Department of Materials

Electronic and Interface Materials Laboratory

Beyond SiO_x for Hole-Selective Poly-Si Passivating Contacts

- The potential of SiN_x or AlO_x

Shona McNab, Peter Wilshaw, Ruy Sebastian Bonilla

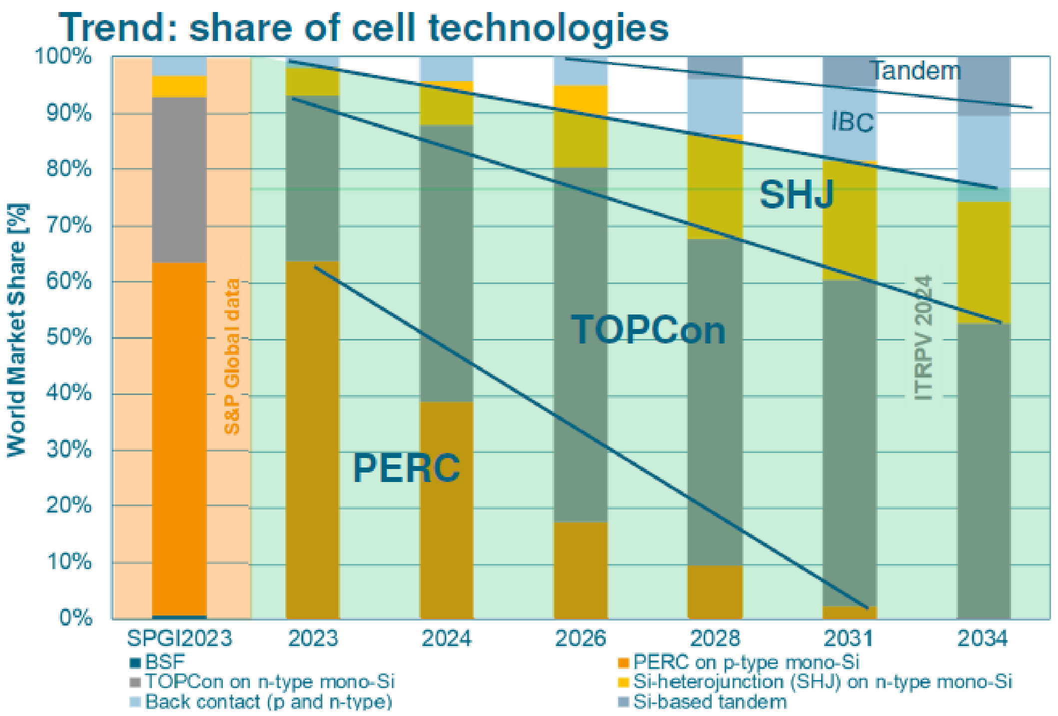
Outline

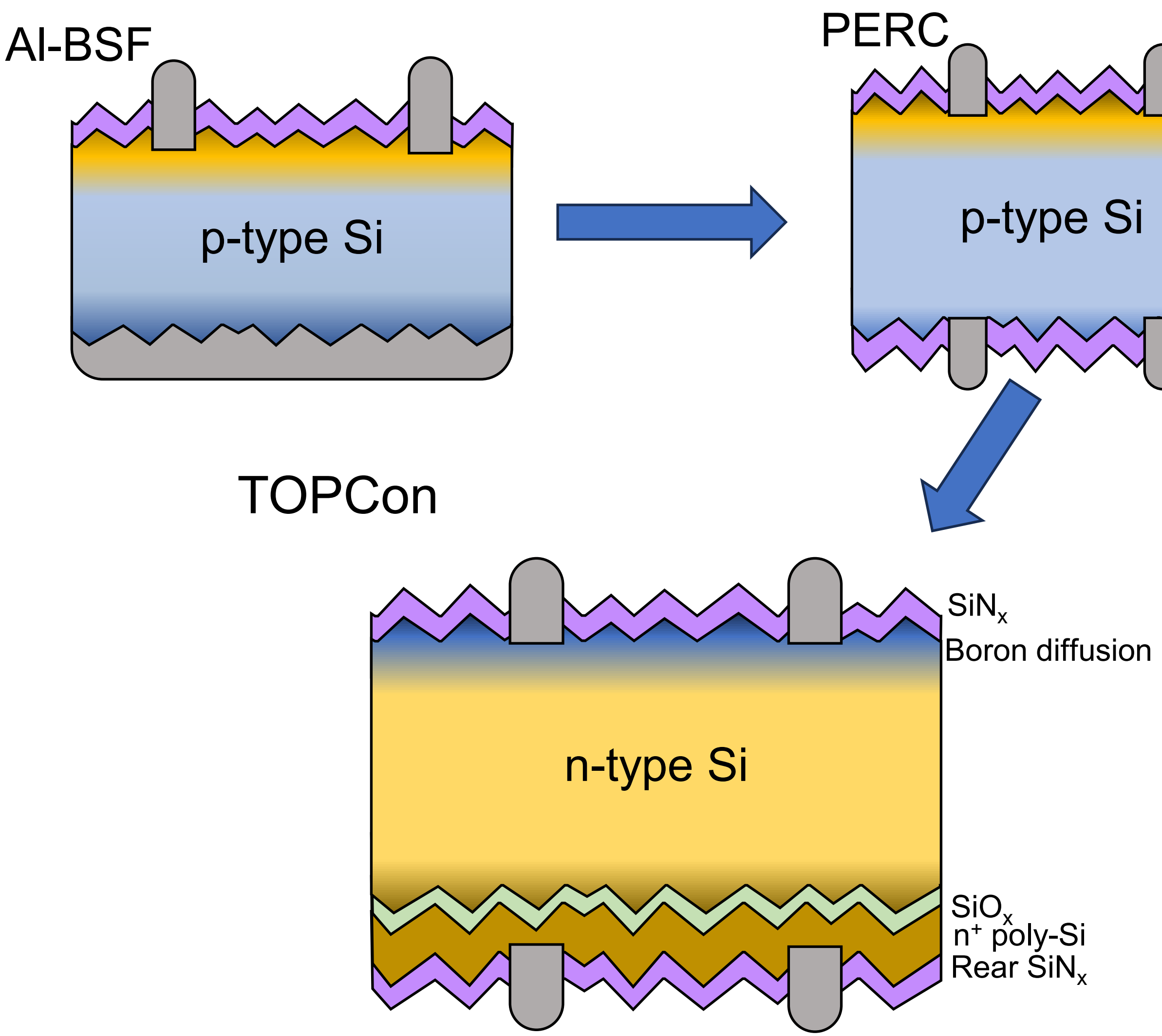
- Poly-Si contacts – or ‘TOPCon’
- Current limitations with SiO_x
- Benefits of SiN_x and AlO_x

- Fabrication
- Transport Properties
- Passivation Properties
- Comparison with other work
- Summary

TOPCon Silicon Cells

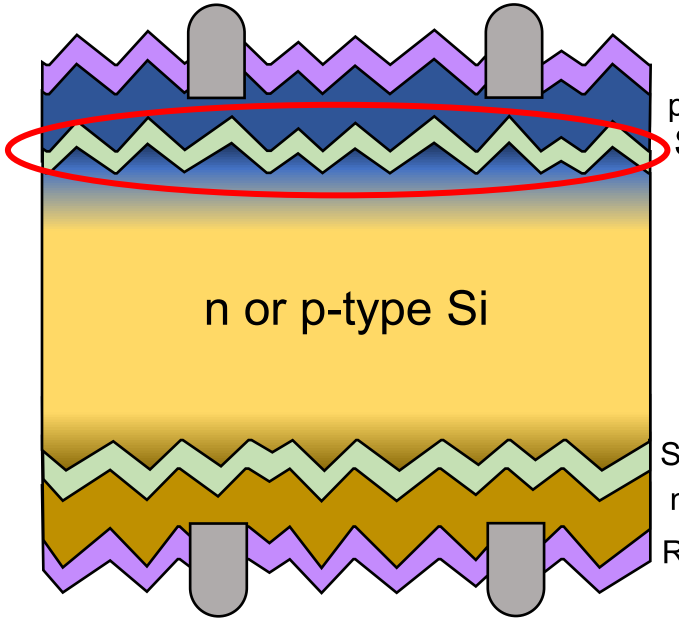
Tunnel **O**xide **P**assivated **Con**tact





[1]*ITRPV 15th edition*, (2024)

What comes next for TOPCon?



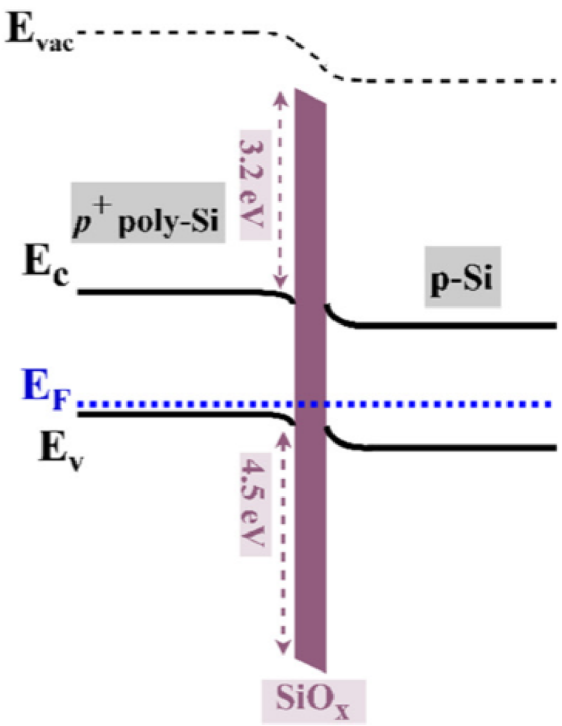
- SiO_x poly-Si hole contacts
  - Both Sides passivated contacts ✅
  - →Potential for higher efficiency
  - So far less effective than electron contacts[1] ❌
  - →Why?

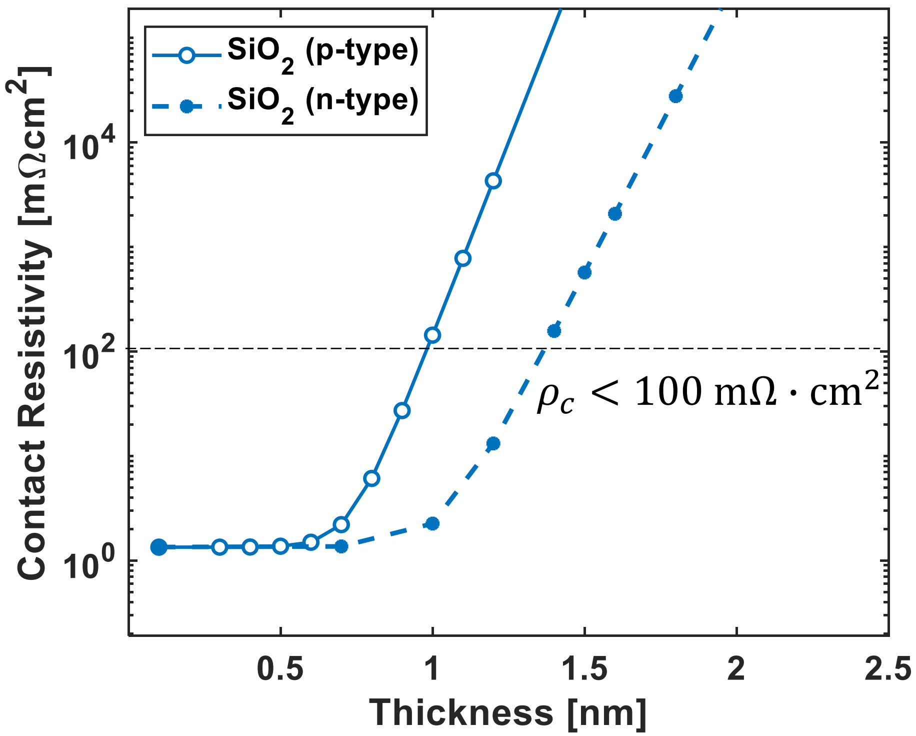
[1]R. Basnet *Appl. Phys. Rev.* (2024), 11, 011311

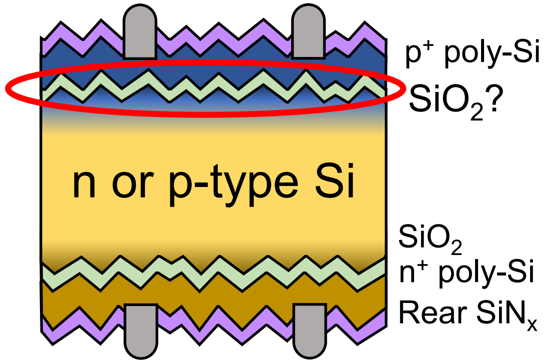
Note: parasitic absorption from poly-Si on the front – not considered today!

Limitations of SiO_x: Part 1
- Hole Transport Properties

- Tunnelling Current < Thickness, Barrier height



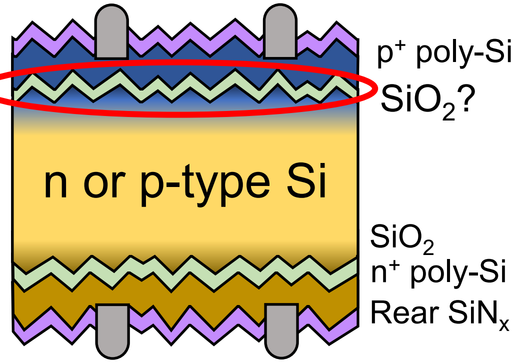




- p-type SiO_x hole contacts rely on **pinhole** conduction

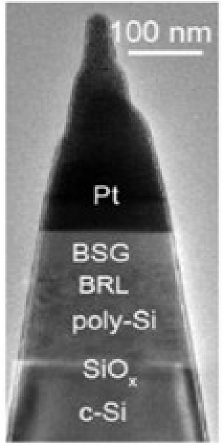
[1]R. Basnet *Appl. Phys. Rev.* (2024), 11, 011311
S. McNab *AIP Conference Proceedings, (2022), 020013*

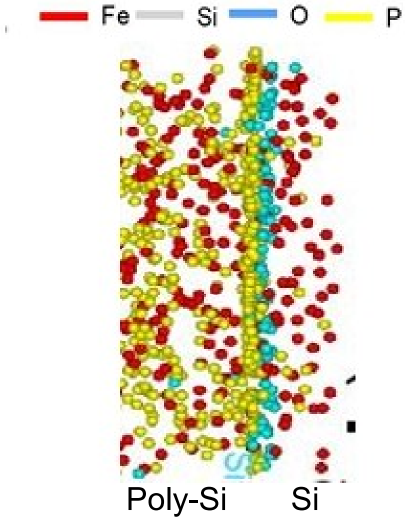
Limitations of SiO_x: Part 2
- P-type Passivation Properties

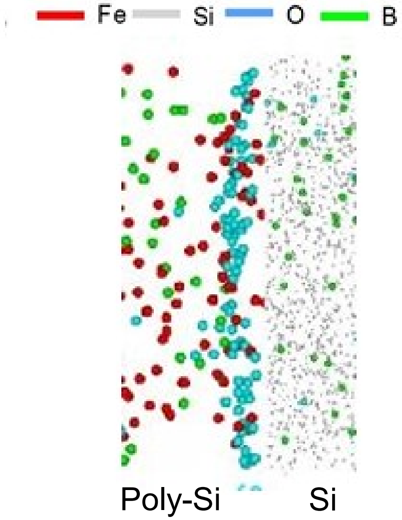


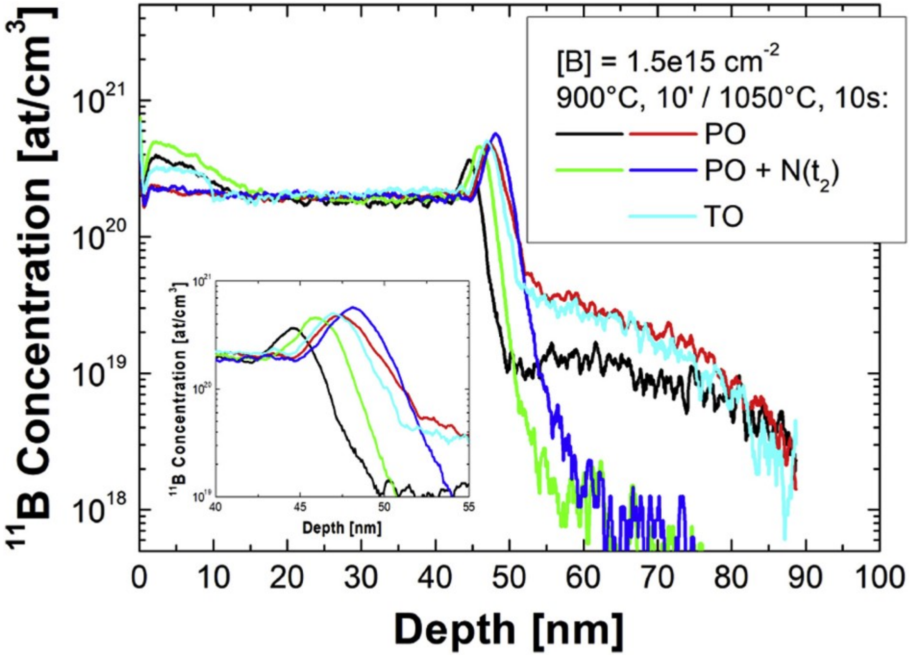
- Boron is more soluble in SiO_x than Phosphorus:
  - Deeper diffusion – more Auger recombination
  - Boron in SiOx introduces defects – higher D_{it}

→ More recombination







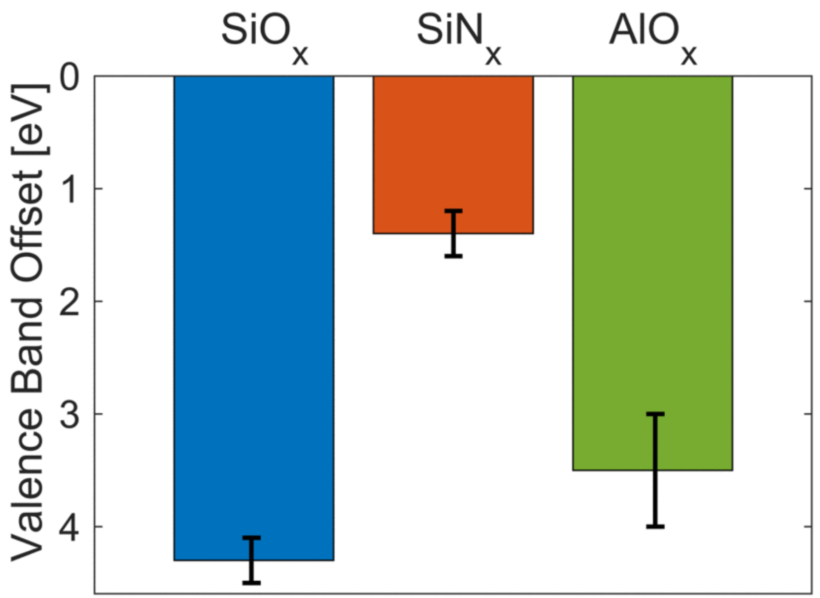


[1]Dan MacDonald, *SPREE Seminar* (2023)- https://www.youtube.com/watch?v=0dYnuhXTGXw
[2]F. Feldmann *Solar Energy Materials and Solar Cells, (2019), 109978, 200*

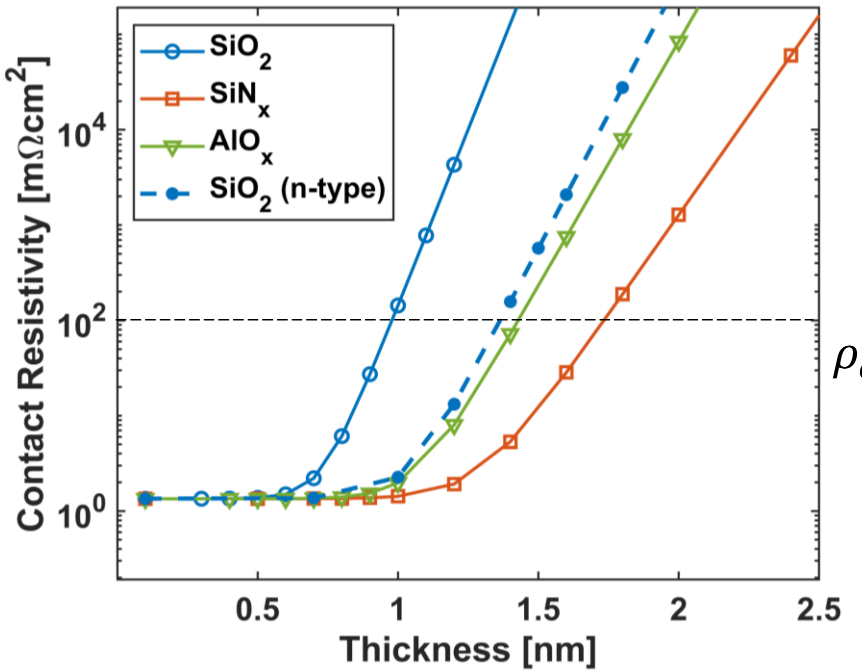
The Benefits of SiN_x and AlO_x: Part 1

- Lower VBO

XPS VBO measurements



Tunnelling current Calculations



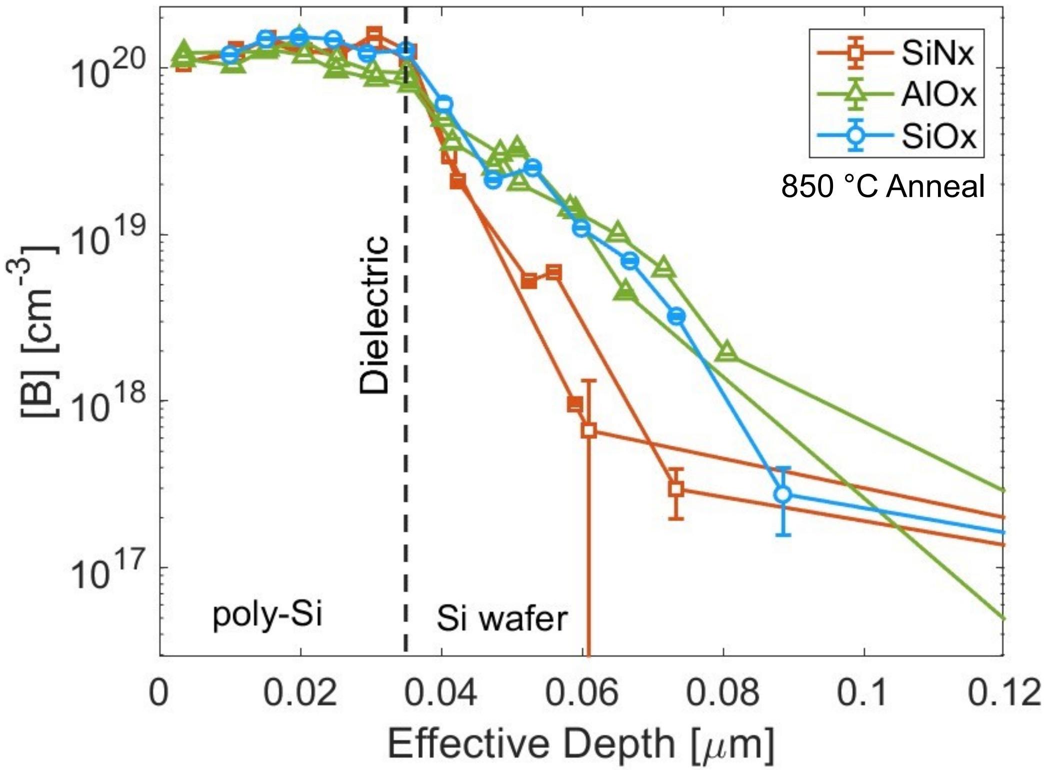
$\rho_c < 100\ \mathrm{m\Omega \cdot cm^2}$

[2]S. McNab *AIP Conference Proceedings, (2022), 020013*

The Benefits of SiN_x and AlO_x: Part 2

- Boron diffusion profile

ECV Doping Profile



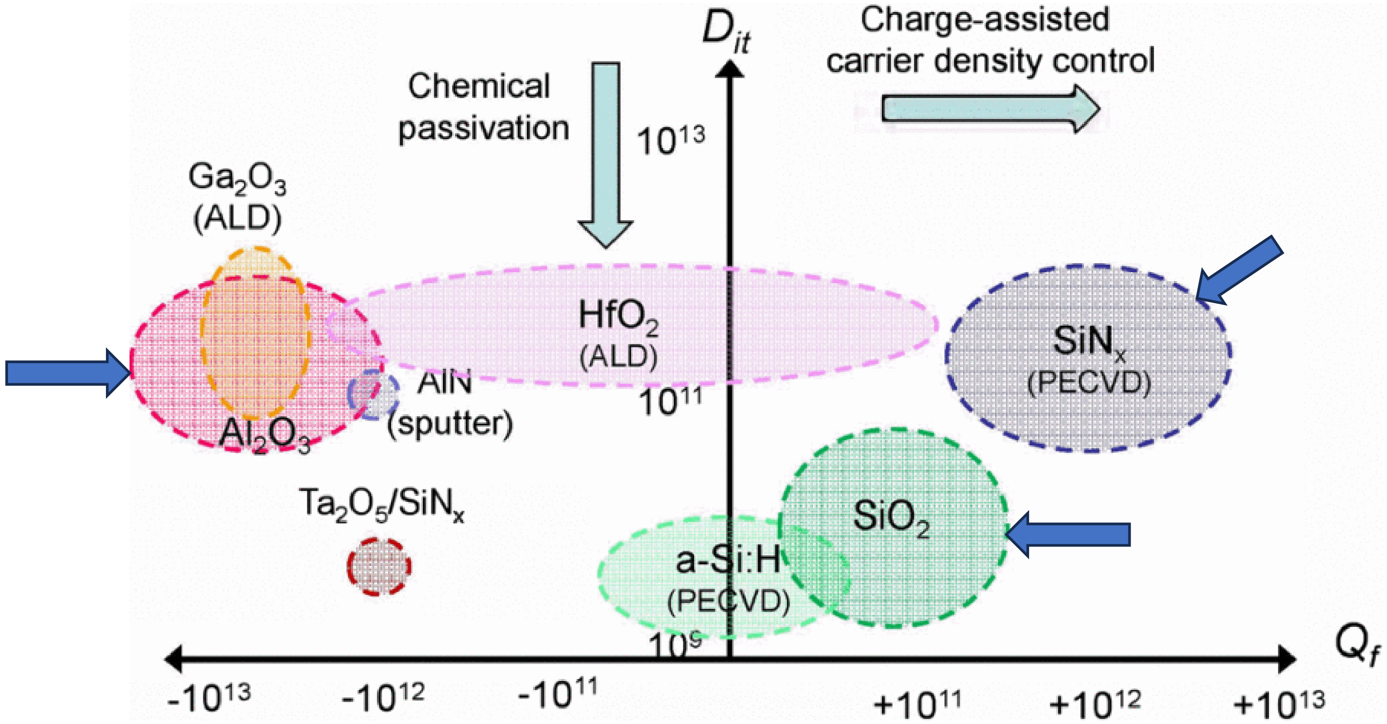
- SiN_x blocks diffusion
- SiO_x and AlO_x deep boron diffusion

[1] S. McNab, *Submitted*

The Benefits of SiNx and AlOx: Part 3

Field effect passivation?

SiOx has very little charge
AlOx has a negative charge
SiNx has a positive charge

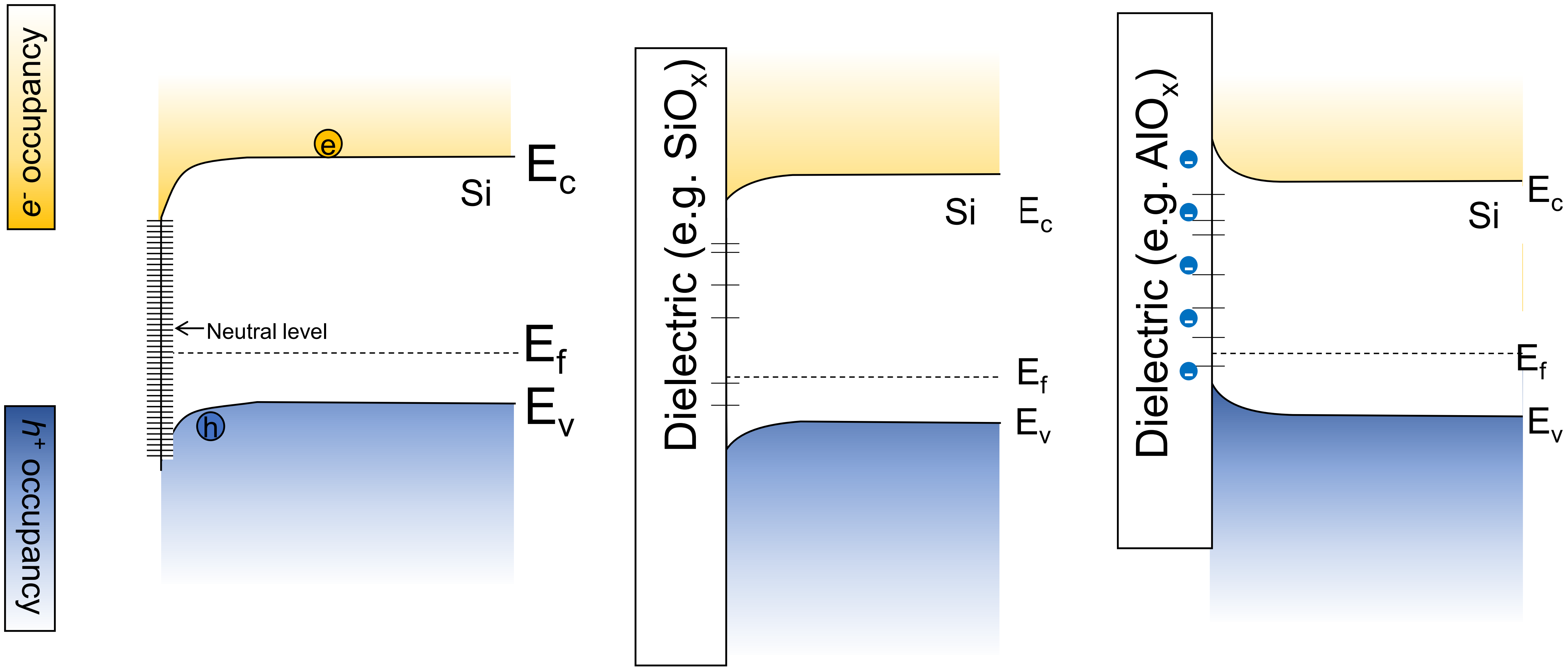


Why is this important?

[1]A. Cuevas, *IEEE 42nd Photovoltaic Specialist Conference,* (2015)

The Benefits of SiN_x and AlO_x: Part 3

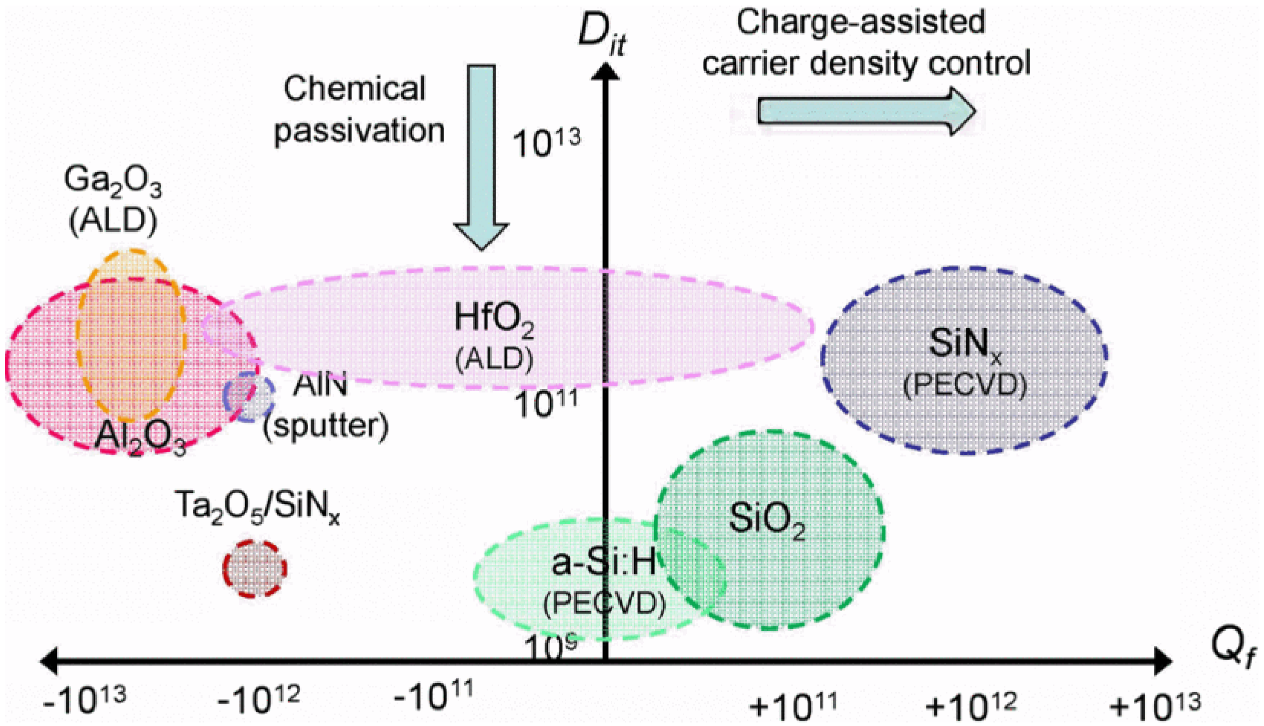
Field effect passivation?



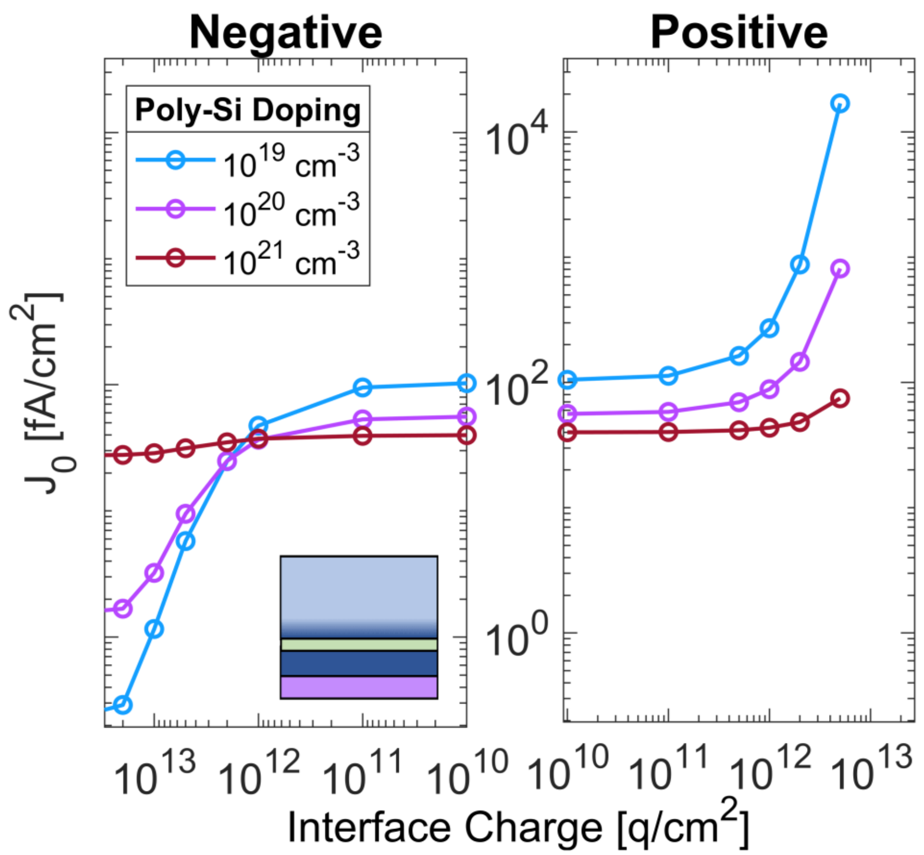
The Benefits of SiNx and AlOx: Part 3

Field effect passivation?

AlO_x has a negative charge – can it help?



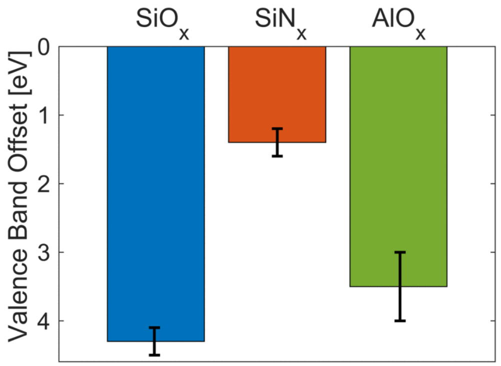
Sentaurus TCAD Simulations

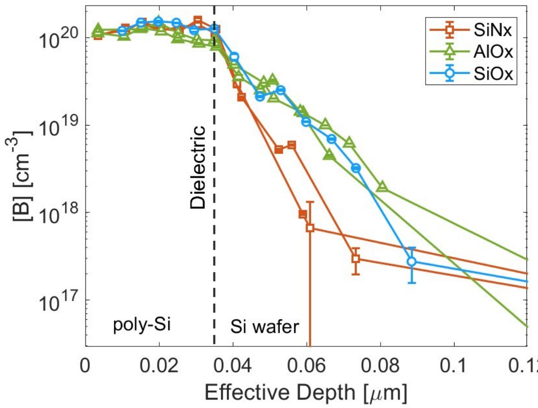


[1]A. Cuevas, *IEEE 42nd Photovoltaic Specialist Conference,* (2015)
[2]S. McNab, *PhD Thesis*, *University of Oxford*, (2023)

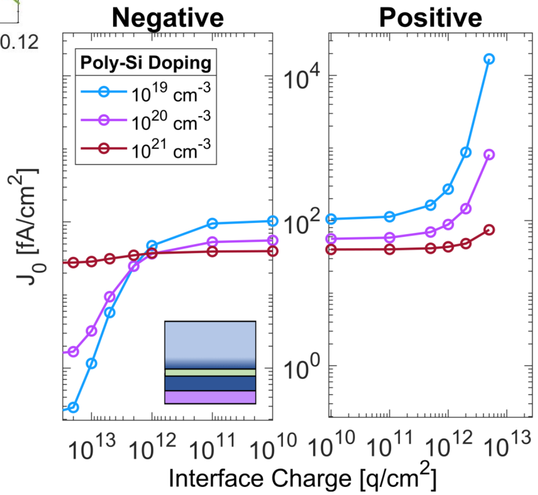
SiN_x or AlO_x Poly-Si Contacts

- Promise:
  - **Lower VBO** enables more tunnelling conduction ✅
  - SiN_x **boron blocking** should reduce Auger recombination ✅
  - AlO_x **negative charge** can add Field effect passivation ✅





- Questions:
  - Can we fabricate these layers at the thickness and uniformity required
  - Does the promise translate to real devices



Outline

- What is TOPCon
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- **Fabrication**
- Transport Properties
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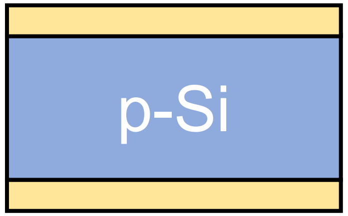
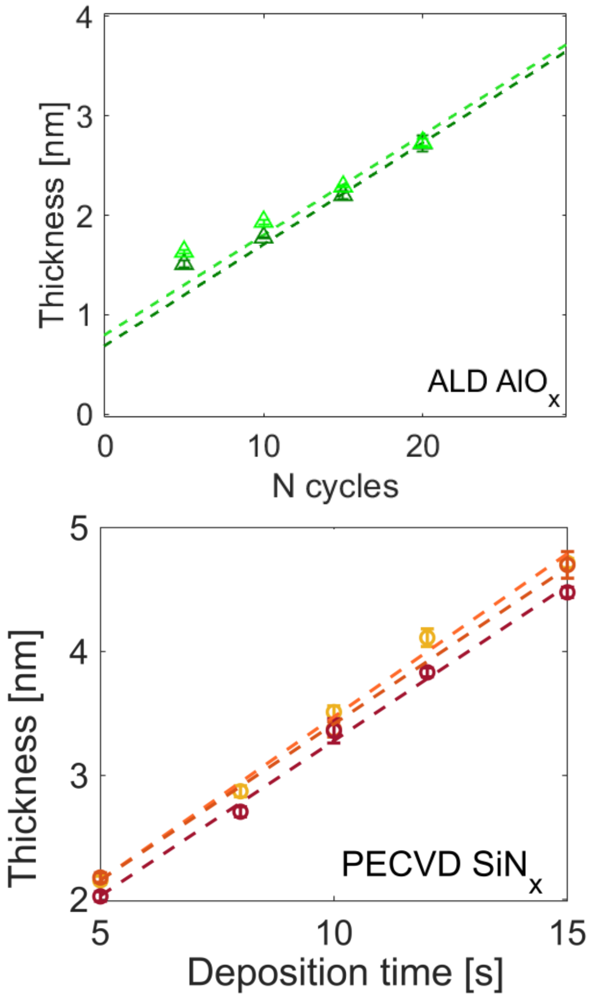
Fabrication Process

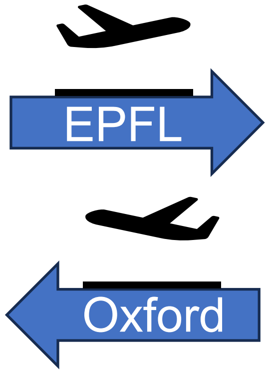
~2 nm Dielectric

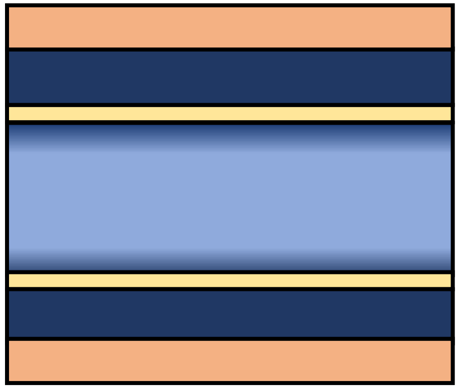


ALD AlO_x
PECVD SiN_x

Ex-situ Ellipsometry





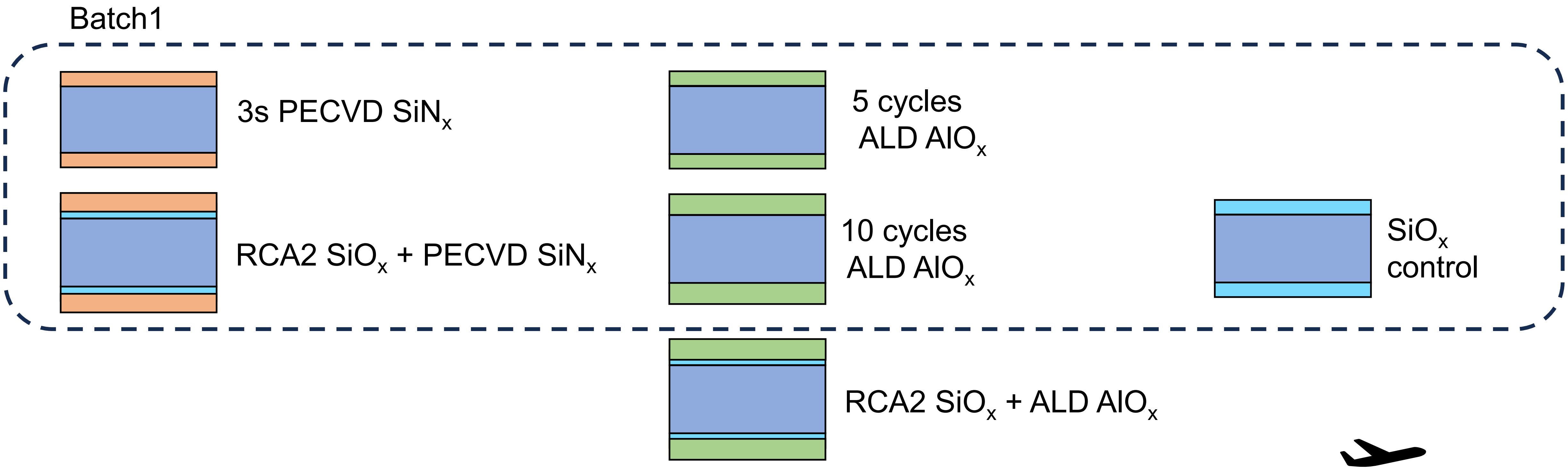


Doped a-Si deposition
High T Anneal
SiN_x Hydrogenation

*Limited samples so focus on **understanding**

[1] S. McNab, *Submitted*
[2] S. McNab, *IEEE Journal of Photovoltaics, (2022), 1-11*

Dielectric layers for Poly-Si deposition



- Why RCA2 SiO_x?
  - Reasonable chemical passivation
  - Very thin → limited effect on the tunnelling conduction

Outline

- What is TOPCon
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- **Transport Properties**
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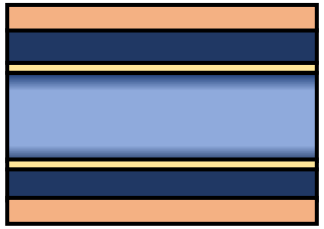
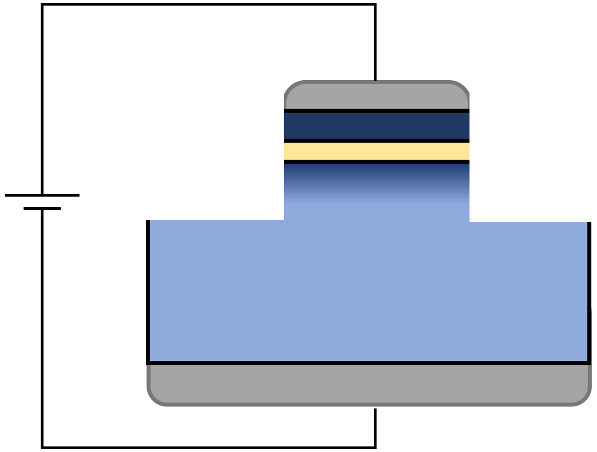
Transport Properties

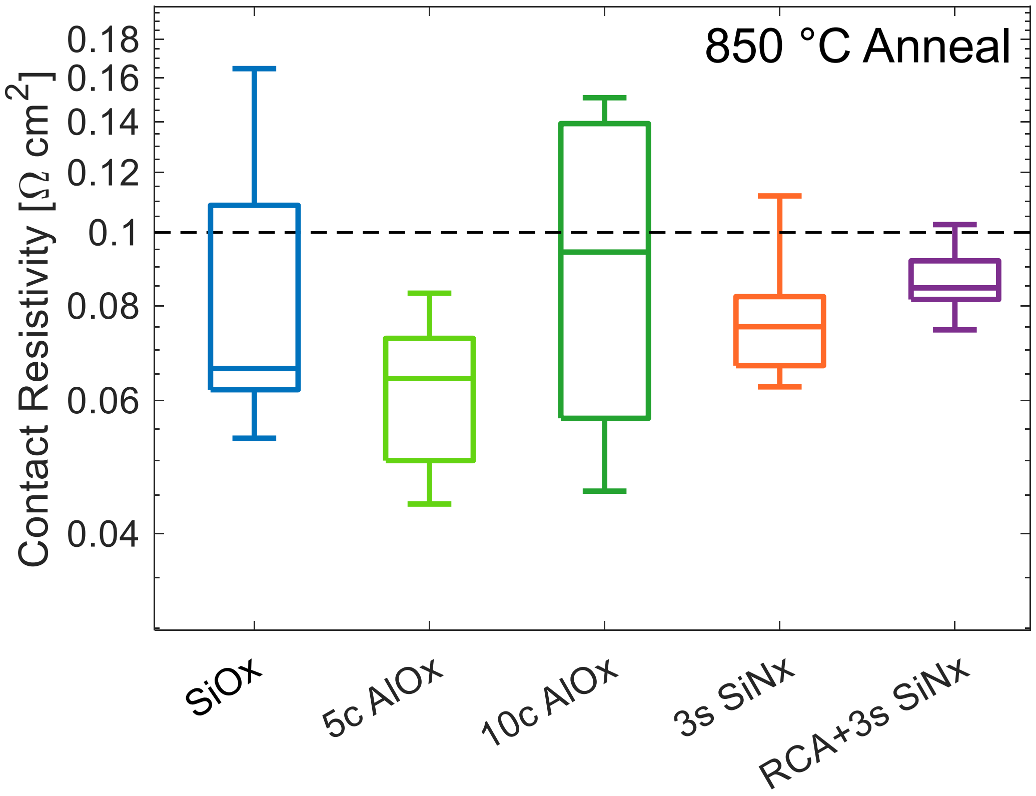
Oxford





$$R_{tot} = \left[\frac{dI}{dV}\right]_{V\cong 0}$$

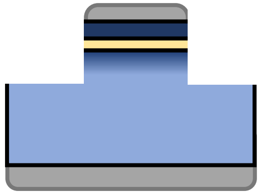
Contact resistivity: $\rho_c = (R_{tot} - R_{spread})A_c$



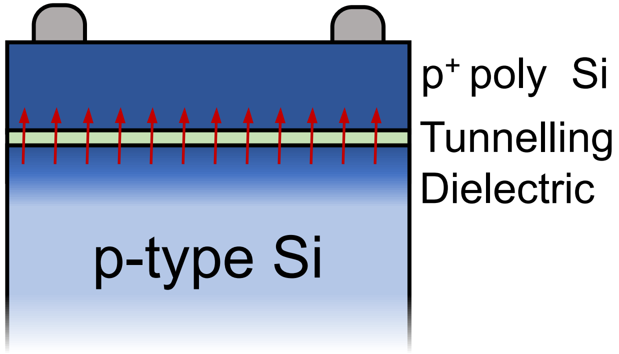
- $\rho_c < 100\ \mathrm{m\Omega \cdot cm^2}$ ✅
- Is it actually tunnelling?

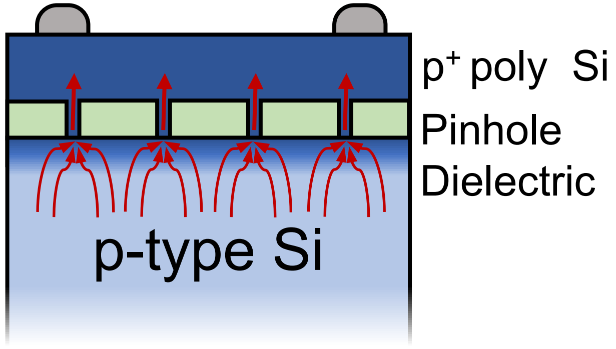
[1] S. McNab, *Submitted*

Understanding Transport Mechanisms



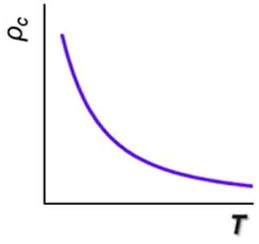
- Temperature Dependent IV measurements

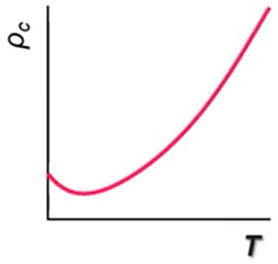


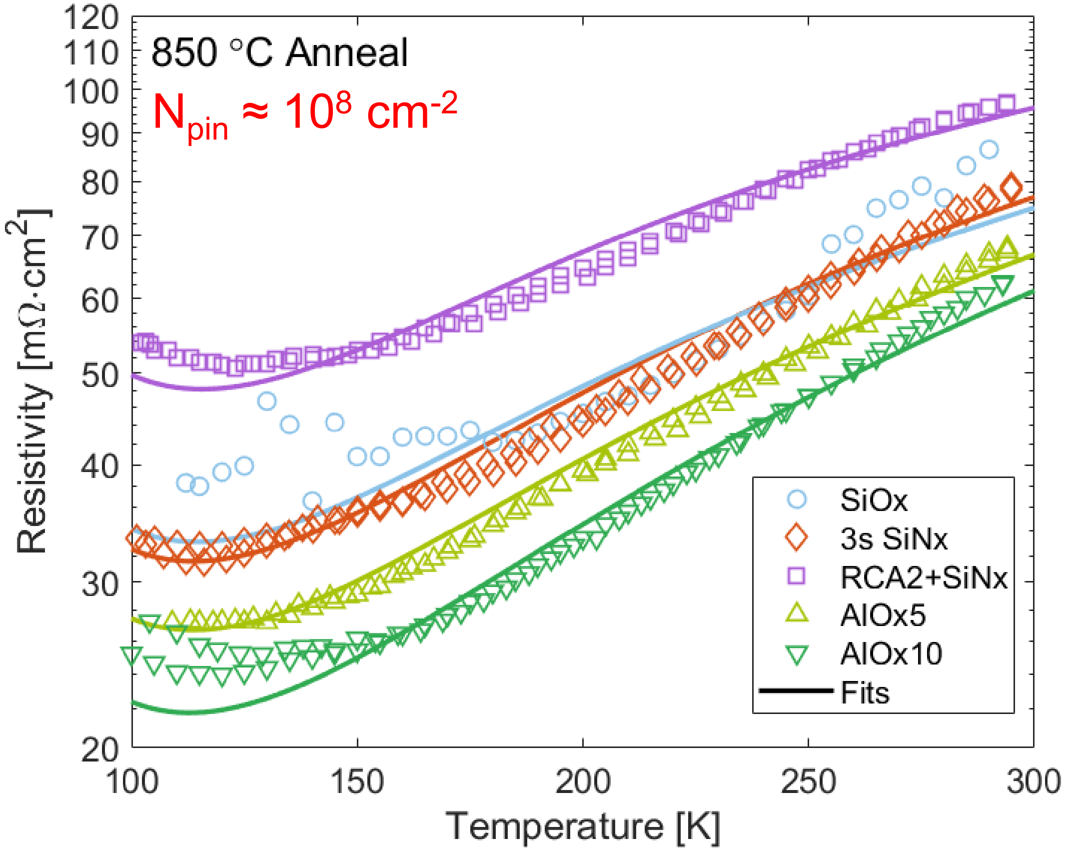


$$\rho_{tun} = \frac{nk_B}{qA^*\boldsymbol{T}} \cdot \exp\left(\frac{q\varphi_B}{k\boldsymbol{T}}\right) \cdot P_t$$

$$\rho_{pin} = \frac{1}{N_{pin}} \cdot \frac{\boldsymbol{\rho_B(T)}}{2\pi r_{pin}} \cdot arctan\left(\frac{2t_{waf}}{r_{pin}}\right)$$

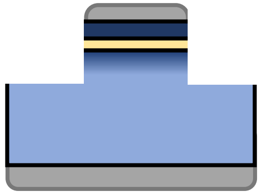




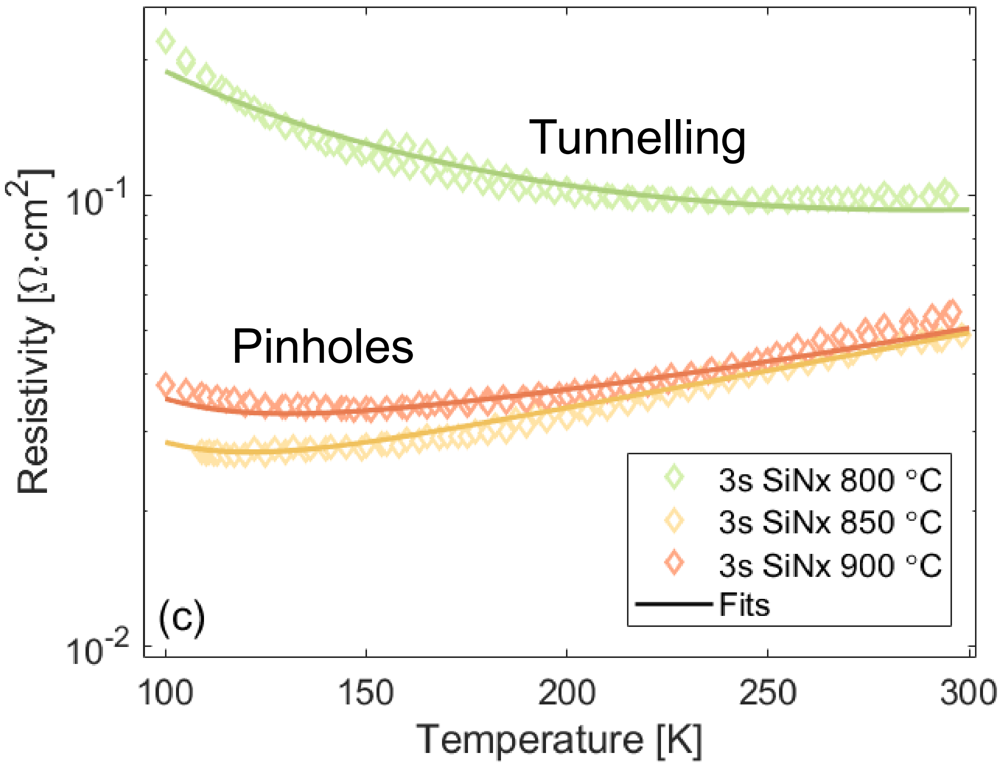


[1] S. McNab, *Submitted*
[2] S. McNab, *IEEE Journal of Photovoltaics, (2022), 1-11*

Understanding Transport Mechanisms



- Batch 1a: Adjust anneal Temperature



- 800 °C anneal shows a purely tunnelling fit
- >850 °C has a high pinhole density

- Pinholes are not required for $\rho_c < 100\ \mathrm{m\Omega \cdot cm^2}$
- But they might form anyway!

[1] S. McNab, *Submitted*

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- What is TOPCon
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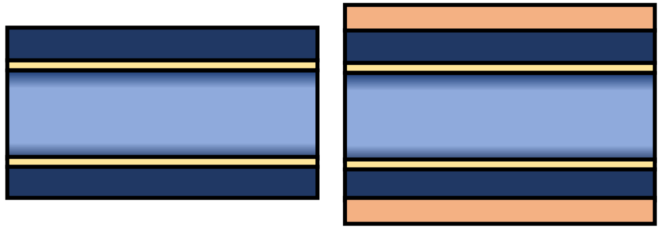
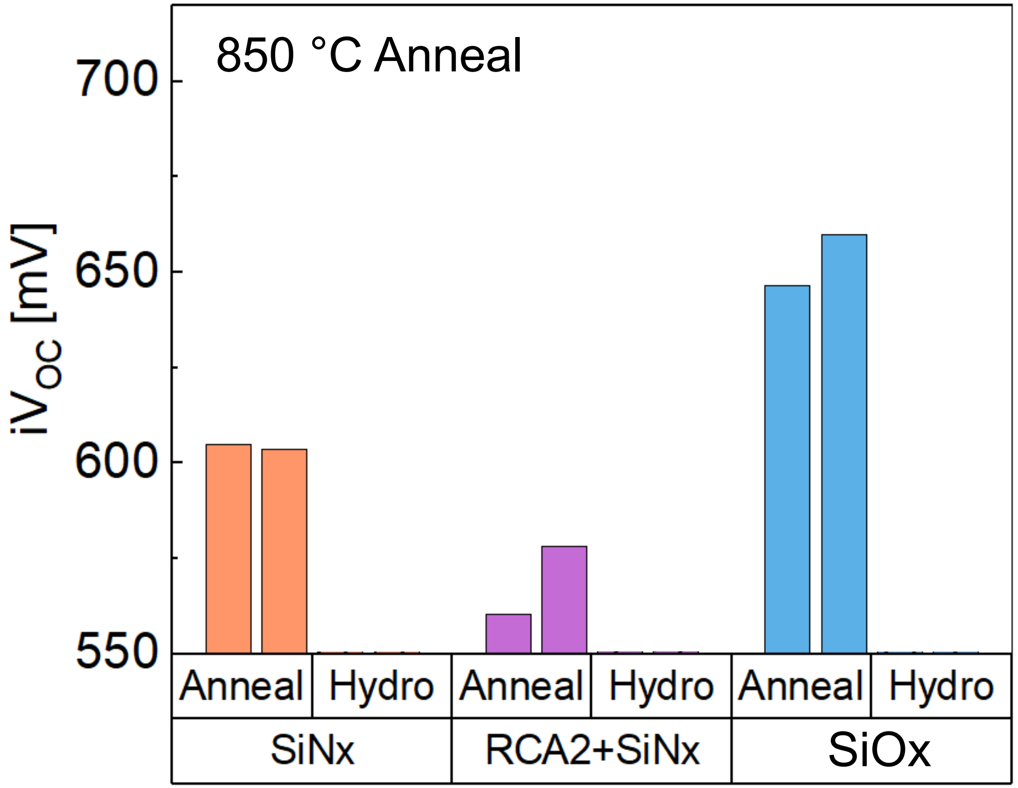
Passivation



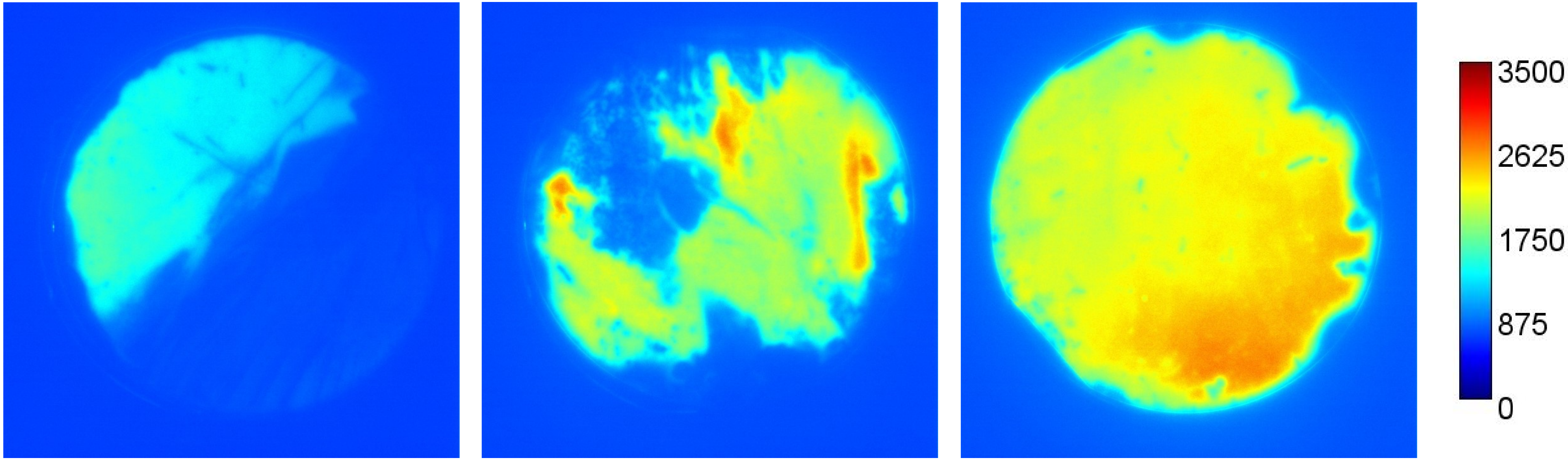


- Low iV_{OC} compared to SiO_x control ❌
- AlO_x too low to even measure!

- **Why?**

[1] S. McNab, *Submitted*

Characterising Passivation: Uniformity

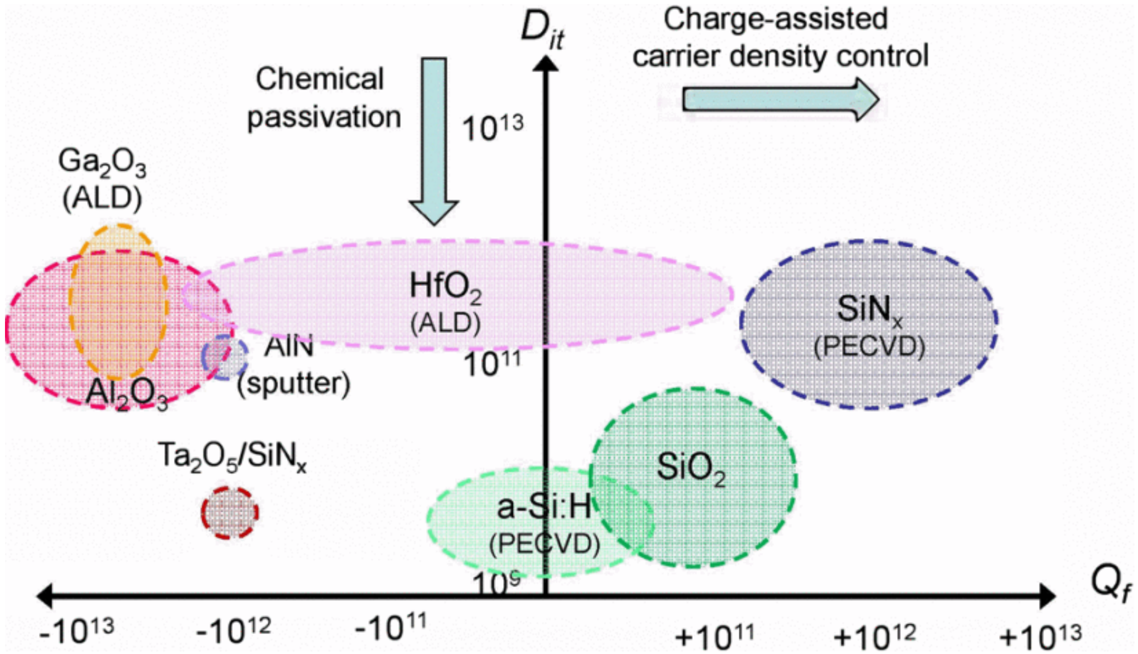


SiNx RCA2+SiNx SiO_x

Severe inhomogeneity issues – but some areas with high passivation

[1] S. McNab, *Submitted*

Characterising Passivation: Q_f and D_{it}

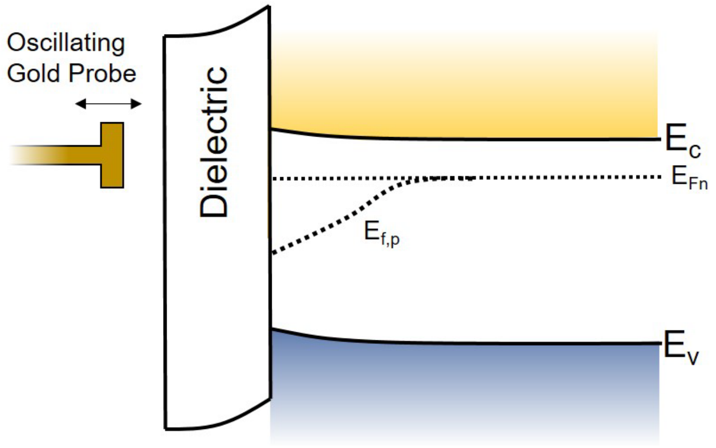


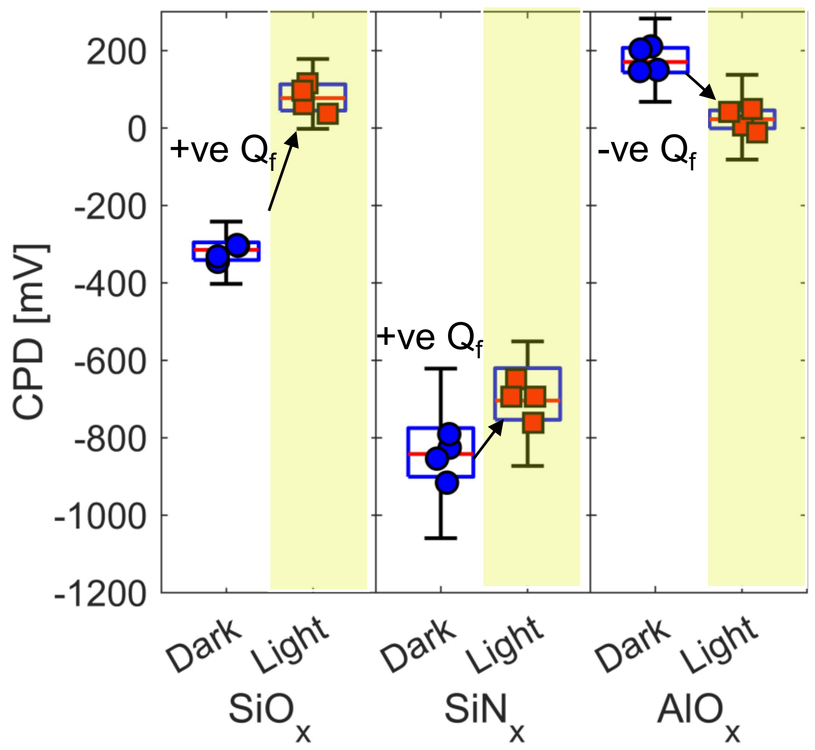
- Thick dielectrics
- How do the properties of <2nm dielectrics compare
- Difficult to measure due to high conductivity

[1]A. Cuevas, *IEEE 42nd Photovoltaic Specialist Conference,* (2015)

Characterising Passivation: Q_f and D_{it}

- Surface Photovoltage
- No direct contact to the dielectric
  - Prevents conduction



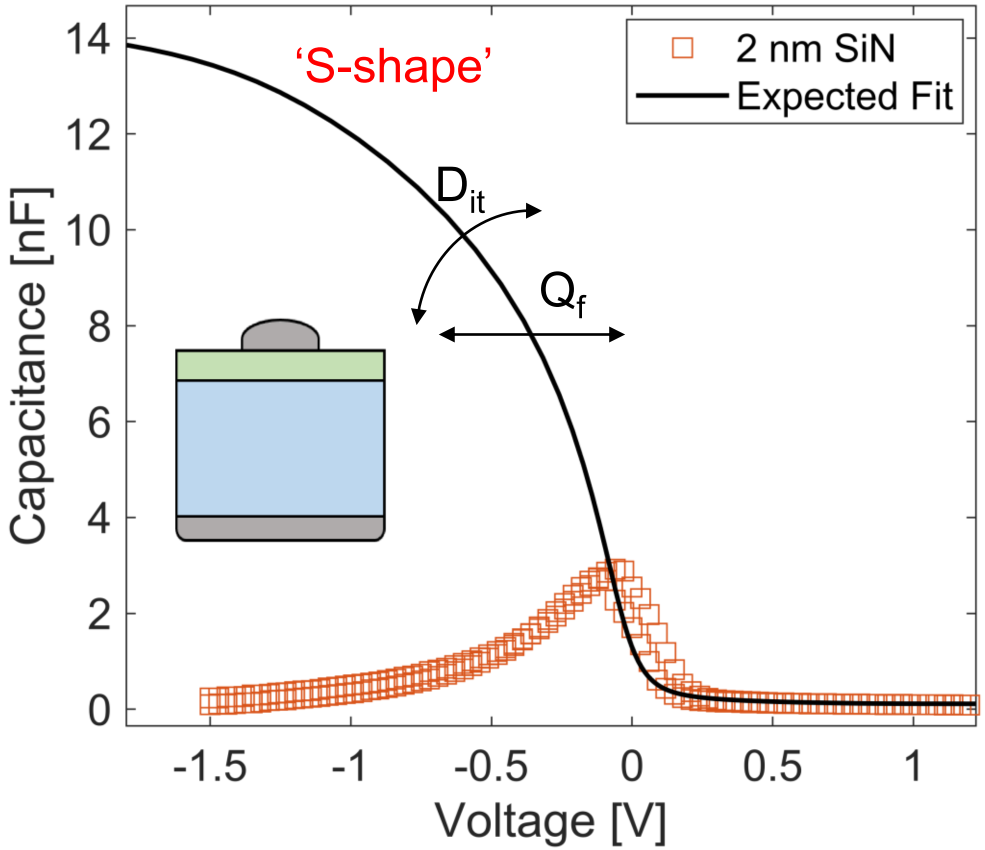


- Effect of D_{it} and Q_f difficult to deconvolute

[1] S. McNab *IEEE Journal of Photovoltaics, (2022), 1-11*

Characterising Passivation: Q_f and D_{it}

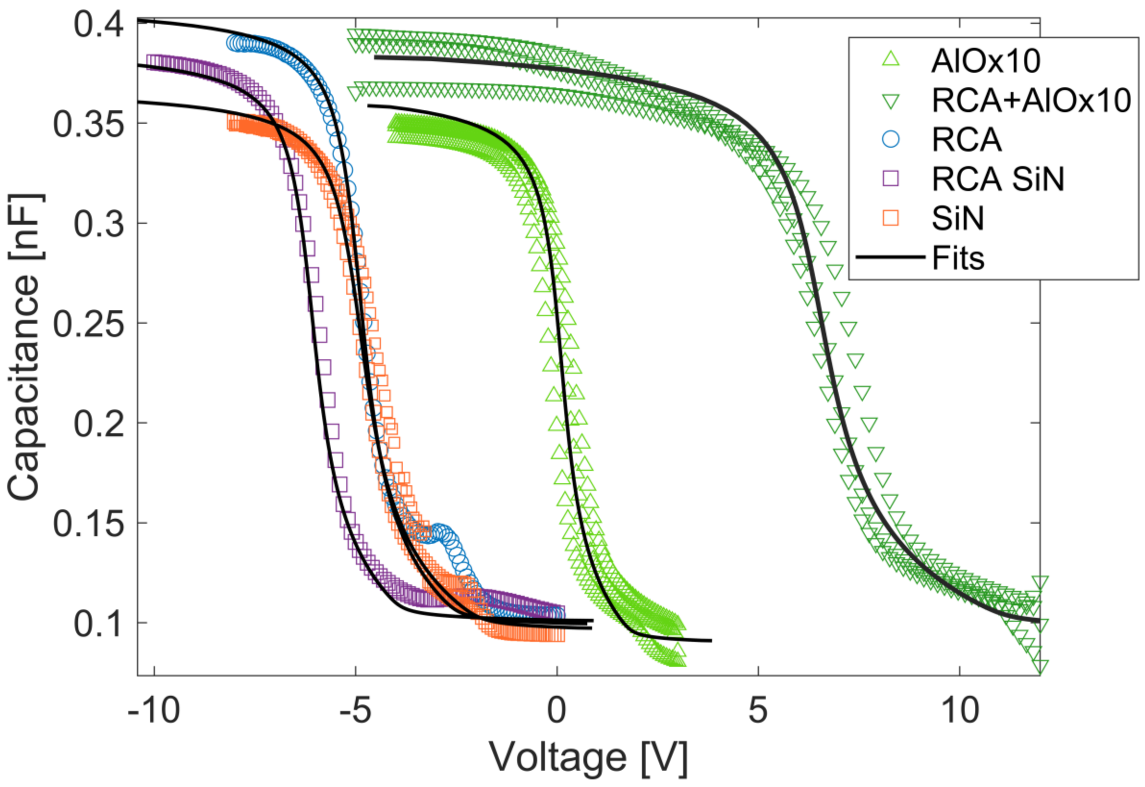
Capacitance-Voltage Measurements



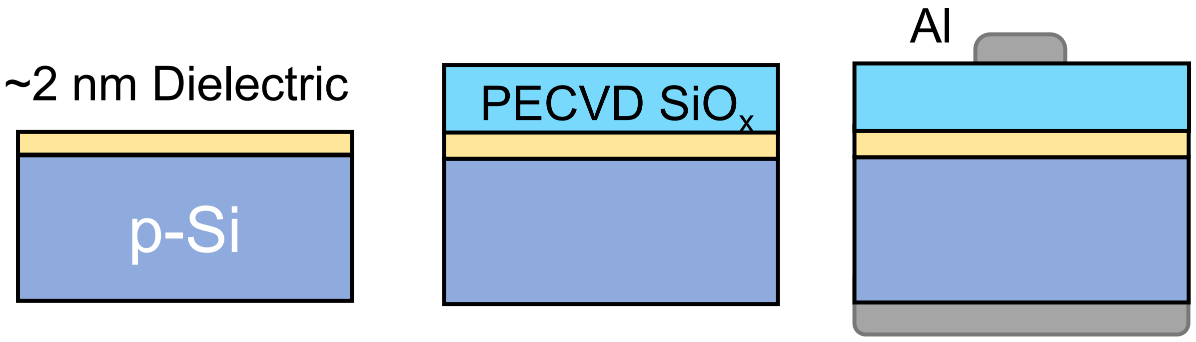
- CV is commonly used for thick dielectrics
  - Q_f shifts curve left/right
  - D_{it} changes the slope
- Sensitive to interface charge
- High conductivity prevents an accurate CV measurement

Characterising Passivation: Q_f and D_{it}

Adapted CV analysis



High Quality CV obtained

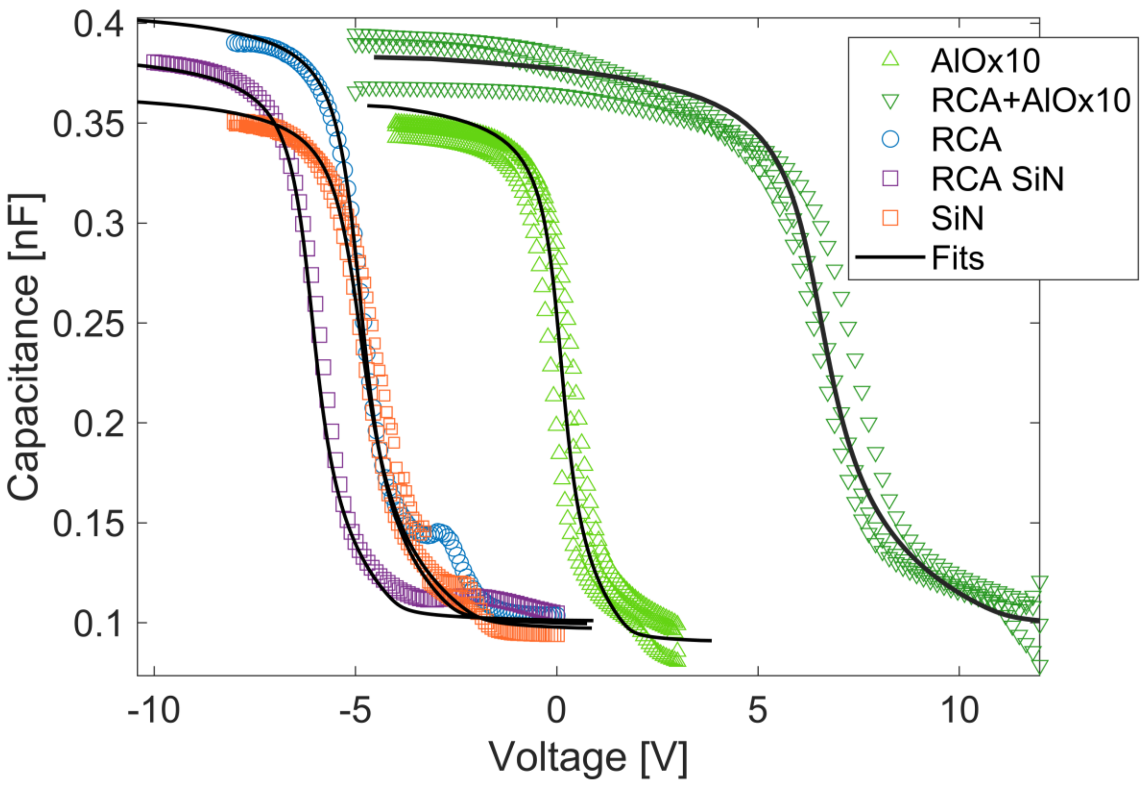


Dielectric	Q_f x10^{12} [q/cm^2]	D_{it} x10^{12} [cm^2]
RCA2 SiO_x	0.7	0.5
3s SiN	0.65	0.6
RCA2 + 3s SiN	1	0.4
10 cycles AlOx	-0.4	0.4
RCA2 + 10 AlOx	-3.2	2

[1] S. McNab, *Submitted*

Characterising Passivation: Q_f ar

Adapted CV analysis



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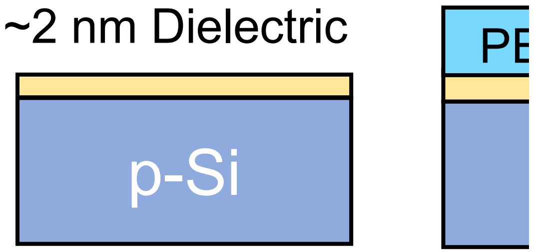

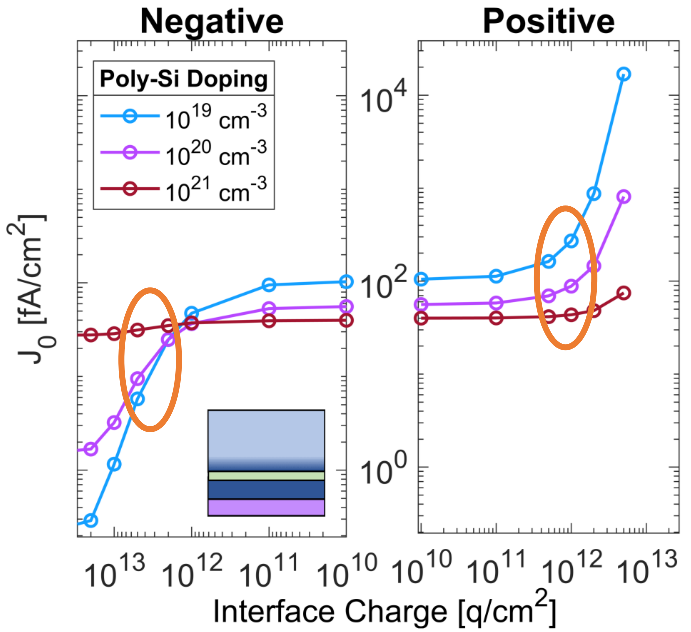

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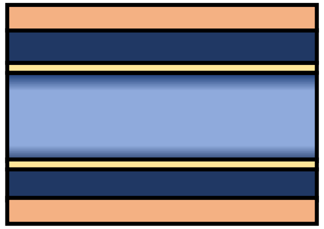
Improved Passivation



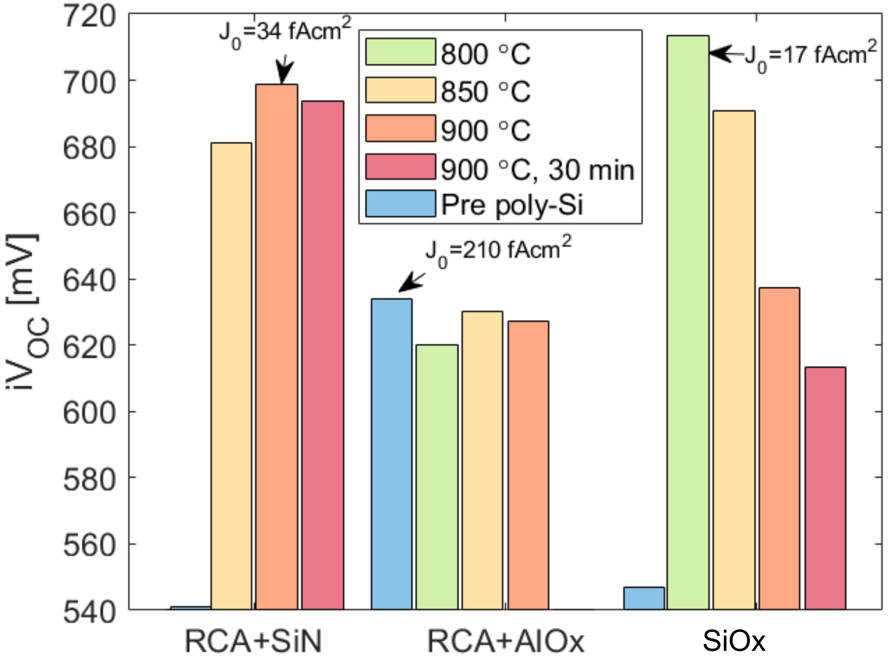
Takeaways from Batch 1

- Tunnelling contacts are possible ✅
- SiN_x blocks boron ✅
- RCA2+AlO_x has high -ve charge ✅

- High pinhole density ❌
- Uniformity issues ❌
- Used anneal optimised for SiO_x

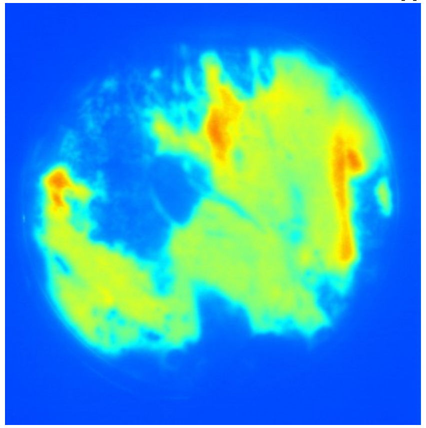
For Batch 2

- Varied anneal conditions
- Improved RCA2 processing and wafer handling
- Focus on most promising interlayers

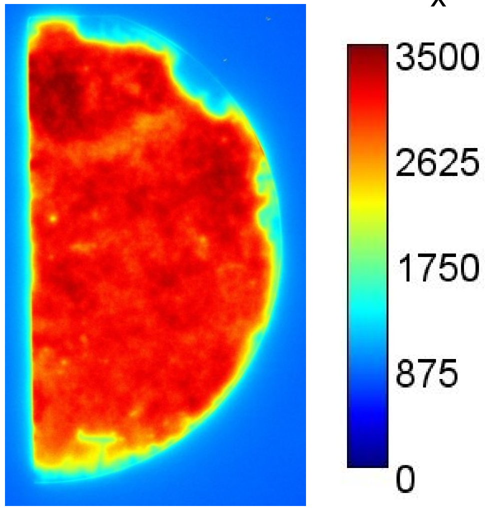


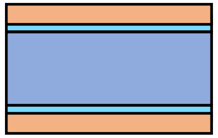
Batch 2 after hydrogenation

1st Batch RCA2+SiN_x

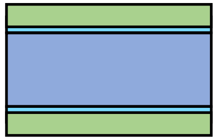


2nd Batch RCA2+SiN_x





RCA2 + SiN_x



RCA2+AlO_x

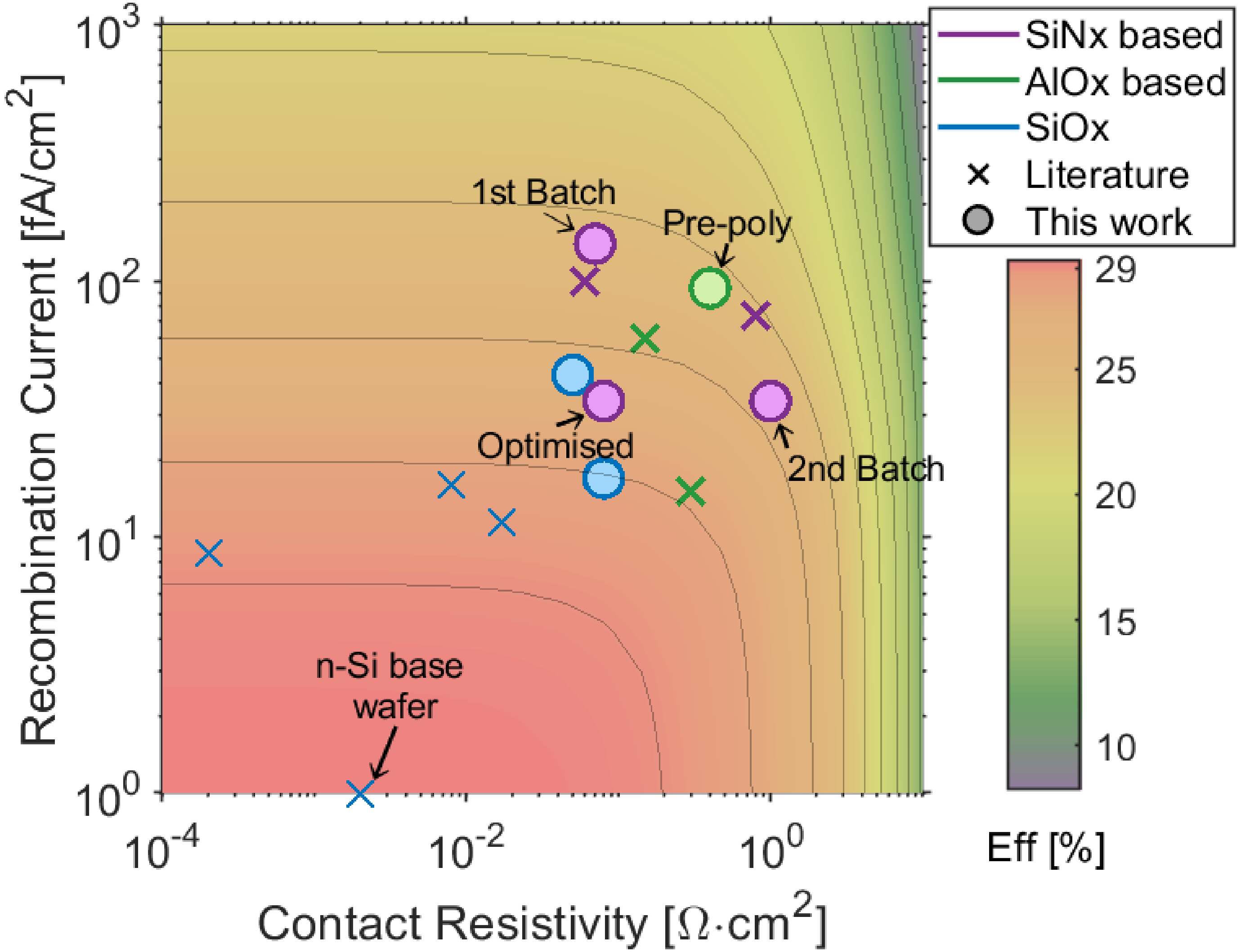
[1] S. McNab, *Submitted*

Outline

- What is TOPCon
- Current limitations with SiO_x
- Benefits of SiN_x and AlO_x

- Fabrication
- Transport Properties
- Passivation Properties
- **Comparison with other work**
- Summary

Comparison to other work



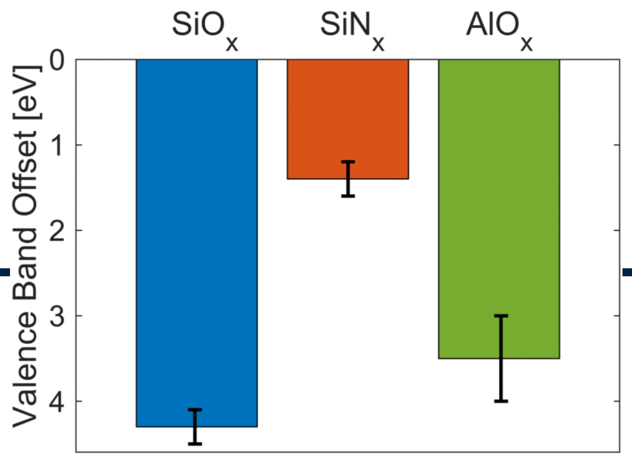
[1] S. McNab, *Submitted*

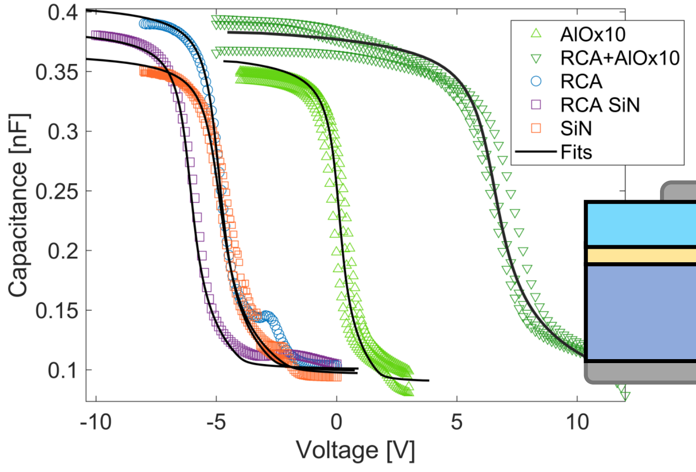
Summary

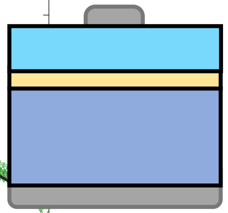
- Potential benefits of PECVD SiN_x and ALD AlO_x as hole selective poly-Si tunnelling contacts

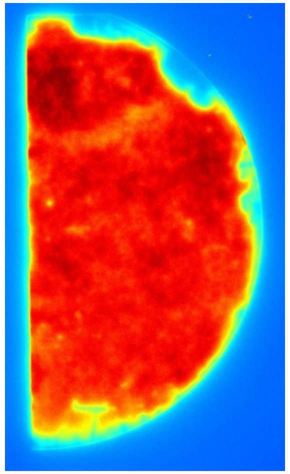
- Developed Methods for Characterising Q_f and D_{it} of 2nm dielectrics

- Significant improvement in 2 batches:
  - SiN_x iV_{OC} 668→699 mV
  - AlO_x shows promise before poly-Si









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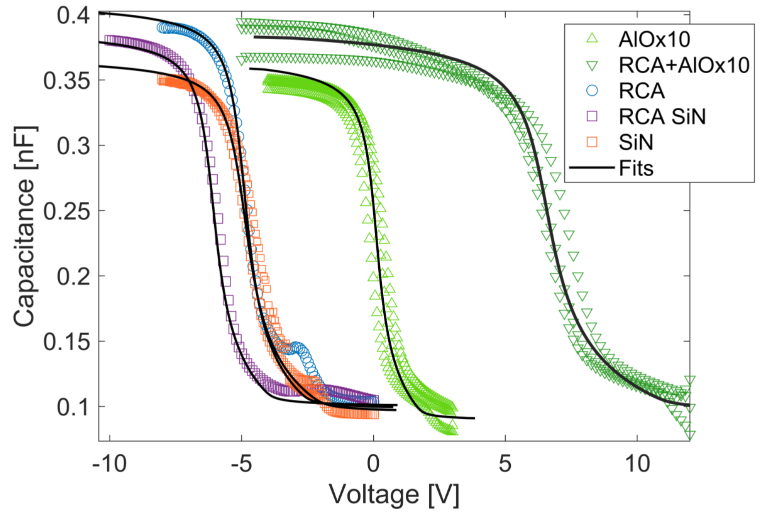
XPS data



- SiNx stoichiometry – low N concentration, close to SiOx
- AlOx – significant increase in Al concentration