A Second Life : PV Cells and Modules from Recycled feedstock

CABRISS

WP4: Fabrication of silicon solar cells using recycled materials

CEA, SOLITEK, SINTEF, IMEC, TU-WIEN

Month 24 Executive Board Meeting, THM

WP4

WP leader: IMEC

08.06.2017

Abdelkarim DERBOUZ DRAOUA

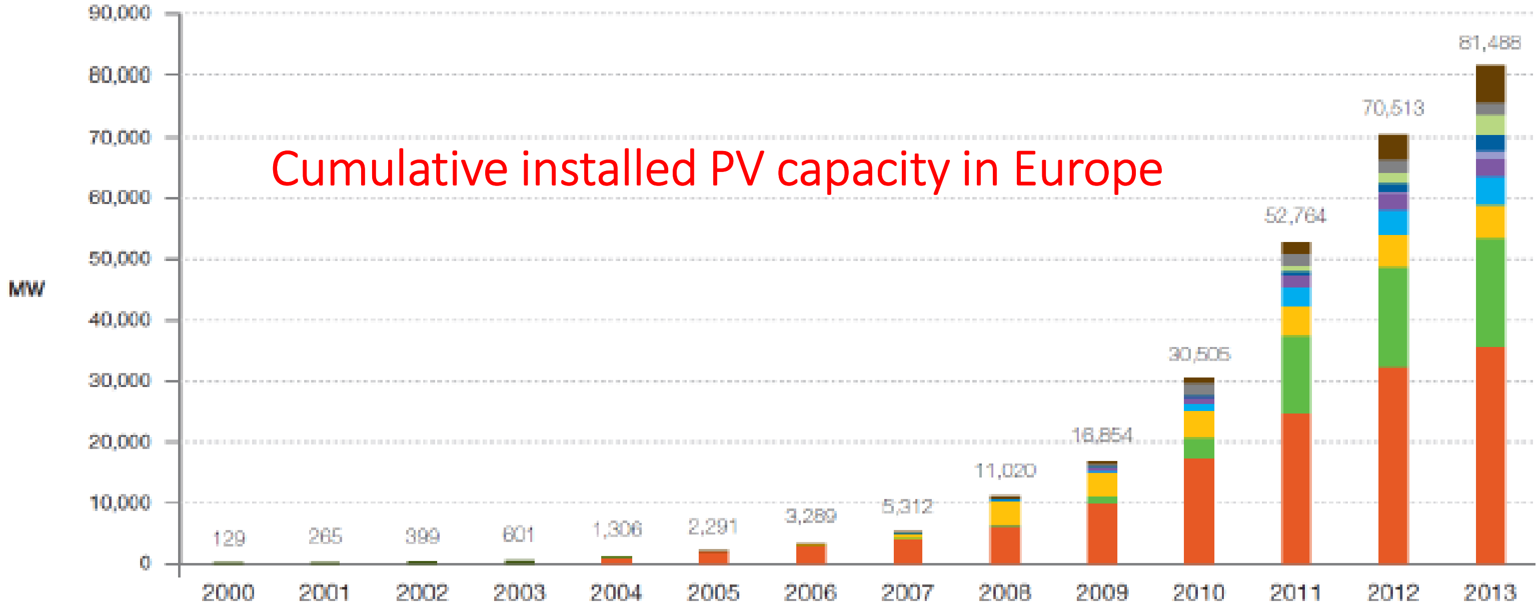
Abdelkarim.DERBOUZDRAOUA@cea.fr

Outline

- Introduction (CABRISS - Motivation)
- Re-Si wafers qualification Prtocol
  - ✓ Re-Si Monolike (ML-Si)
  - ✓ Re-Si Multicrystalline (mc-Si)
- Re-Si Wafers fabrication _ Al-BSF
  - ✓ Comparison between Re-Si material and solar cell results
- Conclusions & Perspectives

Introduction

The cumulative installed PV capacity in Europe is growing exponentially in this last decade.



With an estimated lifetime 20-30 years, ~ 2 M tons of EoL PV are expected in 2020.

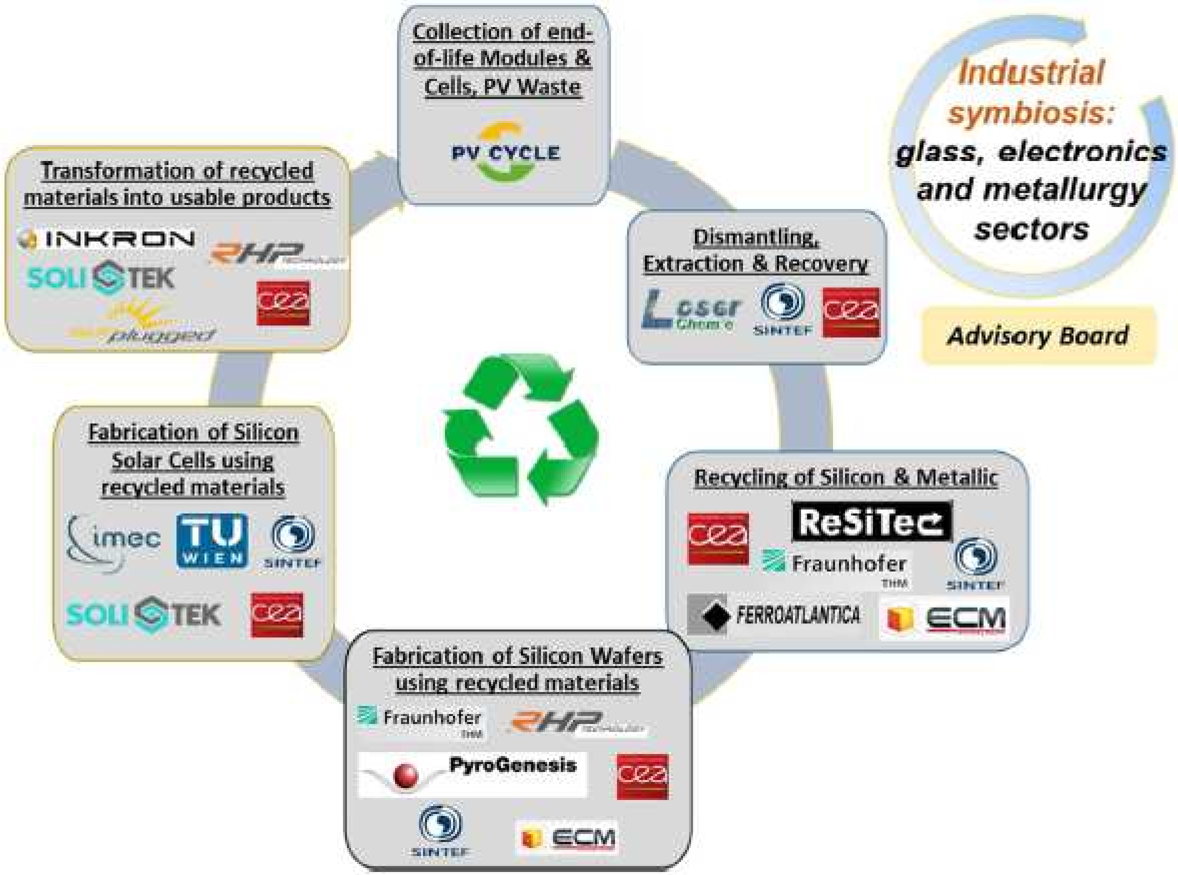
Expected tonnage of EoL modules

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Total Europe	710	690	891	1353	1363	2079	5564	12849	13525	19706

The Enormous amount of EoL modules forecasted requires immediate implementation of a circular PV economy.

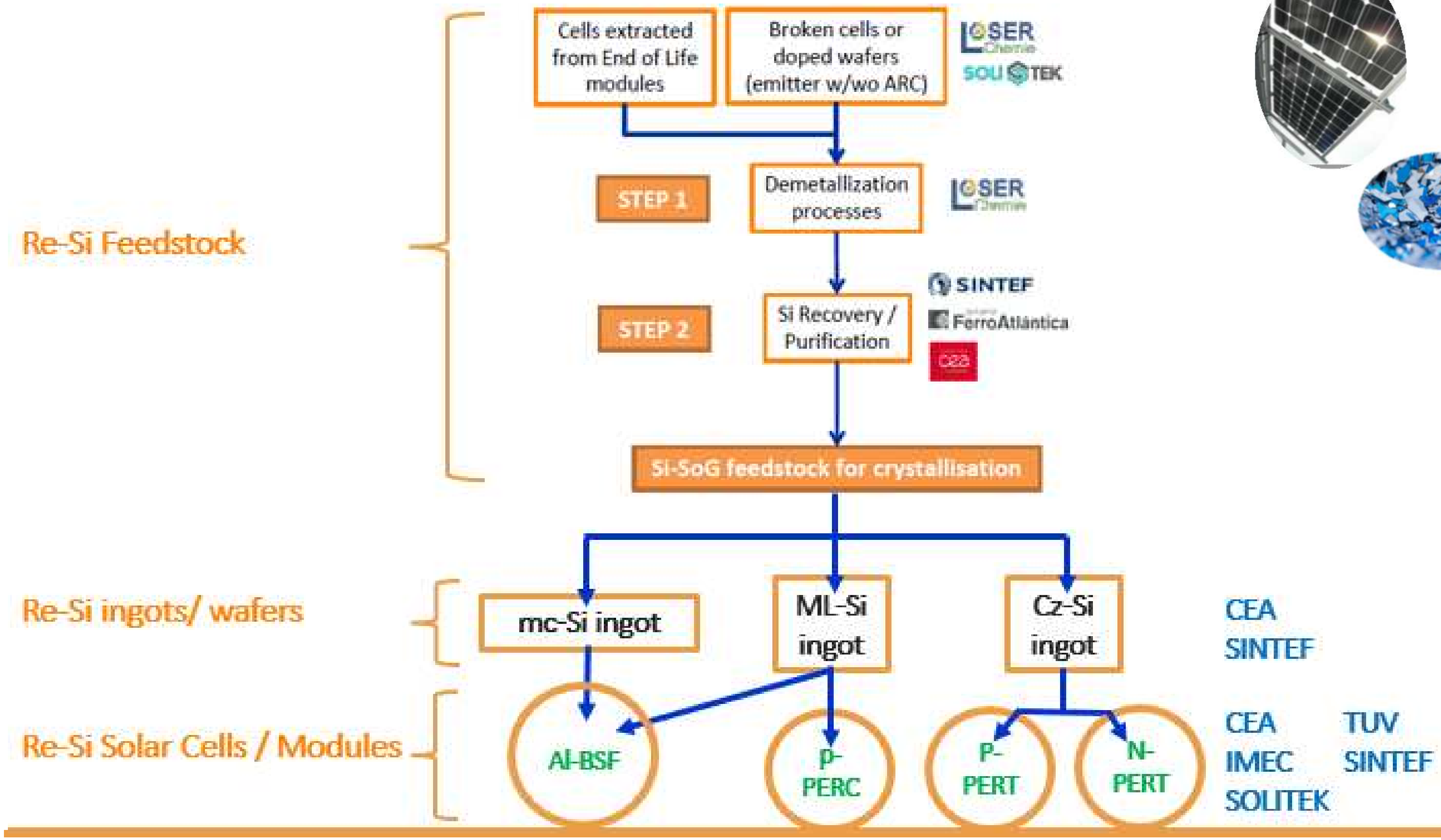
Cabriss Project

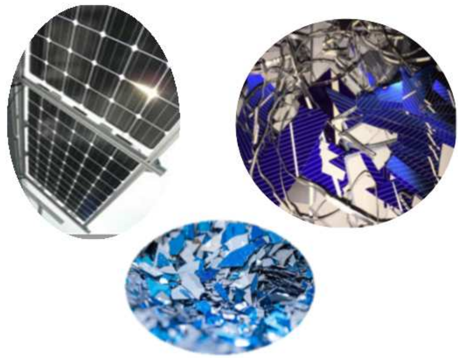
The main vision of the Cabriss project is to develop a circular economy to handle up to 90 % of PV waste (Si, Ag, In, Cu, Glass…).

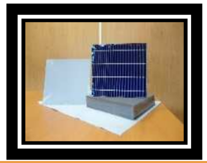


Introduction - Re-Si_PV Chain methodology in CABRISS

Motivation : Demonstrate the recycling of Silicon from PV waste to PV modules







Re-Si Wafer Qualification Protocol for PV Al-BSF Cell

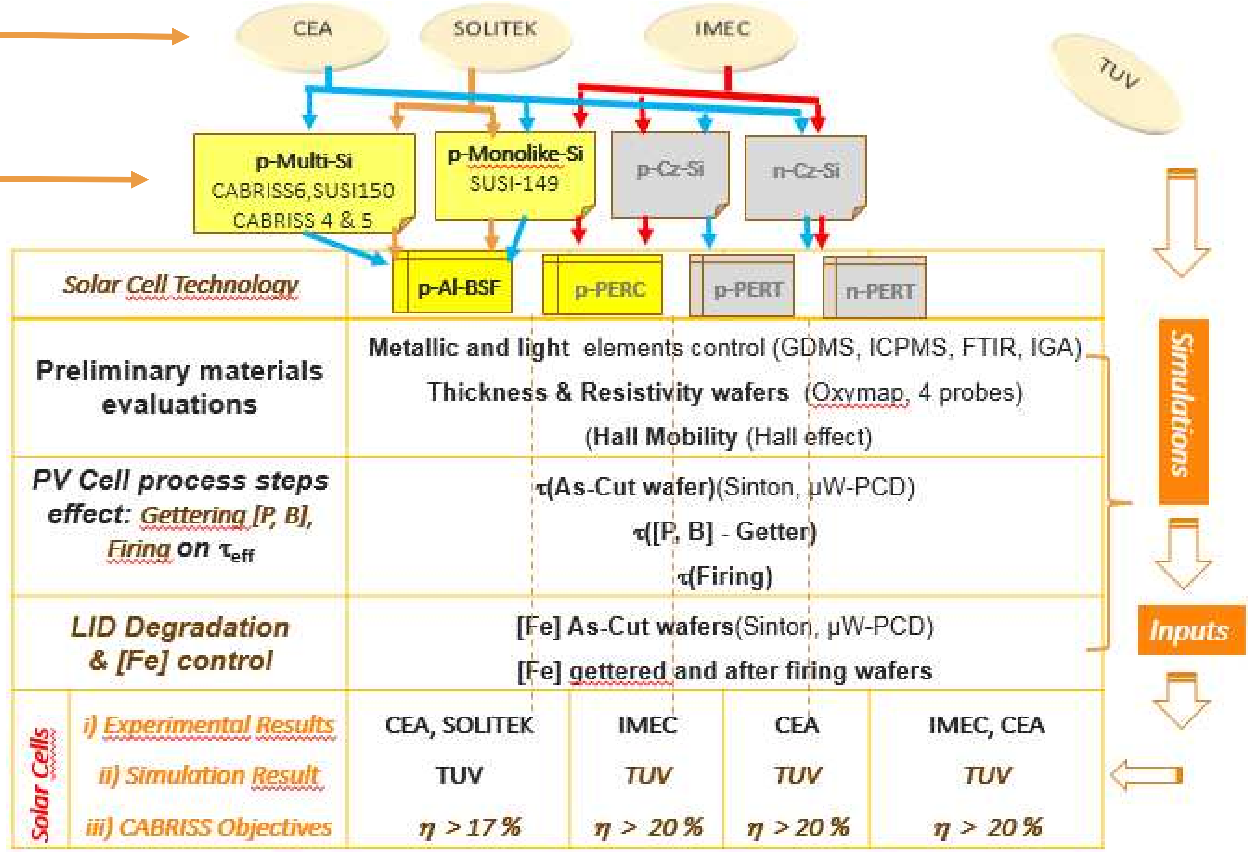
Partners

Re-Si ingots/Wafers

Re-Si PV cells techno.

Re-Si Wafers characterization protocol

Re-Si PV cells Results



We propose an <u>overall protocol</u> to qualify Re-Si wafers coming from different ingots & different Re-Si feedstock and <u>to evaluate</u> their potential in the different solar cell technologies.

Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

✓ Reception of Silicon wafers from Silicon ingots partners

Ingot A	Ingot B	Ingot C
Monolike	Multicrystalline (mc)	Multicrystalline (mc)
G2 (~55 kg)	*G1 (~10 kg)*	*G1 (~10 kg)*
100 % Re-Si Broken Solar Cells	24 % Re-Si Broken Solar Cells	100 % Re-Si As – cut wafers
< 0.6 **Ω**.cm	< 2.0 **Ω**.cm	< 2.0 **Ω**.cm

Different ingots/wafers have been received from WP3, in term of crystallinity (ML, mc-Si) and in term of the origin of Re-Si feedstock (as-cut broken wafers, complete and blending of broken solar cells).

MONOLIKE _ Re-Si

Ingot A (ML – 100 % broken solar cells)

Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

✓ Metallic element impurities control Ingot A (ML)

- High [B] ⇒ low resistivity (measured ρ < 0.4 Ω.cm)
- Low [P] exept @ top part due to segregation effect

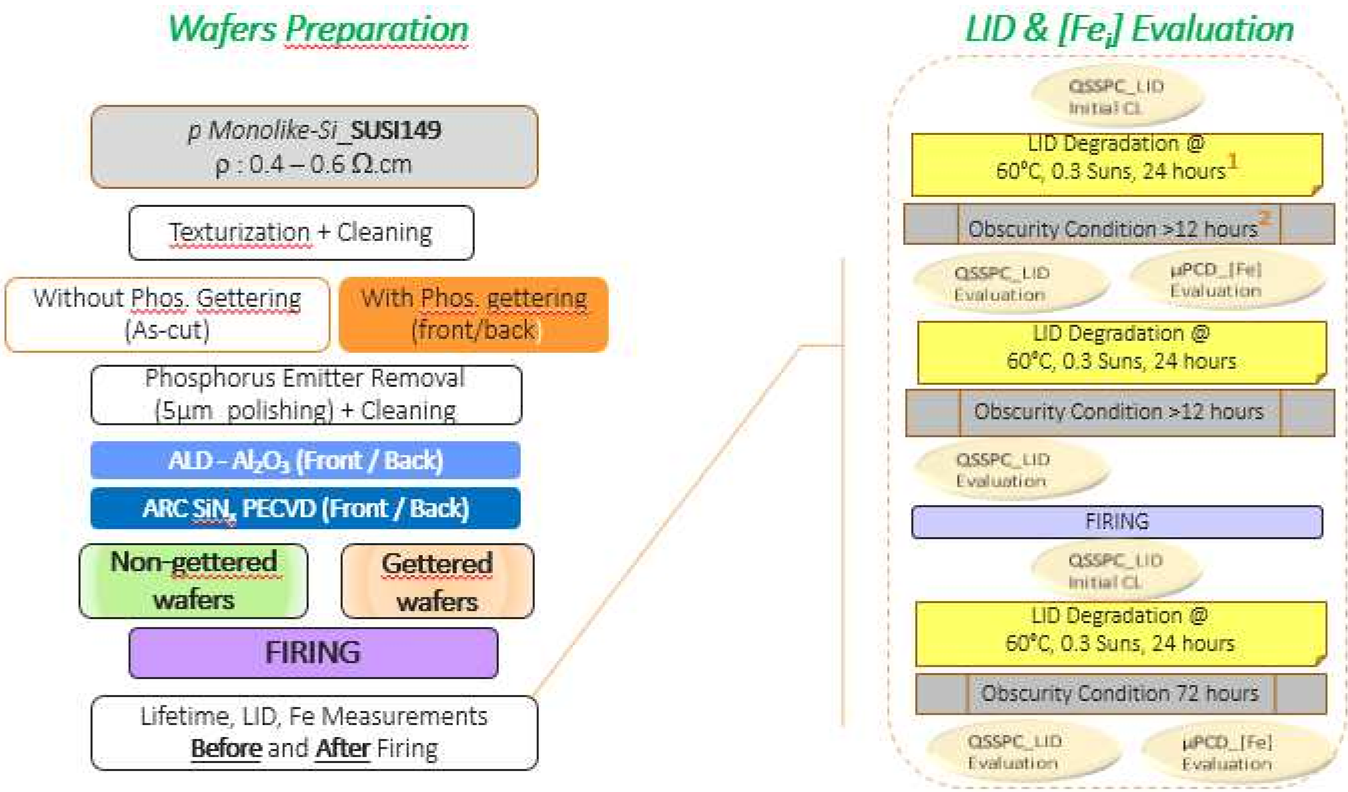
Table 1 – GDMS Analysis at different positions along the mono-like SUSI 149 ingot height.

Elements	Wafer Position		
	Bottom (ppm/wt)	Middle (ppm/wt)	Top (ppm/wt)
B	0.18	0.25	0.21
P	0.06	0.07	0.16
Al	< 0.01	< 0.01	< 0.01
Ag	<0.01	<0.01	<0.01
Cu	<0.01	<0.01	<0.01
Fe	<0.05	<0.05	<0.05
Pb	<0.005	<0.005	<0.005
Zn	<0.01	<0.01	<0.01
Ti	<0.005	<0.005	<0.005
Ni	<0.01	<0.01	<0.01
Cr	<0.005	<0.005	<0.005

- All metal impurities traces remain under the detection limit ⇒ which is an encouraging result. However even lower metal impurities could significantly affect the electrical performances

Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

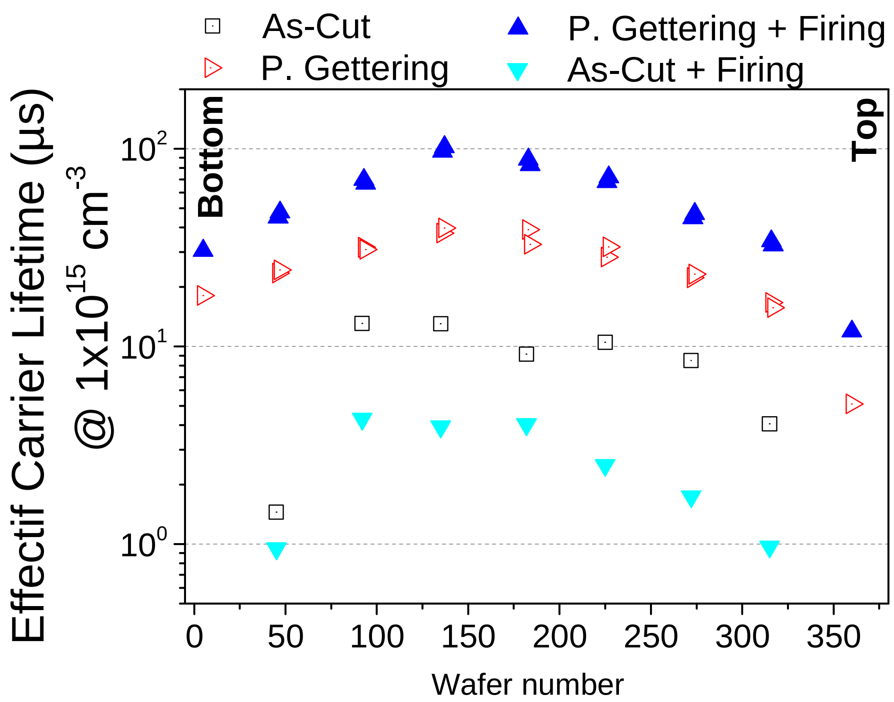
- ✓ Evaluation of τ_{eff} behavior of Re-Si wafer during Al-BSF solar cell process



In order to evaluate Re-Si wafers electrical quality, τ_{eff} of (as-cut, P gettered and after firing wafers), were measured with QssPC and µW-PCD instruments during Al-BSF process.

Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

✓ Evaluation of τ_{eff} behavior of Re-Si wafer during Al-BSF solar cell process for



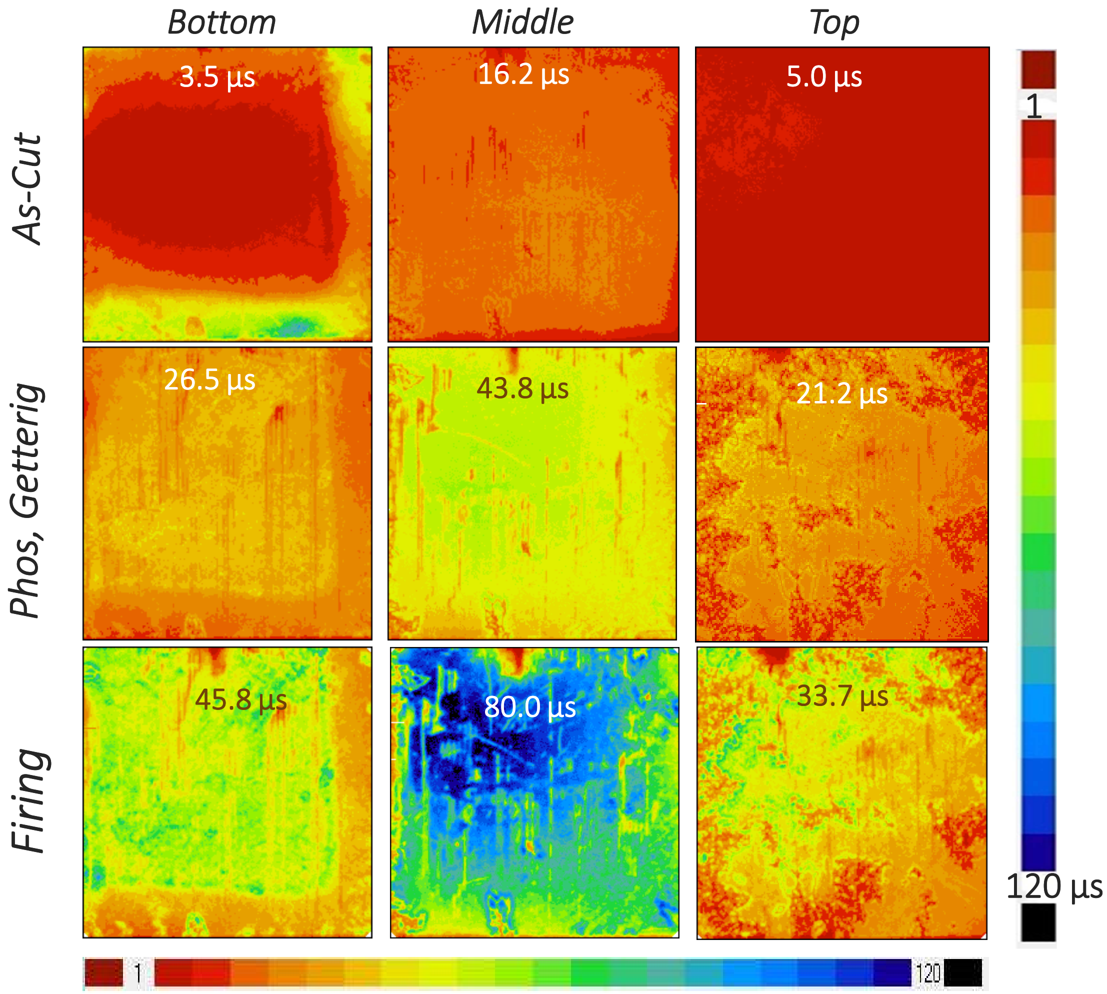
Ingot A (ML)
100% broken solar cells

- Very low as-cut effective lifetime on the whole ingot, 15 µs maximum
- After phosphorus gettering $\Rightarrow$ improvement by factors 2 to 20 of initial τ_{eff}
- Firing step leads to a good improvement by factor 2 of gettered τ_{eff} . Due to effective hydrogen passivation and other mechanisms…

Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

✓ Evaluation of τ_{eff} behavior of Re-Si wafer during Al-BSF solar cell process for

Ingot A (ML)
100% broken solar cells



Lower τ_{eff} @ the bottom and the top parts are probably due to the presence of residual impurities decorating subgrains

Multicrystalline Re-Si

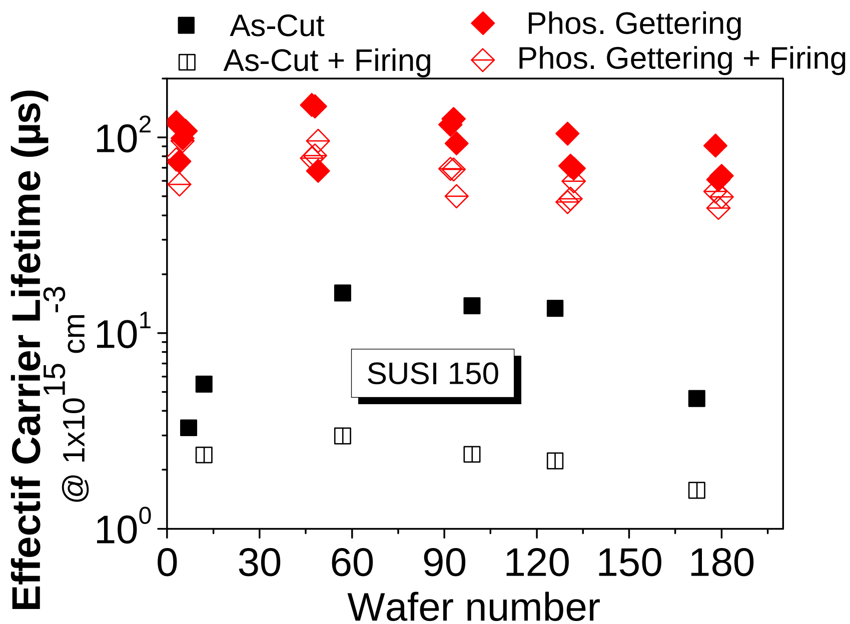
Ingot B (mc – 24 % broken solar cells)

Ingot C (mc – 100 % as cut broken wafers)

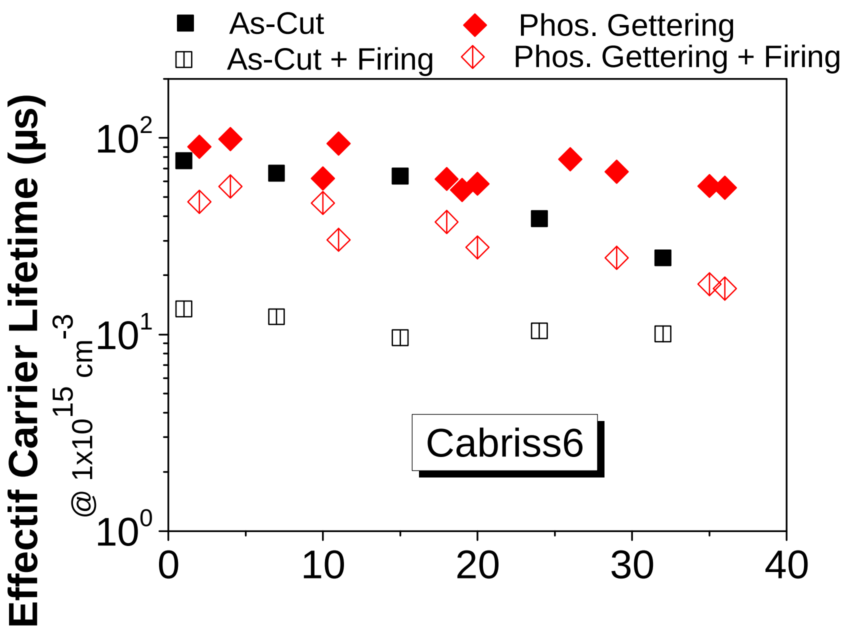
Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

✓ Evaluation of τ_{eff} behavior of Re-Si wafer during Al-BSF solar cell process for

Ingot B
(mc – 24 % broken solar cells)



Ingot C
(mc – 100 % as cut broken wafers)

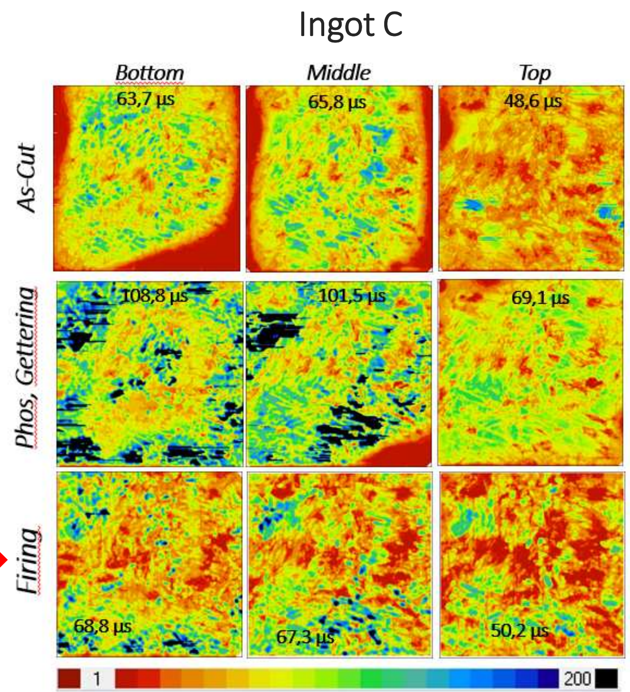


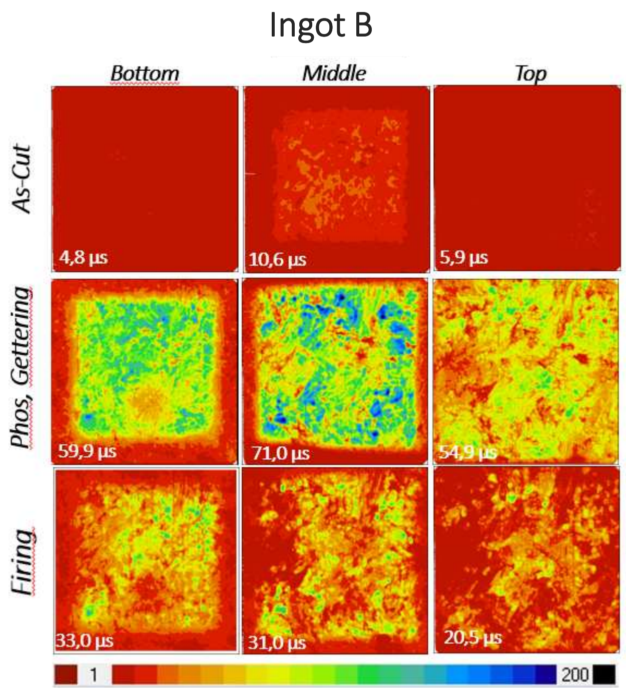
- After phosphorus gettering ⇒ improvement by factors > 10 of initial τ_{eff}
- However, (for as-cut and P-diffused wafers), the firing degrades τ_{eff} due to probably to a dissolution of metallic precipitates located at extended degects.

Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

✓ Evaluation of τ_{eff} behavior of Re-Si wafer during Al-BSF solar cell process for

(mc – 24 % broken solar cells) **(mc – 100 % as cut broken wafers)**



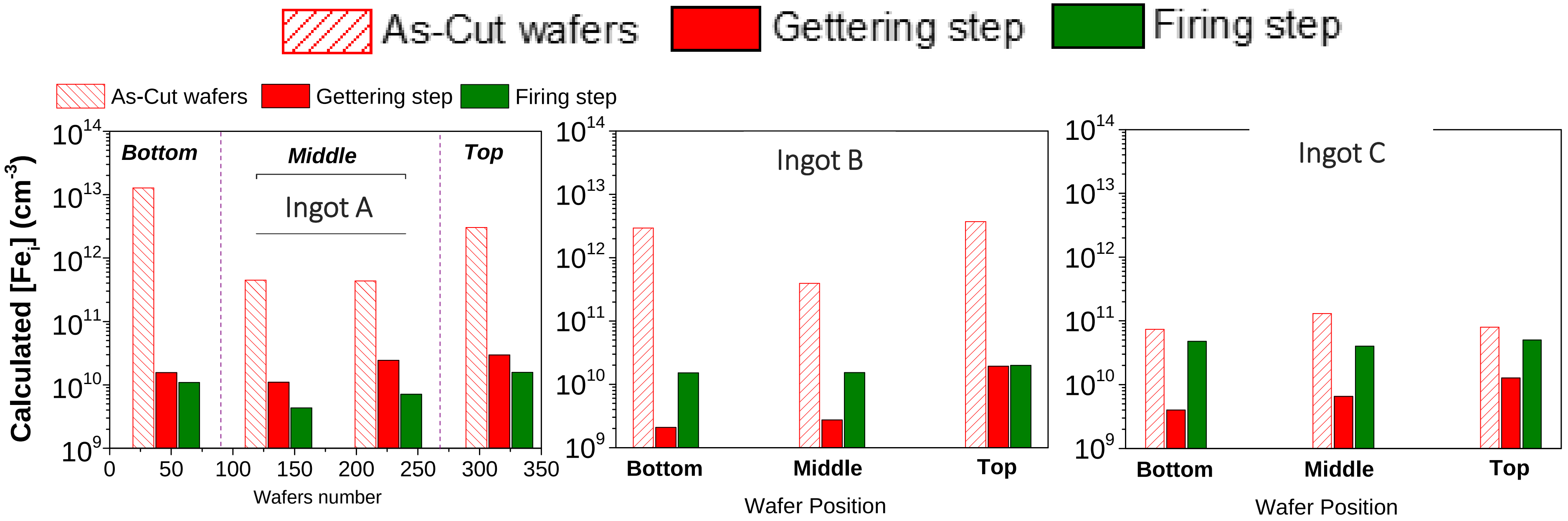


The µWPCD mappings confirm the degradation of the gettered wafers after firing step. We have to notice that this effect will be reduced for solar cell due to the presence of phosphorus emitter[1]

[1] J. Tan et al, Journal of Applied Physics Letters 91, 043505 (2007)

Re-Si Wafer Qualification Protocol for Al-BSF PV Cell

- ✓ Evaluation of $[Fe_i]$ behavior of Re-Si wafer during Al-BSF solar cell process

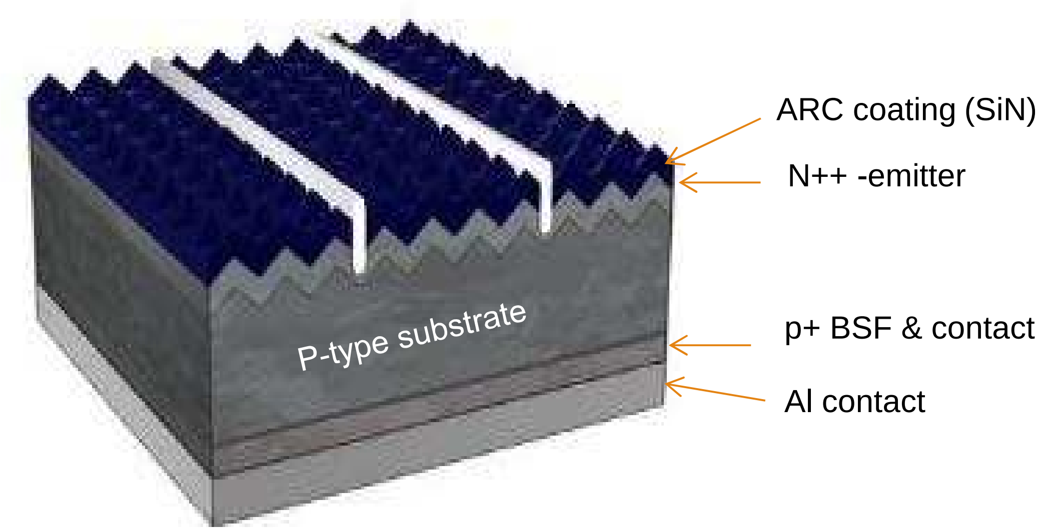


(ML-100% broken solar cells) ***(mc-24% broken solar cells)*** ***(mc-100% as-cut wafers)***

The higher the amount of the Re-Si broken solar cells feedstock, the higher $[Fe_i]$ content in as-cut wafers.

Solar cell fabrication on Re-Si wafers

✓ Al-BSF solar cell process for (A, B and C) ingots

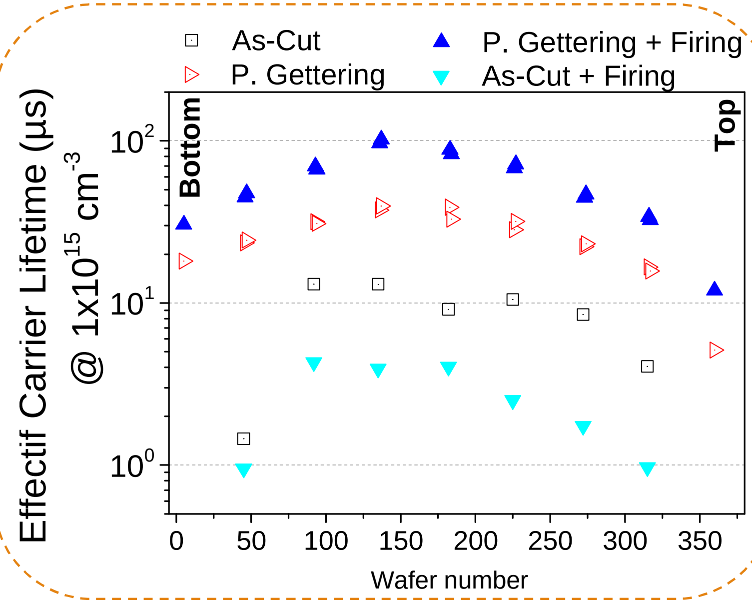


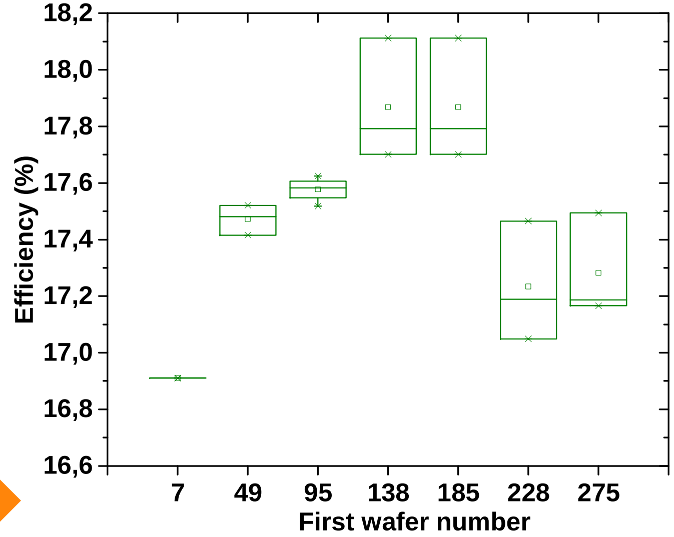
Batches of 4 solar cells at different ingots positions (SUSI149, SUSI150 and Cabriss6) underwent an Al-BSF solar cell fabrication process.

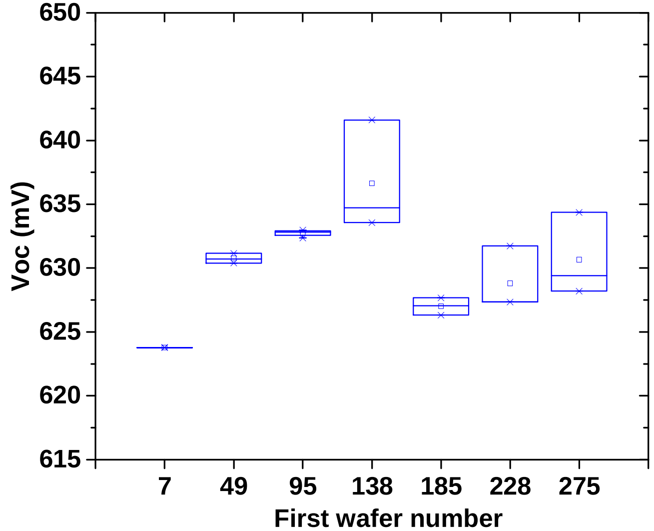
- Texturation + Cleaning
- Front emitter phosphorous
- Phosphorus glass Removal
- Front side diffusion barrier
- 5 µm Back side polishing & Cleaning
- ARC SiNx PECVD front side
- Full Al-BSF Back side metallization
- Al/Ag Front side metallization
- Firing

Solar cell fabrication on Re-Si wafers

- ✓ Solar cells Results on ingot A







Good agreement between Characterization Protocol and Al-BSF solar cells on ingot A wafers.

Solar cell fabrication on Re-Si wafers

✓ Summary of Solar cells results vs. wafers qualification protocol for for (A, B and C) ingots

p-Al-BSF Protocol	Protocol Results	Ingot A G2, mono-like 100% Recyle Solar cells			Ingot B G1, multicrystalline 24% Recyle Solar cells			Ingot C G1, multicrystalline As-cut broken wafer		
		Bottom	Middle	top	Bottom	Middle	Top	Bottom	Middle	Top
Preliminary materials evaluations	**Metallic** elements (ppm/wt)	< detection limit [GDMS]			< detection limit [GDMS]					
	[Oi] ($10^{17}cm^{-3}$)	3,1	0,8	0,1						
	Thickness wafers (µm)	165 – 175 µm			165 – 175 µm			165 – 175 µm		
	Resistivity (Ω.cm)	0.4	0,5	0,6	2,4	2,2	2,1	1,9	2,0	2,1
	Hall Mobility_µ($cmV^{-1}s^{-1}$)	278								
Al-BSF process steps effect on τ_{eff}	**τ(As-Cut wafer)**(µs)	1,5	13,1	4,1	3,3	16,0	4,6	76,5	64,0	24,5
	τ(P-Getter) (µs)	24,4	39,7	16,7	98,8	146,5	90,8	98,5	61,9	56,9
	τ(Firing) (µs)	47,7	102,1	34,1	95.9	78.3	53.0	56,7	37,4	18,0
LID Degradation & [Fe] control	**[Fe] As-Cut wafers** ($x10^{10}cm^{-3}$)	1300	44,6	302	294	39,4	370	7,7	13,0	8,0
	[Fe] gettered wafer ($x10^{10}cm^{-3}$)	3,0	1,1	1,6	0,2	0,3	1,9	0,4	0,7	1,3
	[Fe] Firing wafer($x10^{10}cm^{-3}$)	1,6	0,4	1,1	1,5	1,5	2,0	4,8	4,0	5,0
p AL-BSF Solar Cell Results	**Conversion Efficiency** (%)	17,2	18,1	17,4	15,0	16,3	15,7	17,0	17,1	16,8
	Voc (mV)	628,3	641,6	630,4	605,8	611,2	607,5	625,7	627,5	624,8

These “material” results are in good agreement with the obtained Al-BSF solar cell efficiencies, except for ingot B due to an important inhomogeneity of τeff (red zone effect at the edges).

Solar cell fabrication on Re-Si wafers

- ✓ Summary of Solar cells results at production scale (SOLITEK) for (A, B and C) ingots compared to reference.

p Al-BSF Solar Cell Results	Industrial Results	Ingot A G2, mono-like 100% Recyle Solar cells		Ingot B G1, multicrystalline 24% Recyle Solar cells		Ingot C G1, multicrystalline As-cut broken wafer	
		Average	best	Average	best	Average	best
@ SOLITEK	Conversion Efficiency (%)	16,8	17,5	16,2	16,5	17,3	17,6
	Voc (mV)	621,0	630,0	608,0	610,0	625,0	629,0

p Al-BSF Solar Cell Results	Industrial Results	CABRISS4 G1, multicrystalline Si – Reference extended melting time		CABRISS5 G1, multicrystalline Si – Reference standard	
		Average	best	Average	best
@ SOLITEK	Conversion Efficiency (%)	17,2	17,5	16,9	17,1
	Voc (mV)	627,0	630,0	625,0	629,0

The first solar cells results from SOLITEK at production scale confirms the possibility to use such Re-Si wafers in industrial production lines.

Conclusion

- The external gettering effect developed by the P-diffusion step during Al-BSF process, strongly improves the electrical and physico-chemical properties of the wafers for each ingot.
- These “material” results are in good agreement with the obtained Al-BSF solar cell efficiencies
- A best efficiency of 18.1 % has been reached with Al-BSF solar cell, based Mono-like silicon material based on 100% broken solar cells feedstock.
- The first solar cells results from CEA and SOLITEK at production scale confirm the possibility to use such feedstock in industrial production lines.

Thank you for your attention