Low cost IBC cell processes for industrial application

<u>Valentin D. Mihailetchi</u>*, *Haifeng Chu, Giuseppe Galbiati, Andreas Halm, Joris Libal, Radovan Kopecek

International Solar Energy Research Center e.V., Konstanz, Germany

Outline

➢ PV industry facts and trends

- n-type Si cell technologies
- Industrial fabrication processes

➢ Low cost IBC approach in HERCULES (ZEBRA cell concept)

- Main process steps
  - *Diffusion and passivation*
  - *Patterning method*
  - *Metallization and interconnection*
- Best cell and pilot line results
- Today's technology main limitation
- Potential for further improvements

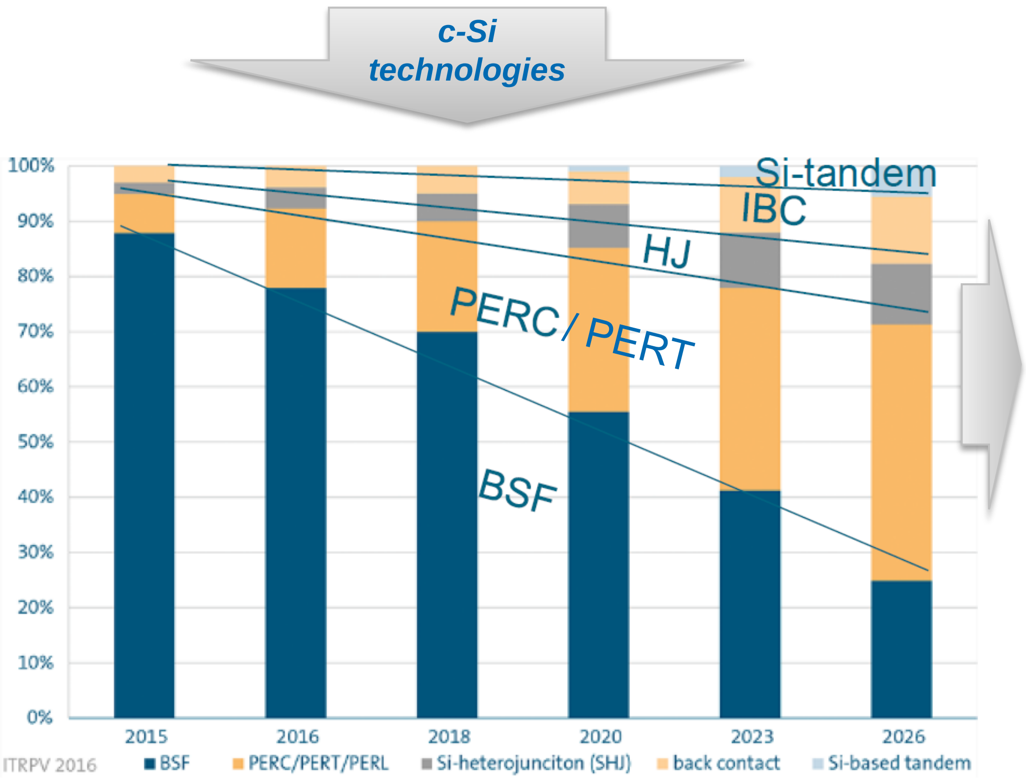
➢ Conclusions

PV industry facts and trends

International Solar Energy Research Center Konstanz

Worldwide market share for different solar cell technologies (end of 2015):

- **~90% c-Si (mono-Si, multi-Si)**
- **~10% Thin film (Cd-Te, a-Si, CIGS)**



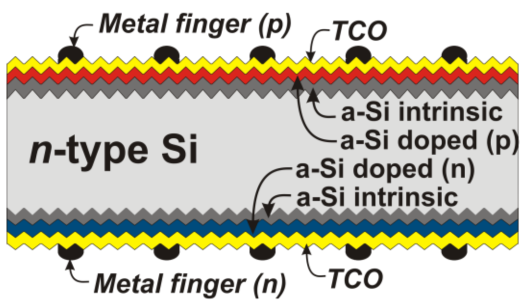
- **Al-BSF**:
  - *p-type* mono or multi wafers
  - low complexity, few process steps
- **PERC**:
  - *p-type* mono wafers
- **PERT**:
  - *p-type* mono and multi wafers
  - *n-type* mono wafers
- **HJ**:
  - *n-type* mono wafers
- **IBC**:
  - *n-type* mono wafers

PV market dominated by p-type cell concepts !

Data from: ***International Technology Roadmap for PV, 2016***

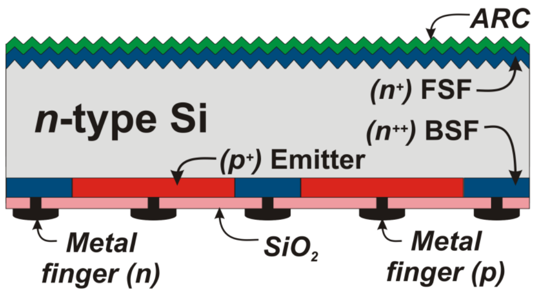
N-type Si solar cells

Most efficient c-Si cells commercially produced (R&D results):



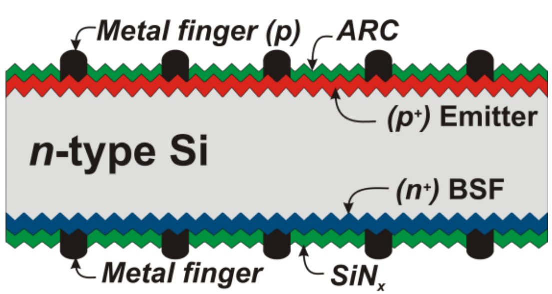
<u>HJ solar cell</u>

- front, emitter: a-Si (p)
- back, BSF: a-Si (n)
- bifacial
- η ≤ 25.6% (Panasonic)



<u>IBC solar cell</u>

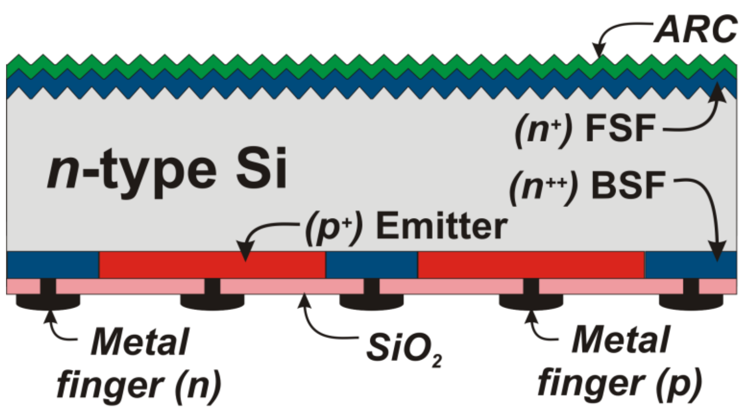
- FSF/BSF: n^+/n^{++} diffusion
- emitter: p^+ diffusion
- η ≤ 25.1% (Sunpower)



<u>n-PERT solar cell</u>

- front, emitter: p^+ diffusion
- back, BSF: n^+ diffusion
- bifacial
- η ≤ 22% (LG)

IBC cell concept



Requirements to make IBC cells in a standard production line:

- *large pitch size (for screen printed metallization)*
- *few masking steps*
- *low cost patterning method*
- *simple and reliable finger interconnection method (BB)*

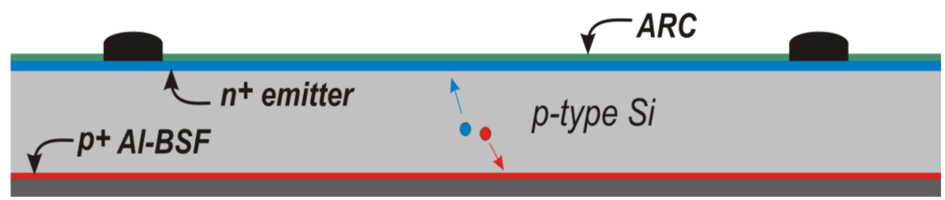
Industrial fabrication processes

International Solar Energy Research Center Konstanz

Processes / steps

- Texturing
- Cleaning
- Diffusion ($POCl_3$)
- PECVD SiN_x
- Screen Printing
- Contact Firing

Used in >70% of PV manufacturing (Al-BSF concept)



- efficiency: *18.5% – 20.0%*
- full Al back side contact (monofacial cell)
- high back side recombination
- p-type Cz wafers 156×156 mm^2 (6-inch)

HERCULES project:
develop low cost and high efficiency IBC cells

HERCULES: Low cost IBC approach

International Solar Energy Research Center Konstanz

Processes / steps

- Texturing
- Cleaning
- Diffusion ($POCl_3$)
- PECVD SiN_x
- Screen Printing
- Contact Firing

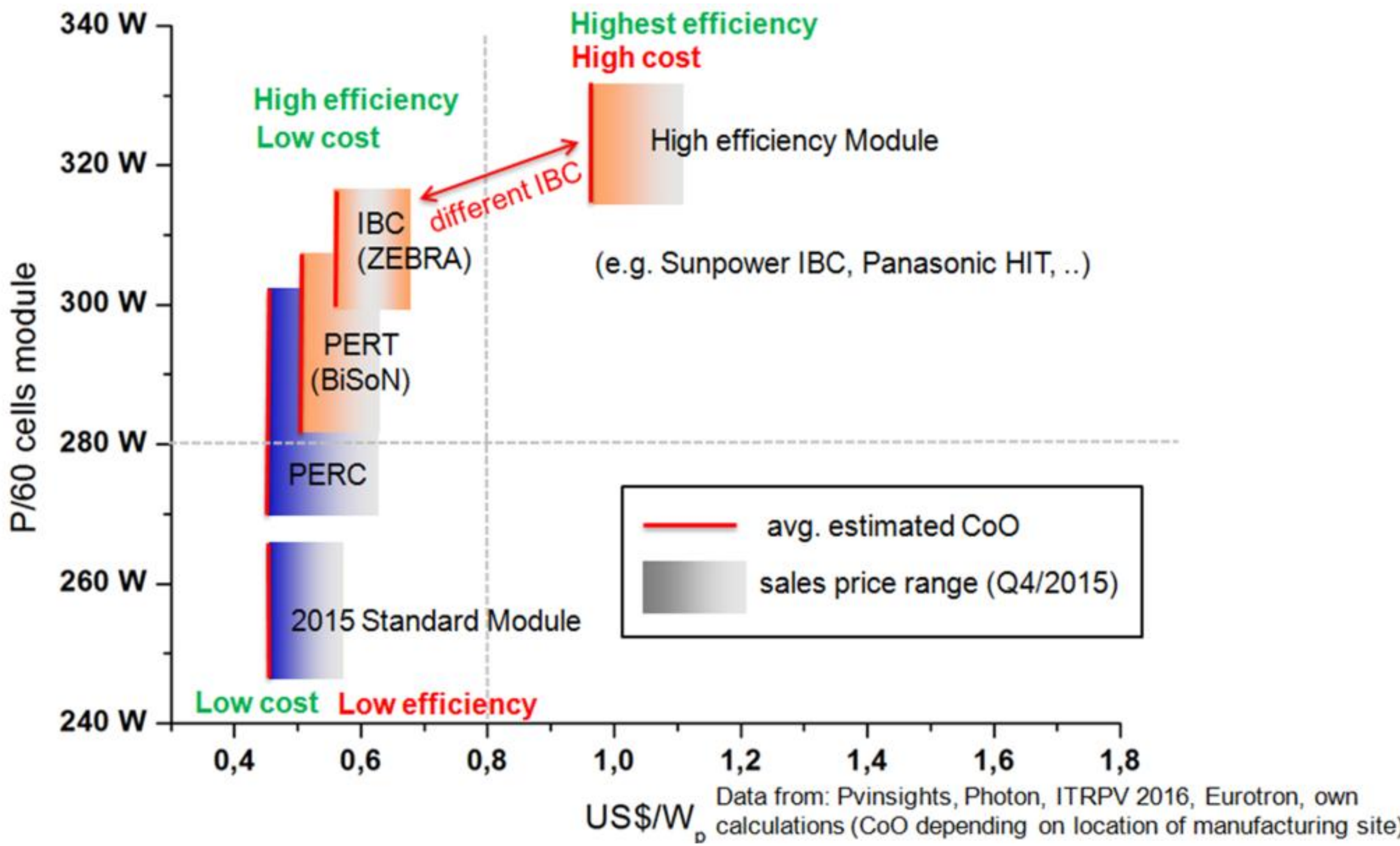
\+

ADDITIONAL STEPS to fabricate our ZEBRA (IBC) cell

- BBr_3 diffusion (p^+ emitter)
- Pre-diffusion cleaning
- PECVD SiN_x
- PECVD masking step
- Laser patterning

HERCULES: Low cost IBC approach

International Solar Energy Research Center Konstanz



R. Kopecek *et al.*, Photovoltaics International Volume 30, May (2016)

ZEBRA (IBC) cell: basic features

International Solar Energy Research Center Konstanz

- **large area:**

industry-standard 156 × 156 mm^2 pseudo square *n*-type Cz wafers

- **screen printed metallization:**

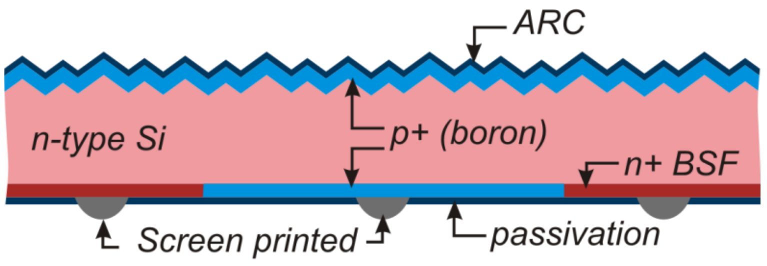
alignment tolerance: ± 150 µm

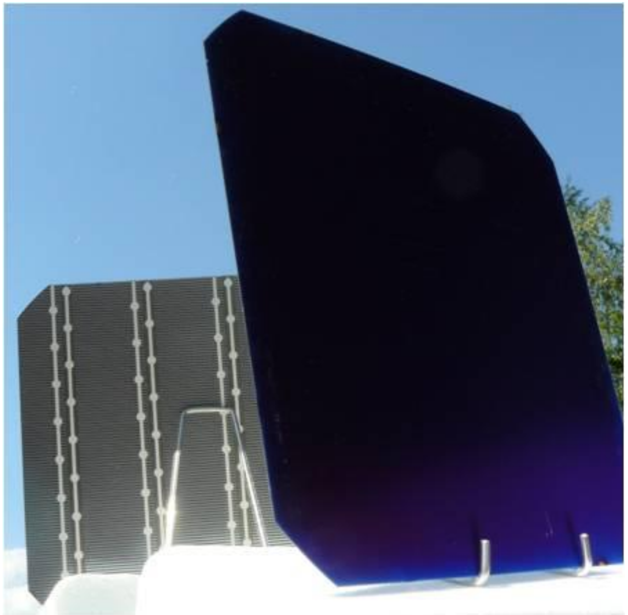
- **variable busbar structure**:

a) conventional stringing methods applicable for cell interconnection

⇨ bifacial: open back side grid

b) rear contact modules based on conductive backsheet technology (as used for MWT-cells & modules)



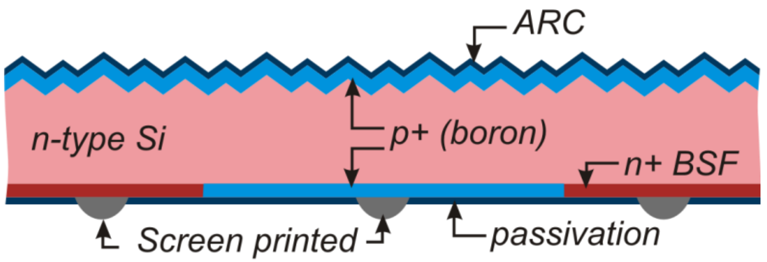


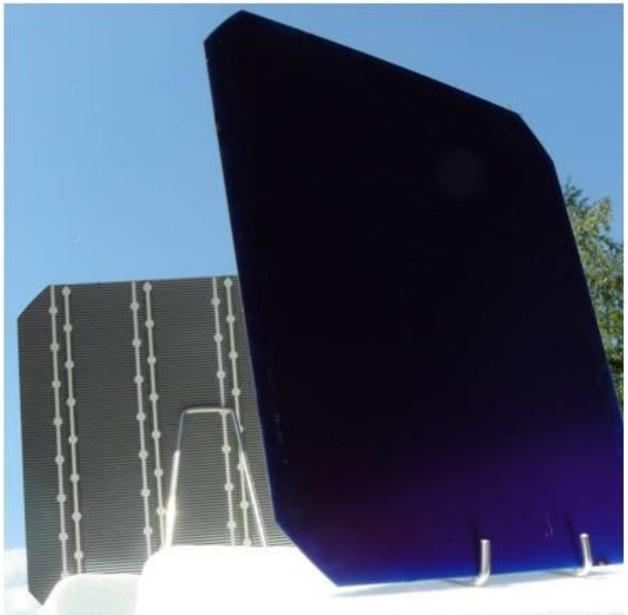
V.D. Mihailetchi *et al.*, **Patent pending**: *WO2013087458A1*
V.D. Mihailetchi *et al.*, Energy Procedia, 77, 534–539 (2015)

ZEBRA (IBC) cell: basic features

Main challenges for industrial implementation:

- p^+ (Boron) emitter and passivation
- patterning technique to form p^+ and n^+ regions
- p^+ and n^+ metallization
- finger interconnection





V.D. Mihailetchi *et al.*, **Patent pending**: *WO2013087458A1*
V.D. Mihailetchi *et al.*, Energy Procedia, 77, 534–539 (2015)

Boron diffusion and passivation

International Solar Energy Research Center Konstanz

Today's industrial techniques for boron doping:

1. BBr_3 thermal diffusion in an open tube furnace (~85%)
2. Ion implantation (~10%)
3. Other methods, *e.g.,* APCVD of doped SiO_2 layers (~5%)

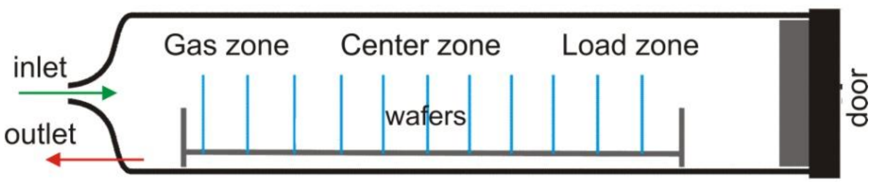
Boron diffusion and passivation

International Solar Energy Research Center Konstanz

Today's industrial techniques for boron doping:

1. **BBr_3 thermal diffusion in an open tube furnace (~85%)**
2. Ion implantation (~10%)
3. Other methods, *e.g.,* APCVD of doped SiO_2 layers (~5%)

Drawing of a open tube system



Inlet gasses: N_2-BBr_3, O_2, N_2

1000 wafers/run

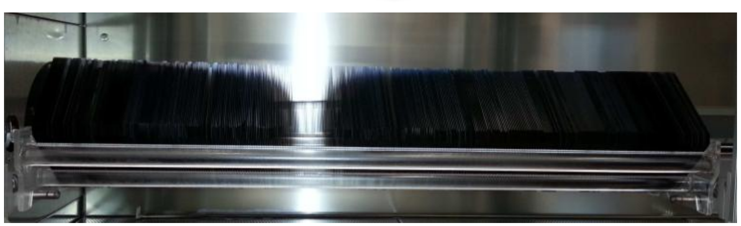


Photo of **centrotherm AG** diffusion system

Boron diffusion and passivation

International Solar Energy Research Center Konstanz

$4\,BBr_3(g) + 3O_2(g) \rightarrow 2B_2O_3(l) + 6Br_2(g)$ ⇒ ***deposition*** *(850-900 ℃)*

$2B_2O_3(l) + 3Si(s) \rightarrow 4B(s) + 3SiO_2(s)$ ⇒ ***drive in*** *(900-1050 ℃)*

(if too much elemental B generated)

$B_2O_3–SiO_2$ system
borosilicate glass (BSG)

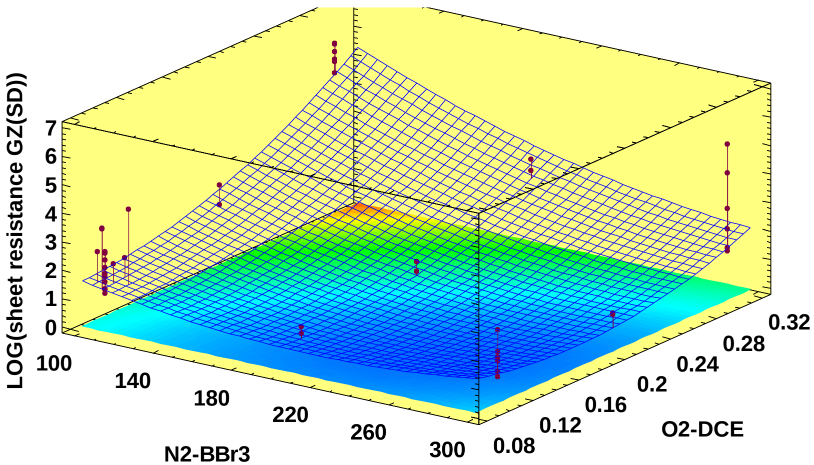
$Si + 6B \rightarrow SiB_6$
boron rich layer (BRL)

A "careful" deposition is required for preventing BRL layer !

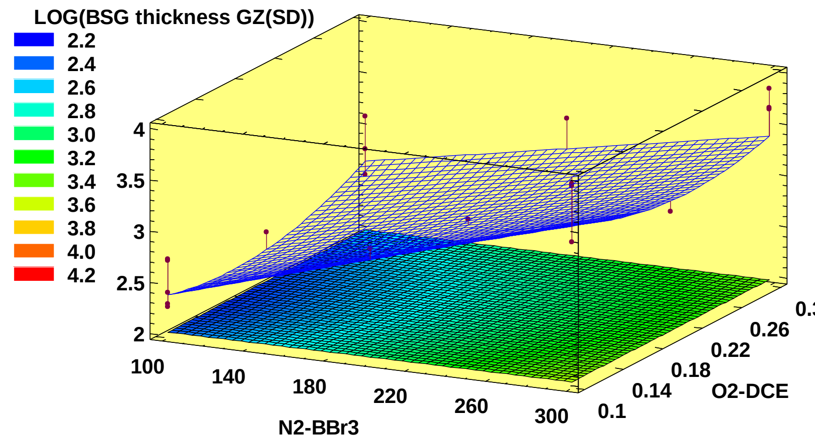
Boron diffusion and passivation

Results of typical diffusion optimization: *Multilevel factorial Design of Experiments (DoE)*

doping uniformity



BSG thickness uniformity



Optimum sheet resistance uniformity at: high BBr3 flow and low O2 flow

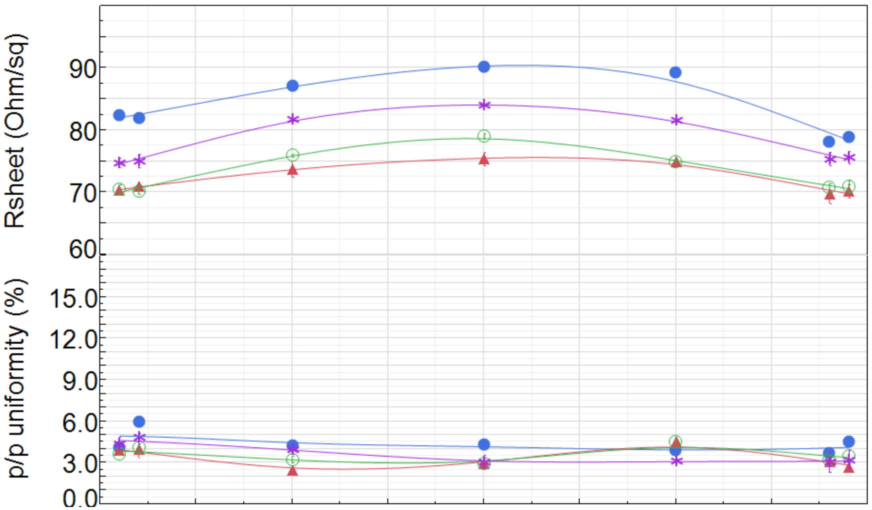
Optimum BSG thickness uniformity at: low BBr3 flow and low O2 flow

Boron diffusion and passivation

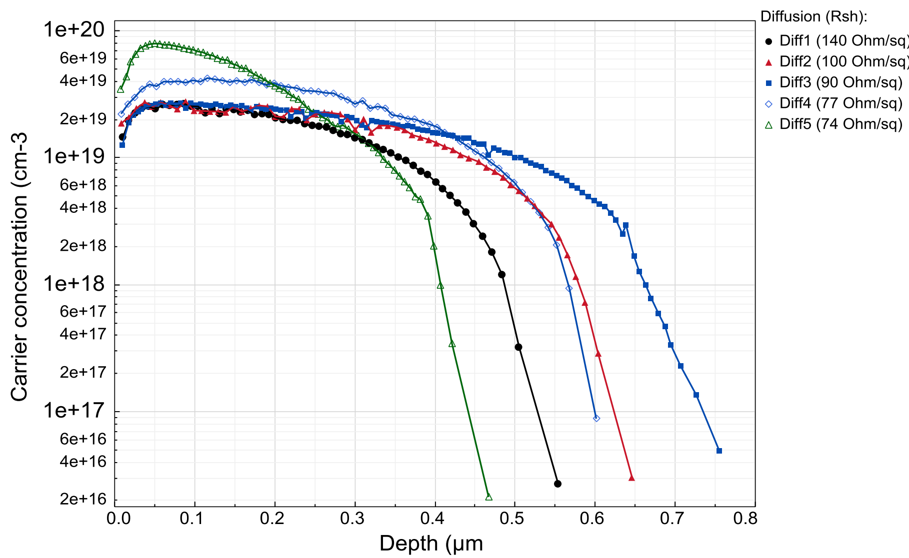
International Solar Energy Research Center Konstanz

Typical Boron diffusion results used in ZEBRA cell concept

Sheet resistance uniformity



Various Boron doping profiles

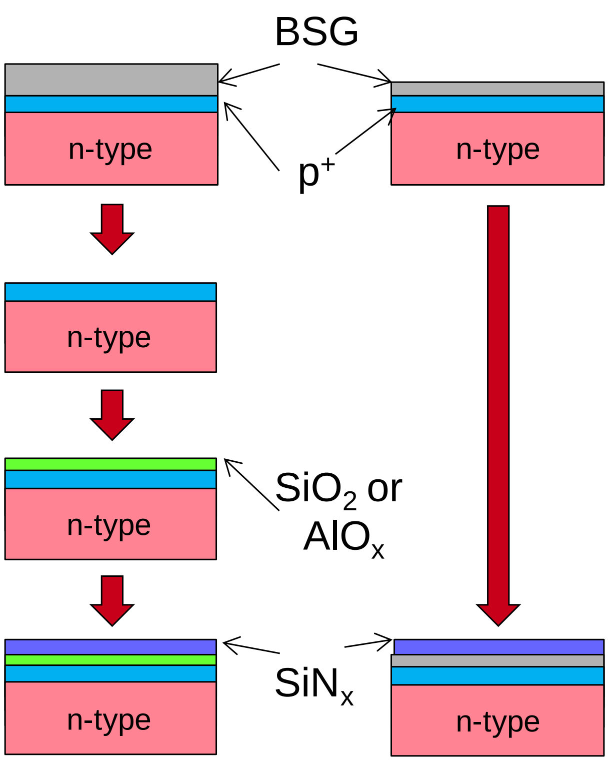


Boron diffusion and passivation

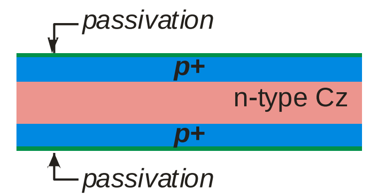
International Solar Energy Research Center Konstanz

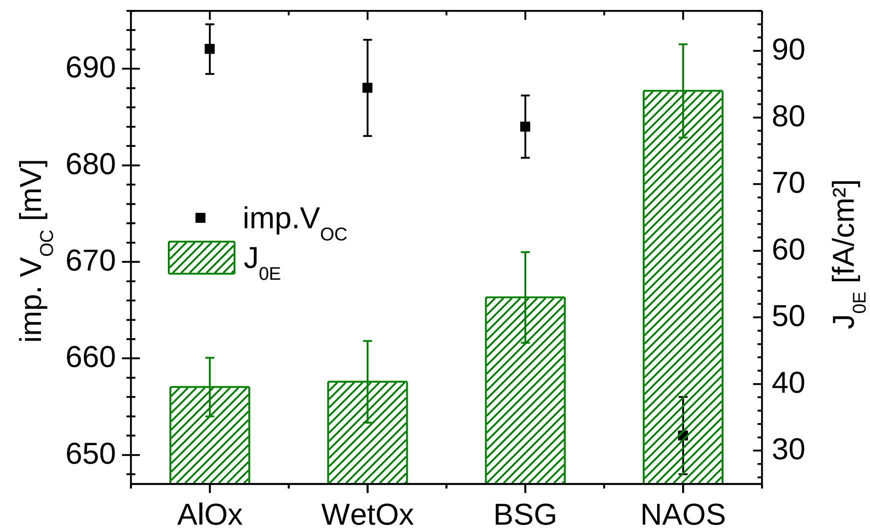
Boron emitter passivation: methods and results

Standard method | Our new method*



Test structure





AlO_x – PECVD AlO_x + SiN_x stack
$WetO_x$ – wet thermal SiO_2 (20 nm) + SiNx stack
***BSG – in-situ boron glass BSG + SiN_x stack**
NAOS – chemical SiO_2 (2-3 nm) + SiN_x stack

*V.D. Mihailetchi *et al.*, **Patent pending**: *WO2011/160814A2*

ZEBRA cell: patterning technique

International Solar Energy Research Center Konstanz

Options studied within HERCULES project:

- Laser patterning of a PECVD masking layer
- Interdigitated p^+ and n^+ patterning using a hybrid process (ion implant and diffusion) by counter-doping of masked implantation*

*R. Müller, J. Schrof, C. Reichel *et al.*, Appl. Phys. Lett. 105, 103503 (2014)

ZEBRA cell: patterning technique

International Solar Energy Research Center Konstanz

Options studied within HERCULES project:

- Laser patterning of a PECVD masking layer
- Interdigitated p^+ and n^+ patterning using a hybrid process (ion implant and diffusion) by counter-doping of masked implantation*

Nanosecond green laser with a rectangular top hat spot profile of 300×600 µm².

Lab throughput (single source): 285 w/h.

Target industrial throughput (dual source): 1440 w/h.

600x300 µm², process line

Metallization and interconnection

Metallization (optimum process):

- screen printing and firing through,
- single printing step for p^+ and n^+, using Ag paste ⇒ less printing steps, self alignment

optimum paste	ρ_C (p^+) [mΩcm^2]*	ρ_C (n^+) [mΩcm^2]*	R_L [Ω/cm]
paste 1 (Ag)	0.8 ±0.3	1.0 ±0.5	0.45
paste 2 (AgAl)	1.2 ±0.5	-	0.5

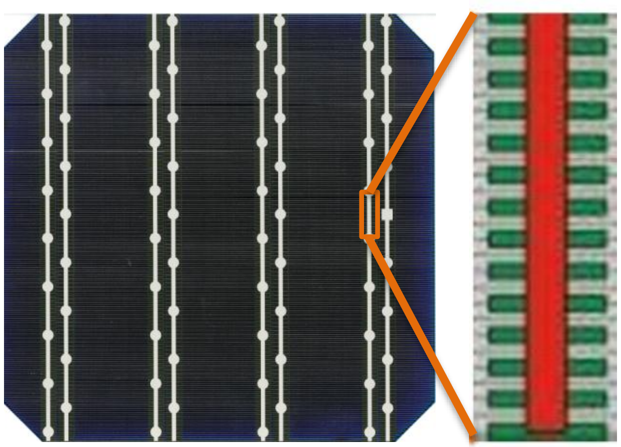
*R_{sh} (p^+) = 74 – 140 Ω/sq
*R_{sh} (n^+) = 45 – 80 Ω/sq

Metallization and interconnection

Interconnection:

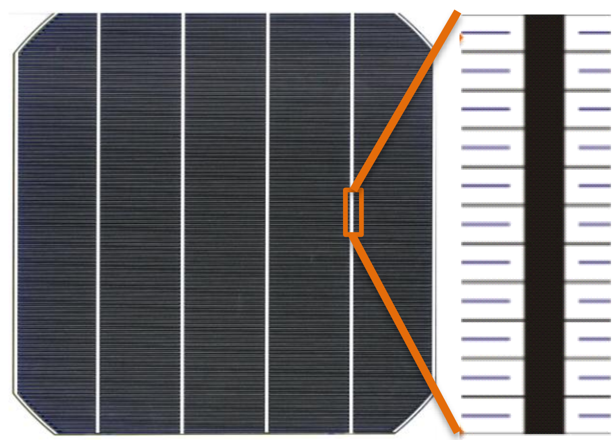
- Multi-layer (3D) vs. co-planar (2D) interconnection
- tested various layouts, busbar pastes, process parameters, etc.

Multi-layer interconnection (3D)



needs low temp. insulation pads
needs low temp. BB paste
flexible BB position

Co-planar interconnection (2D)



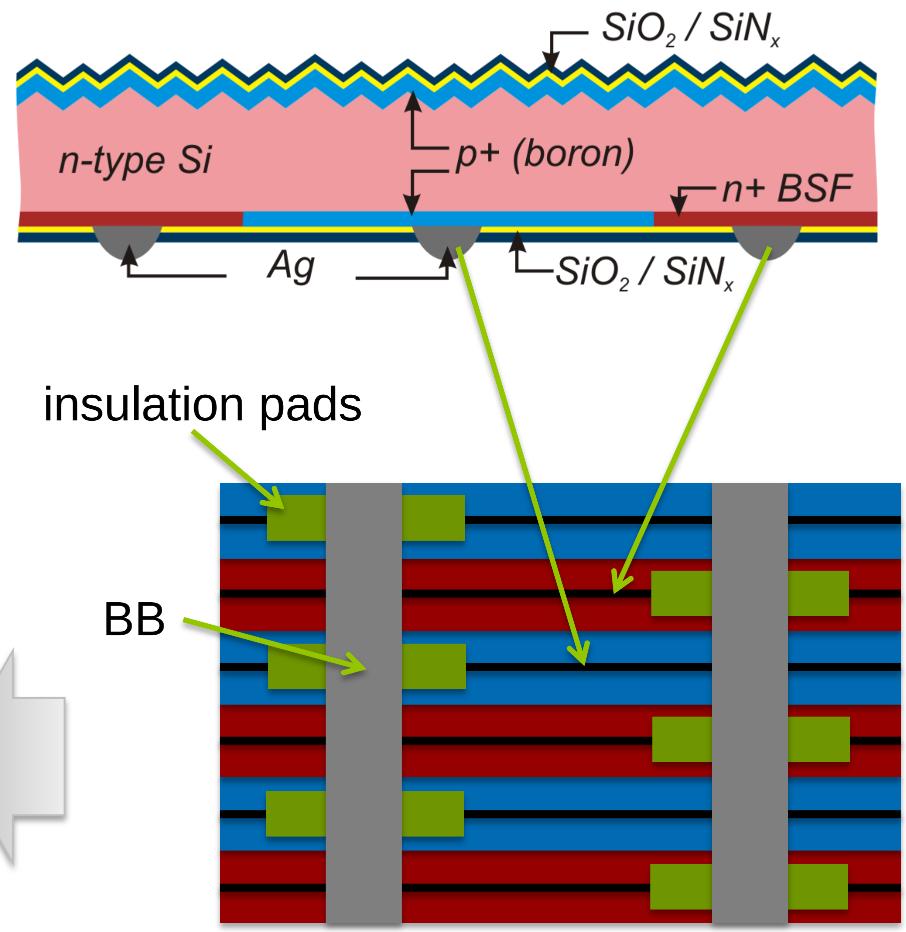
needs very accurate stringing
high temperature BB paste
edge BB needed

Metallization and interconnection

International Solar Energy Research Center Konstanz

Interconnection (optimum process):

- Multi-layer (3D) interconnection



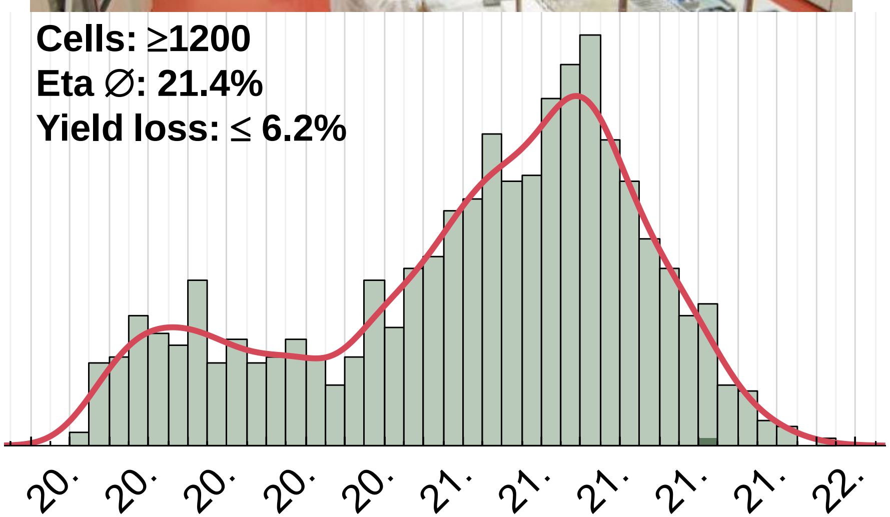
- Reliable and flexible design

- Compatible with wide range of low temp BB pastes

- TC and DH stable*

*A. Halm *et al.*, this workshop

ZEBRA: cell results



Pilot line activity of ZEBRA cells in HERCULES project

Main results:

- Ramp up and pilot production of >1200 n-type 6-inch IBC cells at ISC Konstanz
- ≥75% bifaciality at cell level!
- best cell in pilot line 22%
- best 60 cells module power of 303 Wp*

Best cell results:

J_{SC} [mA/cm²]	V_{OC} [mV]	*FF* [%]	*Efficiency* [%]
41.5	662	80.0	**22.0**

*A. Halm *et al.*, this workshop

ZEBRA: main limitation

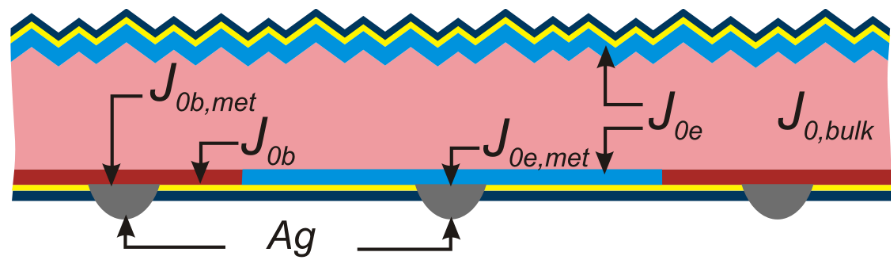
International Solar Energy Research Center Konstanz

	area [cm²]	J_{SC} [mA/cm²]	V_{OC} [mV]	iV_{OC} [mV]	FF [%]	Efficiency [%]
ZEBRA best cell	239	41.5	662	690	80.0	**22.0**

$V_{OC} << iV_{OC}$

Main limitation:

$$V_{OC} = V_T \times \ln(J_{SC} / J_{01})$$



$$J_{01} = J_{0,bulk} + J_{0b} + J_{0e} + MF_e \times (J_{0e,met} - J_{0e}) + MF_b \times (J_{0b,met} - J_{0b})$$

From experimental data:

$J_{0b} \approx 60\ fA/cm^2$

$J_{0e} \approx 25\ fA/cm^2$

$J_{0b,met} \approx 1200\ fA/cm^2$

$\mathbf{J_{0e,met} \approx 2500\ fA/cm^2\ !}$

ZEBRA: main limitation

Reducing metal recombination losses by:

- tuning of (emitter) diffusion profiles
- improving metallization pastes (*actual state-of-the-art: Ag paste*)
- reduce metal contact area (*actual finger width: 50 µm*)

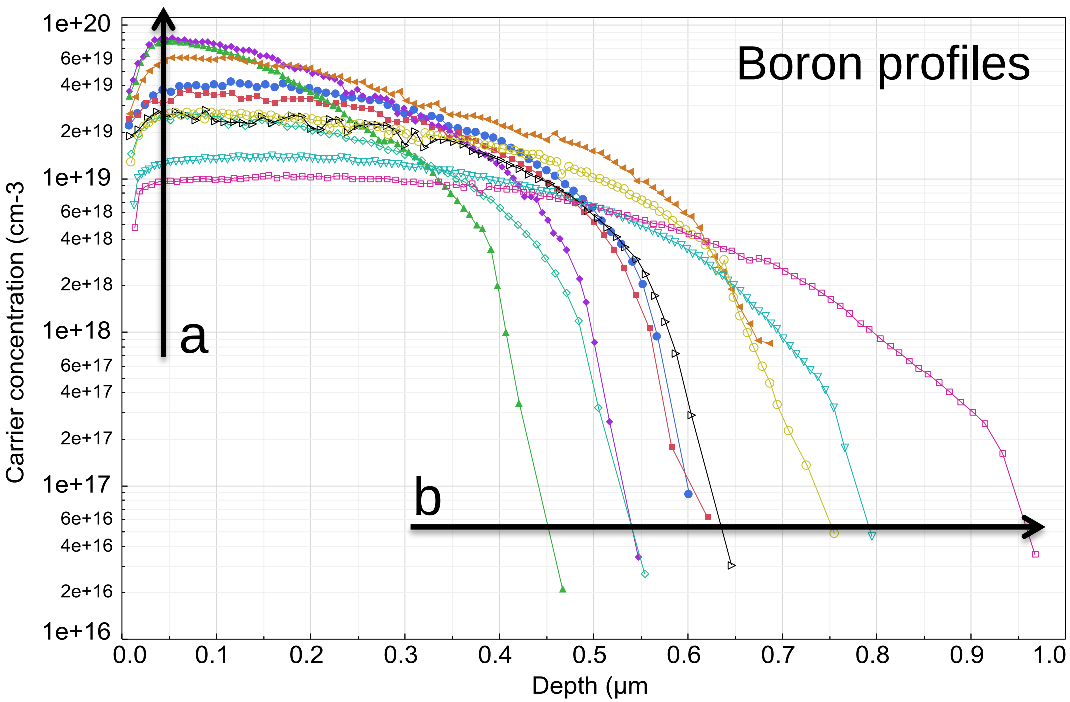
Design of Experiments (DoE) with two factors:

a). Surface concentration, $\boldsymbol{N_S}$

b). Junction depth, $\boldsymbol{d_{pn}}$

Response variables:

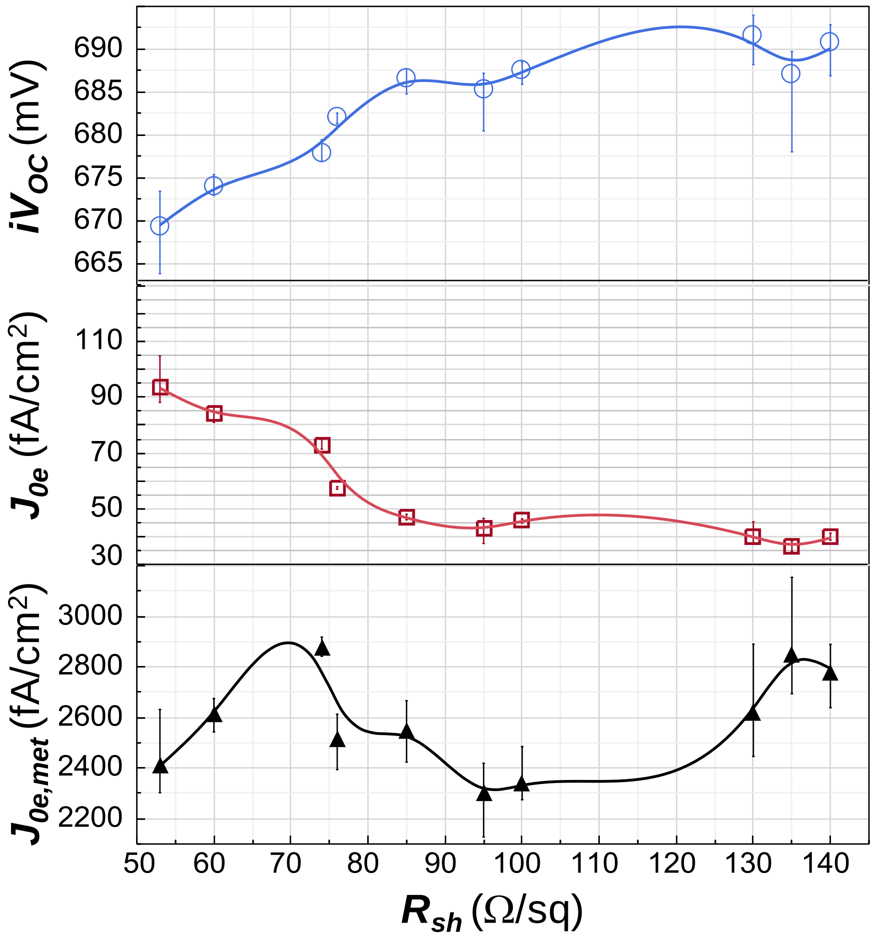
$J_{0e,met}$; iV_{OC}; V_{OC}; *Eta*; R_{sh}



ZEBRA: main limitation

International Solar Energy Research Center Konstanz

iV_{OC}, J_{0e} and $J_{0e,met}$ as a function of boron emitter sheet resistance (R_{sh}):



Boron emitter:

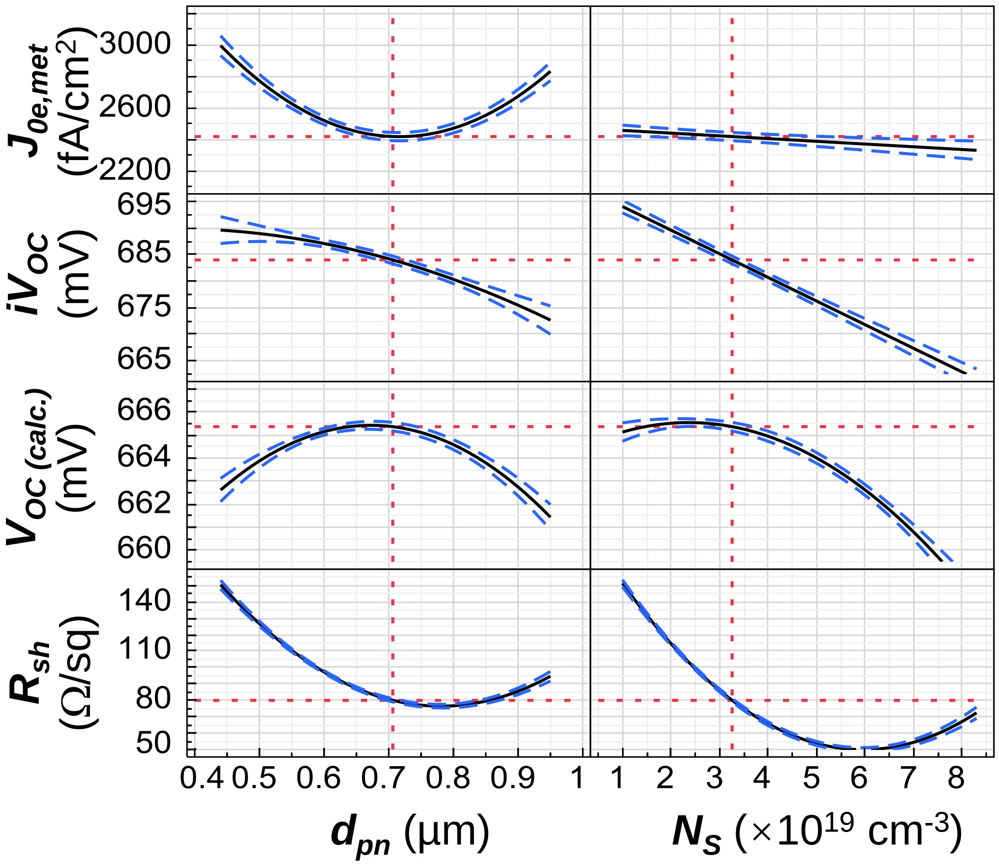
$R_{sh}\uparrow \Rightarrow iV_{OC}\uparrow$ and $J_{0e}\downarrow$

$R_{sh}\uparrow \Rightarrow J_{0e,met}\downarrow\uparrow$!!

no clear trend !

ZEBRA: main limitation

***DoE results; response surface model*:**



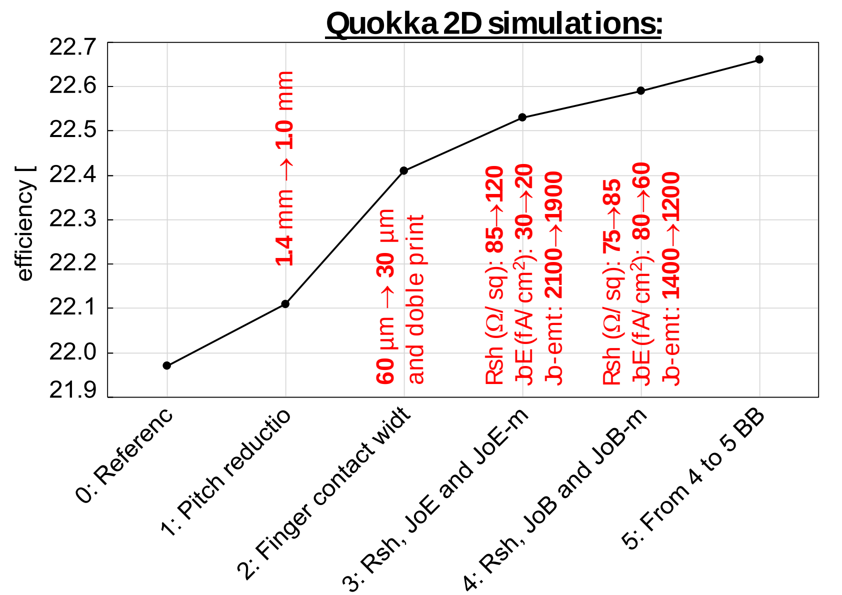
N_S < 3×10¹⁹cm⁻³ and d_{pn} > 0.7µm ⇒ $J_{0e,met}$ ↑ !

optimum V_{OC} = a trade-off between $J_{0e,met}$ and iV_{OC} !

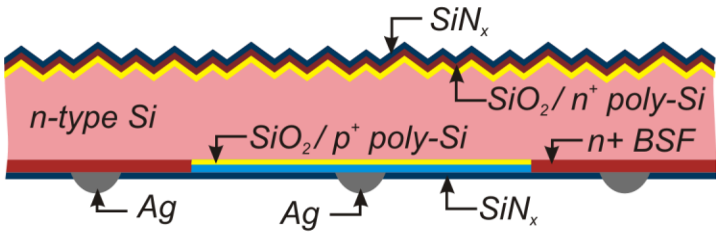
Potential for further improvements

What to do next?

Short term: selective emitter and BSF doping, decrease metal fraction and pitch size ⇒ low complexity, low reward.



Longer term: partially or fully* passivating contacts ⇒ high complexity, high reward.



*Agnes Merkle *et al.*, this workshop

Conclusions

International Solar Energy Research Center Konstanz

- ***we developed*** processes to fabricated ***n-type IBC (ZEBRA) solar cells on 156×156 mm²*** (industry-standard) ***using exclusively process steps that are already used in mass production*** for conventional cells.

- ***we achieved 22% conversion efficiency,*** with short term potential for >22.5%. The main limitation of the technology today are the recombination losses at the metal contacts (especially at boron emitter contact).

- The ***ZEBRA*** technology ***is ready to be transferred into*** the ***industrial production line***.

Acknowledgements

The project HERCULES has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 608498

Thank you for your attention!