DOCTORATE PROGRAM IN ELECTRONIC ENGINEERING

DOCTORAL TRAINING SEMINARS: RESEARCH PROJECTS IN THE DEPARTMENT OF ELECTRONIC ENGINEERING

"Cost-effective technologies for crystalline silicon (c-Si) solar cells"

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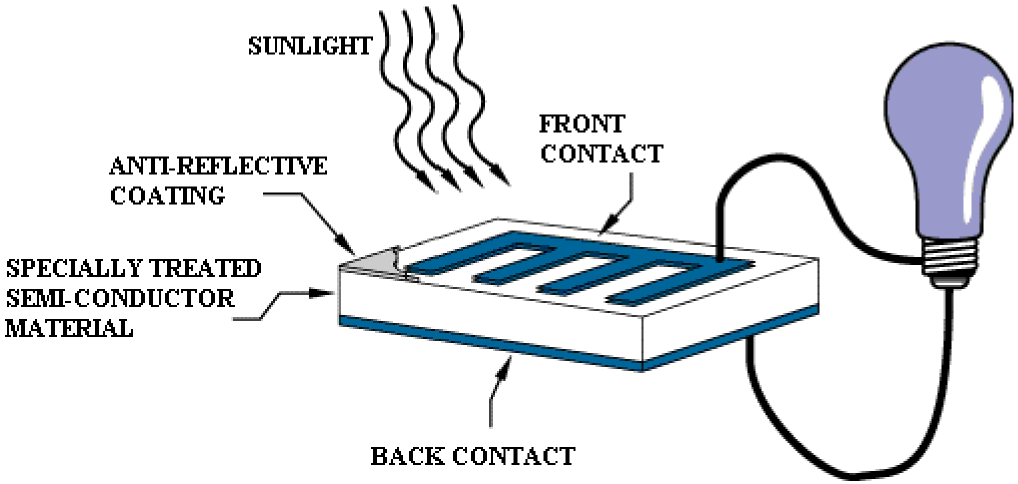
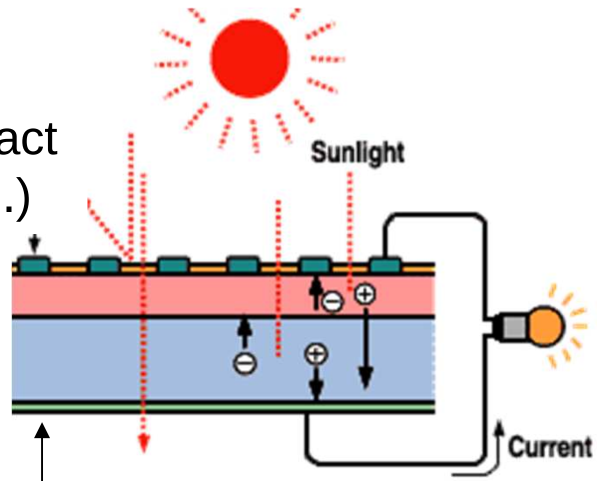
Outline

1. Introduction, description of the problem and objectives
2. Laser processing applied to rear contact schemes
   - Laser fired contacts with Al films
   - Laser doped regions from dielectric films: Al_2O_3 and SiC_x(n) films.
3. Fully low temperature structures
   - DopLa (Doped by Laser) cell.
   - IBC (Interdigitated Back Contacted) cell.
   - Silicon Heterojunction solar cells.
4. Very thin c-Si wafers: mille-feuille concept
5. Resources

Photovoltaic effect

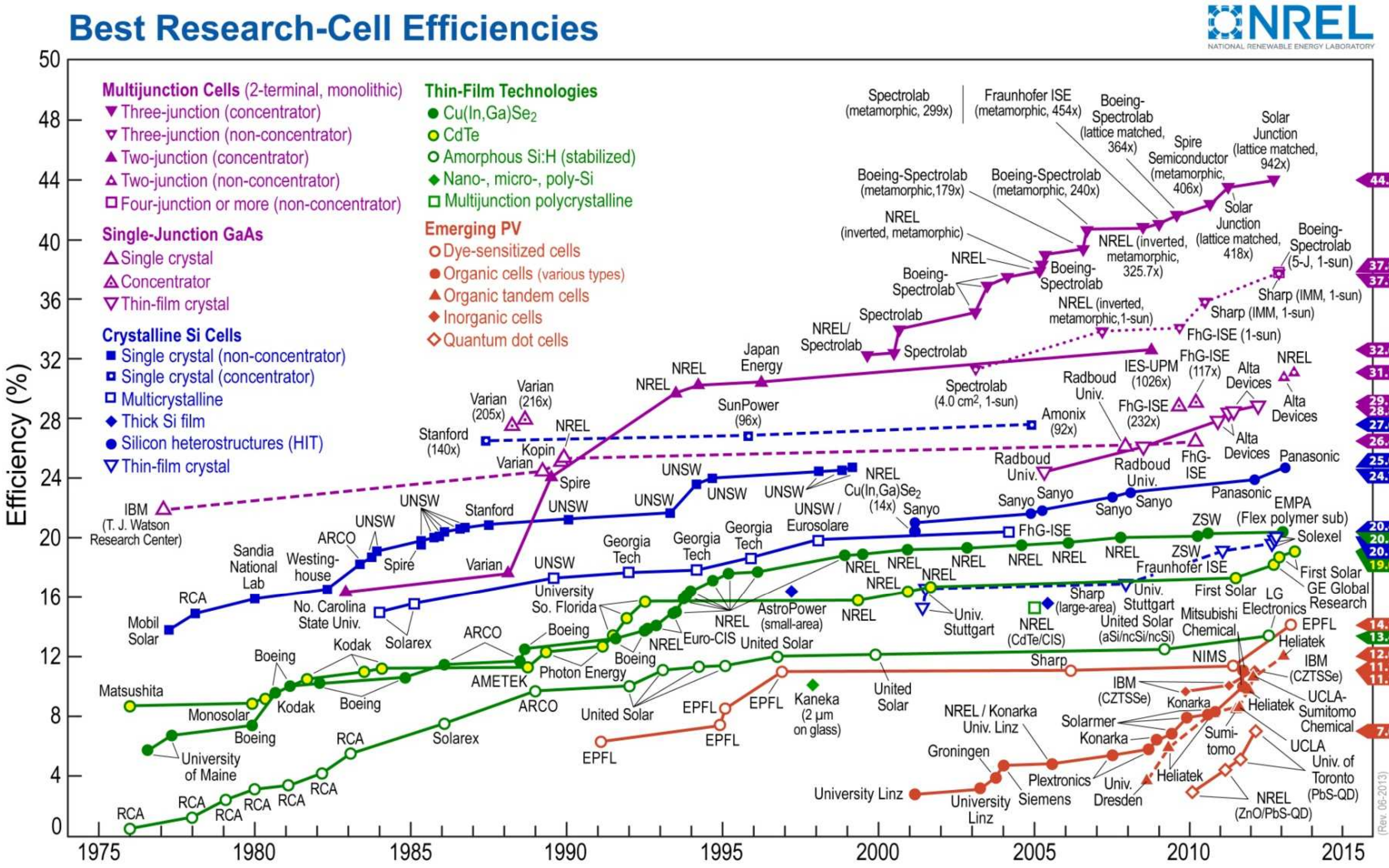


Electron contact
(n+ semicond.)

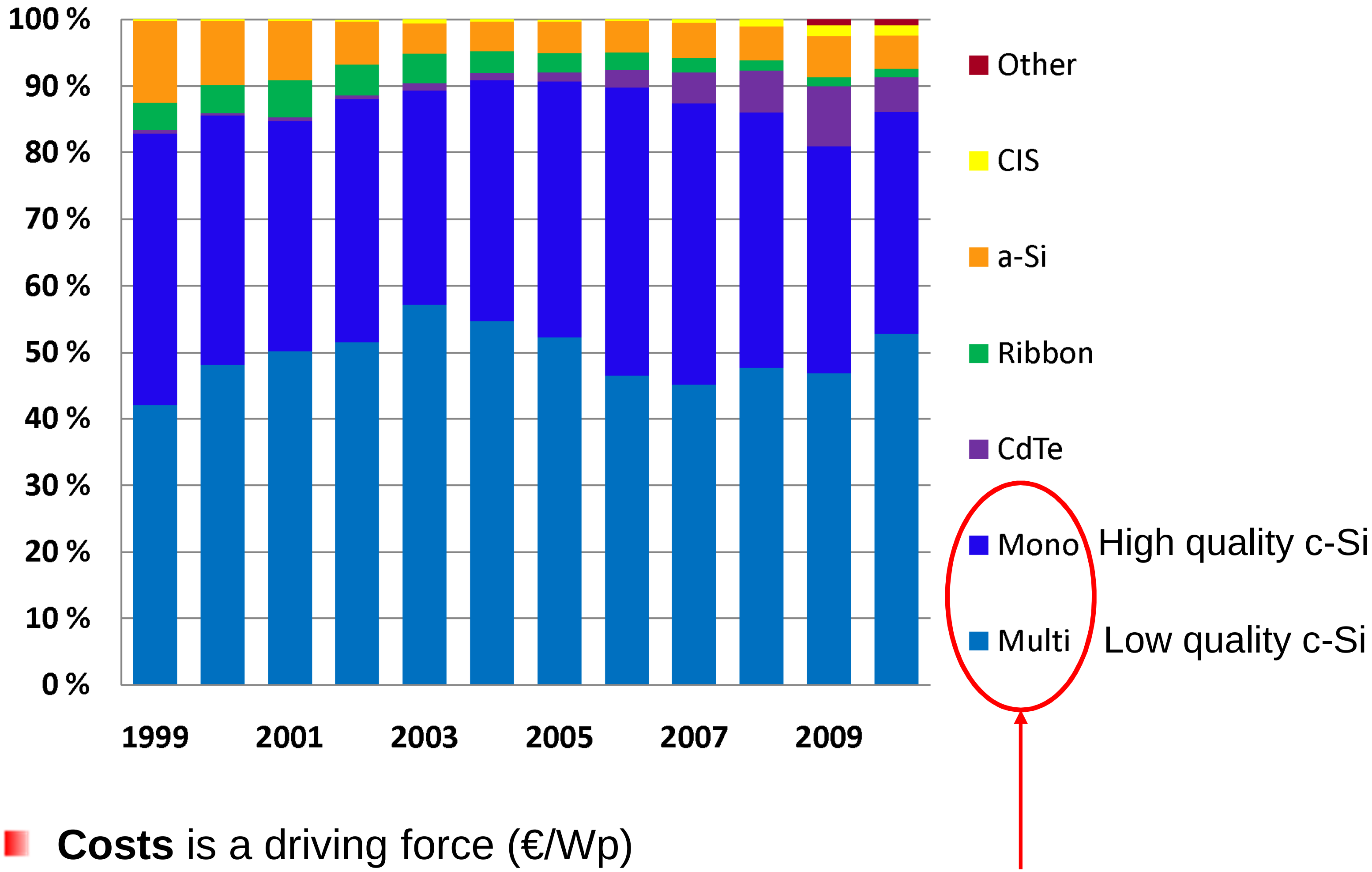


Hole contact
(p+ semicond.)

Many technologies involved

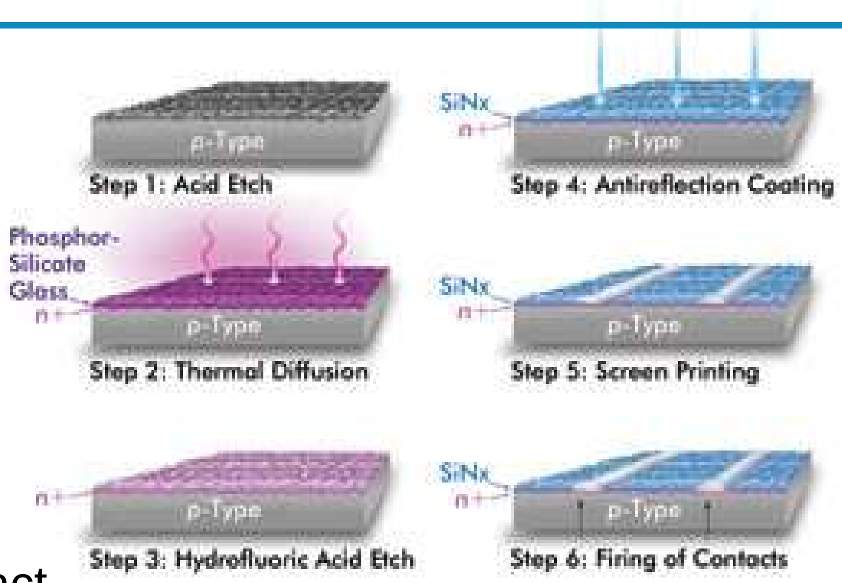


Terrestrial applications market

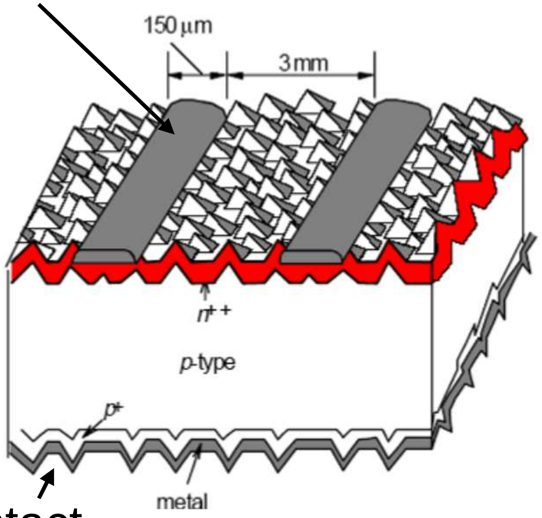


- **Costs** is a driving force (€/Wp)
- Crystalline silicon shares more than 80 % of the market

Very simple fabrication process



Electron contact



Hole contact

Main costs:

- c-Si wafer.
- High temperature steps for the creation of the highly-doped regions.

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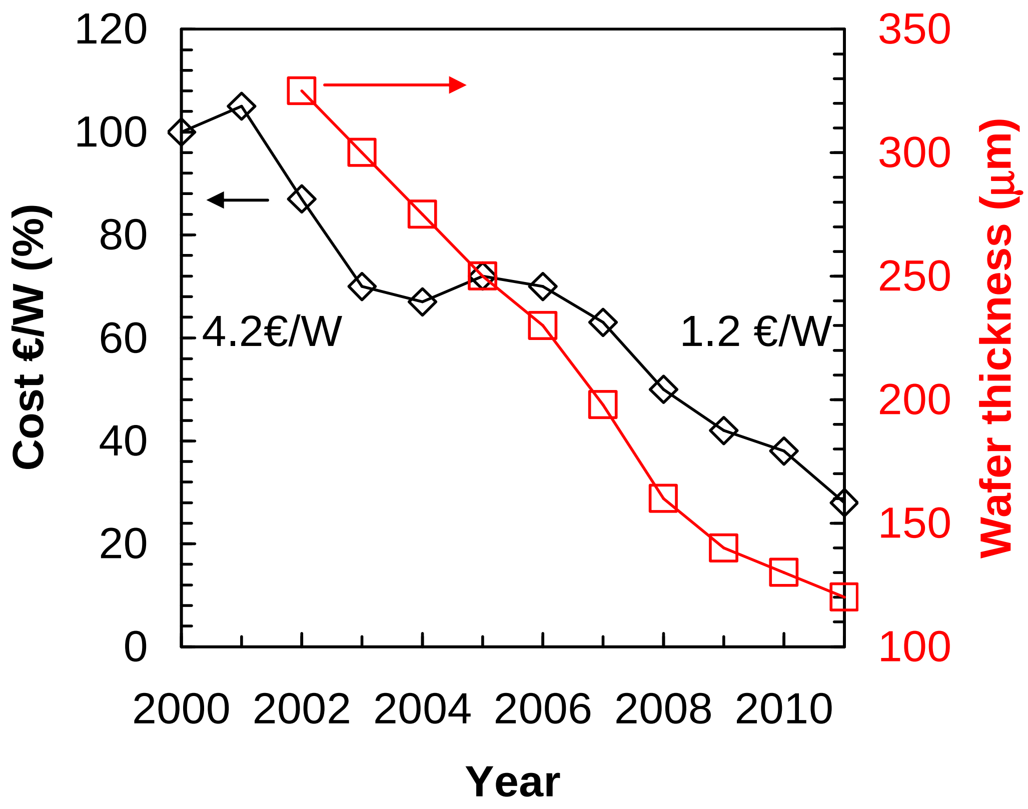
Thinner wafers

Source: SiGen



Silicon is about the 40% of the cost → Reduction of the wafer thickness

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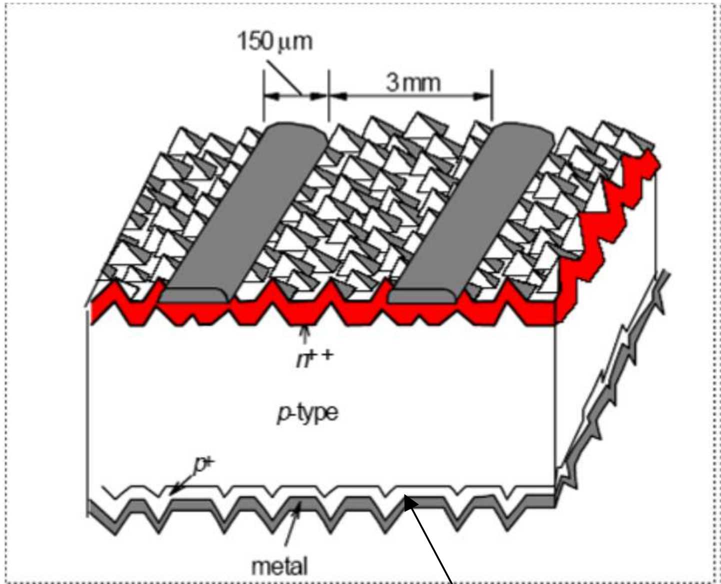
Problems with full Al p+ contact

Scenary of the commercial c-Si solar cells:

Limited by the surface recombination at the back contact

Lower costs (more wafers per ingot) ⇐ **Thinner substrates** ⇒ **$L_D > W$**



S_{eff} ~ 10^4 cm/s

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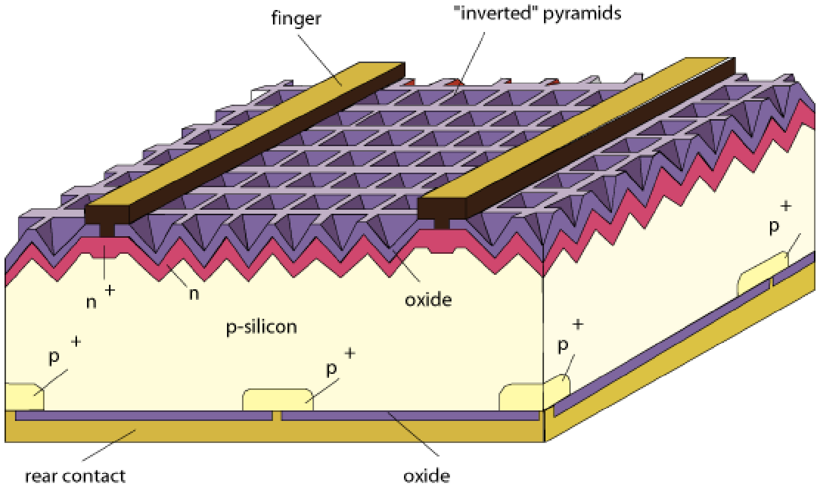
Adptation of PERL concept to thin industrial substrates



- Applied to the world record c-Si solar cell (24.7%, UNSW).
- Rear side passivation based on dielectric layer and point contact.
- Dielectric film (SiO_2) thermally grown at ~1100ºC ☹
- p+ regions created by high temperature step ☹
- Definition of the contacts by lithography ☹

J. Zhao, A. Wang and M.A. Green. Prog. Photovolt.: Res. Appl. ***1999****;7: 471-474.*

MNT activities in c-Si solar cells

Main objective: development of cost-effective technologies to create p+ and n+ regions and compatibles with thin substrates.

Laser processing applied to rear contact schemes:

- p+ regions: laser fired contacts with Al and Al_2O_3 films.
- n+ regions: laser doping from $SiC_x(n)$ films.

Fully low temperature structures:

- DopLa (Doped by Laser) cell.
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Fabrication of very thin c-Si wafers, the “Mille-Feuille” concept.

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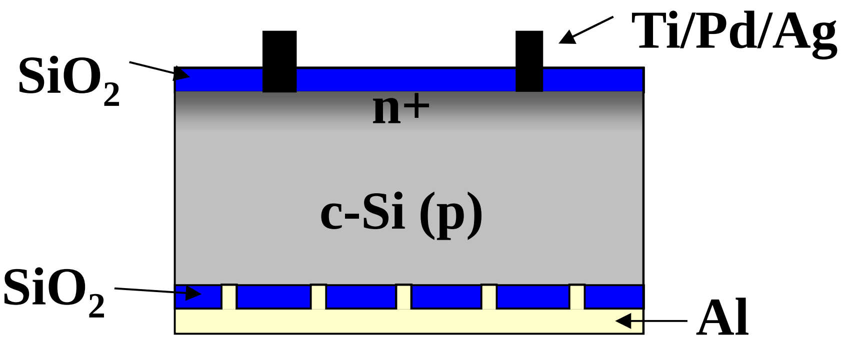
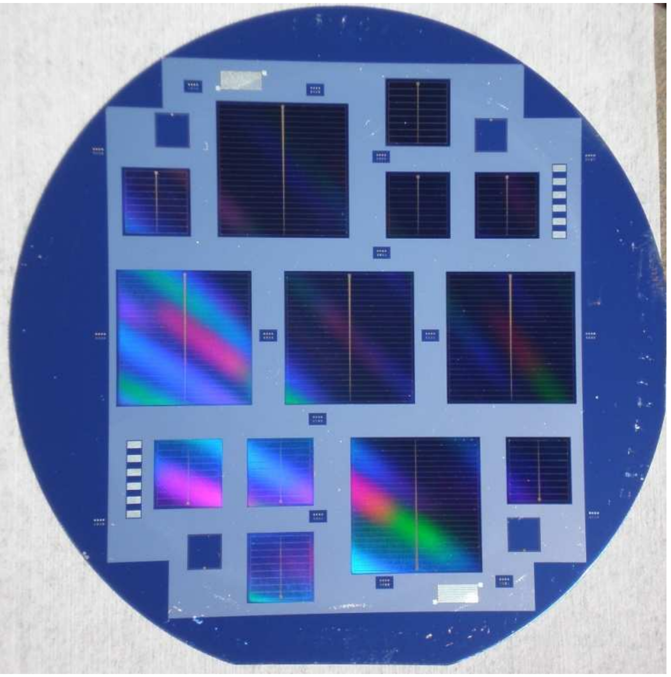
Base line process

We use it as a reference technology, based on PERC structure (Passivated emitter and rear contact).

- Texturization by inverted pyramids.
- $POCl_3$ diffusion (850 ºC).
- SiO_2 passivation (1070 ºC).
- Front and back contact defined by lithography



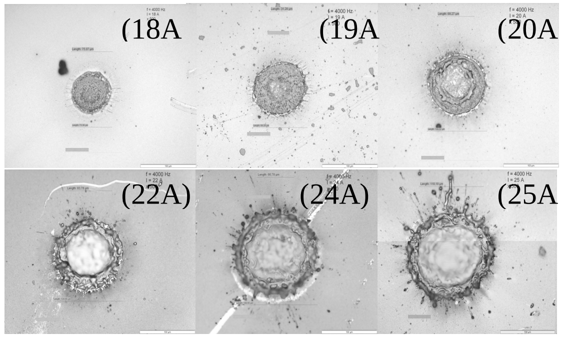


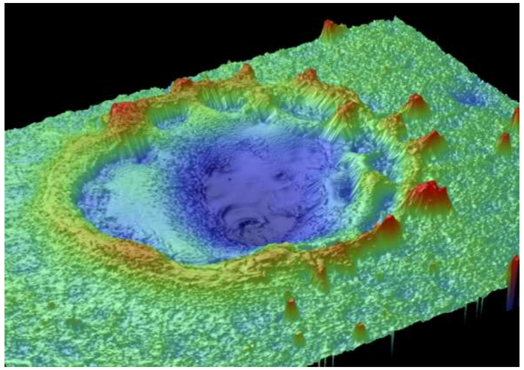
Best result:

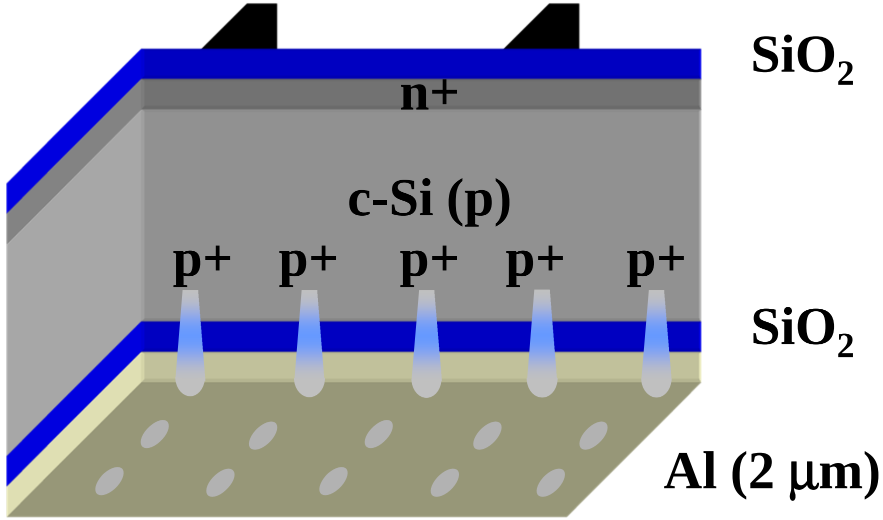
V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
628	39.0	75.9	18.6

Laser Fired Contacts

Replacement of lithography for the rear contact definition by Laser Fired Contacts (LFC).







Best result (1 mm pitch on p-type 0.45 Ω cm c-Si):

V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
670	38.4	80.5	20.7

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c-Si surface passivation

We want to replace thermal SiO_2 by low temperature deposited films

- PECVD: a-SiC_x, a-SiC_xN_y and a-SiC_x(n)

S_{eff}< 12 / 7 cm·s^{-1}, for 1 Ω·cm p/n type planar FZ c-Si substrates.

On industrial 1 Ω·cm p-type CZ silicon, S_{eff} = 220 cm·s^{-1} at 1 sun and passivation of 30Ω/sq diffused emitters obtaining J_{oe} = 250 fA·cm^{-2}

- ALD: Al_2O_3

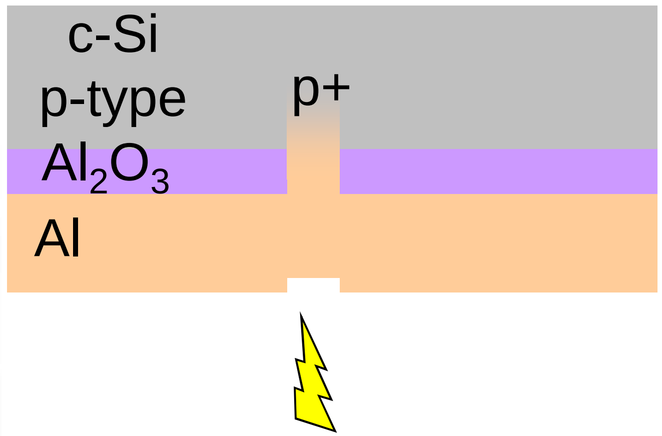
S_{eff}< 2 / 10 cm·s^{-1}, for 2.2 Ω·cm p type planar/texturized FZ c-Si.

S_{eff}< 1 cm·s^{-1}, for 2.8 Ω·cm n type planar FZ c-Si substrates.

Al_2O_3 and SiC_x(n) can simultaneously work as passivating films and dopant sources for laser processes.

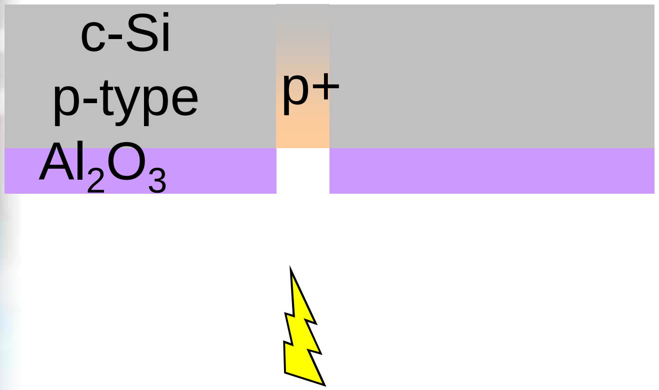
Advanced concept LFC

First approach:



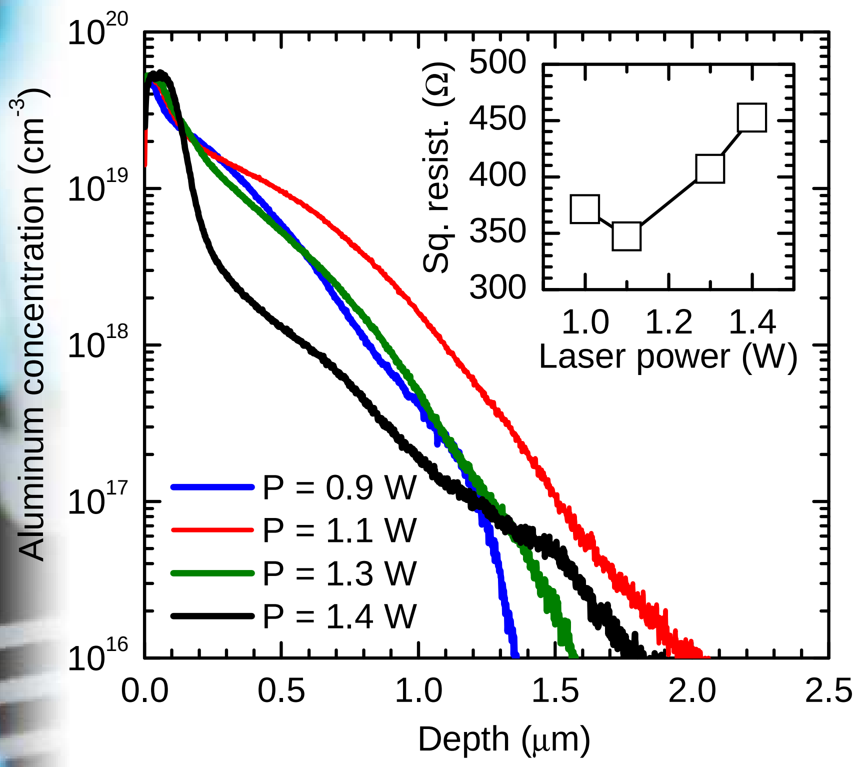
- High power laser process to break through the dielectric film.
- Prone to create crystal damage.
- Laser processing screen-printed Al pastes is difficult to the dependence on the Al thickness.

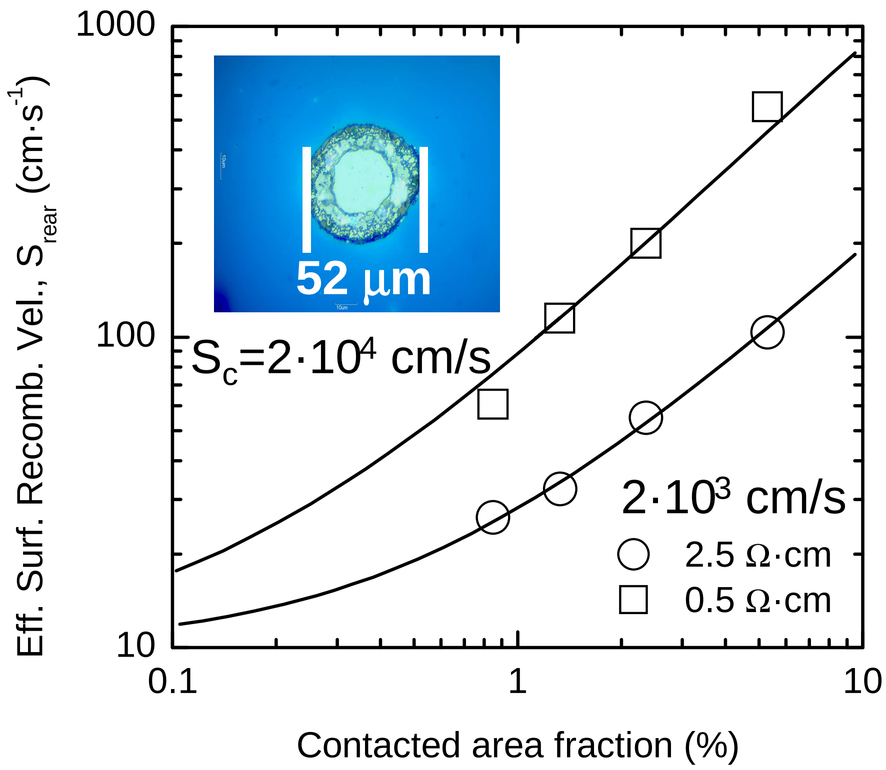
Advanced concept:



- Low power laser process just to melt the c-Si surface and ablate the dielectric
- Less crystal damage
- Better back reflector properties

High quality p+ regions



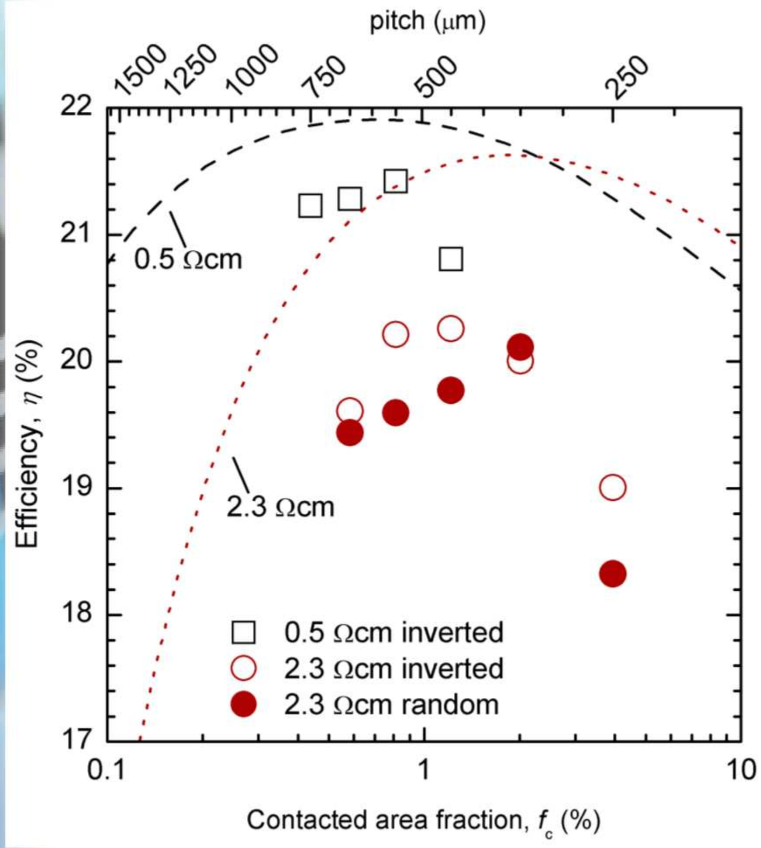


Soft laser processes result in p+ regions with very low S_{rear}

I. Martín et al., *Prog. Photovolt: Res. Appl*., 21, 1171–1175 (2013).

Application to solar cells

Cell	ρ (Ωcm)	pyramids	p (μm)	f_c (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)
#1	0.5	inverted	550	0.76	38.6	678	81.9	21.4
#2	2.3	inverted	450	1.13	38.6	640	82.1	20.3
#3	2.3	random	350	1.87	39.3	637	80.5	20.1



η beyond 21 %! (only about 10 labs in the world have reached this efficiency)

- Better results than with conventional LFC process.
- Good results also in 2.3 Ωcm substrates.
- Main trend of the dependence of efficiency on pitch well modelled.

P. Ortega et al., Sol. Energy Mat. Sol. Cells 106, 80 (2012)

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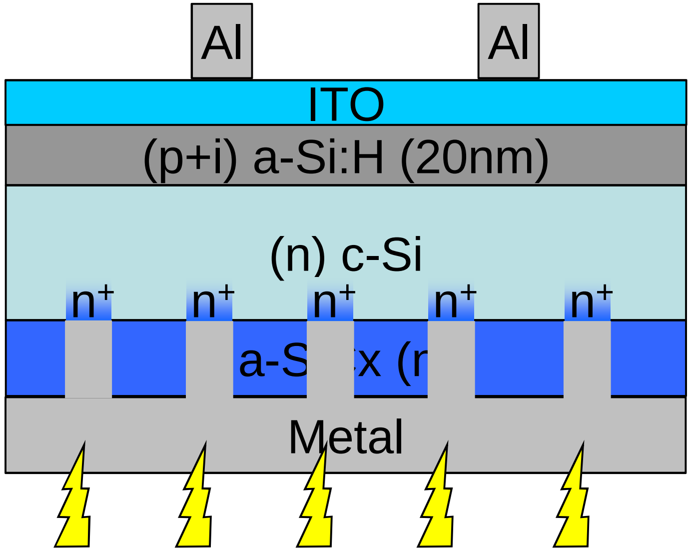
n^+ regions by laser doping from SiC_x(n)

Applied to the rear surface of n-type HIT solar cells (LPICM, INES)



~50 µm Ø elliptical spots

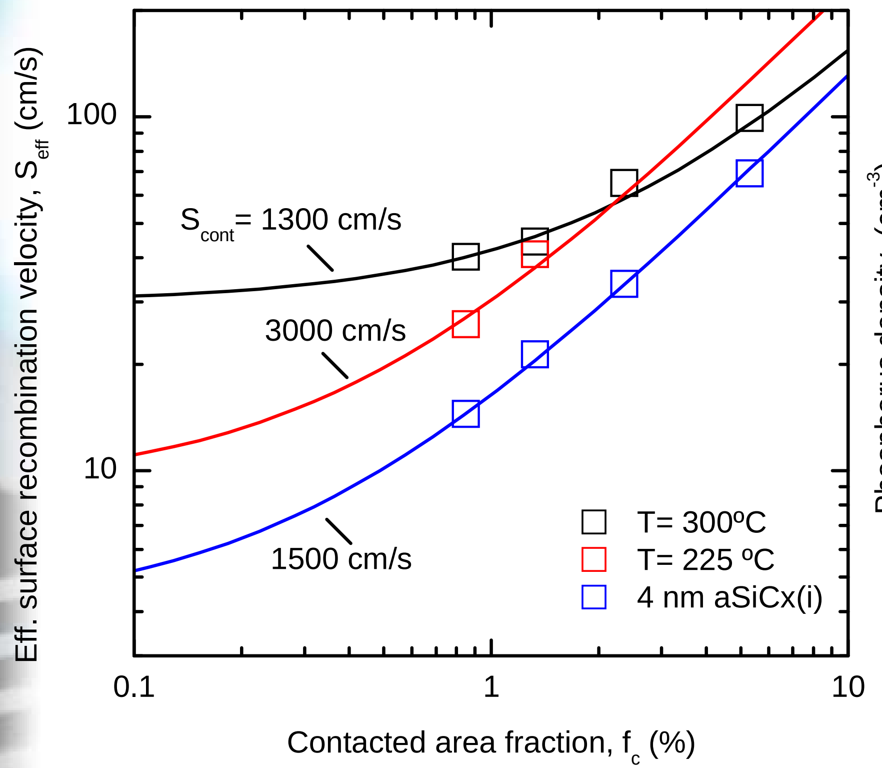
The a-SiC_x:H(n) is a stack of three layers:

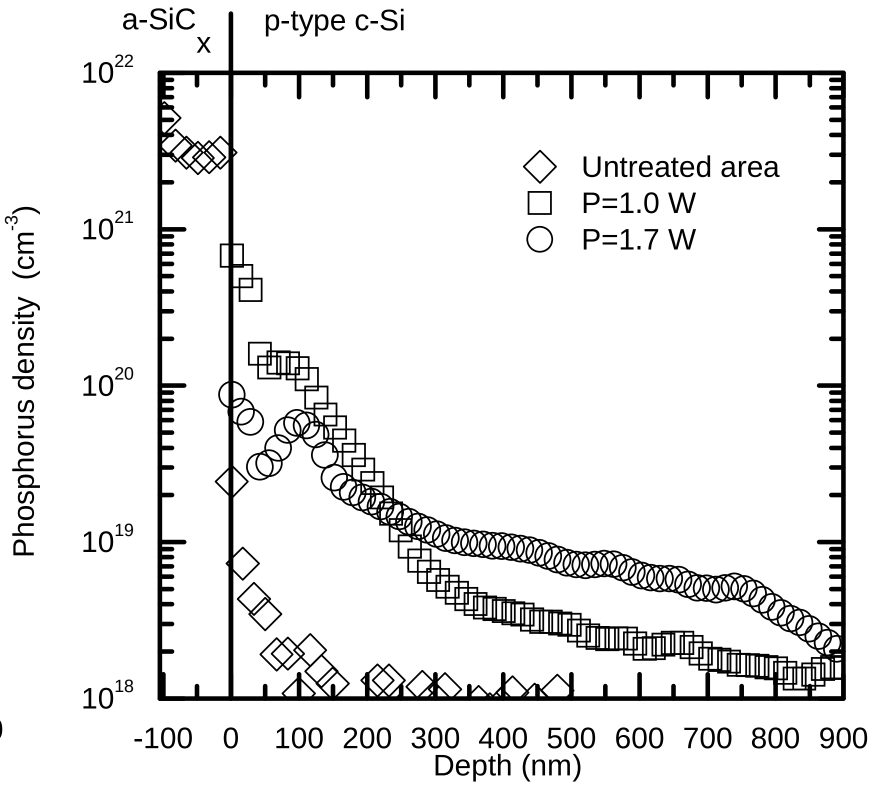
- Rear surface passivation: a thin (2 nm) intrinsic Si-rich a-SiC_x:H film is previously deposited onto c-Si surface.

- Doping source: next 15 nm of Si-rich film with a high phosphorus content (1.8% of PH_3 in gas phase).

- Back reflector and electric isolation: finally a dielectric a-SiC_x film (n=2.0 and 80 nm) with phosphorus but in a much less percentage.

High quality n+ regions





Rear configuration	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)	pFF (%)	R_s (Ω cm^2)
Amorphous BSF	30.25	696	74.8	15.7	82.9	2.24
SiC_x +laser	30.05	672	72.5	14.6	80.5	2.22

I. Martín et al., presented at 27th EUPVSEC, Frankfurt (2012)

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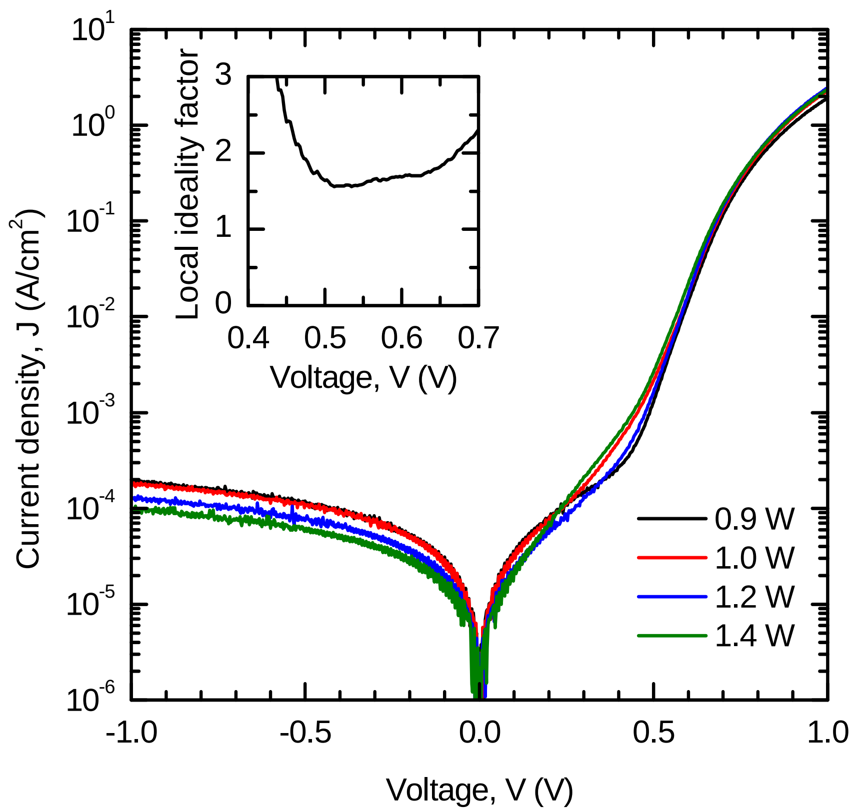
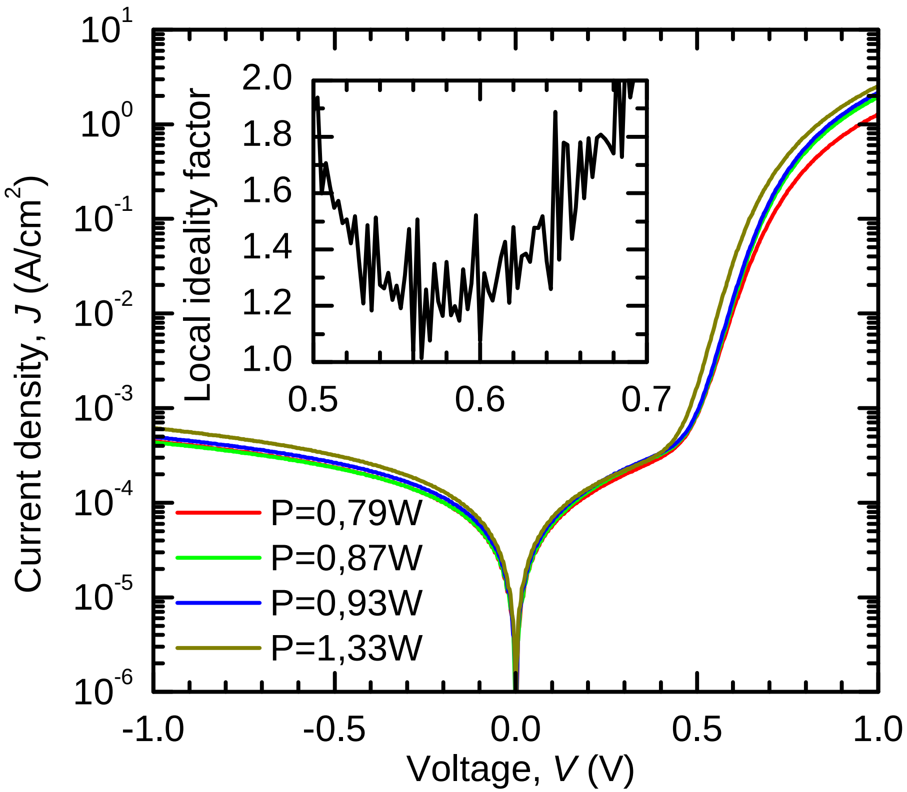
n+/p and p+/n junctions

- n+ regions were formed from T=225 ºC aSiC_x(n) stacks into p-type c-Si wafers.
- p+ regions are created from Al_2O_3/SiC_x stack into n-type c-Si wafers.

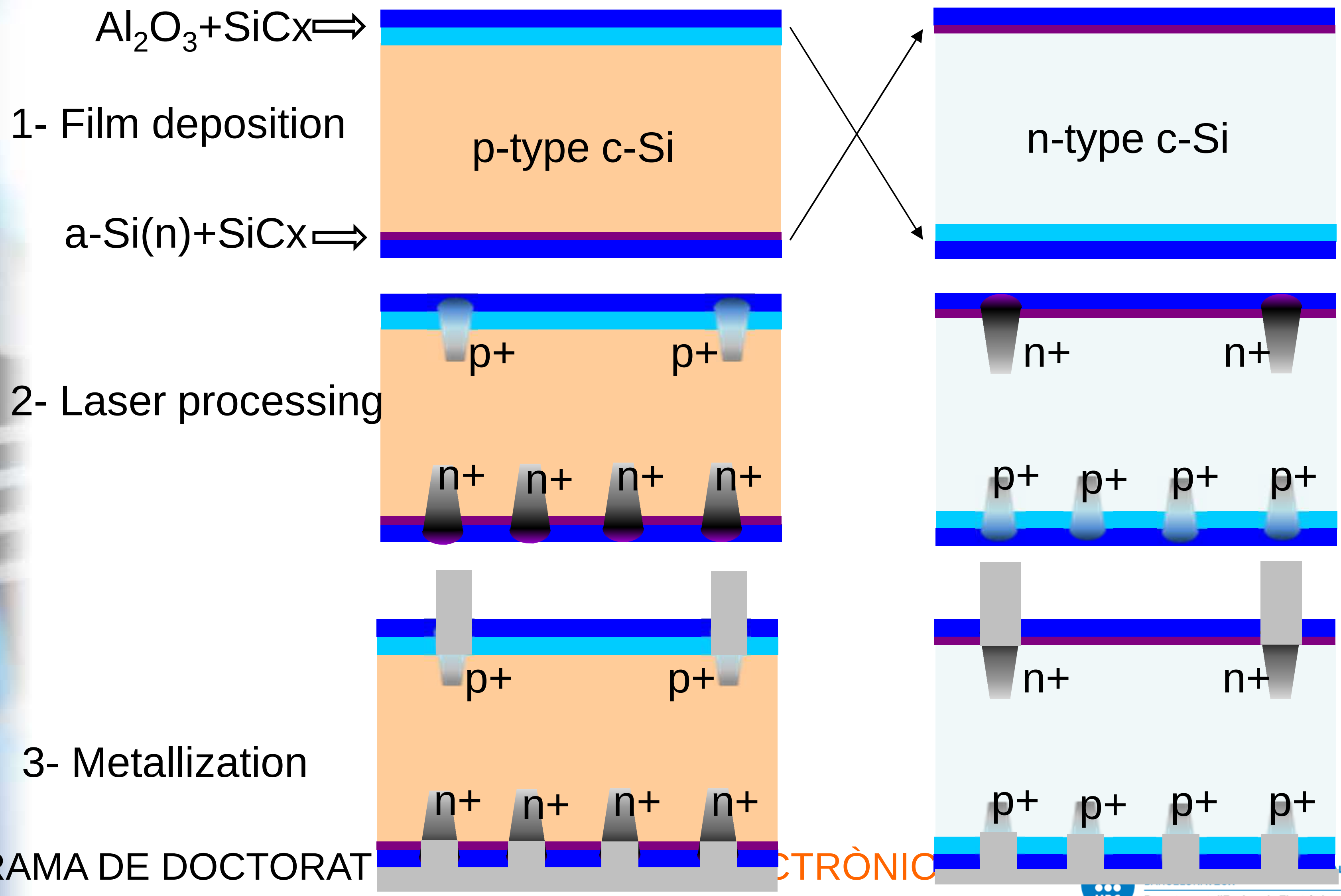




M. Colina et al., presented at 27th EUPVSEC, Frankfurt (2012)

DopLa cell concept

DopLa (Doped by Laser) cell: fully low temperature process without TCO



DopLa cell geometrical characteristics

Main characteristics (1x1 cm^2 devices):

- Front surface: non-texturized surface, square matrixes with 1 mm pitch leading to 10 fingers.
- Rear surface: hexagonal matrixes with pitch ranging from 200 to 350 µm

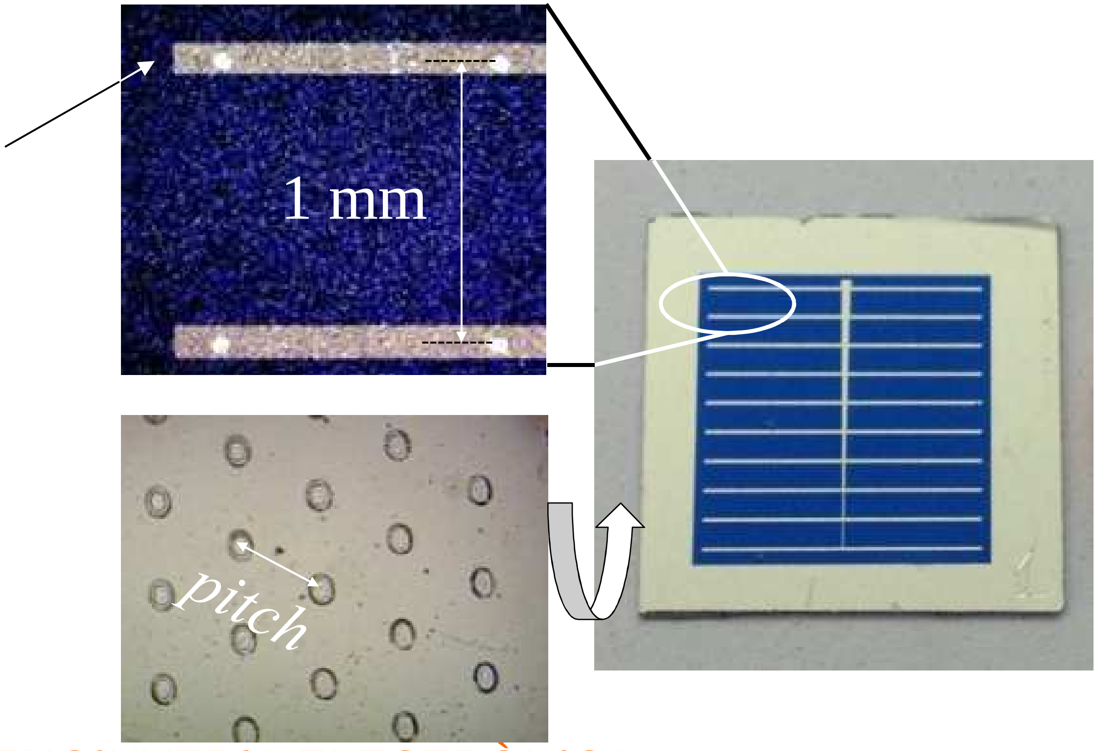
Shadow factor:

- 10 fingers 120 µm wide (≈ 11.5 %)

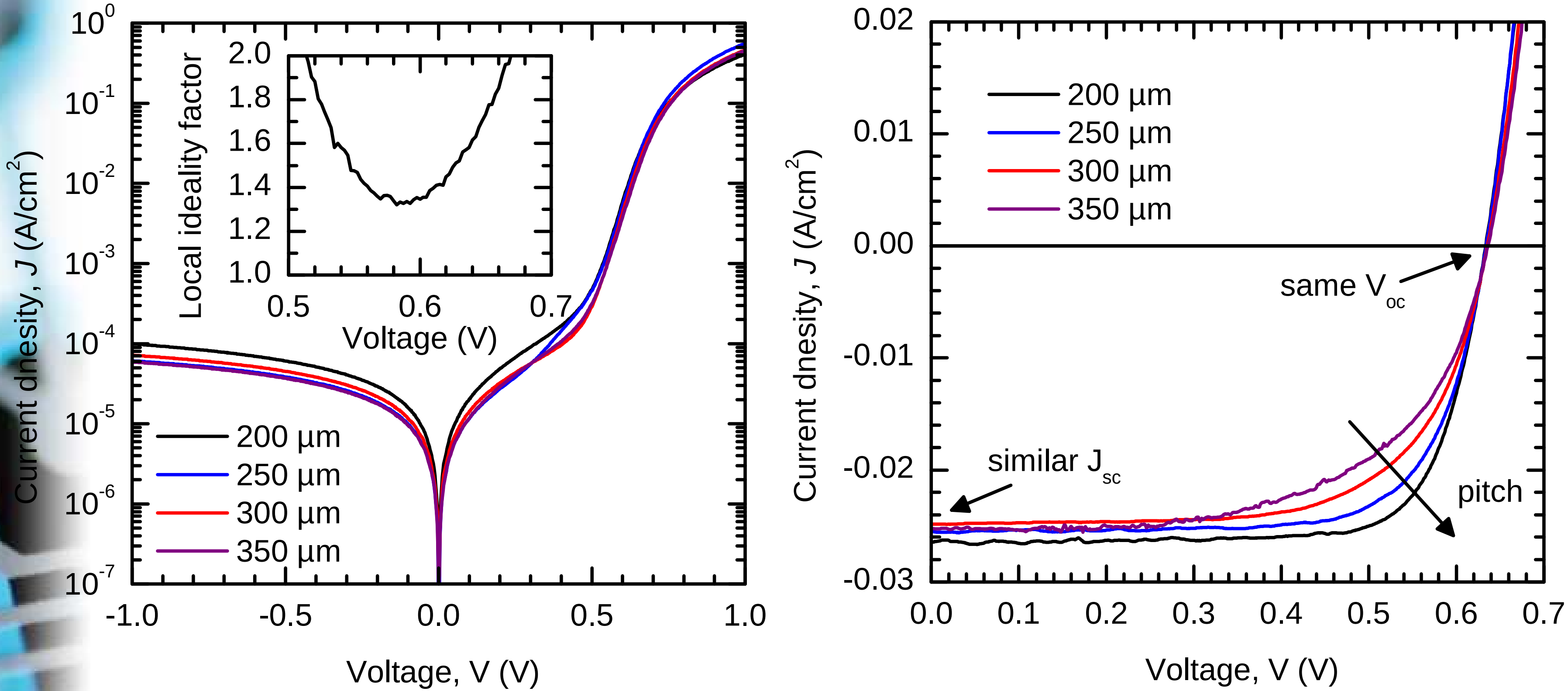
- Triangular bus bar

(≈ 1.3 %)

Shadow ≈ 12.8 %



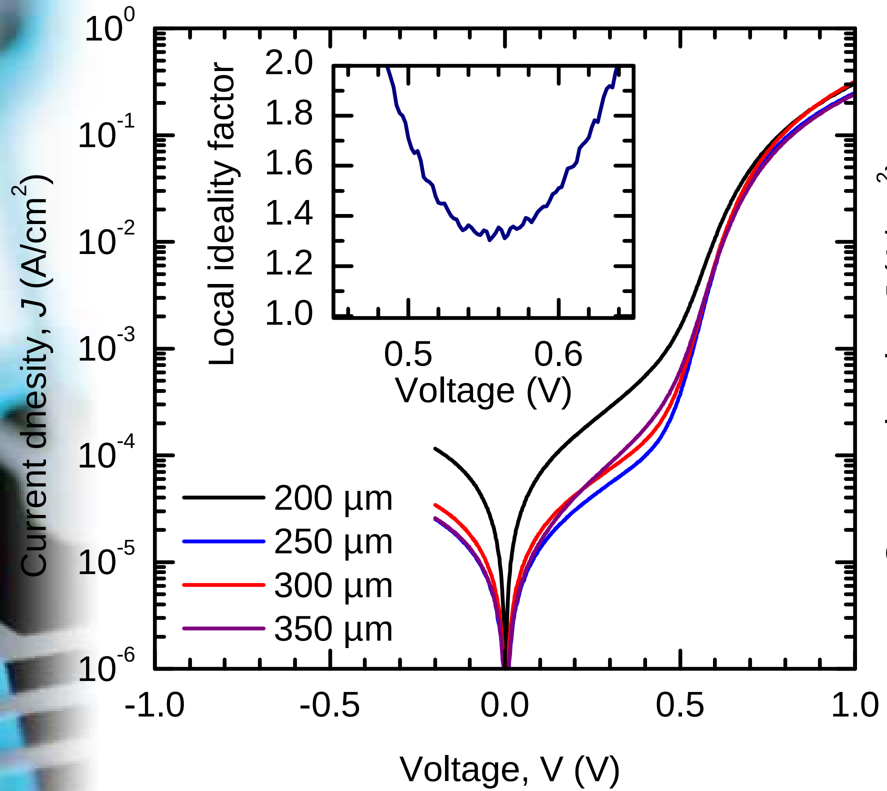
DopLa cells on p-type substrates

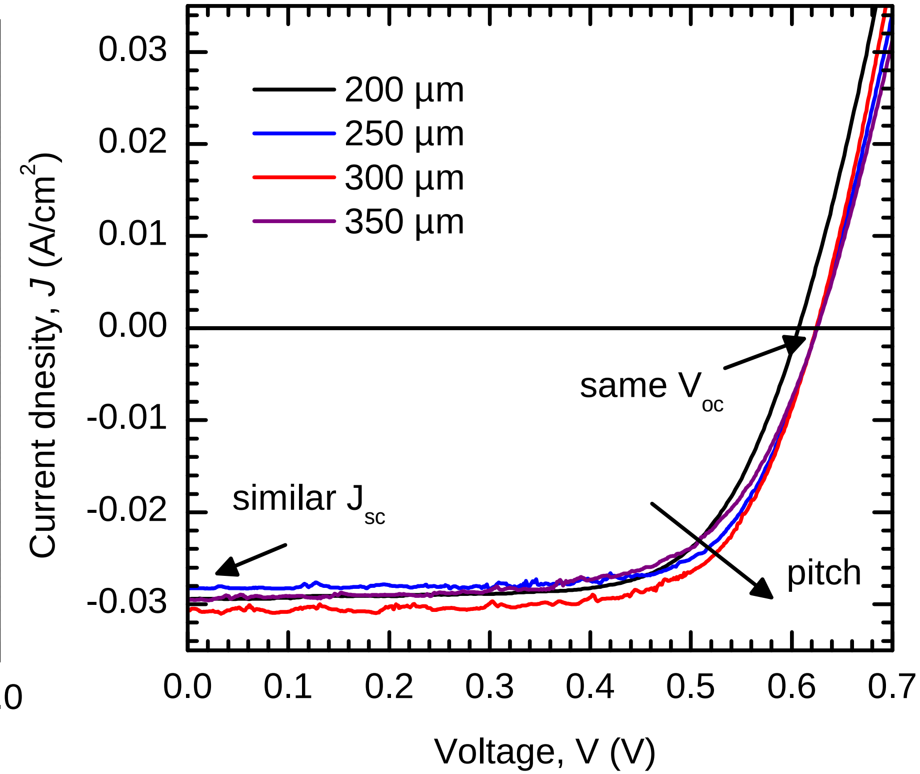


Pitch (µm)	J_{sc} (mA/cm²)	V_{oc} (mV)	FF (%)	η (%)
200	26.5	634	75.4	**12.64**
250	25.5	634	72.4	**11.62**
300	24.8	635	66.5	**10.47**
350	25.2	636	59.4	**9.52**

I. Martin et al., presented at 28th EUPVSEC, Paris (2013)

DopLa cells on n-type substrates





Pitch (µm)	J_{sc} (mA/cm²)	V_{oc} (mV)	FF (%)	η (%)
200	29.5	608	68.5	**12.3**
250	28.2	625	71.3	**12.6**
300	30.6	625	69.5	**13.3**
350	29.5	625	65.0	**12.0**

I. Martin et al., accepted in 4th SiliconPV, 's-Hertogenbosch (2014)

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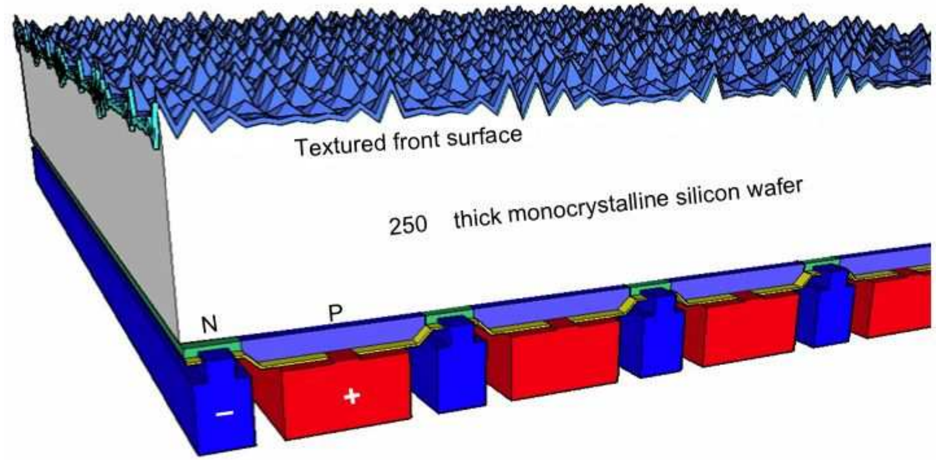
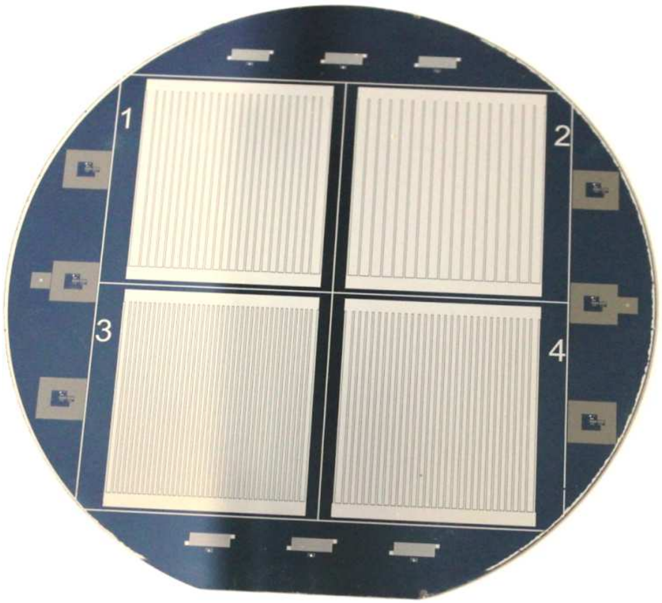
IBC solar cell concept

Interdigitated Back-Contacted (IBC) solar cell: all contacts at the rear surface, so no front metallization shadowing. Commecially available by SunPower with high efficiencies (>23%).

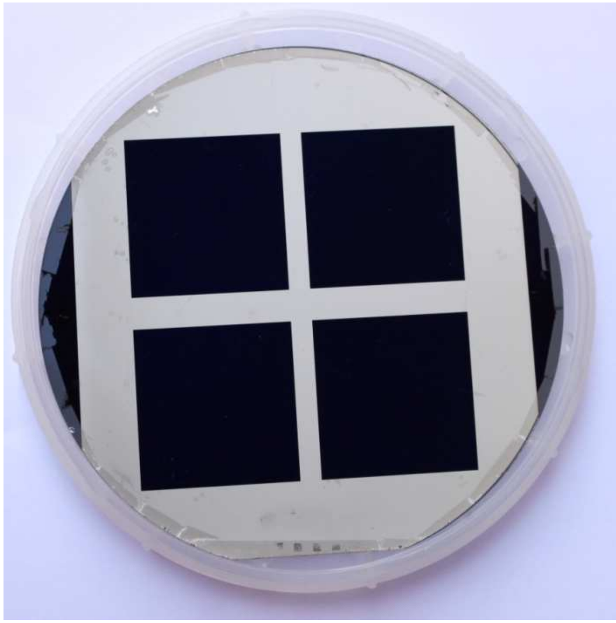


IBC base line process

Rear side (contacts side)
Reference wafer



Front side (illuminated side)
Reference wafer



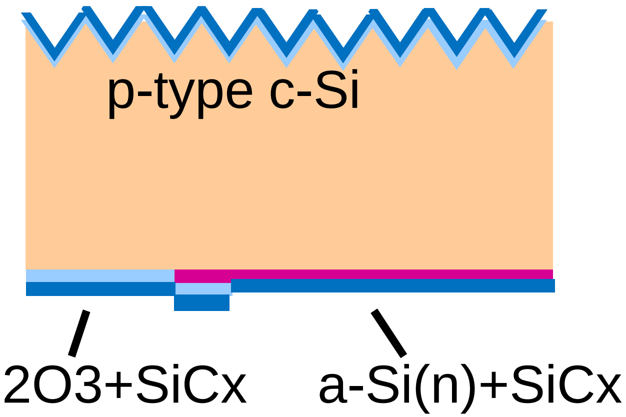
Cell	Emitter coverage	J_{sc} (mA/cm^2)	V_{oc} (mV)	*FF* (%)	η (%)
#2	86 %	41.0	652	75.0	20.0
#1	80 %	40.9	651	72.4	19.3
#4	**75 %**	**40.6**	**648**	**77.2**	**20.3**
#3	67 %	40.0	644	77.1	19.9

η > 20 % in c-Si IBC cells! (only 5 labs in the world have reached this efficiency)

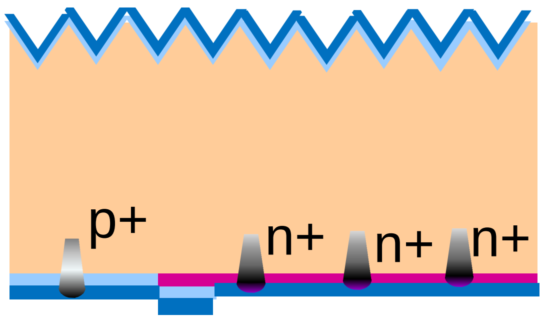
DopLa-IBC solar cell concept

Interdigitated Back Contact (IBC): definition of both p+ contacts and n+ emitters on the rear side of the cell. Patterning of the films by lithography and etching. No alignment of the laser needed. Fully low temperature.

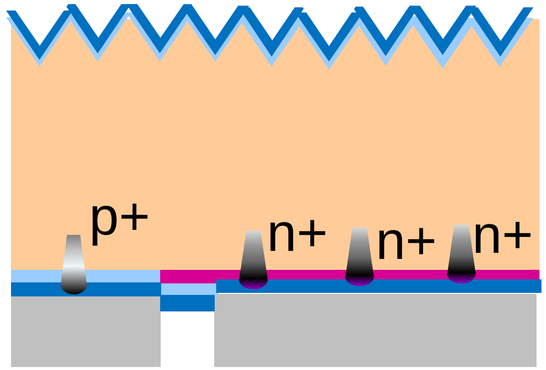
1- Film deposition and patterning

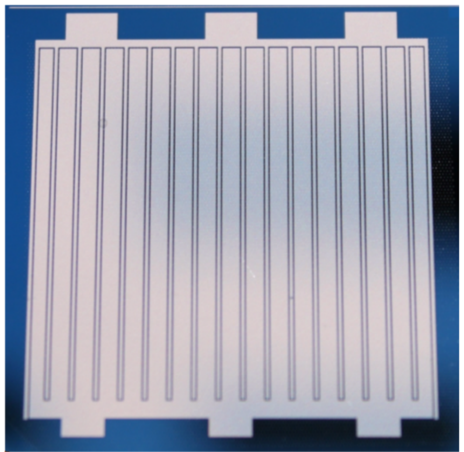


2- Laser processing

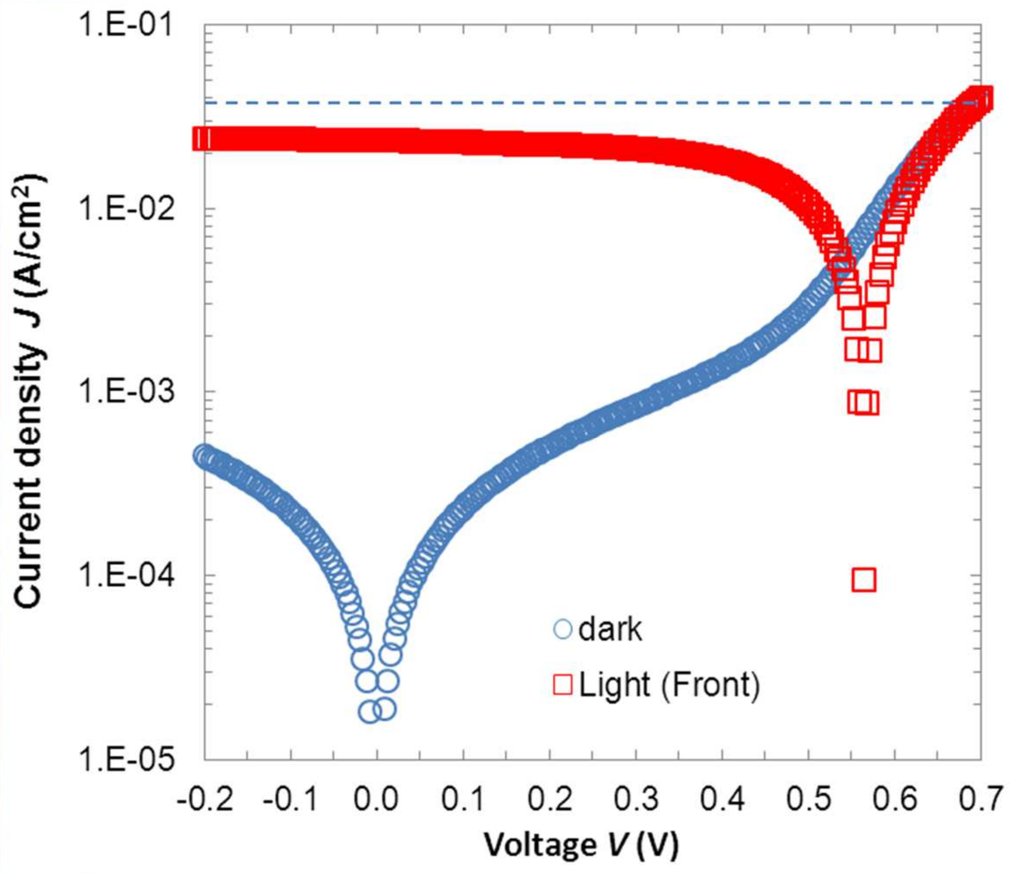


3- Metallization





DopLa-IBC cell results



Oblea 0.45 Ωcm

J_{ph} (mA/cm^2)	V_{oc} (mV)	*FF* (%)	η (%)
21.4	564	60.3	7.3

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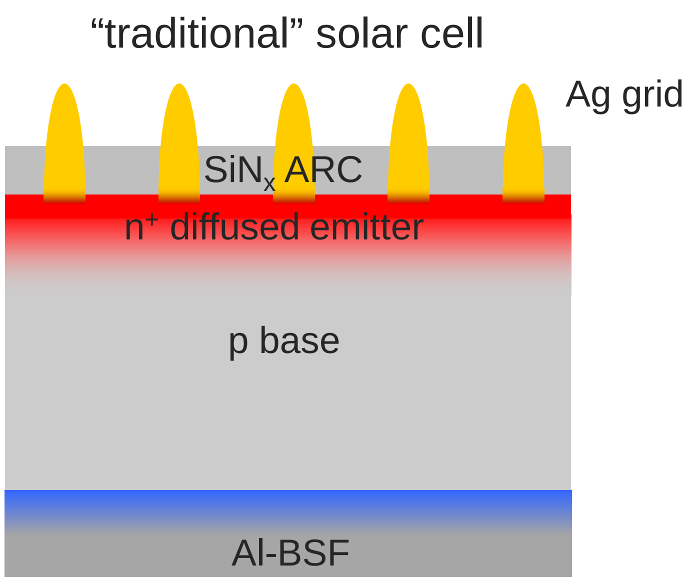
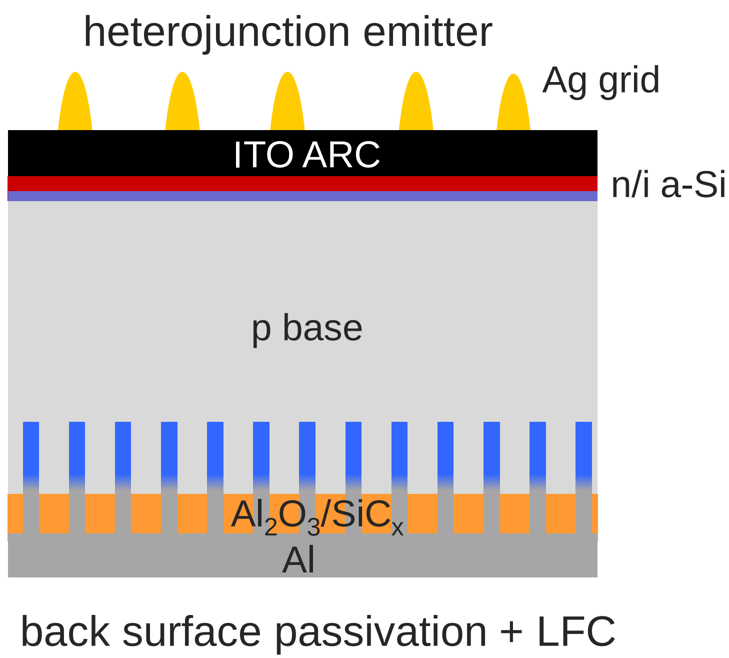
HIT solar cell concept

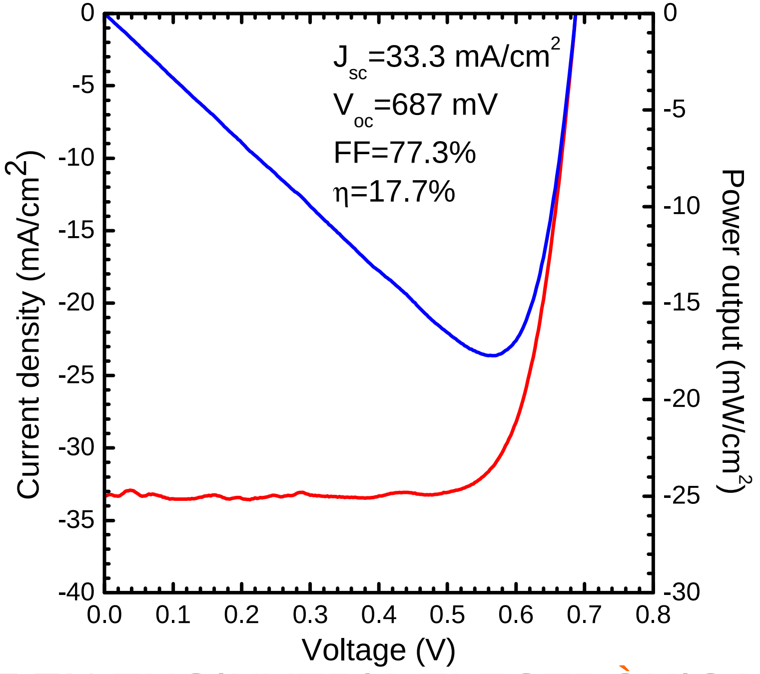
Heterojunction with Intrinsic Thin film (HIT) solar cell: the n+ region is not created by high temperature diffusion but by deposition of phosphorus-doped amorphous silicon (a-Si) film. A thin intrinsic a-Si film is deposited in between to improve surface passivation.





HIT solar cell results

Affiliation	η (%)	V_{oc} (mV)	J_{sc} ($mA \cdot cm^{-2}$)	FF (%)	A (cm^2)	Status	Year
EPFL [123], Switzerland	19.7	717	37.9	72.7	4, FZ	–	2011
NREL [71], USA	19.3	678	36.2	78.6	0.9, FZ	IC	2010
Titech [148][#], Japan	19.1	680	36.6	76.9	0.8, FZ	PR	2011
HZB [149], Germany	18.5	633	36.8	79.1	1	PR	2009
Univ. Stuttgart [150], Germany	18.1	670	35.7	75.6	2	–	2010
LPICM [151], France	17	662	33.0	77.6	25, Cz	PR	2009
ENEA [152], Italy	17	601	37.1	76.3	2.25	PR	2004



Outline

1. Introduction, description of the problem and objectives
2. Laser processing applied to rear contact schemes
   - Laser fired contacts with Al films
   - Laser doped regions from dielectric films: Al_2O_3 and SiC_x(n) films.
3. Fully low temperature structures
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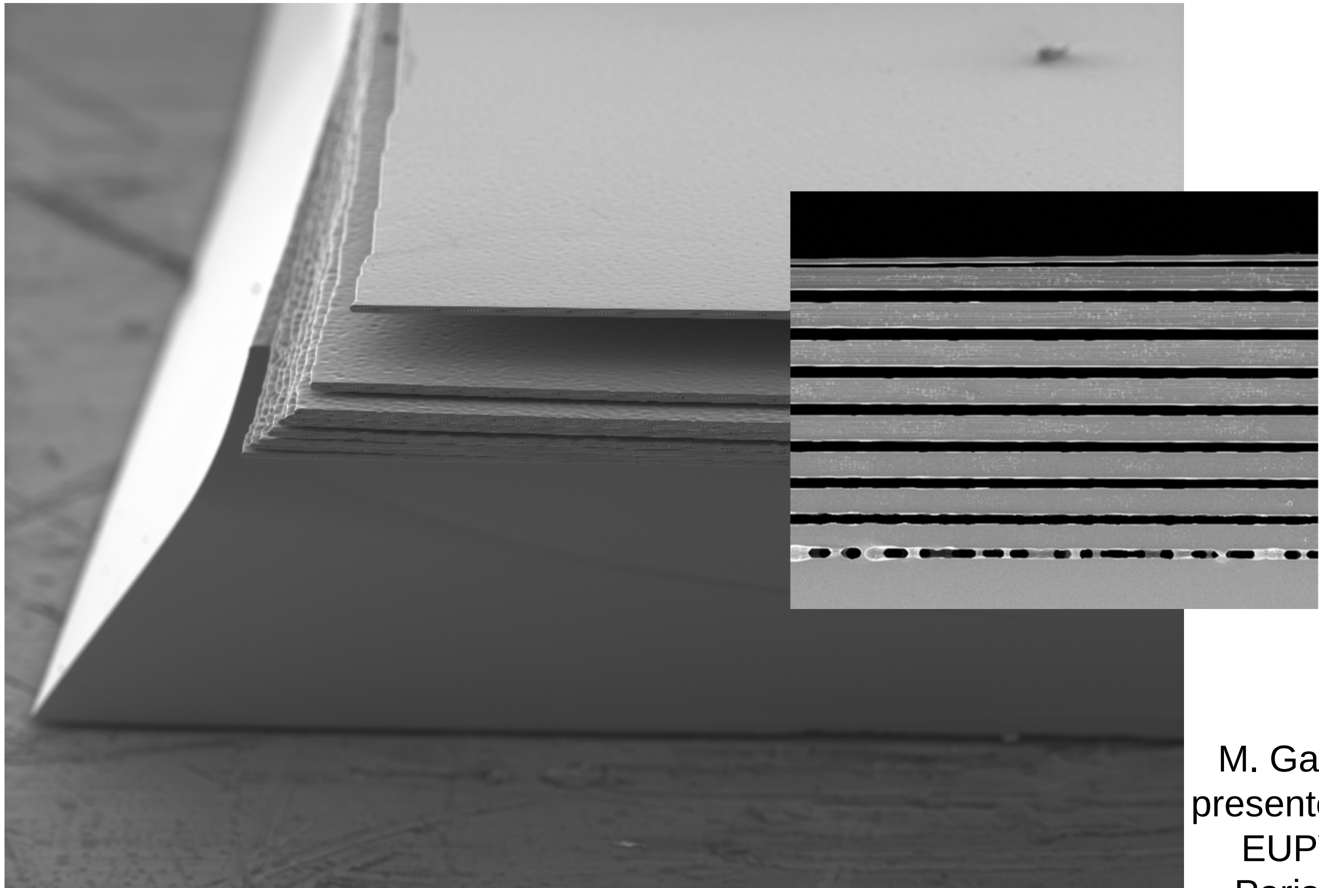
4. Very thin c-Si wafers: mille-feuille concept
5. Resources

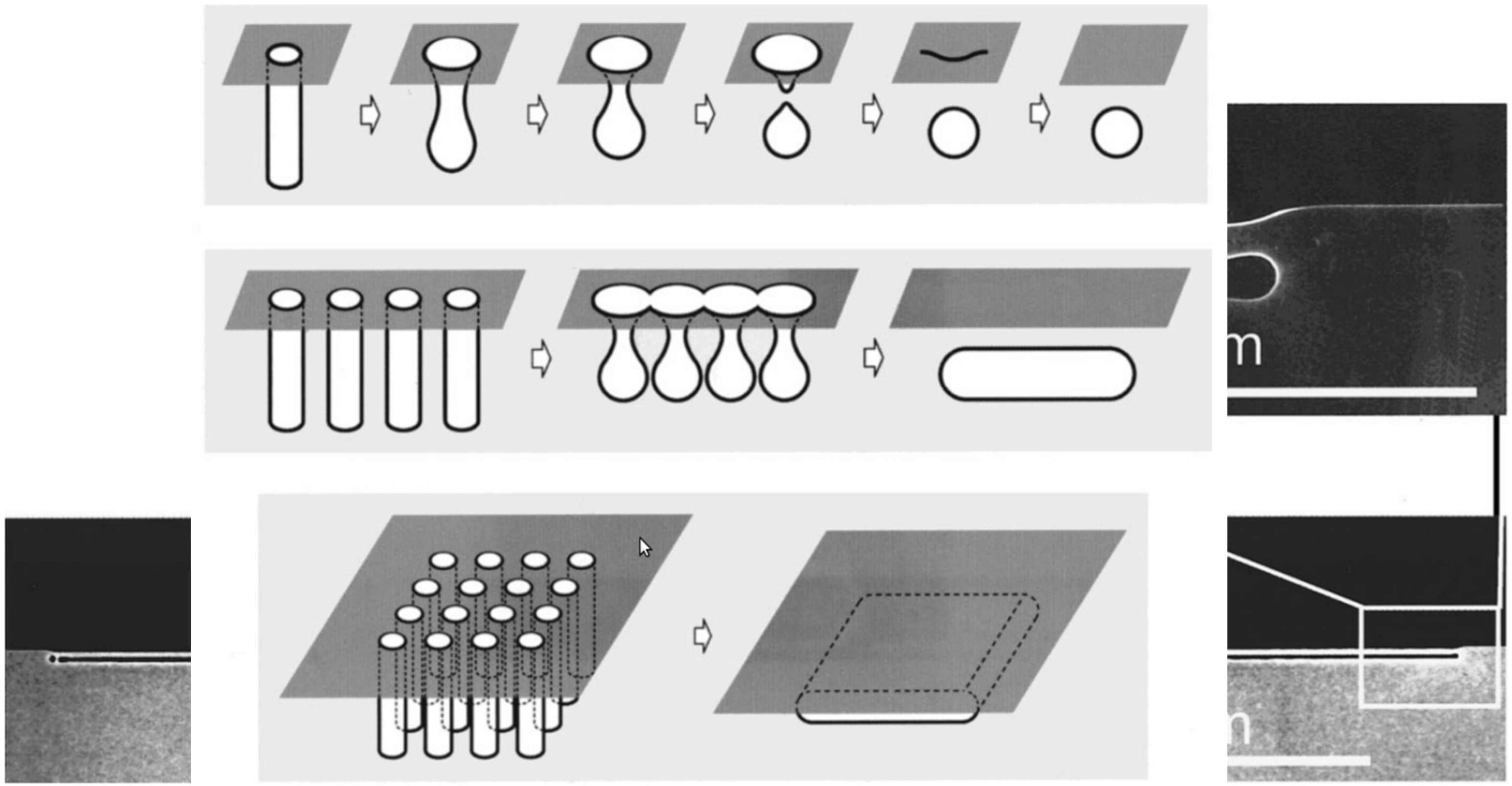
Mille-Feuille concept

Objective: very thin (<40 µm) high quality c-Si films from reusable c-Si substrates.



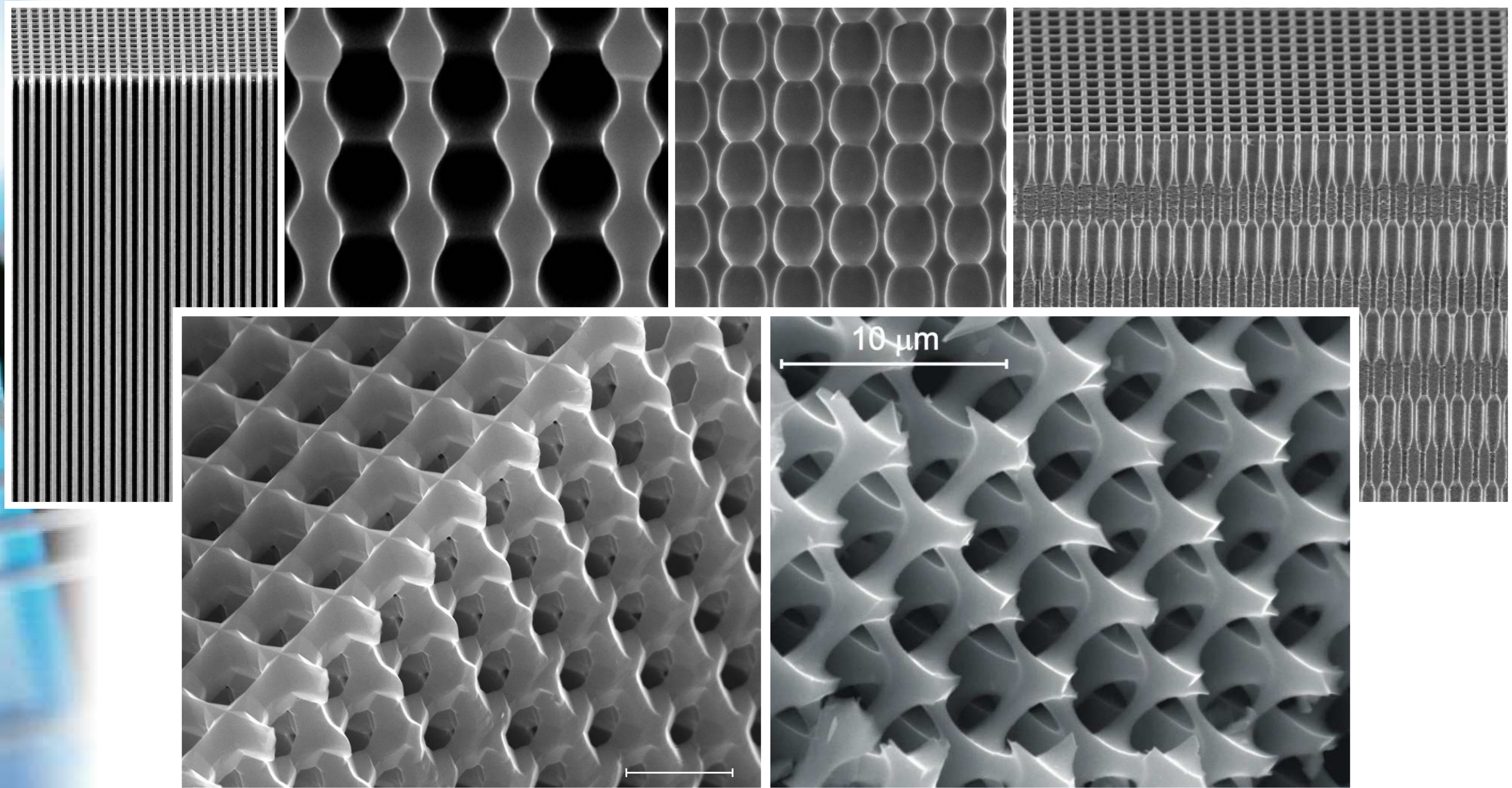
M. Garín *et al.* presented at 28th EUPVSEC, Paris (2013)

State of the art.
Empty-space-in-silicon (ESS) technique

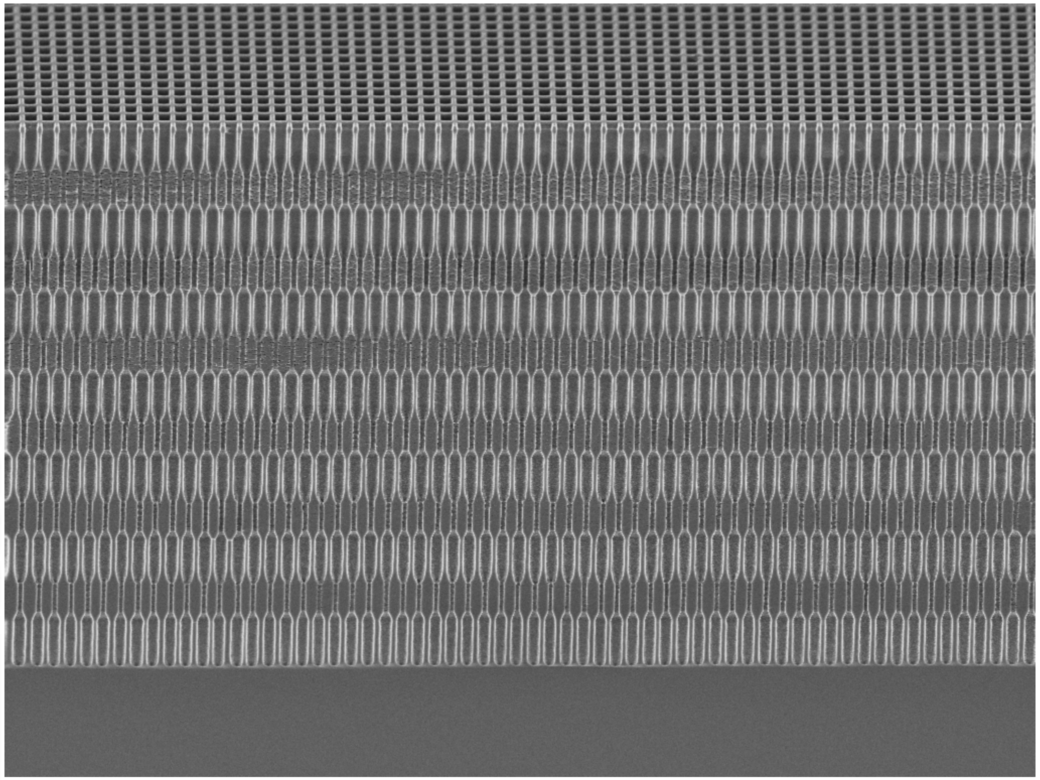


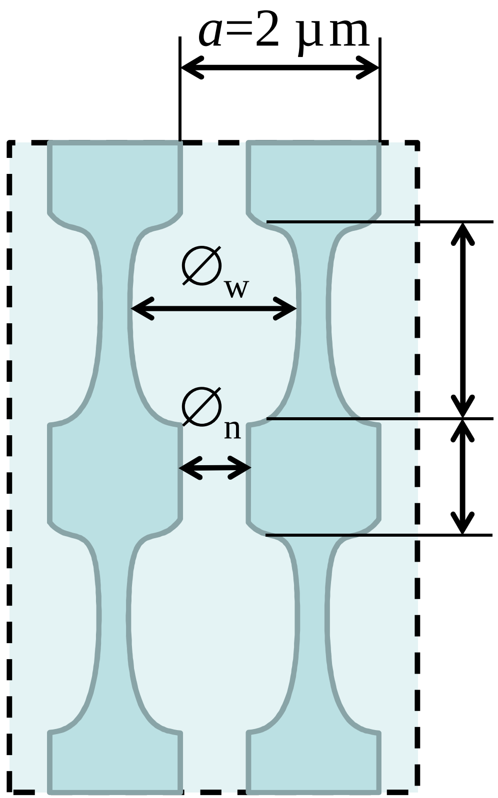
I. Mizushima, *et al.* Appl. Phys. Lett. **77**, 3290 (2000)
T. Sato, *et al.* Jpn. J. Appl. Phys. **43**, 12 (2004)
Process and Manufacturing Engineering Center, Toshiba Corp., Japan

The fine art of etching pores in c-Si

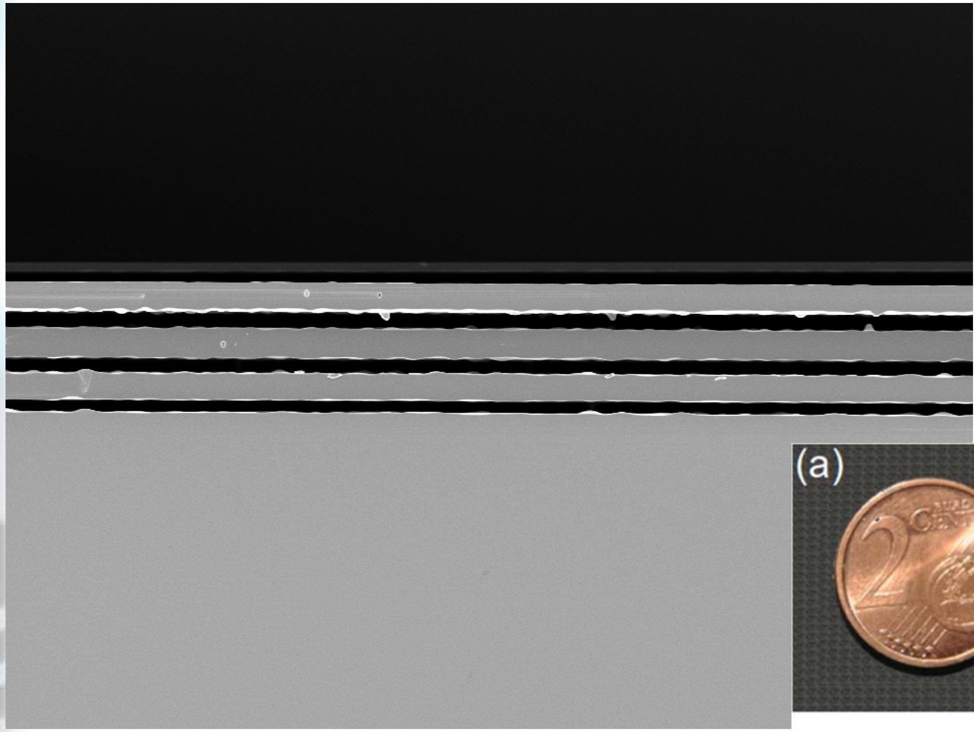


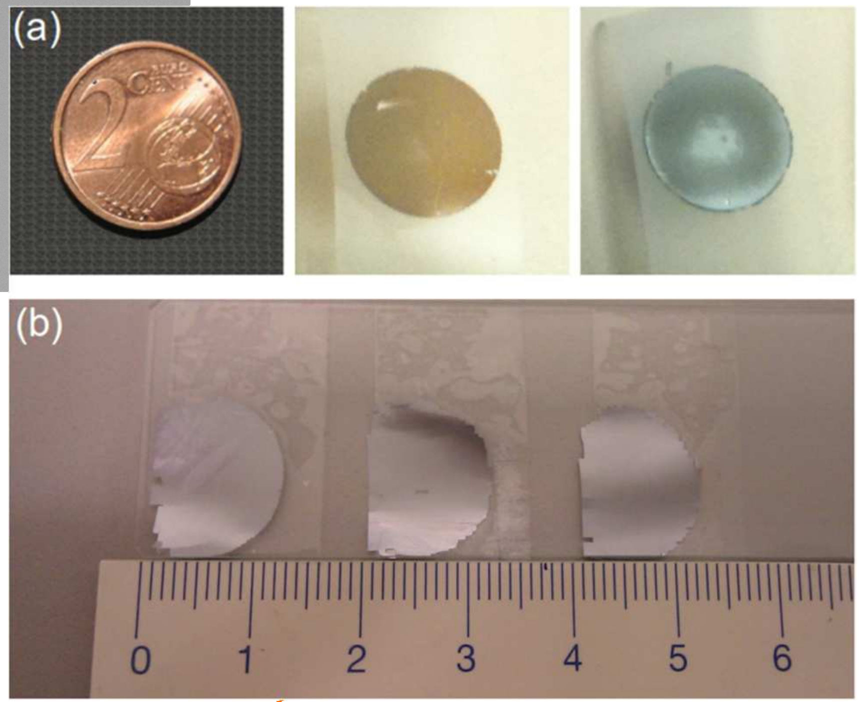
Initial pore profile





Several free standing c-Si layers





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Summary of mille-feuille characteristics

Monocrystalline

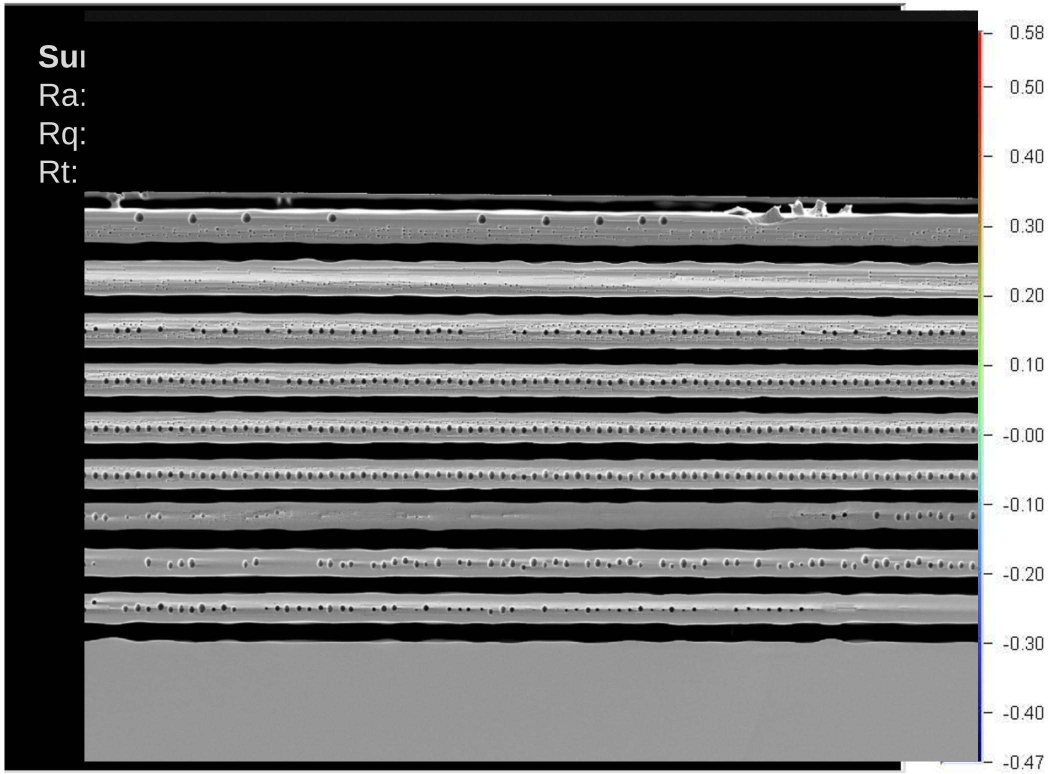
Roughness:

- Ra: 0.11 um
- Rq: 0.14 um
- Rt: 1.05 um

Thickness

- <= 6.5 µm
- Up to 35 µm
- with voids inside

Up to 10 layers



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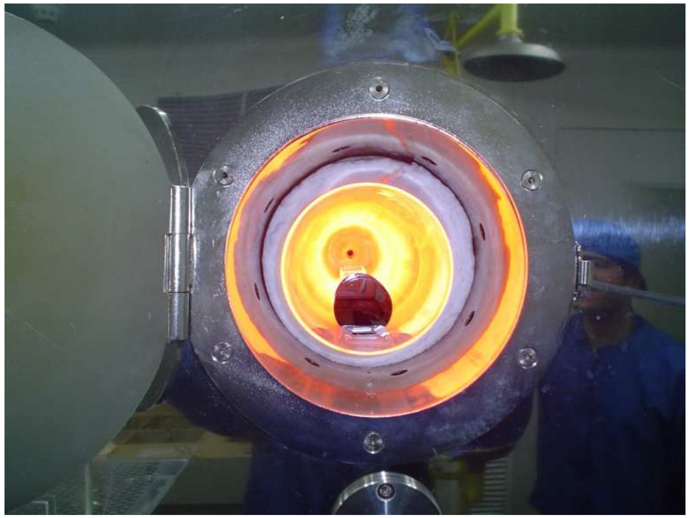
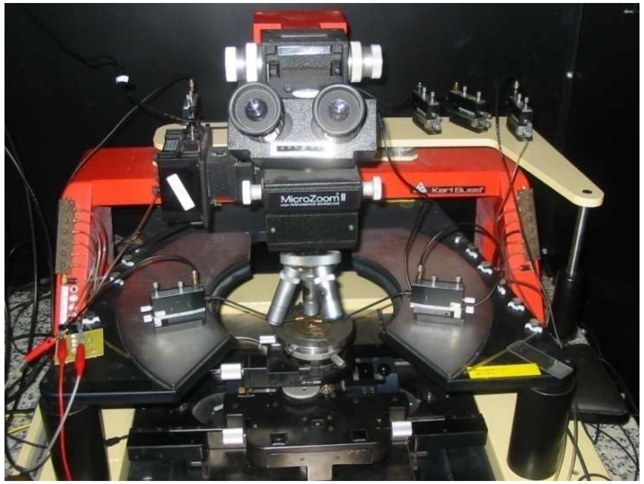
Resources: clean room

- Diffusion and oxidation furnaces
- PECVD(a-Si, a-SiCx, a-SiN, SiO_2)
- Thermal evaporation + e-gun
- 2 RF Sputtering reactors
- Lithography 2 μm
- 1064 nm Nd-YAG laser



Resources: device characterization lab

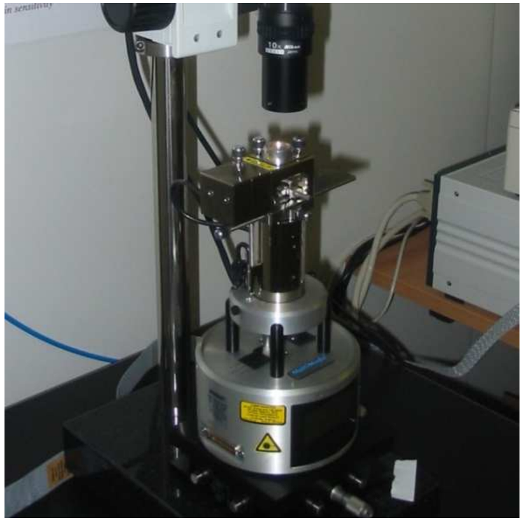
- Electrical characterization (I-V-T, C-V, solar simulator, $\tau_{eff}(\Delta n)$, etc.)
- Optical characterization (spectrophotometer, EQE, etc.)
- Solar simulator.
- Cryostat.

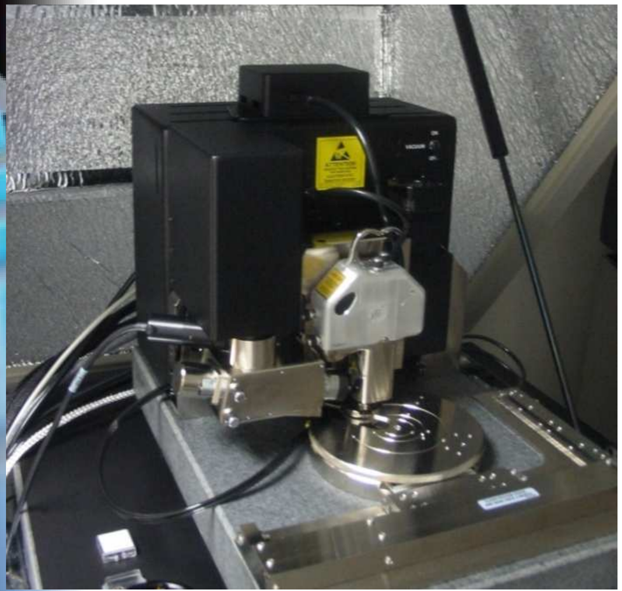


Resources: nano-scale characterization

Centre recerca en nano-enginyeria (CrNE).

- Atomic Force Microscopes
- Mechanical Profiler
- Optical Surface Profiler
- SEM/FIB
- XPS





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Part of PV group at UPC

DOCTORATE PROGRAM IN ELECTRONIC ENGINEERING

DOCTORAL TRAINING SEMINARS: RESEARCH PROJECTS IN THE DEPARTMENT OF ELECTRONIC ENGINEERING

"Cost-effective technologies for crystalline silicon (c-Si) solar cells"

Dr. Isidro Martín
(isidro.martin@upc.edu)

11th February 2014