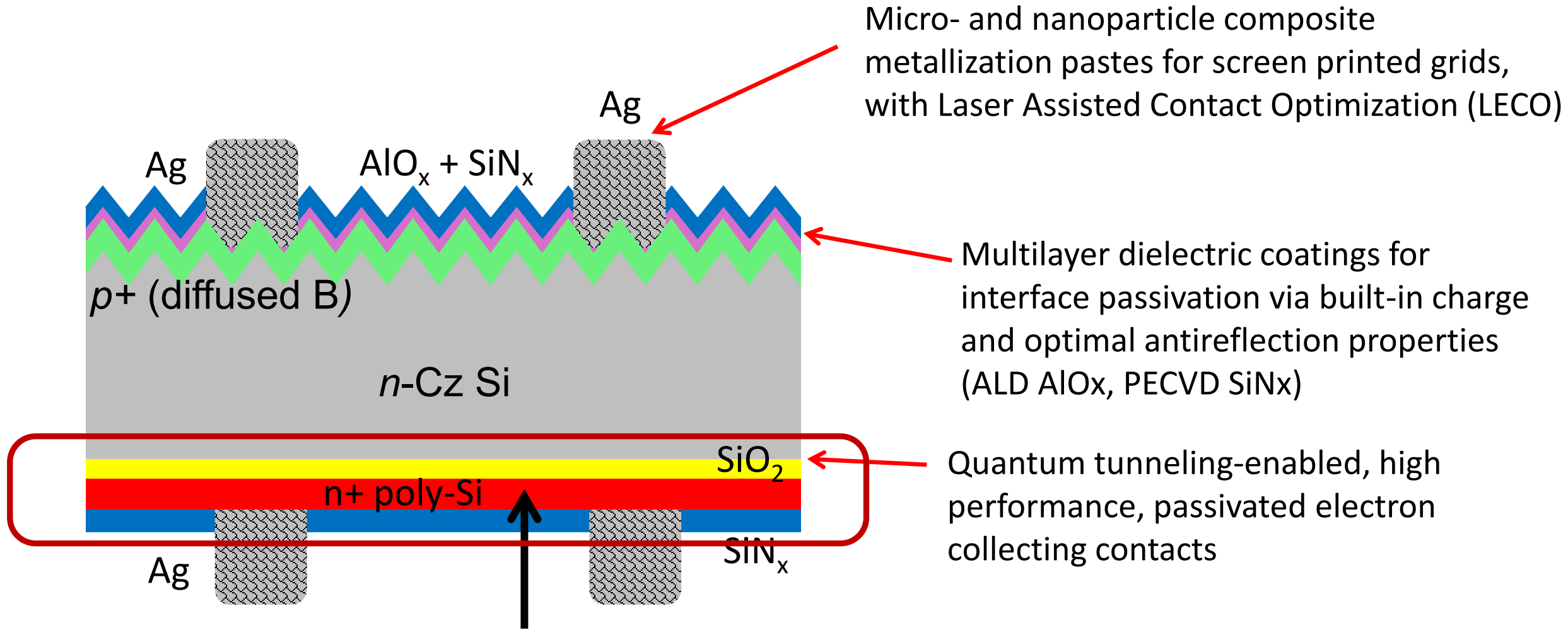


Possible Alternative to TOPCon: Engineered Nanopinhole Passivated Contacts

Paul Stradins
National Laboratory of the Rockies

TOPCon cell – PV mainstream technology

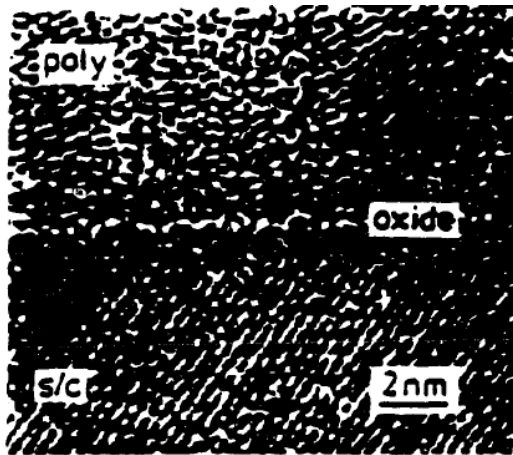


TOPCon tunneling passivated contact based on ~ 50 nm n^+ poly-Si and thin (~ 1.4 nm) tunneling SiO_2 .

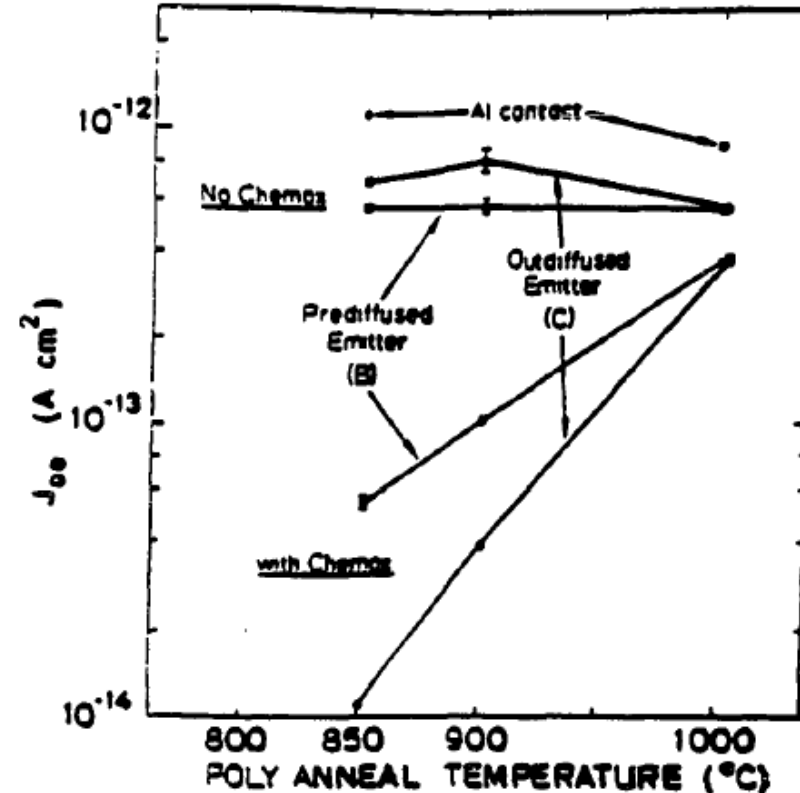
An extra-low recombination e-collecting, passivated contact.

Poly-Si/SiO₂/c-Si Contact History: R.M. Swanson's lab at Stanford University

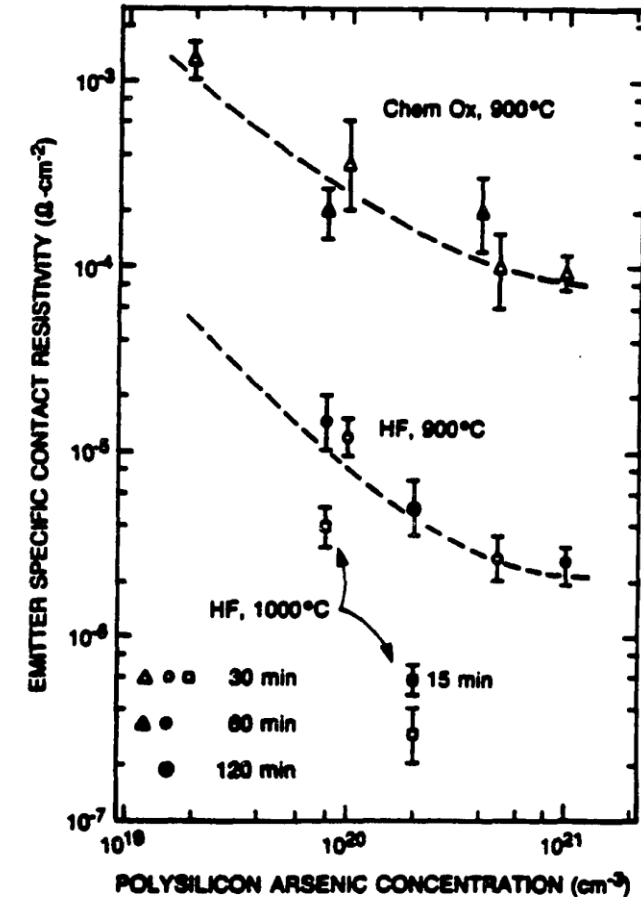
Poly/Oxide/Si contact TEM



Poly/Oxide/Si contact
 $J_0 \sim 10 \text{ fA/cm}^2$



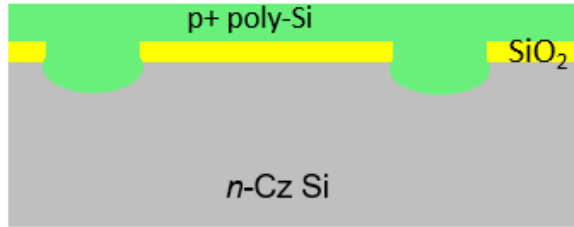
Poly/Oxide/Si contact
 $\rho_{\text{cont}} < 10^{-3} \Omega\text{-cm}^2$



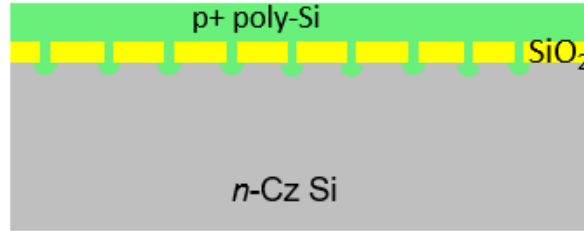
- Jon-Yiew Gan, Ph.D Thesis, (1990)
- Y. Kwark, R. A. Sinton, and R. M. Swanson. "Low J_0 Contact Structures Using SIPOS and Polysilicon Film s," In *18th IEEE Photovoltaic Specialists Conference*, page 787, 1985.

Nanosized pinholes at high areal density enable the highest contact performance

$r = 10 \mu\text{m}$ pinholes



$r = 10 \text{ nm}$ pinholes



Recombination prefactor J_0 :

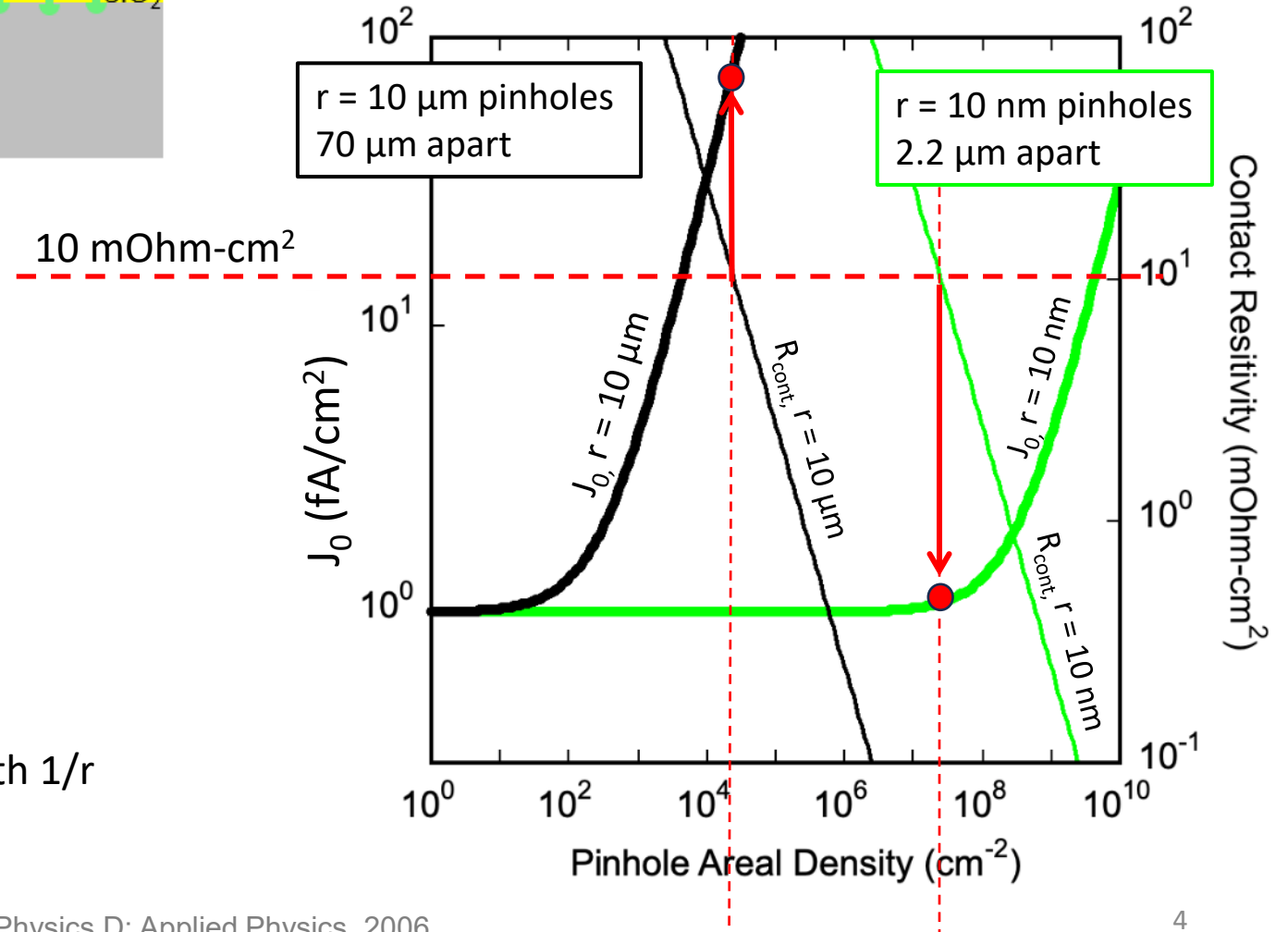
$$J_0 = J_{0,\text{diel}} + \pi r^2 \times J_{0,\text{doped}} \times N_{\text{areal}}$$

Contact resistivity R_{cont} :

$$R_{\text{cont}} = \frac{\rho_{\text{wafer}}}{4r} \times \frac{1}{N_{\text{areal}}}$$

J_0 scales with pinhole area πr^2 , while R_{cont} scales with $1/r$ due to spreading resistivity

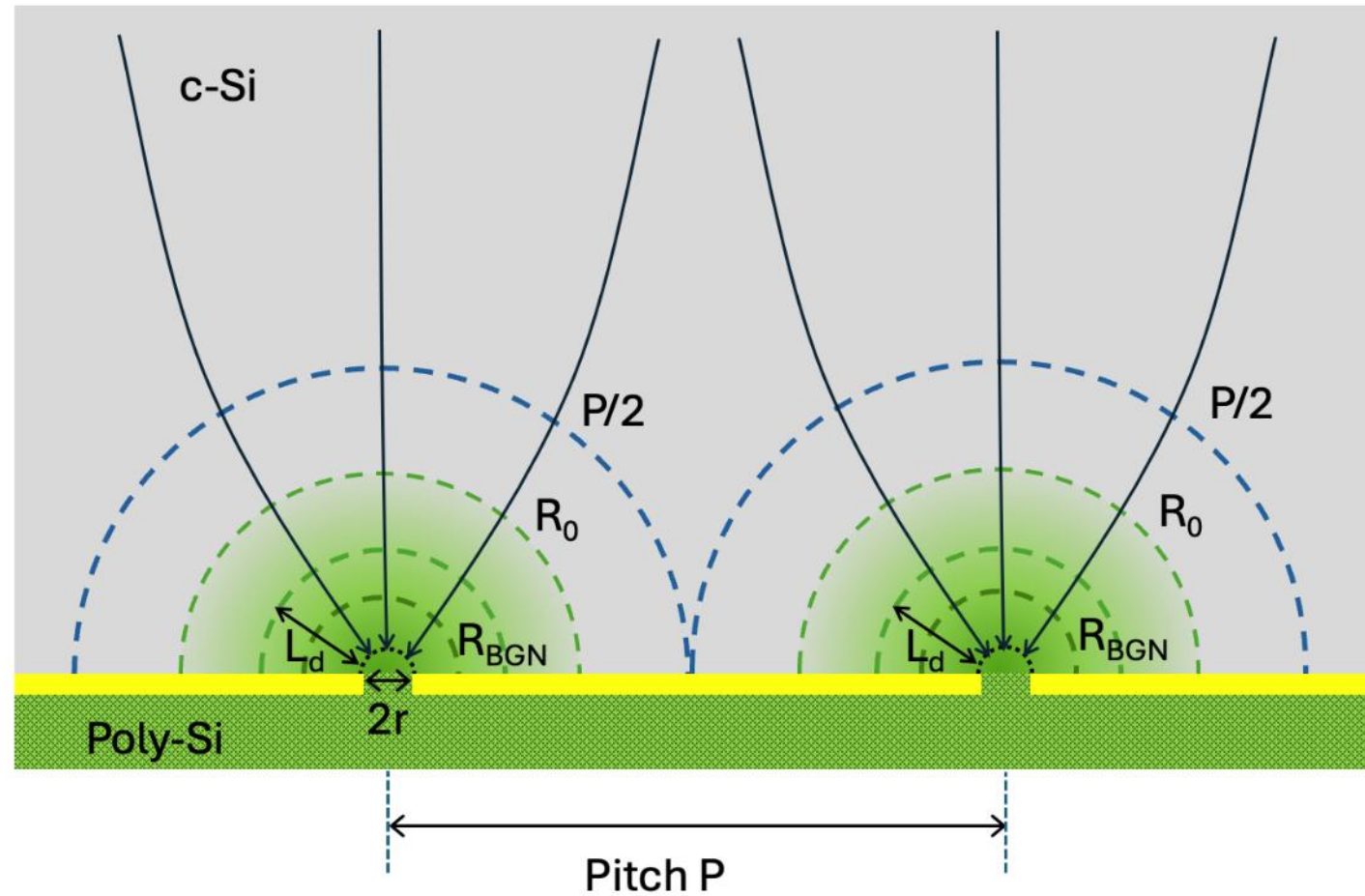
10 nm pinholes enable $R_c = 10 \text{ mOhm-cm}^2$ contact with $\sim 1 \text{ fA/cm}^2$ passivation loss; 10 μm pinholes loose $> 50 \text{ fA/cm}^2$



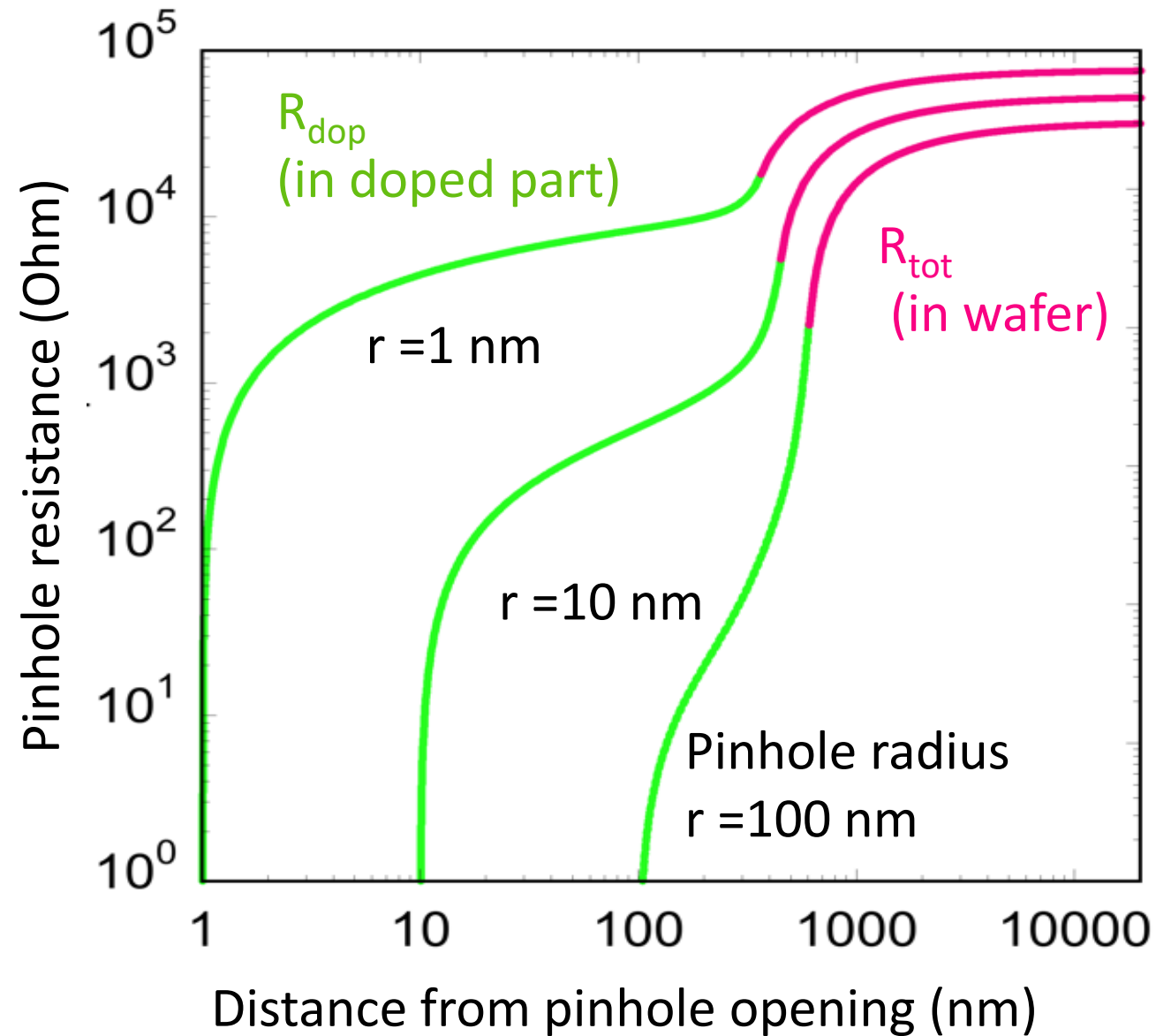
[1] Denhoff, "An accurate calculation of spreading resistance," Journal of Physics D: Applied Physics. 2006.

[2] Stradins et al, SolMat, 2026 (accepted)

Nanosized Doped pinholes offer additional advantages

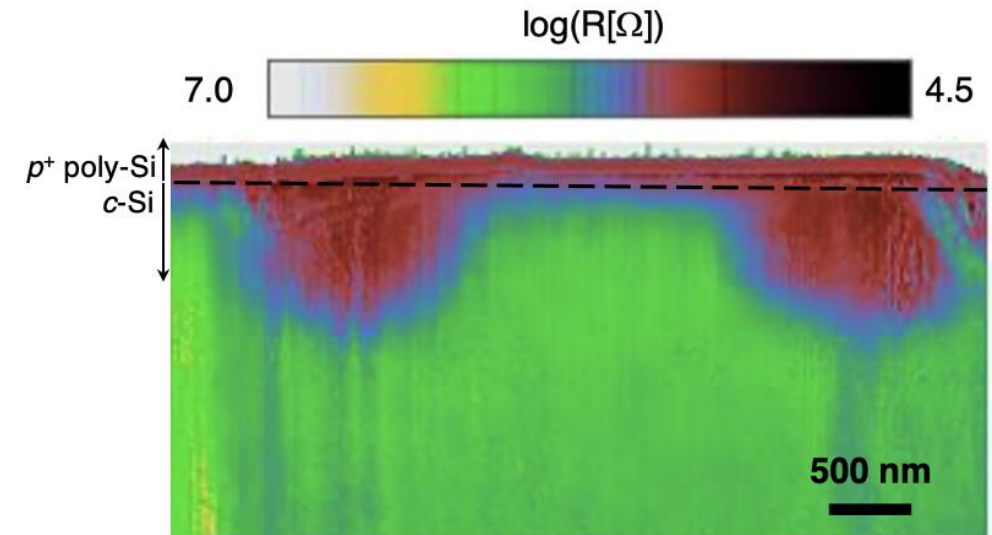


Advantage of Nanosized Doped pinholes: Large spreading radius $\rightarrow$ Low R_{cont}

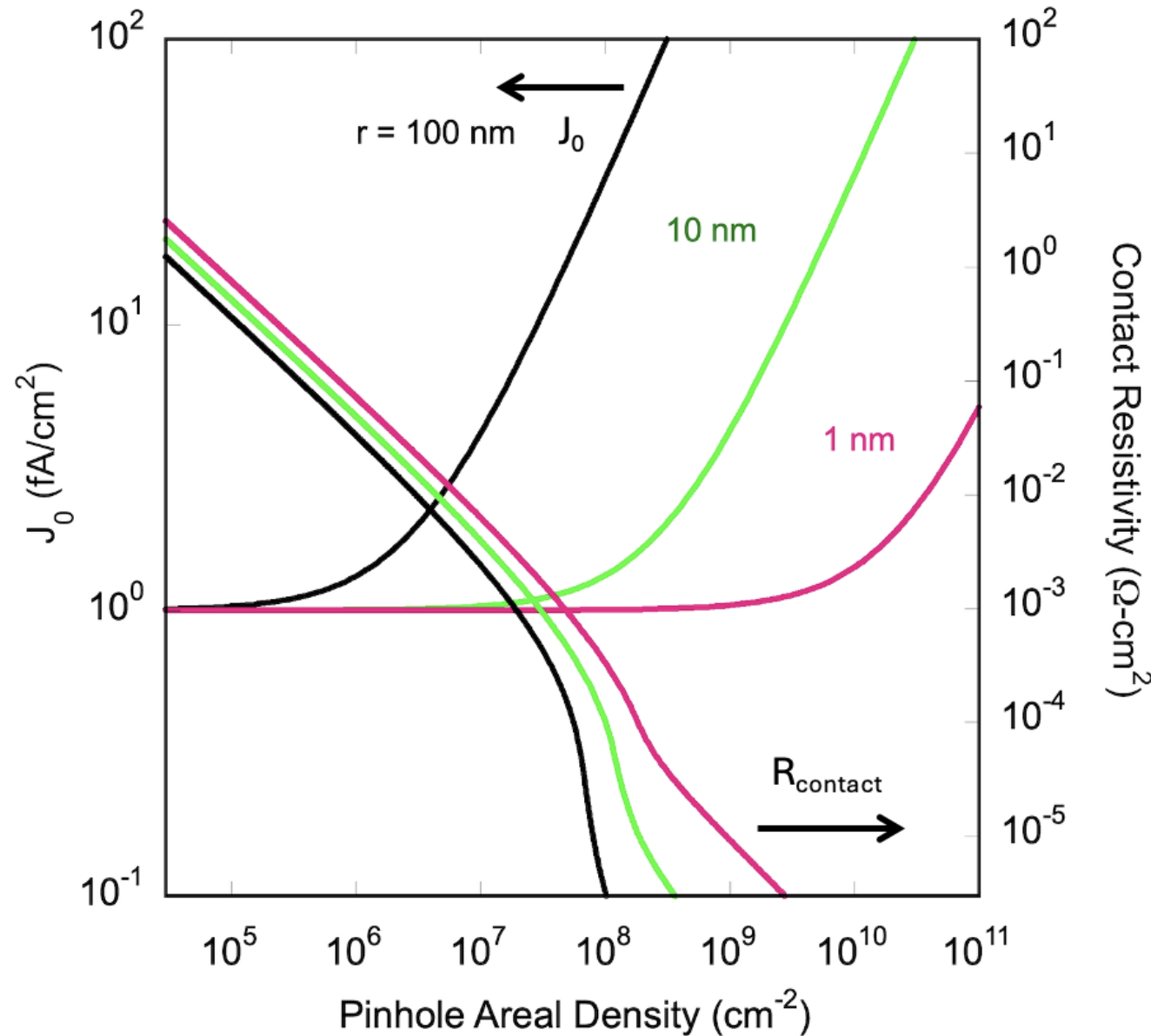


Over large range of pinhole openings, 1 nm – 100 nm, their metallurgical radii after doping are similar, in 350 – 600 nm range.

This results in their resistances in a narrow range of 30 – 70 kOhm.



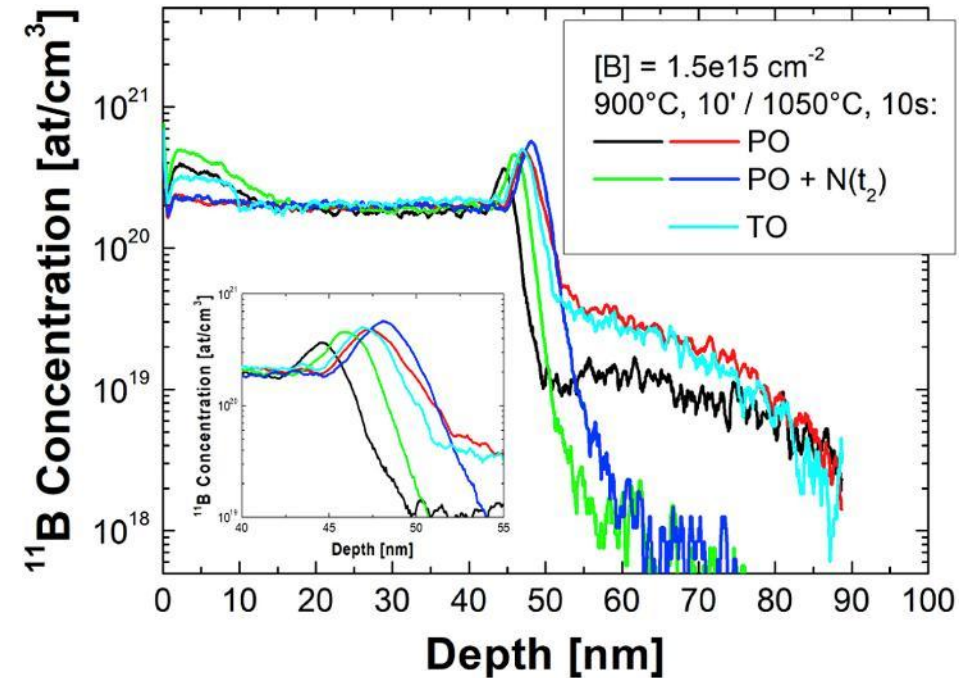
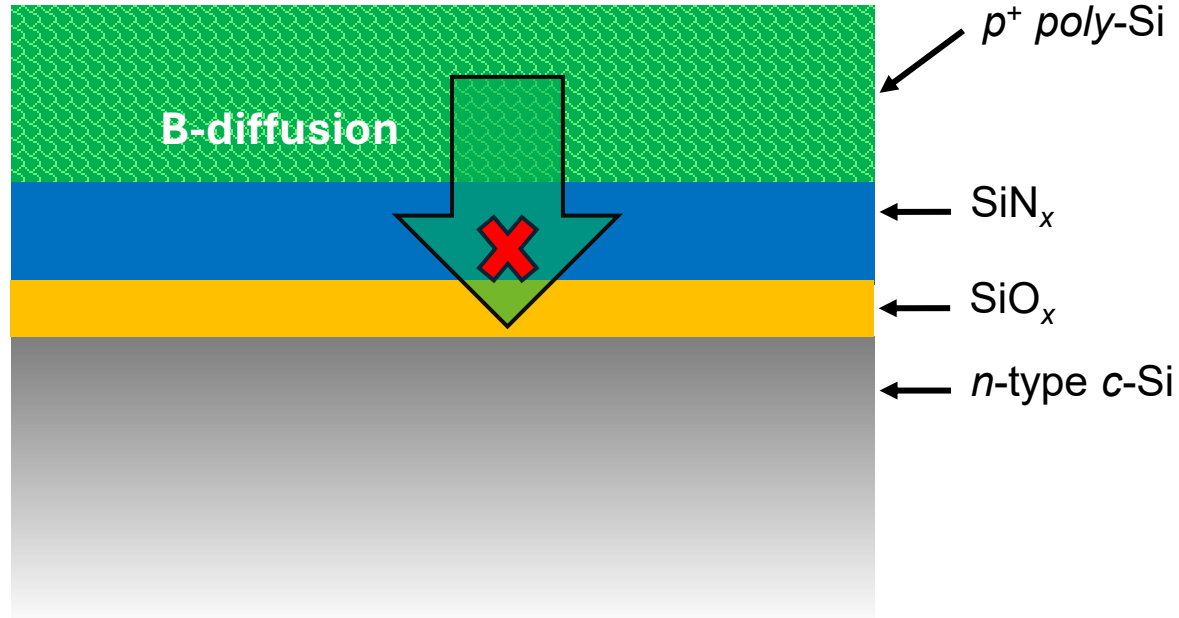
Nanosized Doped pinholes expected to enable high performance on par with TOPCon



Doped pinholes at areal density $\sim 10^8 \text{ cm}^{-2}$ and for pinhole radii below $\sim 30 \text{ nm}$:

- Low $R_{\text{cont}} < 1 \text{ m}\Omega\text{-cm}^2$
- Very low $J_0 < 1 \text{ fA/cm}^2$

Nanopinholes enable high passivation via B diffusion blocking

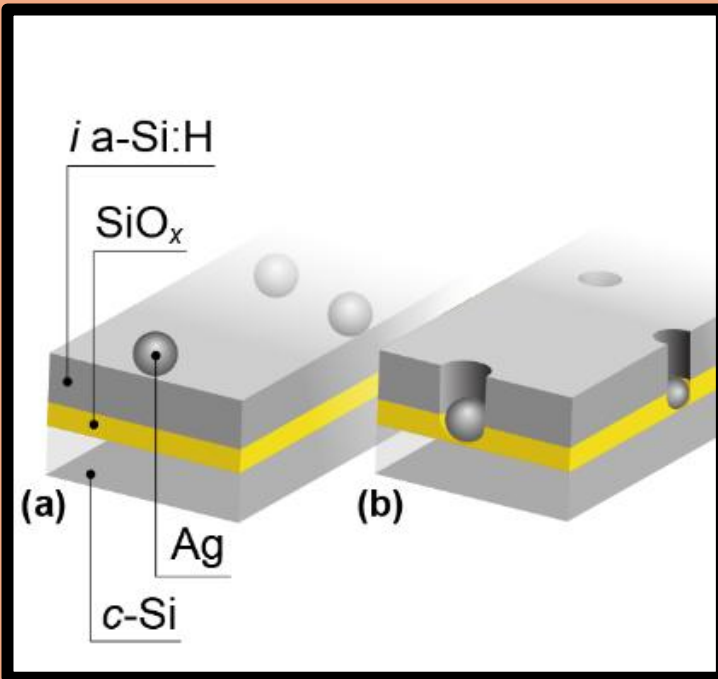


Feldmann, F., *et al.* (2019). Studying dopant diffusion from poly-Si passivating contacts. *Sol. Energy Mater. Sol. Cells* 200, 109978

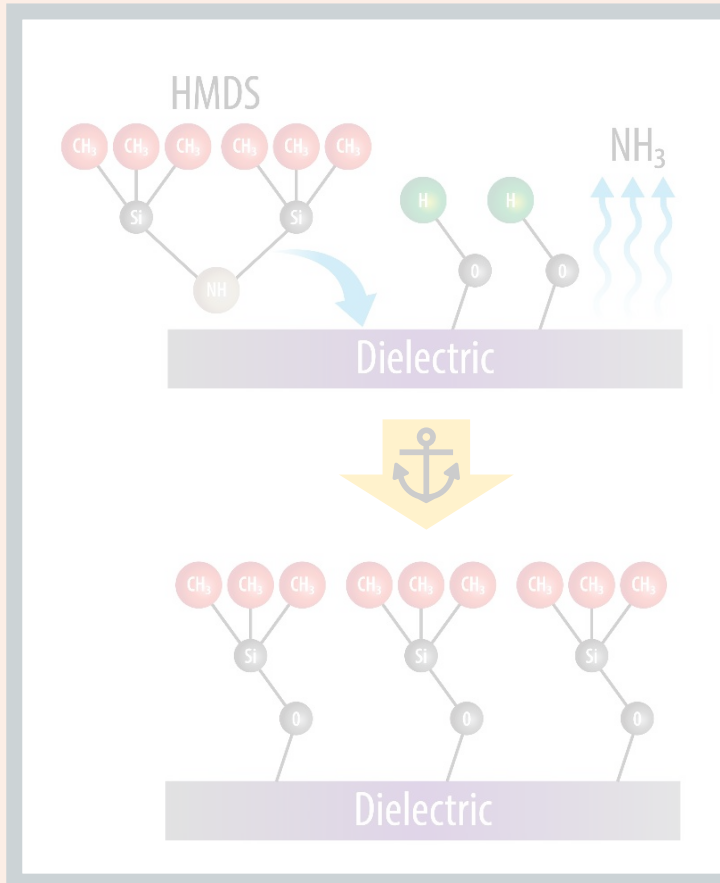
- B tends to accumulate the $\text{SiO}_x/\text{c-Si}$ as shown by DFT simulations and SIMS
- B diffusion through the oxide is mitigated by SiN_x layer
- To use nonconductive dielectric layers for passivation, conductivity must be enabled by pinholes

Three New Methods to Create Nanosize Pinholes

Metal-Assisted Chemical Etching



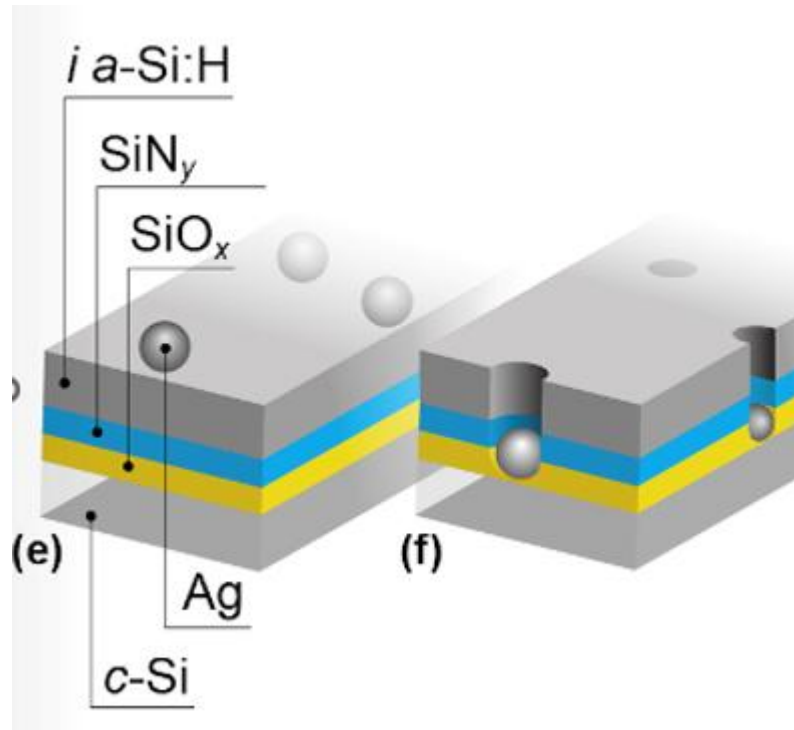
Self-Assembled Monolayers



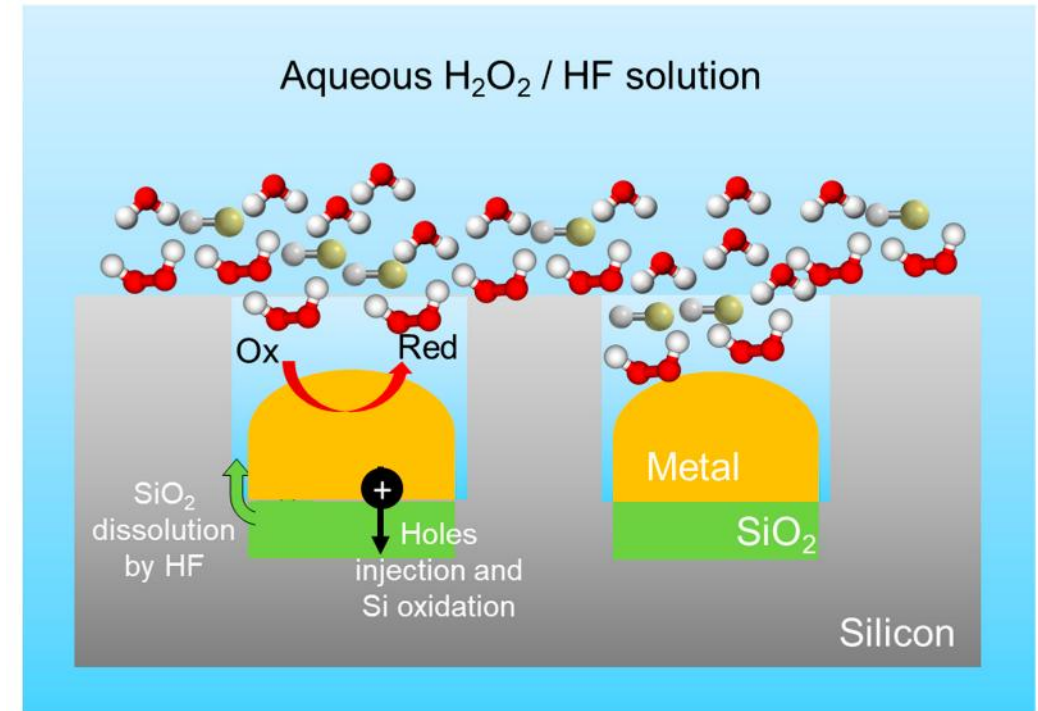
Laser-enabled pinholes



Metal Assisted Catalytic Etch (MACE): Ag nanoparticles “drill holes”



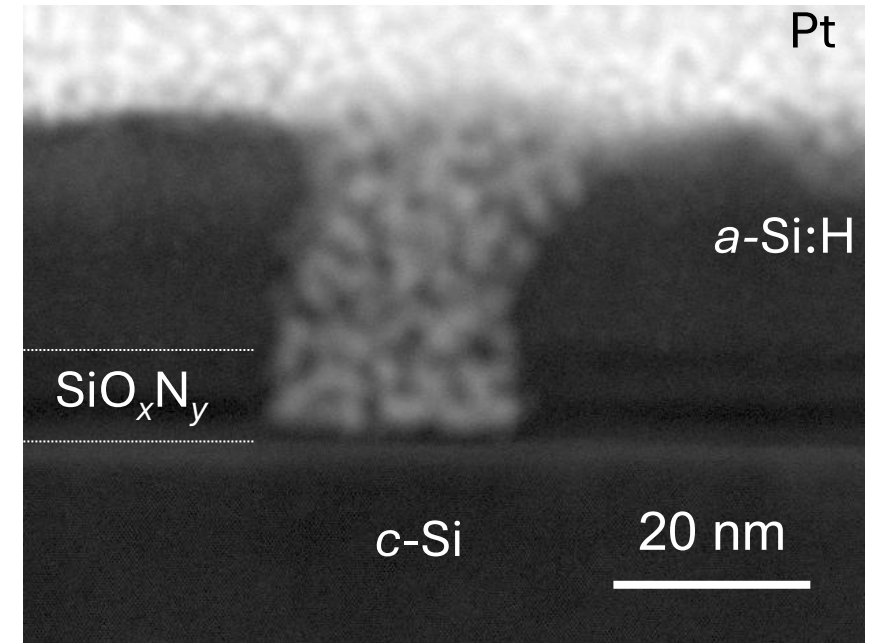
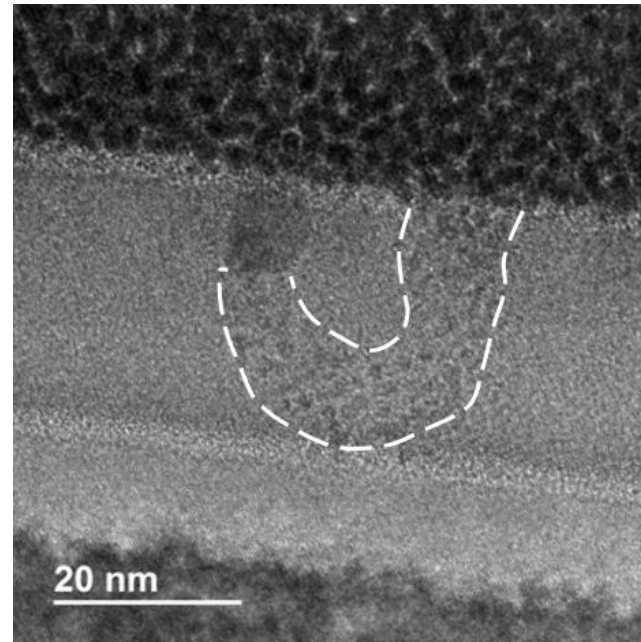
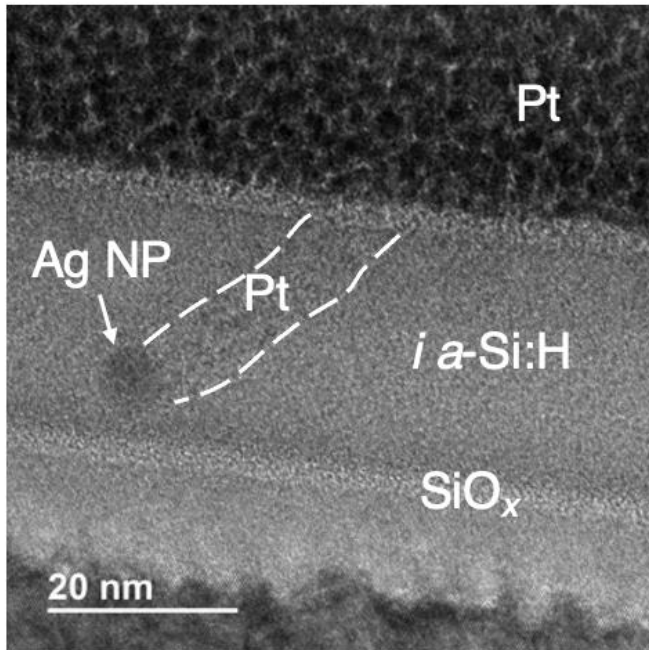
(a) **Deposit Ag nanoparticles** by immersing in AgNO₃ solution (7 ppm):
a-Si in AgNO₃(aq)
 $\text{Ag}^+ + \text{e}^- \rightarrow \text{Ag}^0$



(b) **Metal assisted etching (MACE)** via local galvanic corrosion result in Ag particles “sinking” onto substrate:

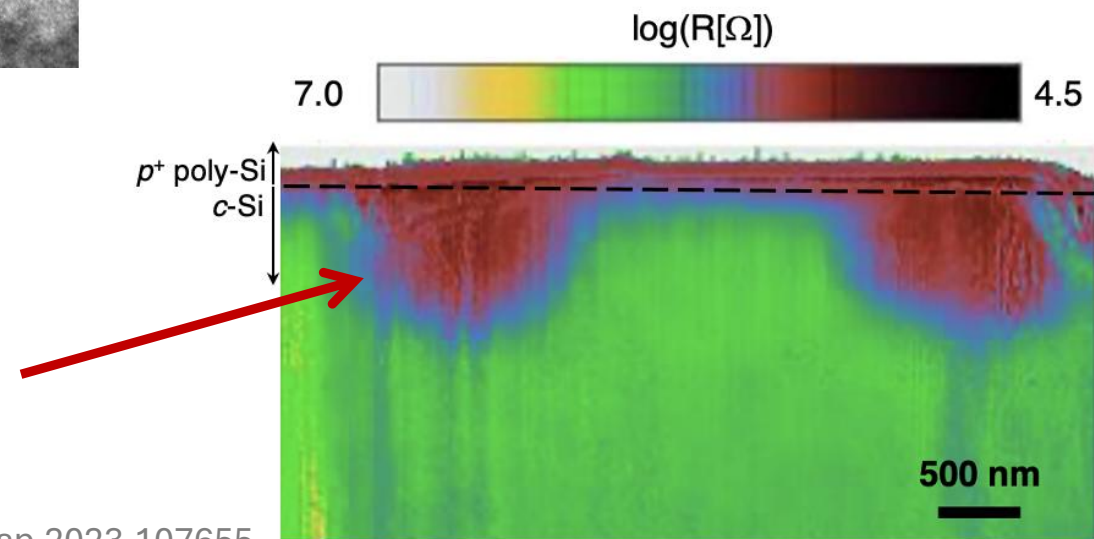
Ag-loaded a-Si in HF:H₂O₂ (aq)
 Cathode reaction: $\text{H}_2\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow 2\text{H}_2\text{O}$
 Anode reaction: $\text{Si} + 2\text{H}^+ \rightarrow \text{Si}^{4+} + \text{H}_2 + 2\text{e}^-$
 Chemical dissolution: $\text{Si}^{4+} + 6\text{HF} \rightarrow 6\text{H}^+ + \text{SiF}_6^{2-}$

Ag Nanoparticles etch through a-Si:H or poly-Si mask layer

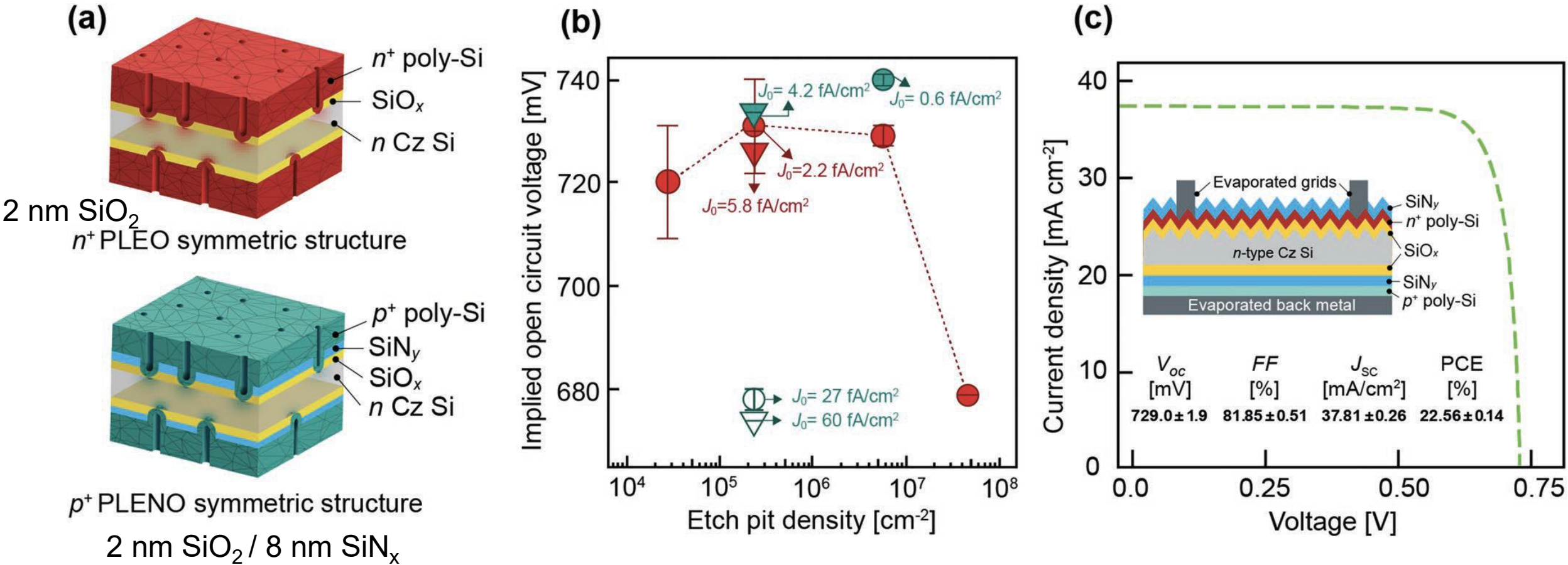


Mesopores created by Ag nanoparticles are not always straight, but the c-Si acts as an etch stop

Dopant indiffusion through 50 nm mesopores result in micron- sized, hemispheric, p⁺ doped “doped transport pinholes” (SSRM nanoprobe measurement at NLR)



Contact and cell results with MACE engineered



Surface morphology	Contact structure ^{a)}	Metal/poly-Si/c-Si junction resistivity [$\text{m}\Omega \text{ cm}^2$]	J_0 [fA cm^{-2}]	iV_{oc} [mV]	MACE solution strength [%]
Planarized	p-PLENO	26 ± 4	0.6	739	50
Textured	p-PLENO	45 ± 14	4.2	733	33

^{a)} Junction resistivity measured on p-type Cz Si; J_0 and iV_{oc} measured on n-type Cz Si.

Industrial relevance – MACE/PLENO

Pros:

- High-performance p-type passivated contacts
- Spatial selectivity (Ag NPs don't plate on oxidized surface)
- Contact on textured surfaces
- Use of dielectric stacks, tolerance to thickness variations
- Might be tolerant to overfiring

SolarTech in-line MACE tool



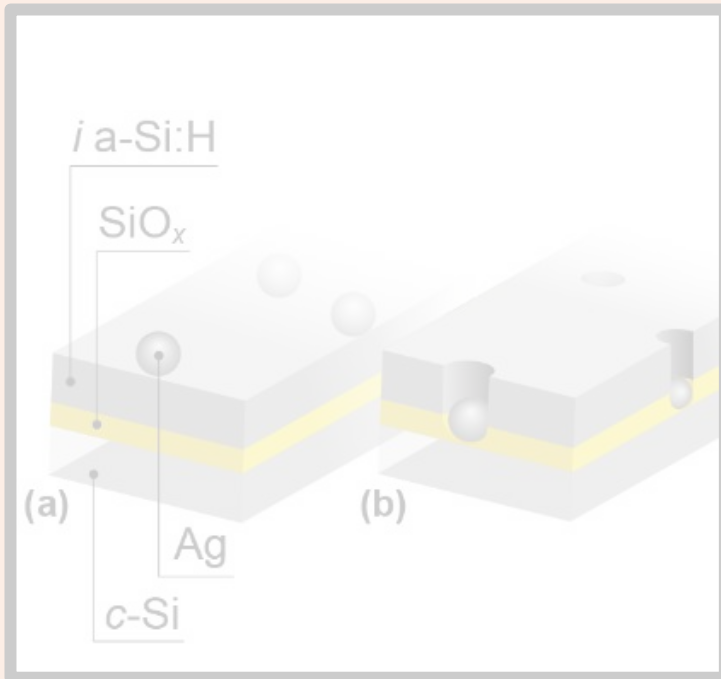
Cons:

- Extra process steps (3 wet chem, 1 extra poly LPCVD)
- Presence of tiny Ag amounts (7 ppm) in wet chemistry
- 1-sided oxide masking, edge isolation needs development

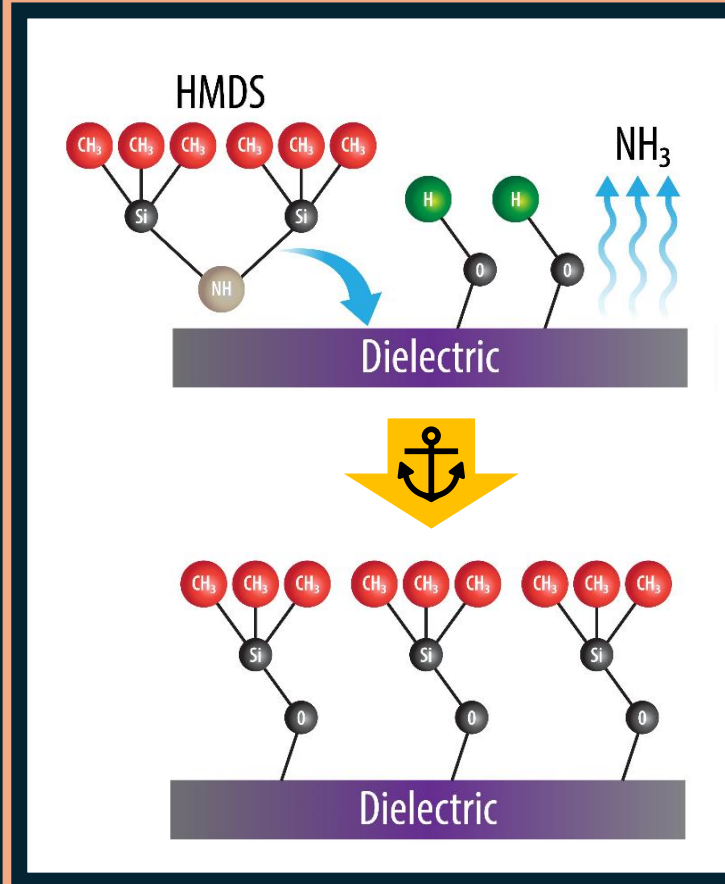
In-line tools compatible with room temperature pinhole creation by MACE existed PV industry for texturing of wafers [1]

Three New Methods to Create Pinholes

Metal-Assisted Chemical Etching



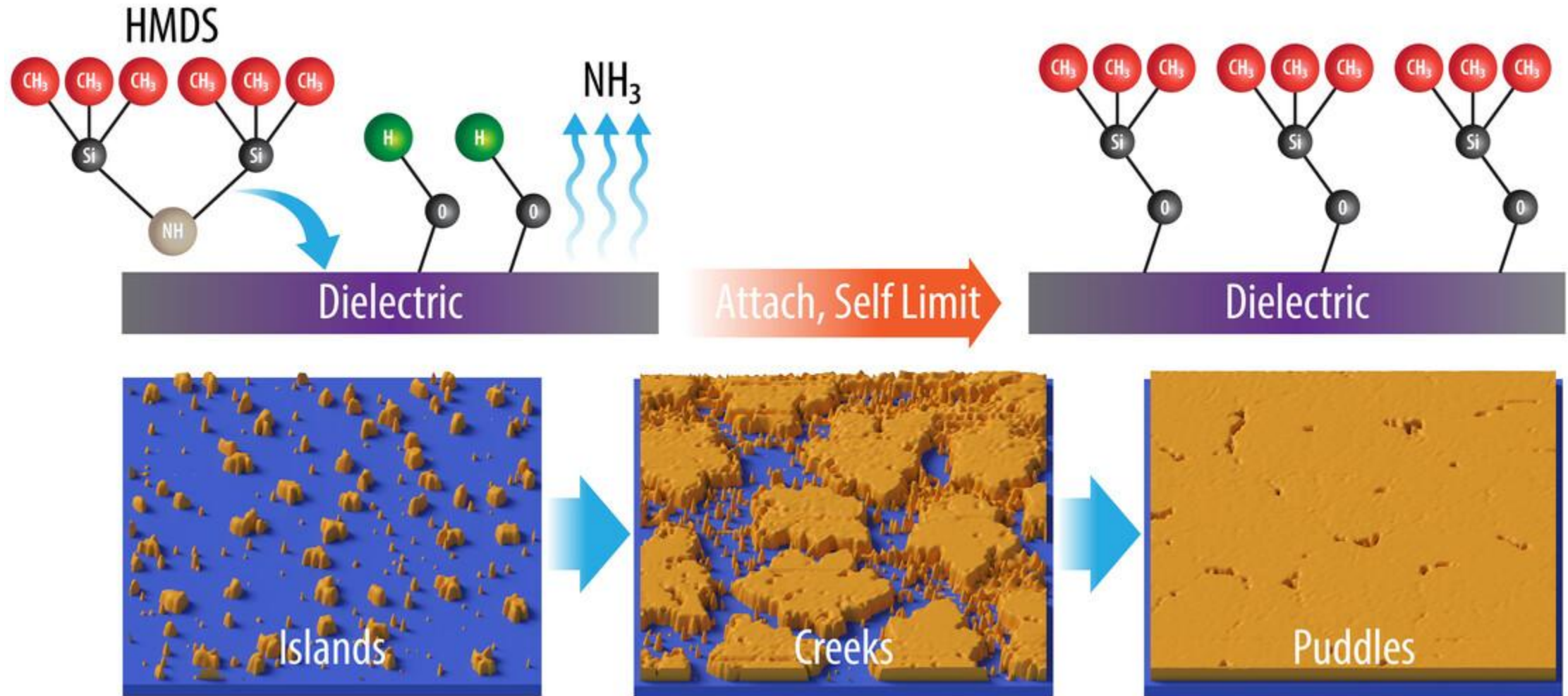
Self-Assembled Monolayers



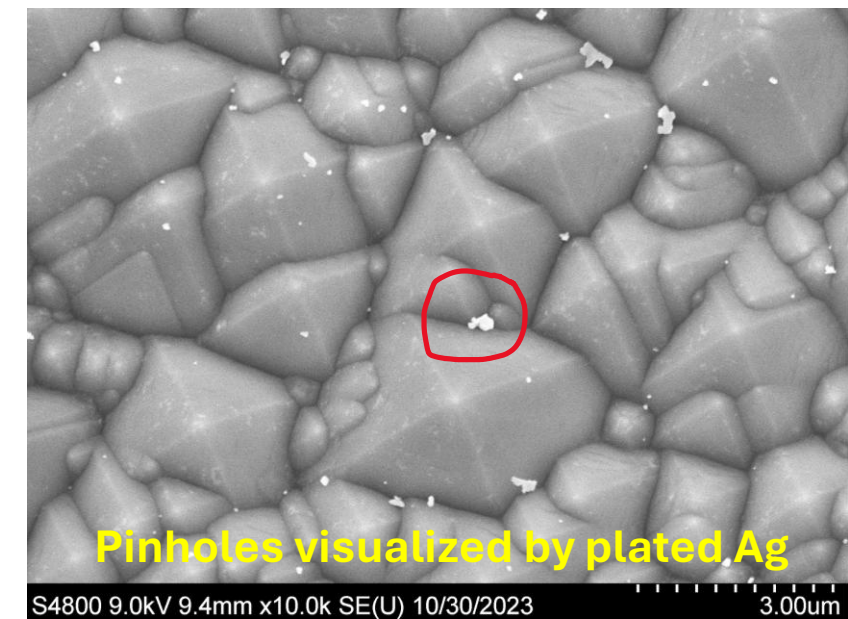
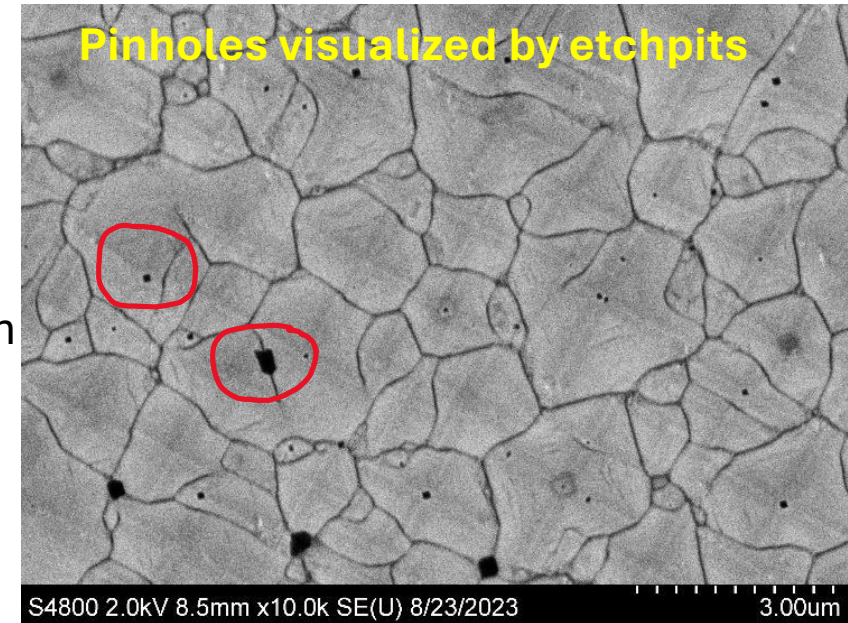
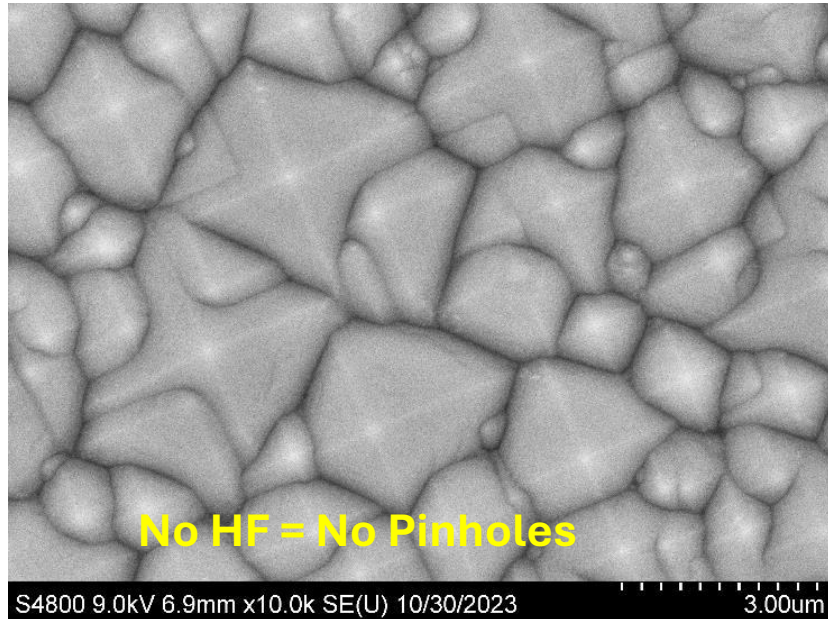
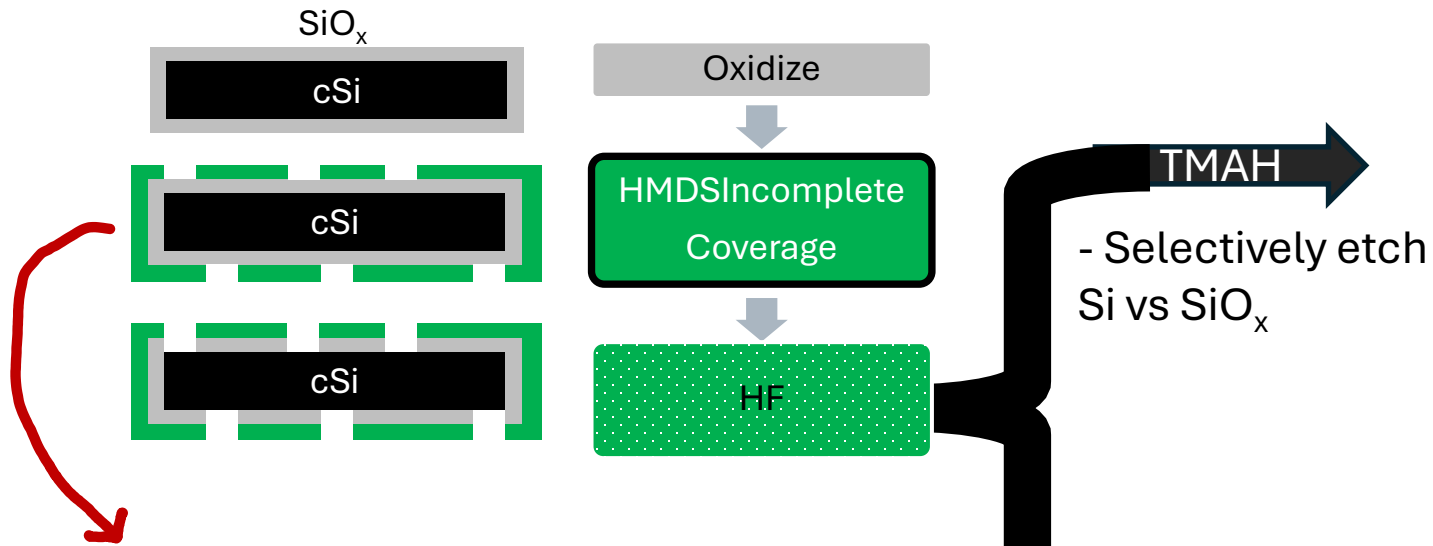
Laser-enabled pinholes



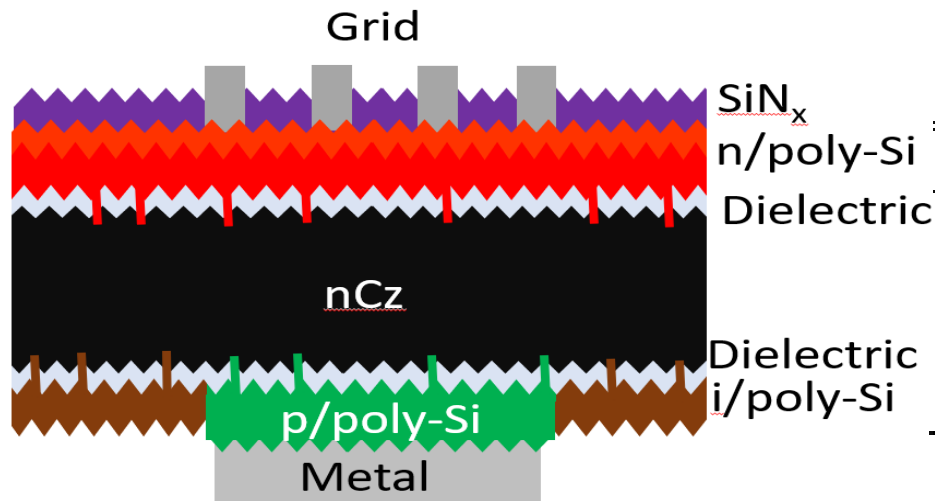
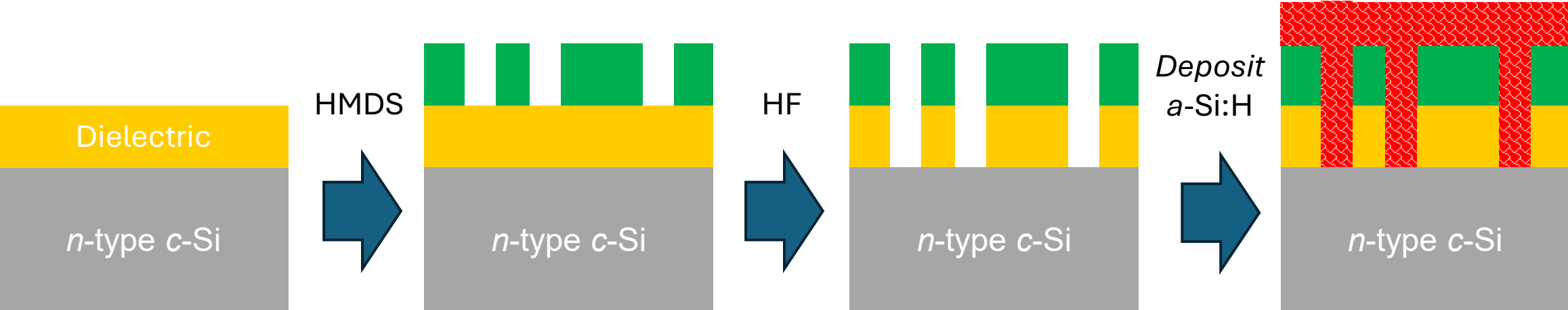
Engineered Pinholes in Dielectric Interlayer Using Self Assembled Monolayer



Proof of SAM-induced Nanopinholes



Proof of Concept Devices with SAM-induced Nanopinholes



Morphology: Dielectric Interlayer (T_{anneal})	V_{oc} (V)	J_{sc} (mA/cm ²)	FF (%)	η (%)
DSTXT: 10 nm SiN _x (850°C)	0.692	36.4	74	18.7
DSTXT: 2 nm SiO ₂ (850°C)	0.691	38.0	77.9	20.5
DSTXT: 2 nm SiO ₂ (925°C)	0.686	37.7	79.8	20.6
SSTXT: 2 nm SiO ₂ + SiN _x (925°C)	0.723	38.0	80.3	22.1

Industrial relevance - SAMs

Pros:

- Pinholes created directly in dielectric, no poly-Si mask
- SAMs can be made spatially selective
- Industrial inline tools exist
- Use of dielectric stacks, tolerance to thickness variations
- Might be more tolerant to overfiring

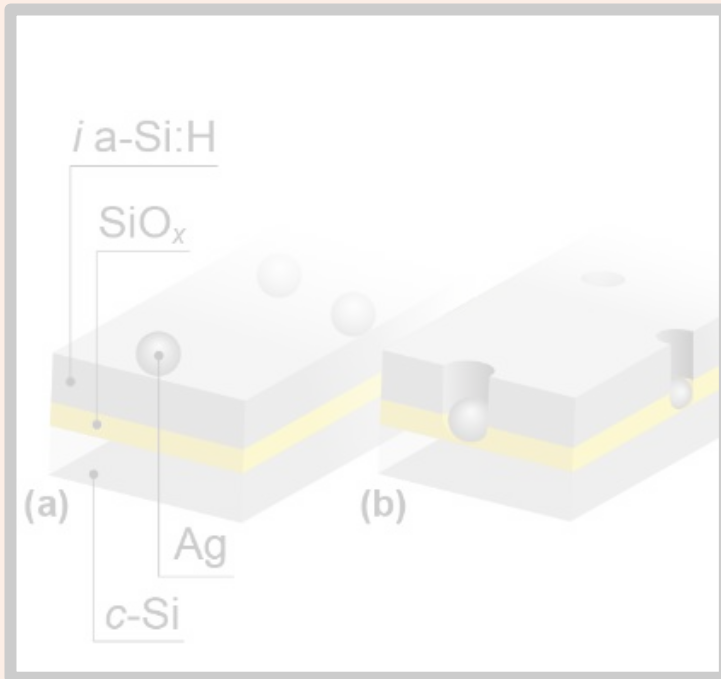


Cons:

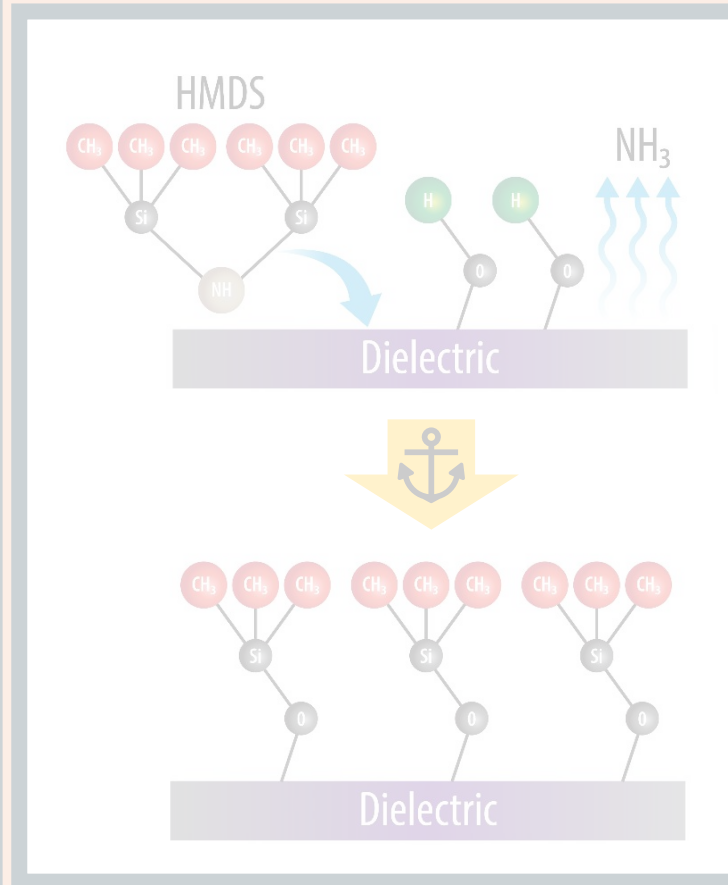
- Extra process steps (2-3 wet chem)
- Pinhole density control with narrow process window

Three New Methods to Create Pinholes

Metal-Assisted Chemical Etching



Self-Assembled Monolayers

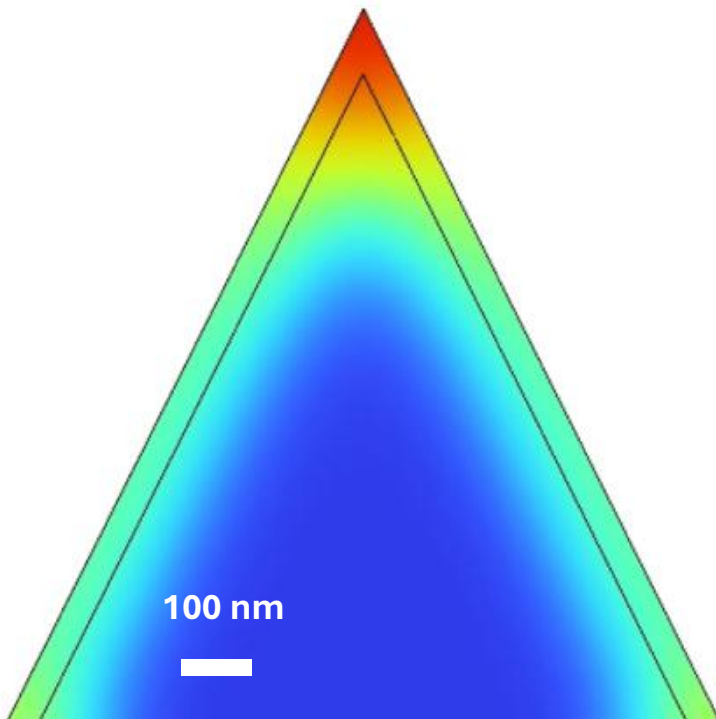


Laser-enabled pinholes



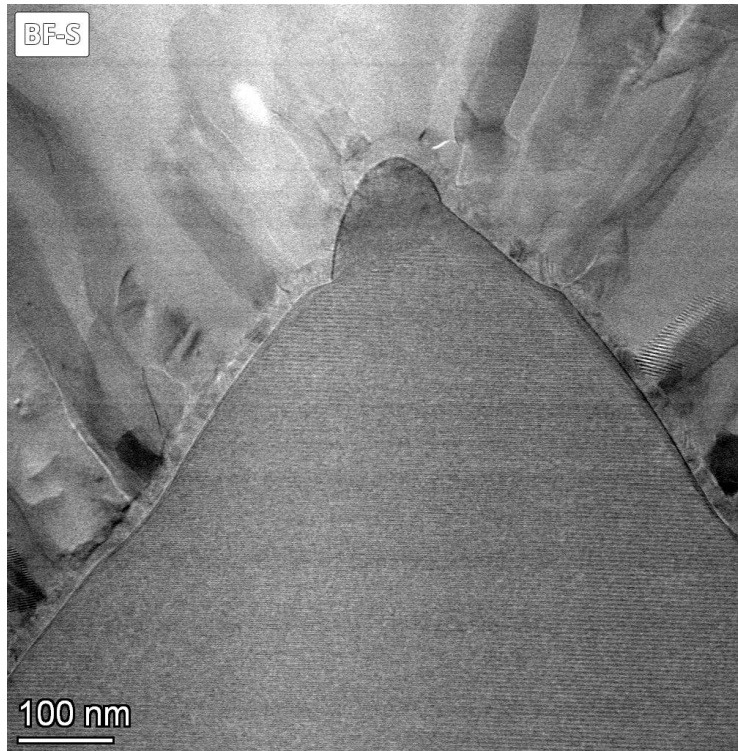
Conductive, passivating contacts enabled by laser pulses

Pyramid geometry concentrates
laser pulse-released heat into
pyramid tip

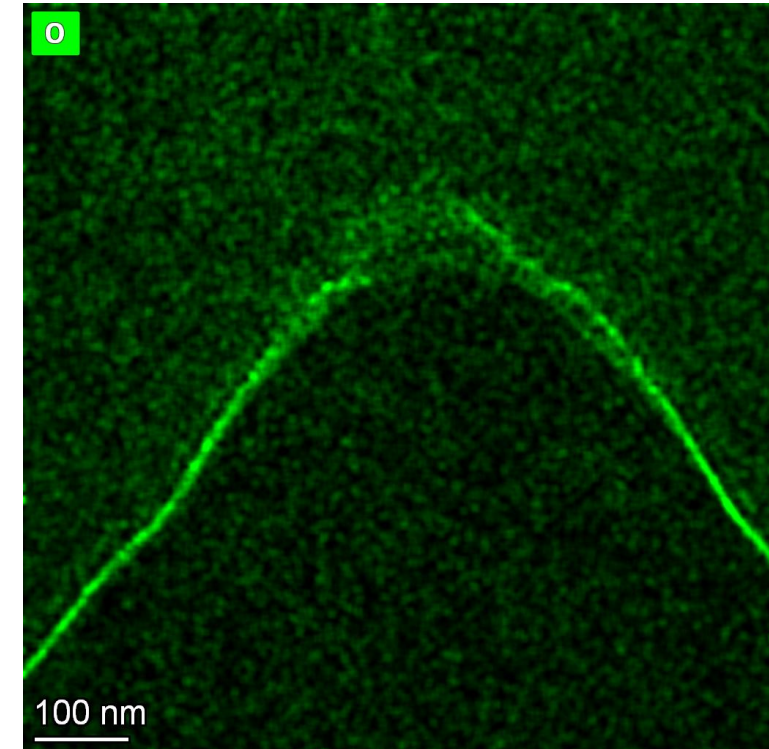


< 100 nm absorption depth at high T

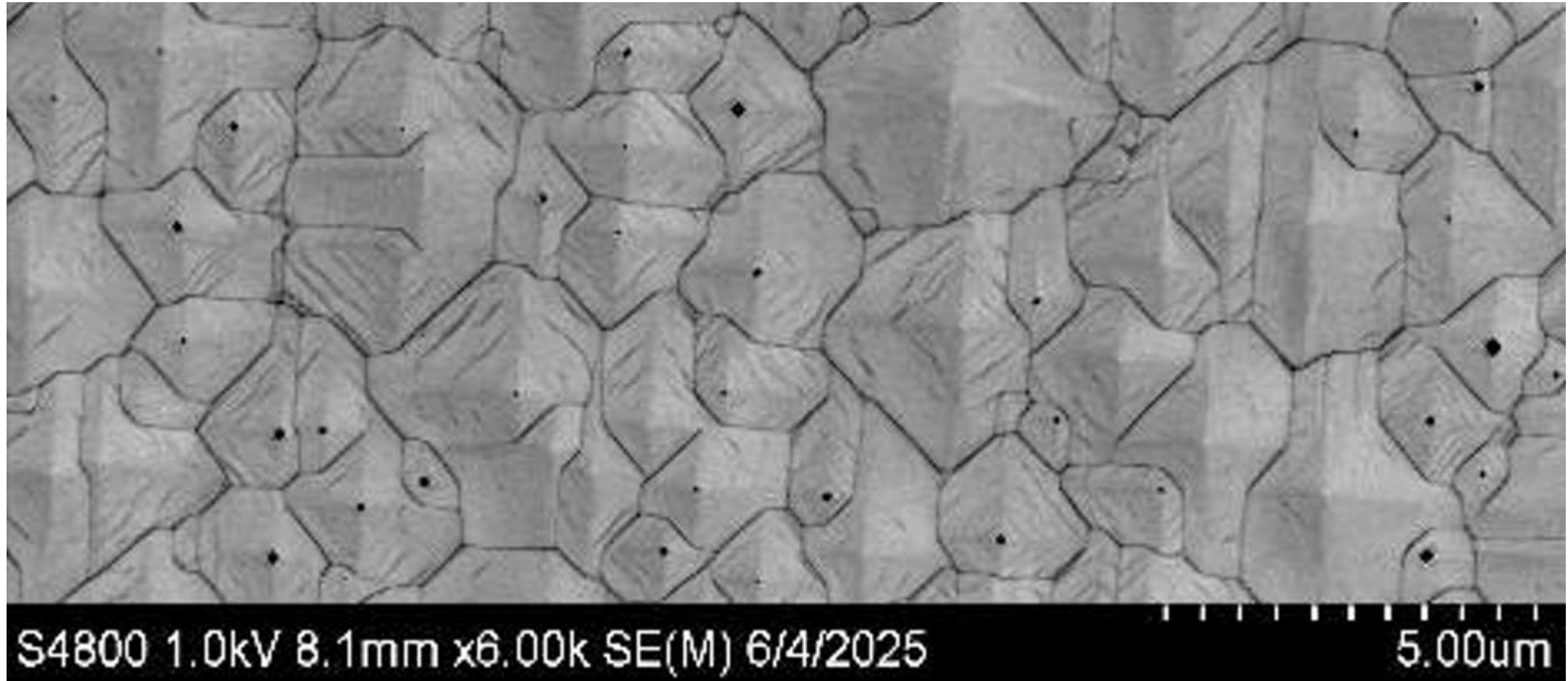
TEM: deformed pyramid tip



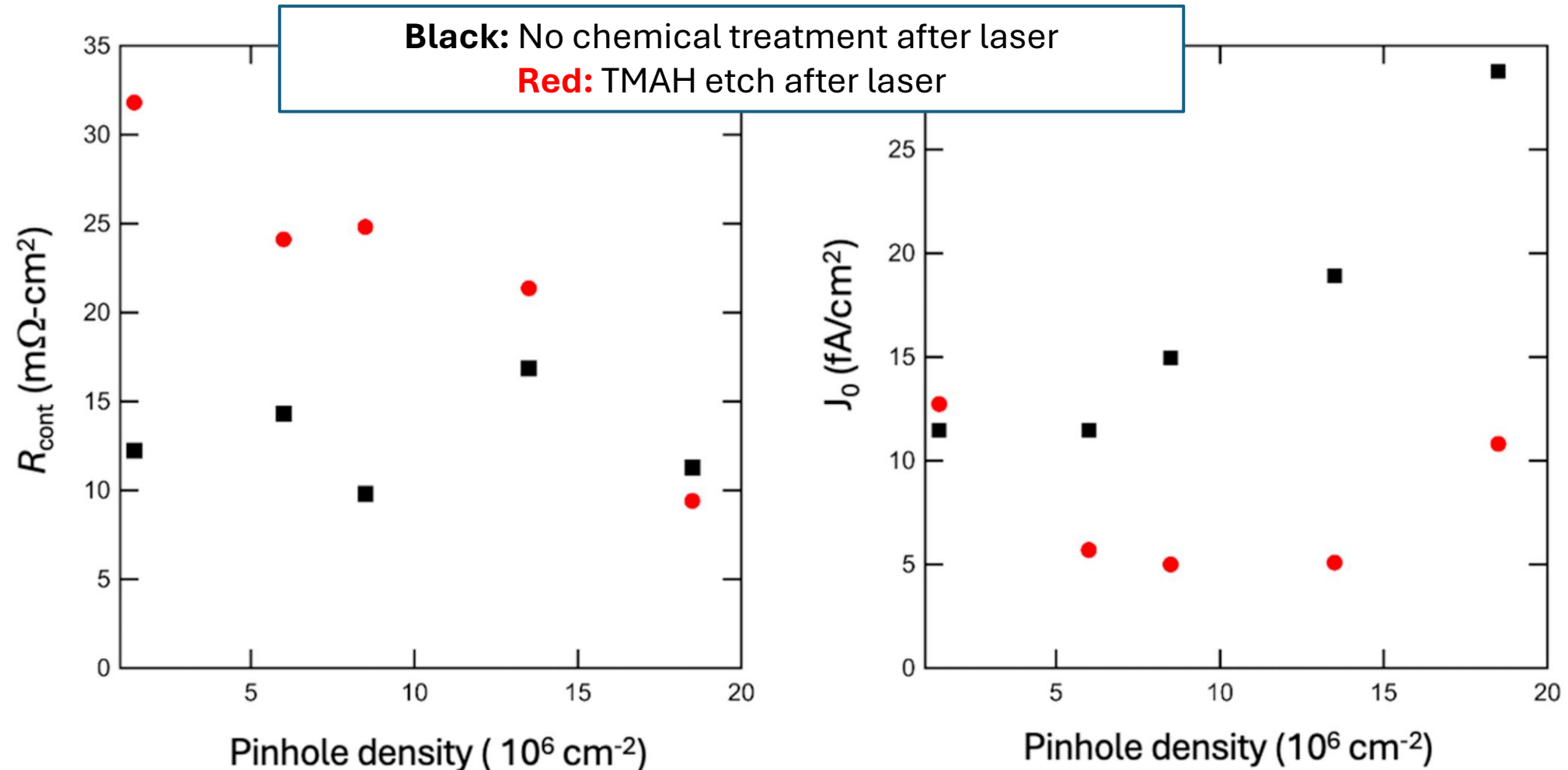
Pinhole in O-map



Laser pinholes visualized by TMAH selective Si etch



Conductive, passivating nanopinhole contacts made by laser pulses



- Low J_0 and contact resistivity seen from symmetric *n*-type samples
- SEM shows smallest pyramids get damaged by laser

Industrial relevance - Laser



DR Laser tool for TOPCon and BC

Pros:

- Pulse laser systems are widely used in TOPCon and BC cell production
- Inexpensive, high throughput
- Spatial selectivity: pinholes in poly-fingers, under grid, on IBC contact pads

Cons:

- Pinholes accompanied by some laser damage
- Couple extra process step (laser + wet chem)

Conclusions

- Different scaling laws for nanopinhole transport and recombination enable exceptional contact performance
- Nanopinholes can be engineered on textured and planar wafers with dielectric stacks not limited to quantum tunneling, to block B accumulation, and likely more resistive to firing.
- Successfully demonstrated passivated contacts with nanopinholes engineered by MACE, SAMs, and Laser pulses with relevance to PV industry.



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Breckenridge, Colorado

2027

This work was authored in part by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Critical Minerals and Energy Innovation Integrated Energy Systems Office, under agreement DE-EE00052781. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.