cracks with Multiwire
- High efficiency, aesthetic modules for vehicle integrated PV especially with IBC

[1] M. Hendrichs *et al.*, Proc. of the 42nd IEEE PVSC (2015), DOI: 10.1109/PVSC.2015.7355645

Conclusion and Outlook

- TOPCon and POLO do not limit the cell anymore
- **Various cell concepts** / process sequences / poly-Si depositions **under investigation** with n- and p-type wafers
- TOPCon cell is the mature industrial-type passivated contact solar cell
- **26.1%** record efficiency with **POLO^2-IBC** with 27% efficiency potential
- **24.3% POLO-BJ** and **25% POLO-IBC** industrial-type cells simulated with measured input parameters

Acknowledgments

Many thanks to

- … director Prof. R. Brendel and the whole team @ ISFH and MBE
- … industrial partners
- … the federal state of Lower Saxony, the German Ministry for Economic Affairs and Energy, and the European Commission for funding
- **… you for your kind attention!**

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on the basis of a decision by the German Bundestag

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