A study of the “short-circuit” effect during the fast firing process

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Motivation

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– Lightly doped Si surfaces → higher Voc → higher Eta

– Current status

	Screen-printed and firing-through Ag contacts [1,2,3]	**Evaporated Al contacts (PVD) [4]**
sheet resistance	100 Ω/sq	170 Ω/sq
surface concentration	8 x 10^{19} cm^{-3}	1.8 x 10^{19} cm^{-3}
$J_{0,pass}$	75 fA/cm^2	11 fA/cm^2
ρ_c (contact resistance)	2 mΩ·cm^2	1 mΩ·cm^2

→ Need better understanding of contact formation

[1] ITRPV, 2019 [2] H. Li *et al*., IEEE J. Photovoltaics, 7(1), 2017 [3] S. Werner *et al*., Energy Procedia, 124, 2017 [4] J. Sheng *et al*., Sol. Energy Mater. Sol. Cells, 152, 2016

Formation of Ag contacts: Kim´s model [5, 6]

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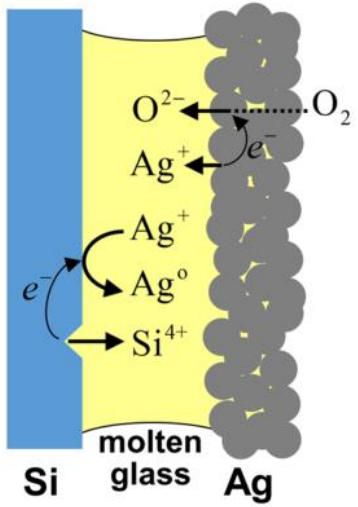
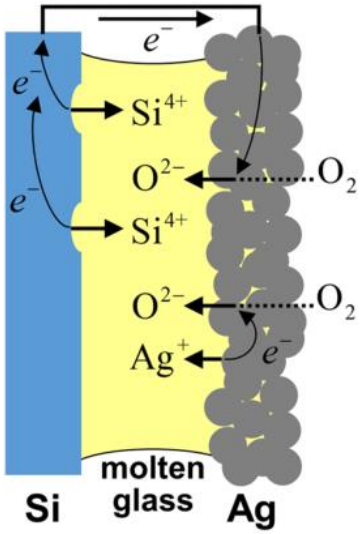
- Reaction 1 (open-circuit state): the reduced Ag atoms precipitate into Ag crystallites
- Reaction 2 (short-circuit state): **no reduction** of Ag^+ ions
- To trigger short-circuit state: local Ag contacts that are formed earlier than others

- open-circuit



$$4Ag^{+}_{(in\ glass)} + 2O^{-2}_{(in\ glass)} + Si_{(solid)} \rightarrow 4Ag_{(in\ glass)} + SiO_{2(in\ glass)}$$

- short-circuit



$$Si_{(solid)} + 4xAg_{(solid)} + (1-x)O_{2\,(gas)} \rightarrow Si^{4+} + 4xAg^{+}_{(in\ glass)} + 2(1-x)O^{-2}_{(in\ glass)}$$

[5] H.-S. Kim *et al*., Prog. Photovolt: Res. Appl., 24 (9), 2016 [6] H.-S. Kim and J.-Y. Huh, 7th Metallization workshop, Konstanz, 2017

Formation of Ag contacts: fast firing and temperature gradient

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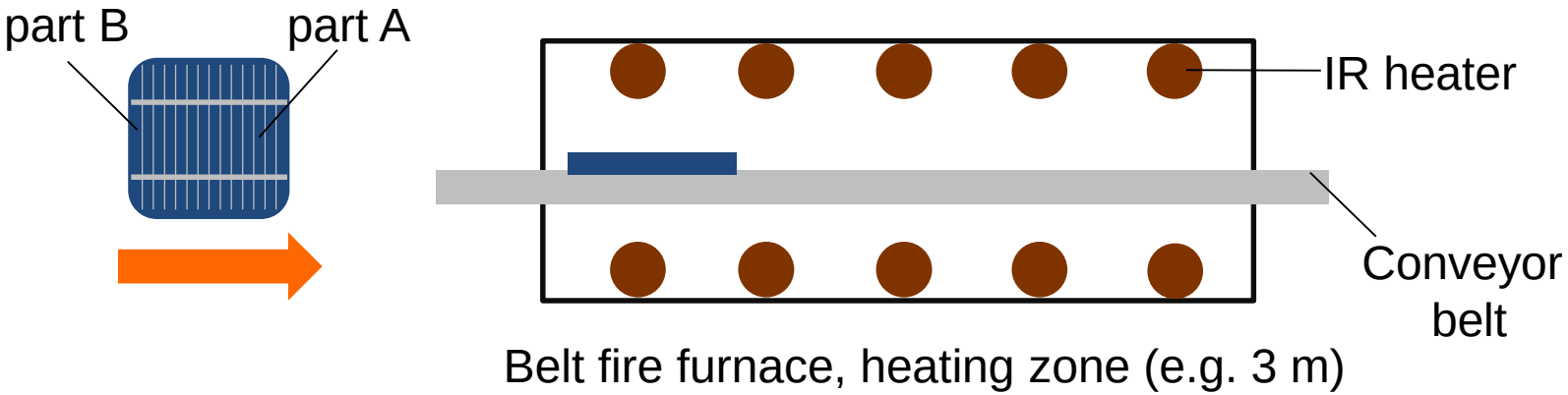
– To trigger short-circuit state: local Ag contacts that are formed earlier than others

• temperature gradient exists over the cell surface (a likely case)

• Ag crystallites formed in part A, which may occur earlier than in part B, become the short-circuiting sites that influence the contact formation in part B



Formation of Ag contacts: influence from busbars

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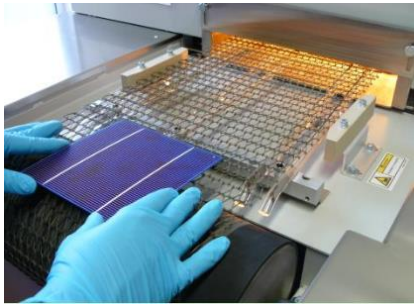
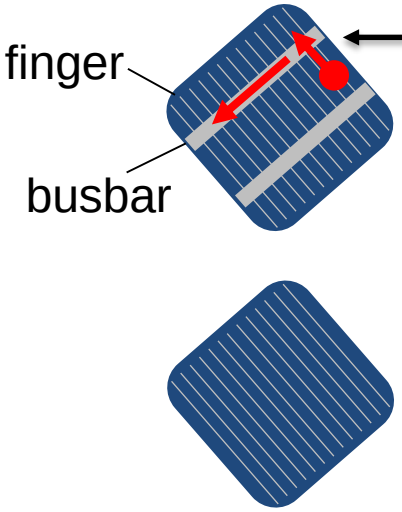
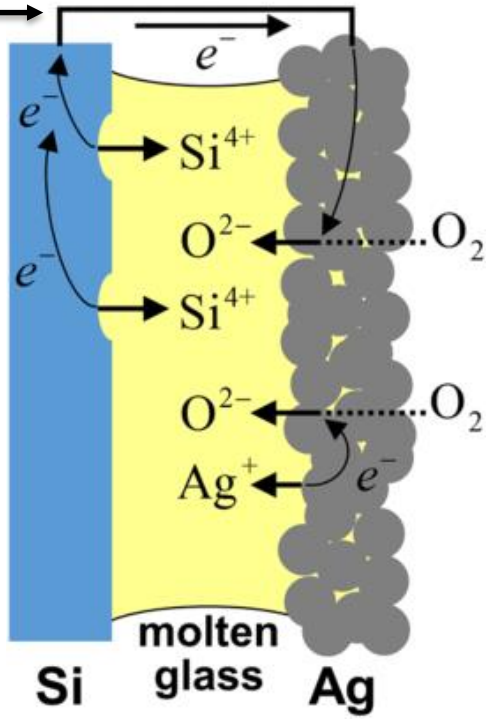
- Reaction (short-circuit state): **no reduction** of Ag+ ions [5, 6]
- To trigger short-circuit state: local Ag contacts that are formed earlier than others
- Mitigate this effect by omitting the busbars ?







- short-circuit

$$Si_{(solid)} + 4xAg_{(solid)} + (1-x)O_{2\,(gas)} \rightarrow Si^{4+} + 4xAg^{+}_{(in\ glass)} + 2(1-x)O^{-2}_{(in\ glass)}$$

[5] H.-S. Kim *et al*., Prog. Photovolt: Res. Appl., 24 (9), 2016 [6] H.-S. Kim and J.-Y. Huh, 7th Metallization workshop, Konstanz, 2017

Experiment 1: solar cell

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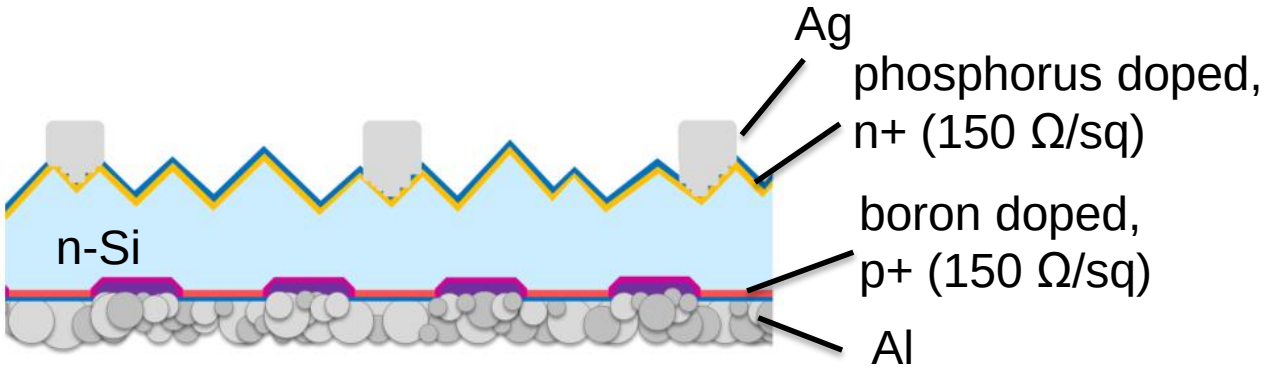
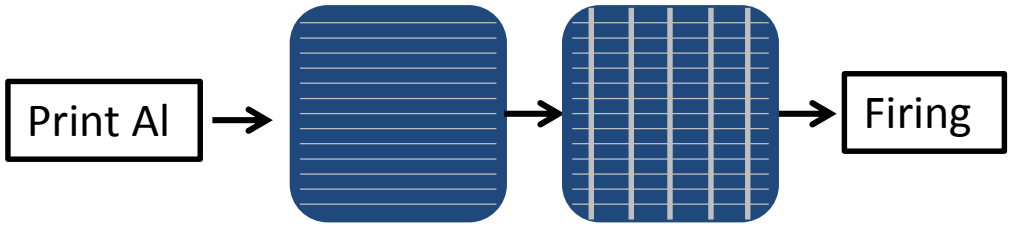
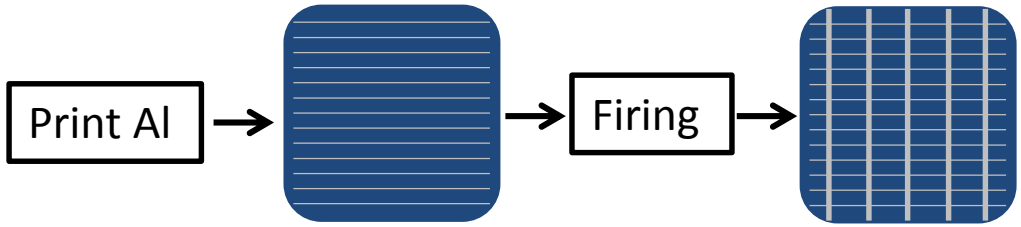
– Mitigate this effect by omitting the busbars (BBs) ?
  • 6-inch n-type PERT rear junction solar cells [7]



(a) fire with BBs



(b) fire without BBs



[7] Z. Peng *et al.*, AIP Conference Proceedings, 1999(1), 2018

Experiment 1: solar cell IV and ρ_c

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Ag Paste	Firing	Jsc (mA/cm²)	Voc (mV)	FF (%)	Eta (%)	$\rho_{c_{Ag}}$(mΩ·cm²)
paste A	with BB	39.7 ± 0.2	686 ± 1	75.9 ± 1.4	20.7 ± 0.4	12.2 ± 8.7
	without BB	39.7 ± 0.1	688 ± 1	80.2 ± 0.1	21.9 ± 0.1	2.4 ± 0.8
paste B	with BB	39.7 ± 0.1	680 ± 1	52.2 ± 4.9	14.1 ± 1.3	76.1 ± 34.4
	without BB	39.6 ± 0.1	682 ± 1	80.1 ± 0.3	21.6 ± 0.1	1.9 ± 1.0

5BBs, 100 fingers
~10 cells each group
$\rho_{c_{Ag}}$: contact resistance of the Ag grid; for each group (two cells, totally 36 measurement points)

Experiment 1: solar cell PL/EL image

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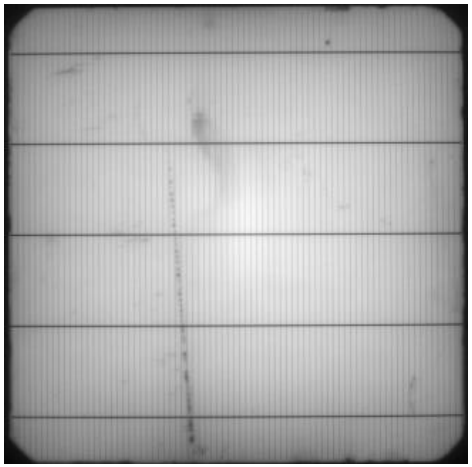
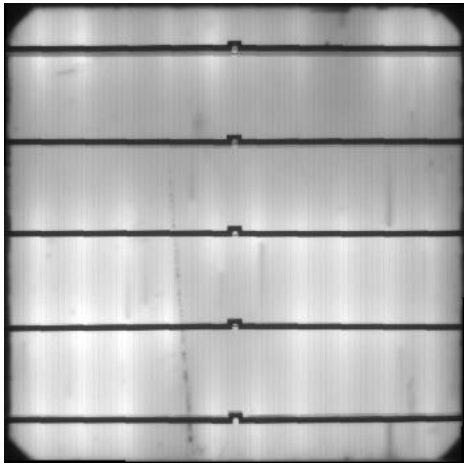
PL

EL, 2.5A

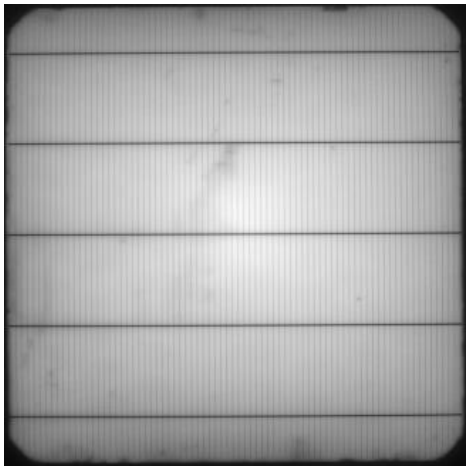


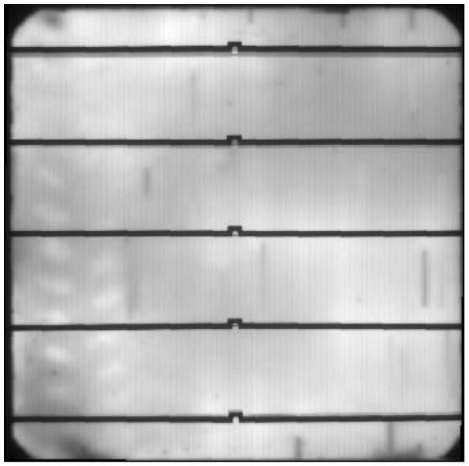


Paste A

fire without BB

Eta = 21.9 %





fire with BB

Eta = 21.0 %

Experiment 2: contact resistance

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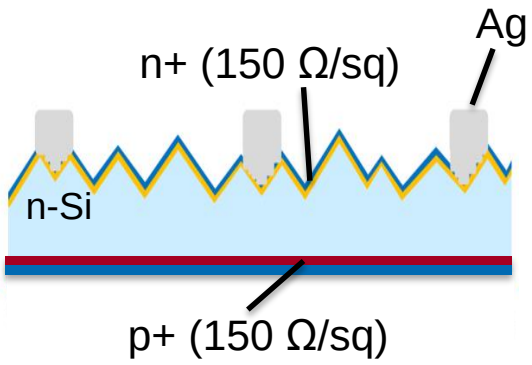
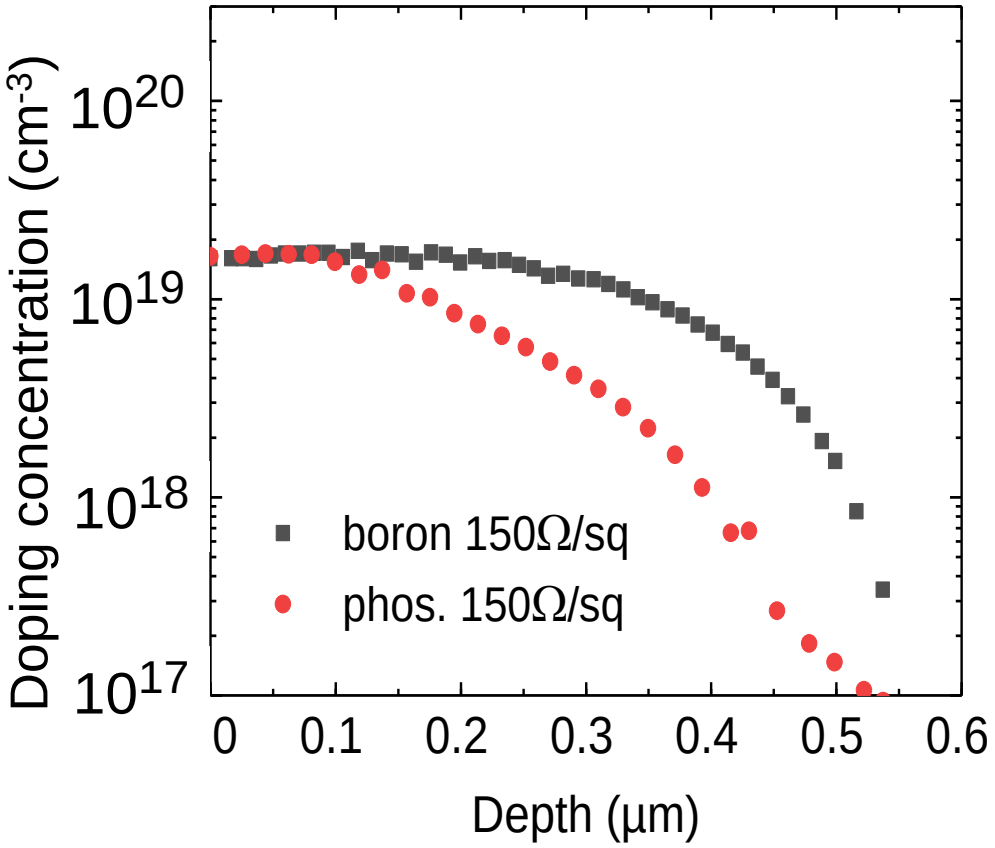
– Is it an effect that is valid in specific pastes ?

  • Test with another five Ag pastes on cell precursors





5BBs, 78 fingers
~36 measurement points for each group

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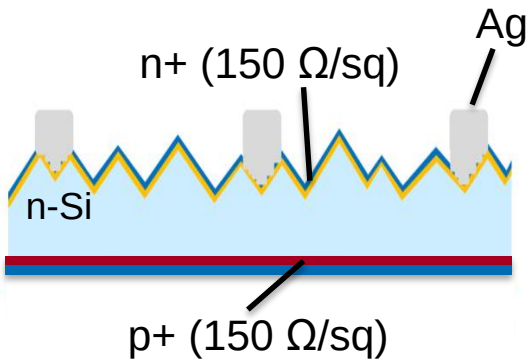
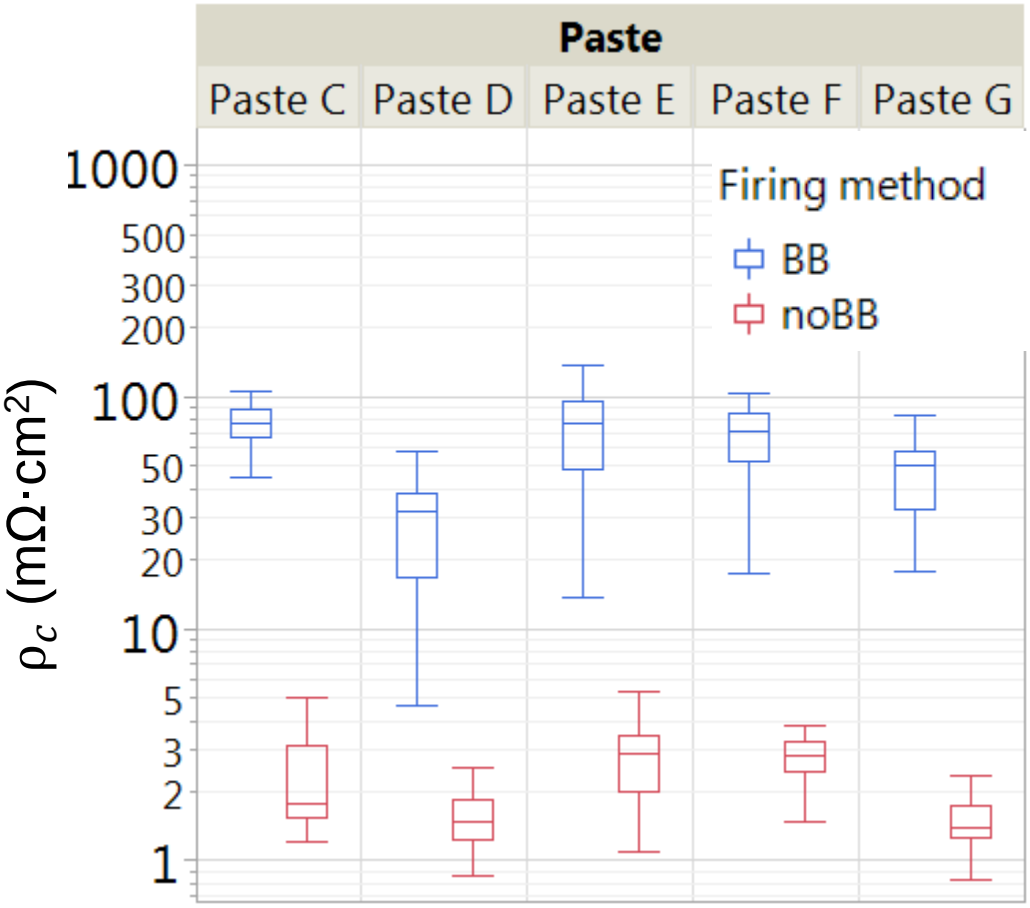


textured n+ surfaces



5BBs, 78 fingers
~36 measurement points for each group

Experiment 2: contact resistance

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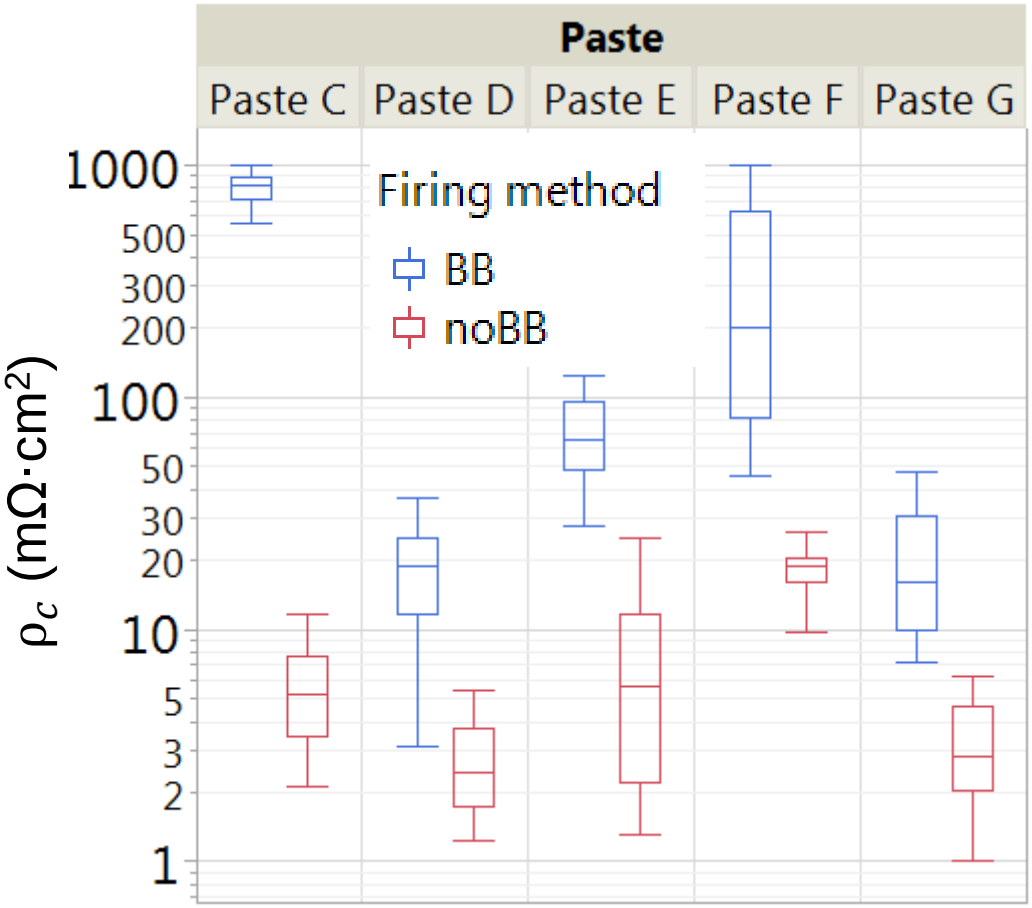
- Is this effect valid for the p+ surface as well ?
  - test on the p+ surface of the cell precursor

- Similar trend was observed for
  - different firing recipes
  - different surface morphologies and doping profiles [8]
  - p-type cells [8, 9]
  - passivated contact [9]

flat p+ surfaces

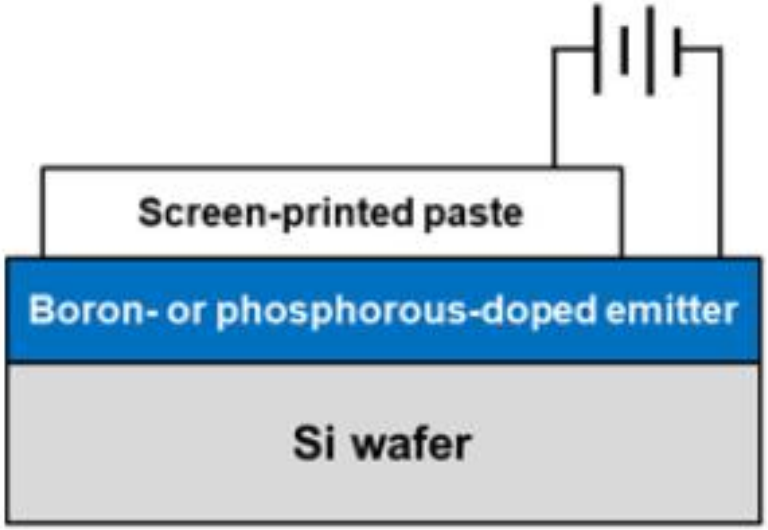


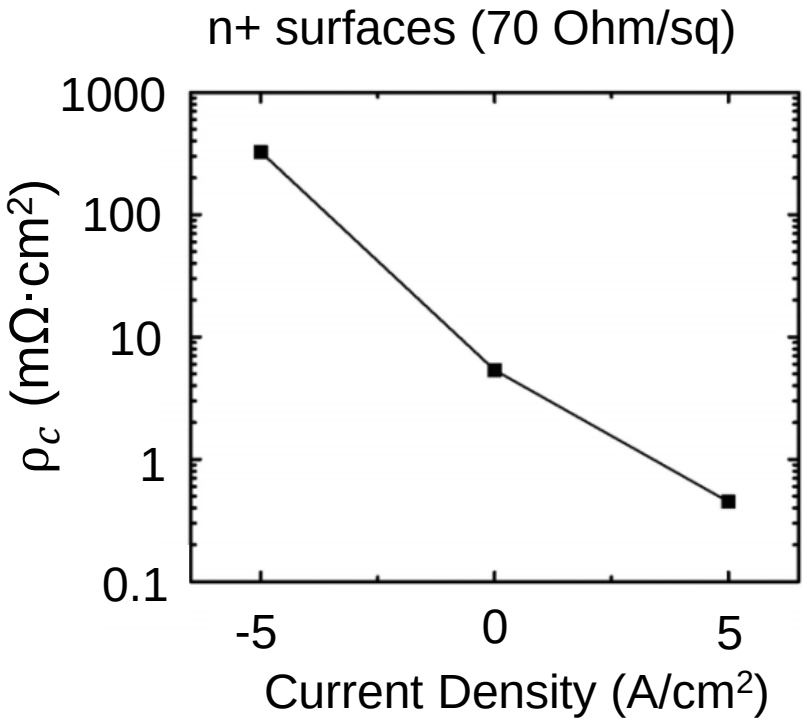
5BBs, 78 fingers
~36 measurement points for each group

[8] H. Chu *et al*., IEEE J. Photovoltaics, 8 (4), 2018 [9] S. Mack *et al*., Phys. Status Solidi RRL, 186, 2019

Other related experiments

Literature review: current injection between Ag and Si [10]





[10] S. Bae *et al*., IEEE J. Photovoltaics, 9 (2019) More works about this topic: [11] C. Kim *et al*., Scientific Reports, 6, 2016 [12] M. Hörteis *et al*., 7th Metallization workshop, Konstanz, 2017

Summary

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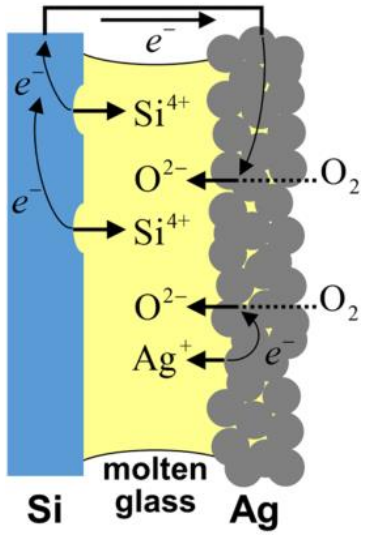
Observation in the lab:

- Firing without BBs leads to a decrease of ρ_c for all seven tested Ag pastes (from four suppliers)

→perhaps a general effect for all screen-printed and firing-through Ag pastes, instead of an effect valid for specific pastes

- The decrease of ρ_c also hold in solar cells, leading to better Eta

figure taken from [5]



short-circuit state

$$Si_{(solid)} + 4xAg_{(solid)} + (1-x)O_{2\,(gas)} \rightarrow Si^{4+} + 4xAg^{+}_{(in\ glass)} + 2(1-x)O^{-2}_{(in\ glass)}$$

A possible theory to explain:

- Short-circuit effect [5, 6]

[5] H.-S. Kim *et al*., Prog. Photovolt: Res. Appl., 24 (9), 2016 [6] H.-S. Kim and J.-Y. Huh, 7th Metallization workshop, Konstanz, 2017