Investigation of Next-generation Silicon Radiation Detectors Enabled by Tunnel Oxide Passivating Contact

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Silicon Radiation Detectors

Advantages (vs typical gas-filled detectors)

- ✓ Good energy resolution
- ✓ Fast timing characteristics
- ✓ Compactness and ruggedness

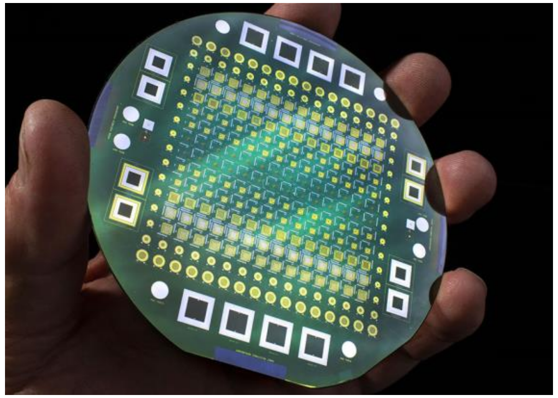
Applications

- ❖ Alpha particle spectroscopy
- ❖ Heavy ion and fission fragment spectroscopy
- ❖ Energy loss measurements – particle identification
- ❖ X-ray spectroscopy
- ❖ Personnel monitors

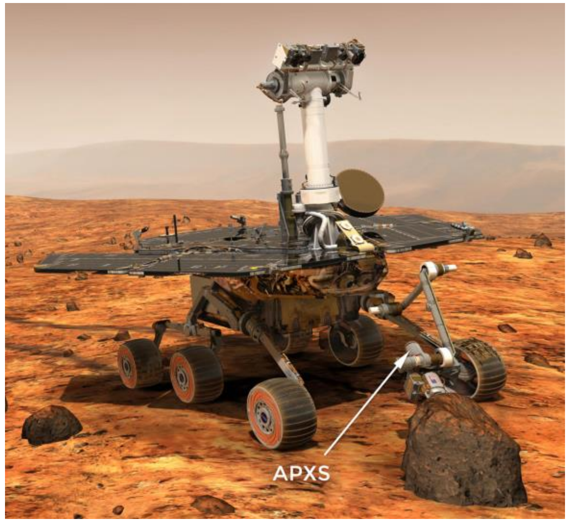
Configurations

- Diffused junction detectors
- Surface barrier detectors
- Fully depleted detectors
- Passivated planar detectors
- Position-sensitive detectors

} **heavily doped p^+ and n^+ regions ("dead" areas or layers)**



http://bnl.gov



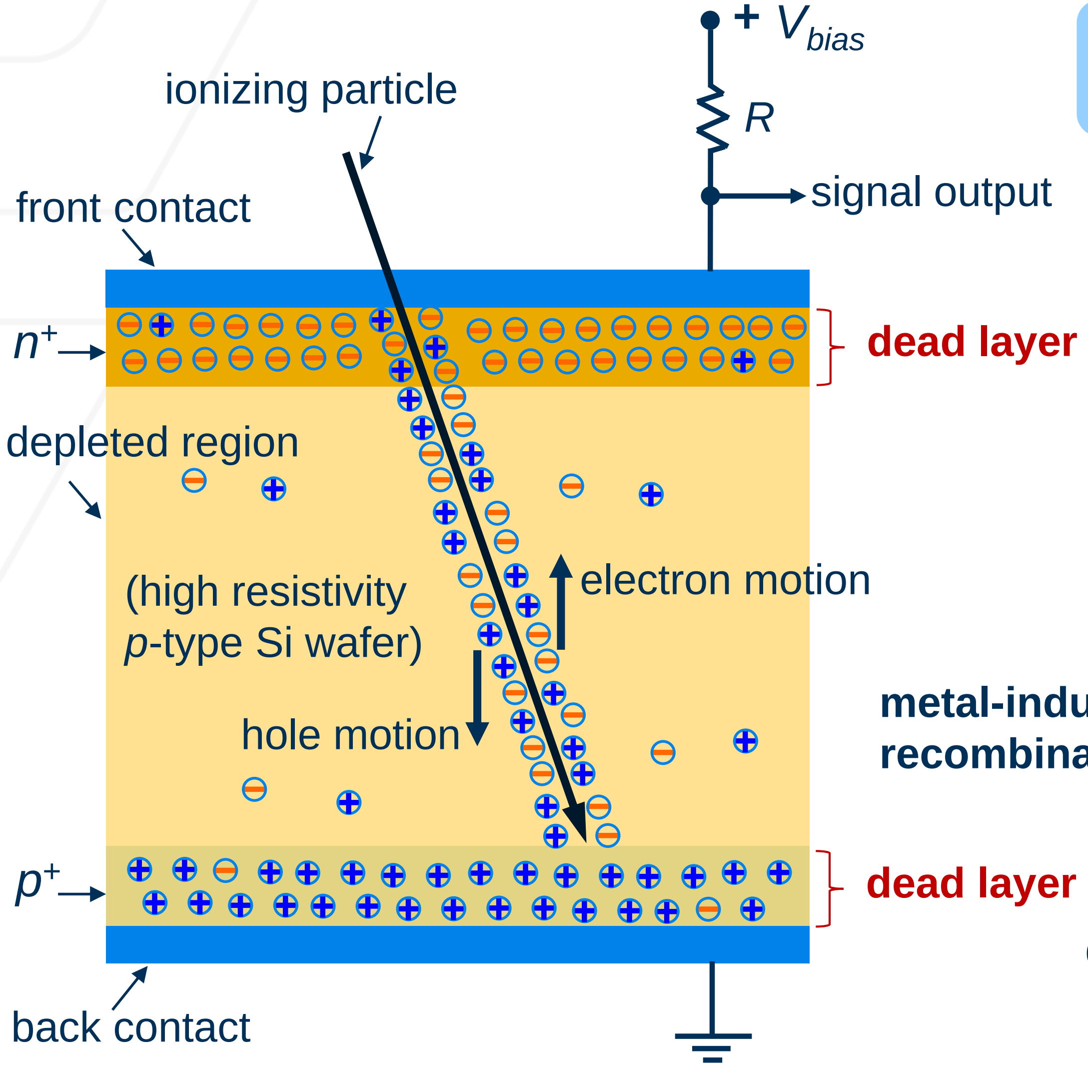
Alpha Particle X-Ray Spectrometer (APXS) *www.nasa.gov*

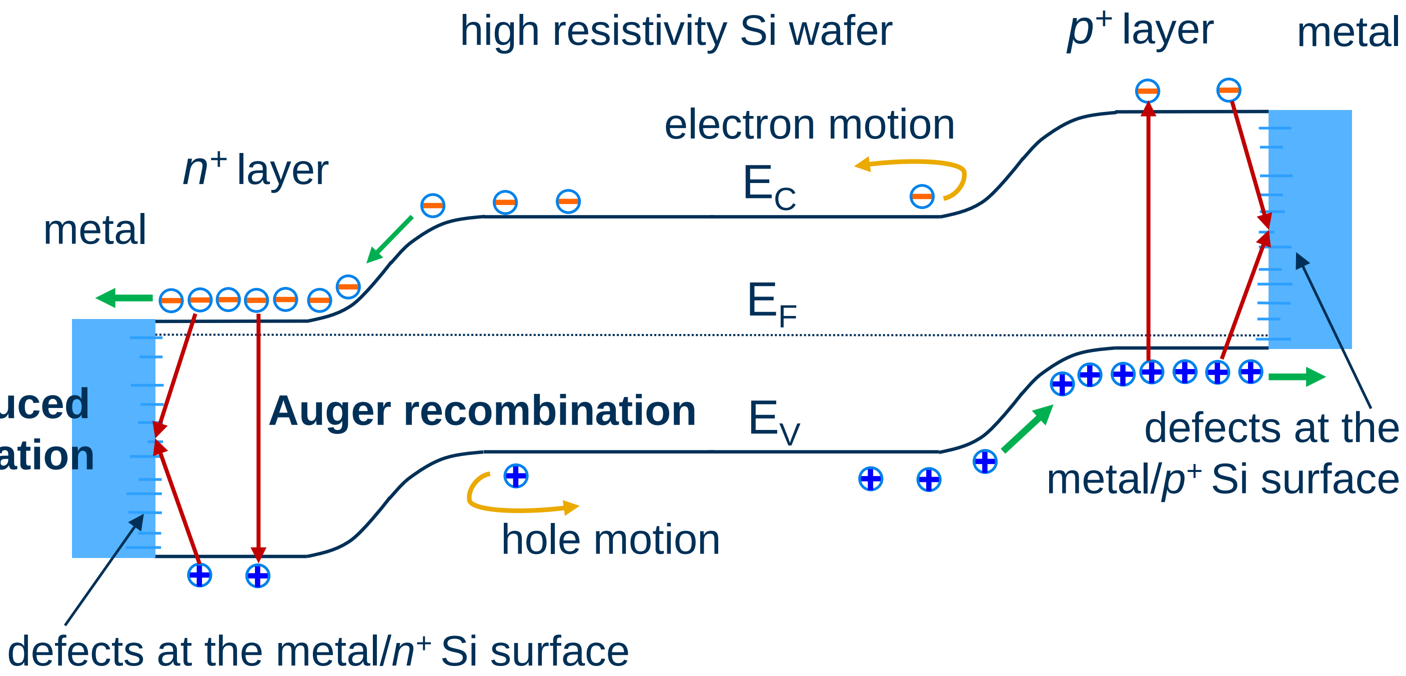
www.mirion.com

micronsemiconductor.co.uk

Operating Mechanism of Conventional Silicon Detectors

Auger recombination
metal-induced recombination → dead layer → **energy resolution** ↓





The Leaking Bucket Story

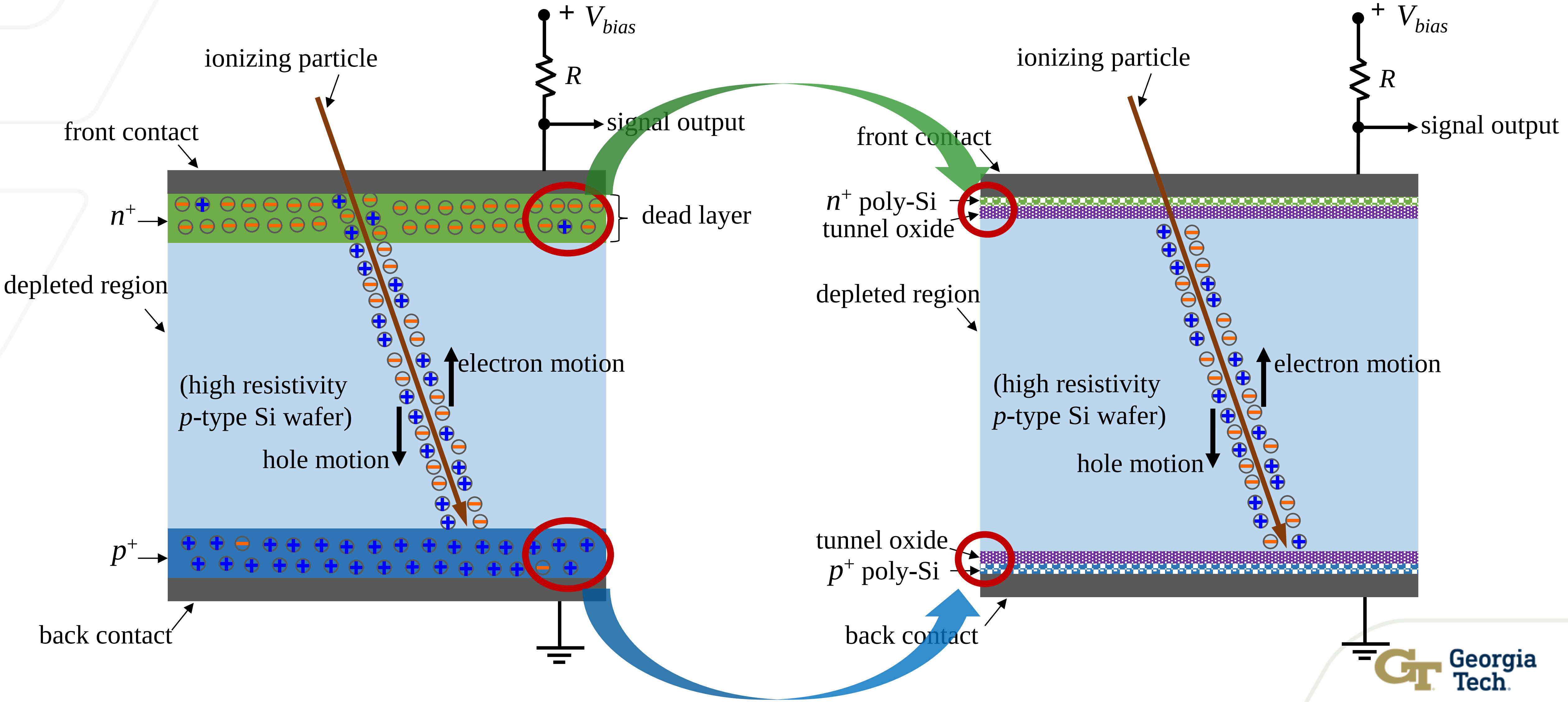
Option 1
keep as is

Option 2
fix it

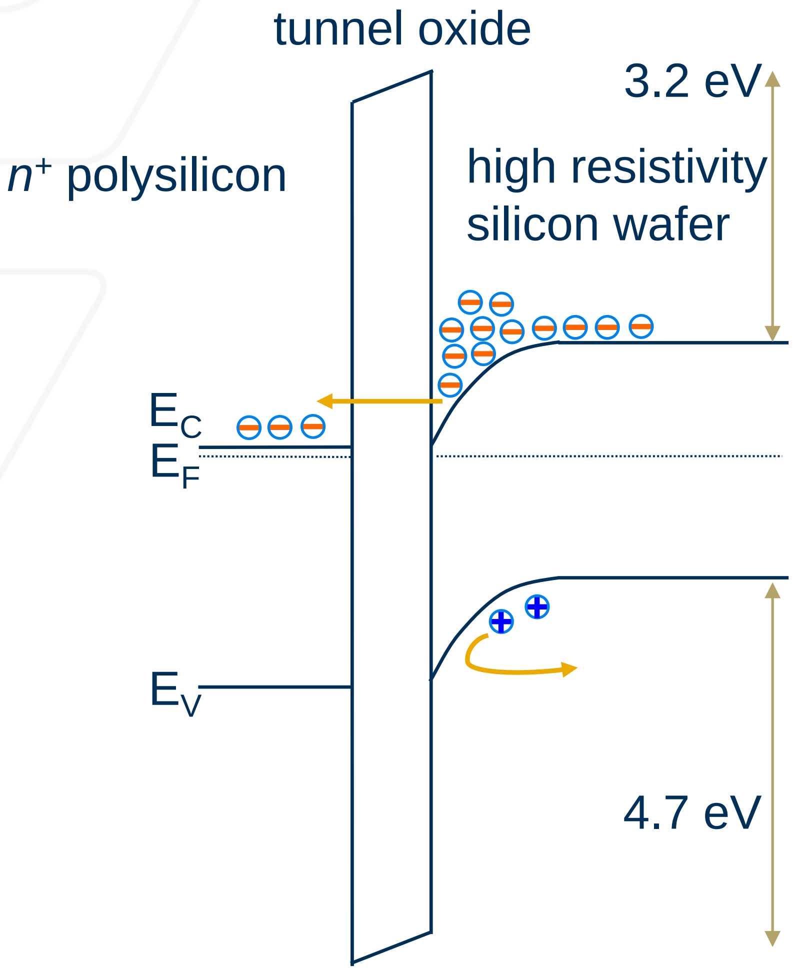
Option 3
trash it

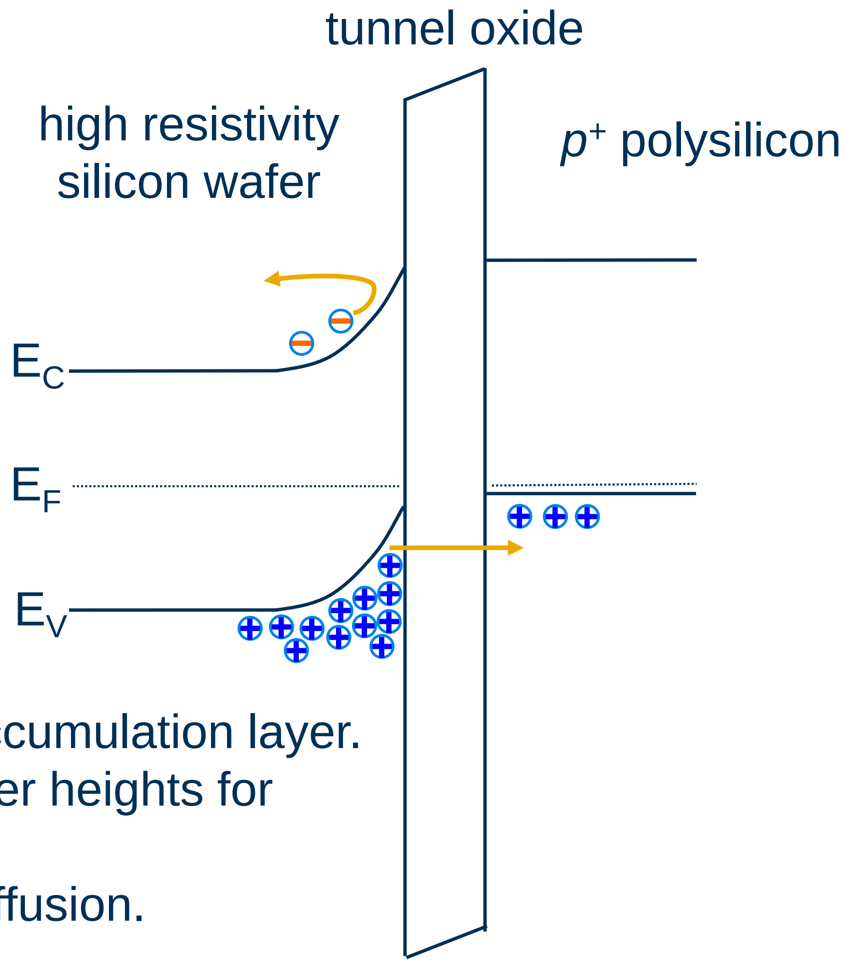
Image courtesy: Andar Software

Fix the “Leaking Bucket”: Reduce the Carrier Recombination by Tunnel Oxide Passivating Contact



Operating Principle of Tunnel Oxide Passivating Contact





- Band bending by creating an accumulation layer.
- Difference in the tunneling barrier heights for electrons and holes.
- Properly controlled dopant in-diffusion.
- Appropriate pinhole density.

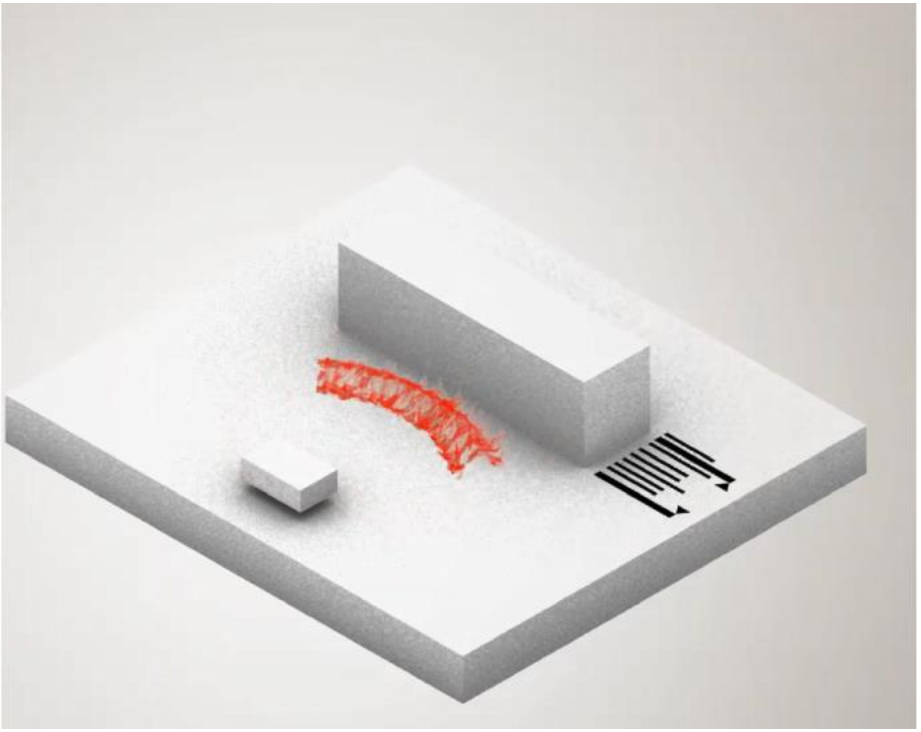
Lee, Wen-Chin, *et al.*, *IEEE Transactions on Electron Devices* 48, no. 7 (2001): 1366-1373.
Glunz, Stefan W., *et al.*, *Progress in Photovoltaics: Research and Applications* (2021).
Hollemann, Christina, *et al., Progress in Photovoltaics: Research and Applications 27, no. 11 (2019): 950-958.*

Tunneling ---- Quantum Tunneling, or Barrier Penetration

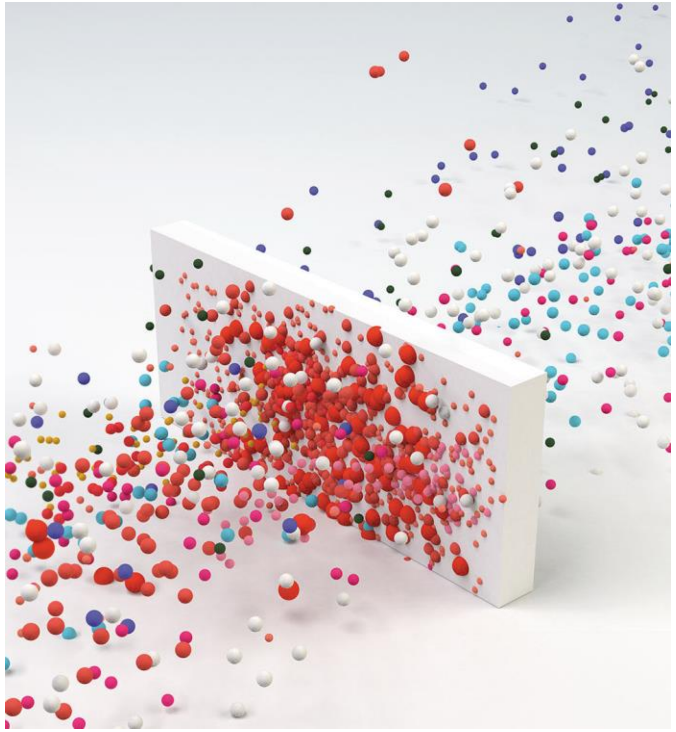
It is a quantum mechanical phenomenon in which an object such as an electron passes through a potential energy barrier that, according to classical mechanics, the object does not have sufficient energy to surmount.

The wider the barrier and the higher the barrier energy, the lower the probability of tunneling.

Wave

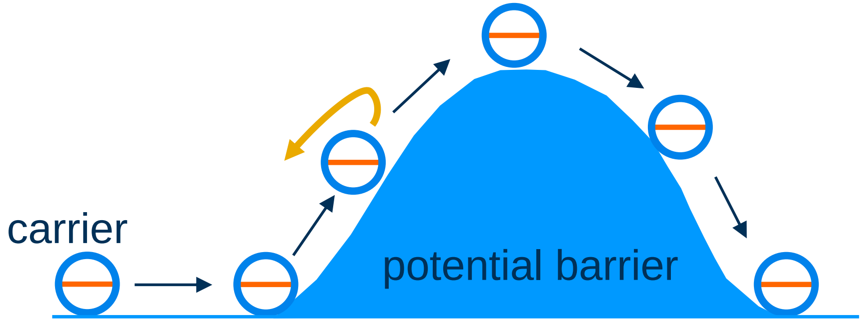


Particle

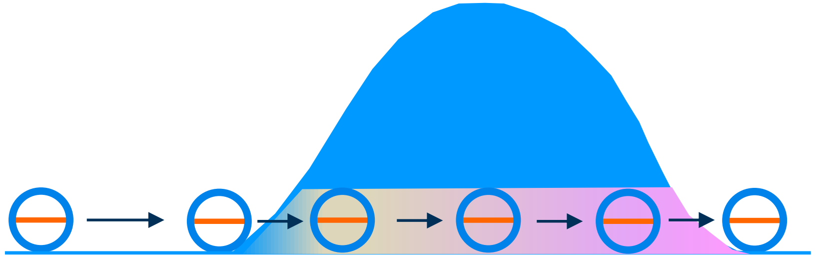


https://toutestquantique.fr/en/tunnel-effect

Classical mechanics

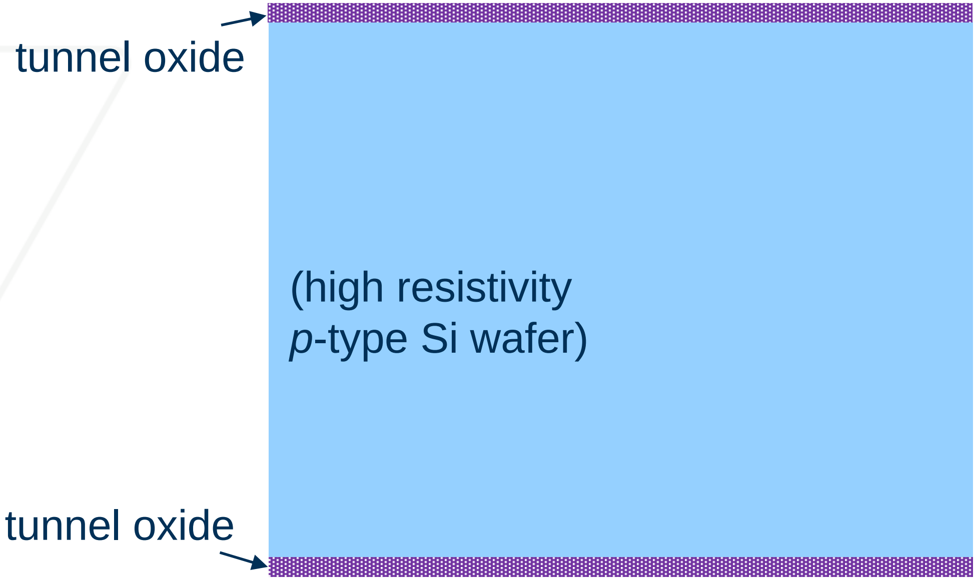


Quantum mechanics



Fabrication of Tunnel Oxide Passivating Contact

Growth of an ultra-thin oxide layer
(~1.5 nm ≈ 15 angstroms)



$$4HNO_3 \rightarrow 4NO_2 + 2H_2O + O_2$$
$$2NO_2 + Si \rightarrow SiO_2 + 2NO$$

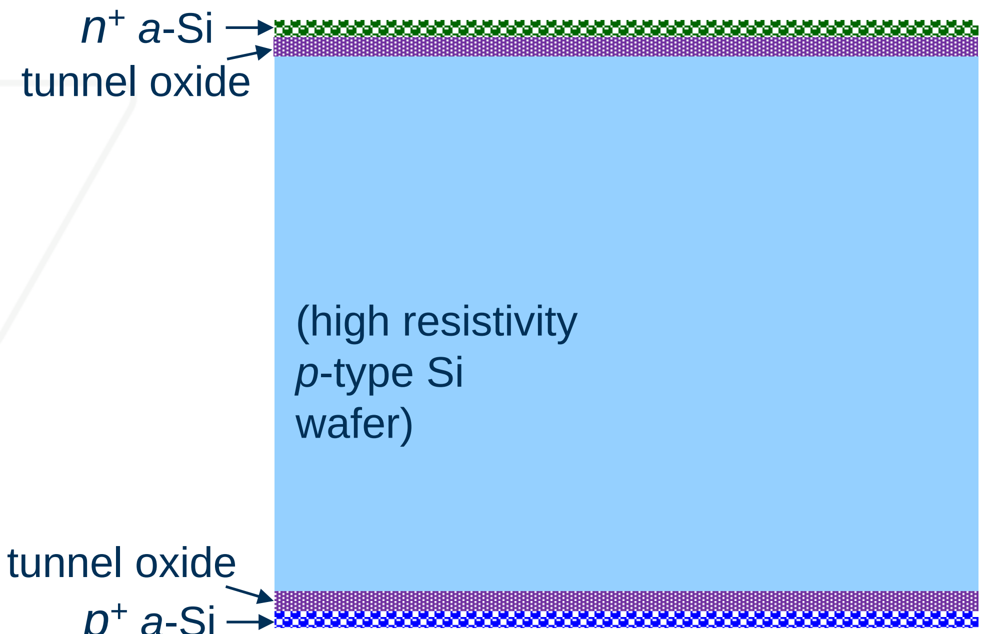
HF
DI water rinsing
SC-I ($NH_4OH + H_2O_2$)
SC-II ($HCl + H_2O_2$)
Piranha ($H_2SO_4 + H_2O_2$)
Heated HNO_3 acid

(SC: Standard Clean)

Fabrication of Tunnel Oxide Passivating Contact (cont.)

Growth of phosphorus doped (n^+) and boron doped (p^+) amorphous silicon thin films

(< 20 nm)



Plasma Enhanced Chemical Vapor Deposition (PECVD)

(using He diluted B_2H_6 and PH_3 as dopant precursors, mixing with SiH_4 and H_2)

Fabrication of Tunnel Oxide Passivating Contact (cont.)

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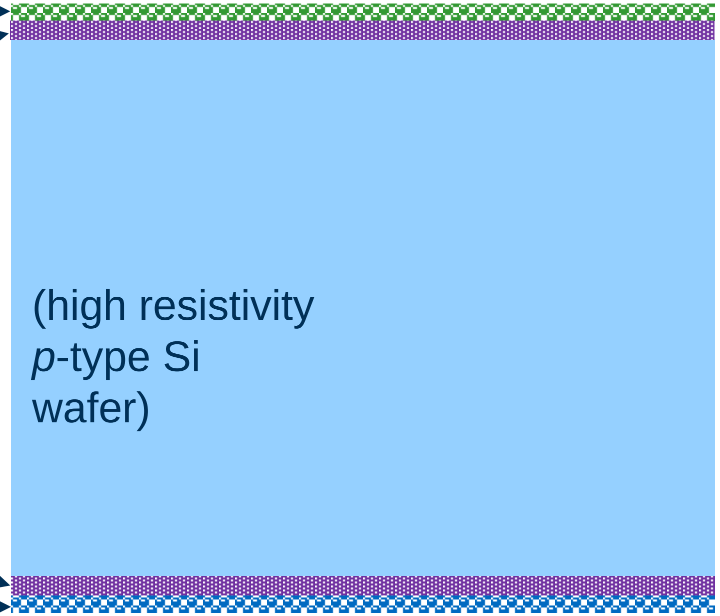
Obtaining polysilicon thin film by thermal annealing at high temperature

(800 ~ 900 ºC in N_2)

- Solid phase crystallization of amorphous silicon thin film.
- Dopant activation.

n+ poly-Si
tunnel oxide



tunnel oxide
p+ poly-Si

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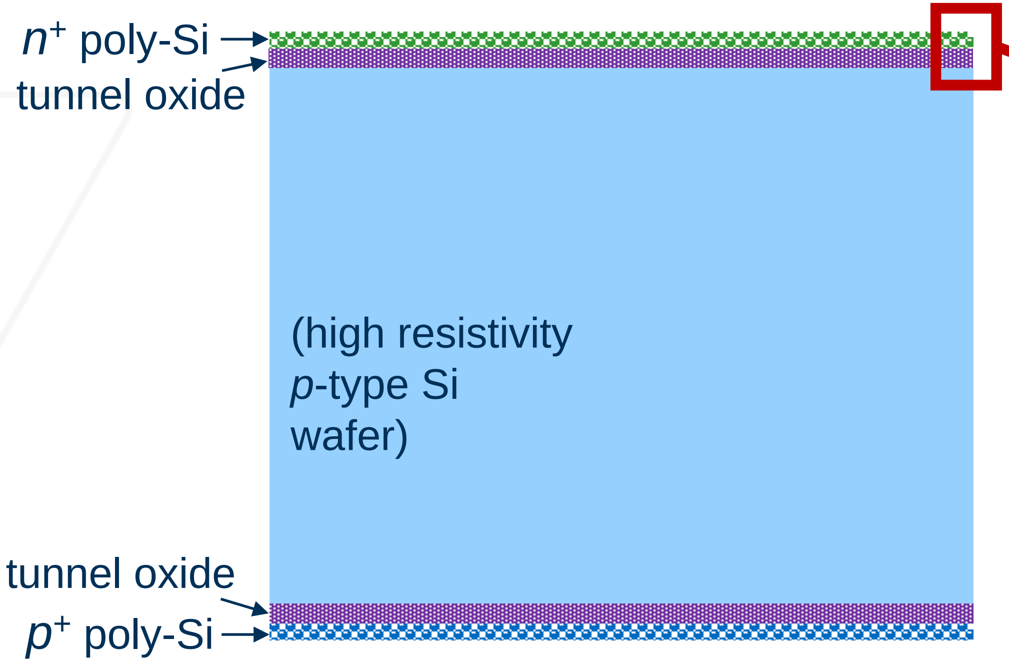
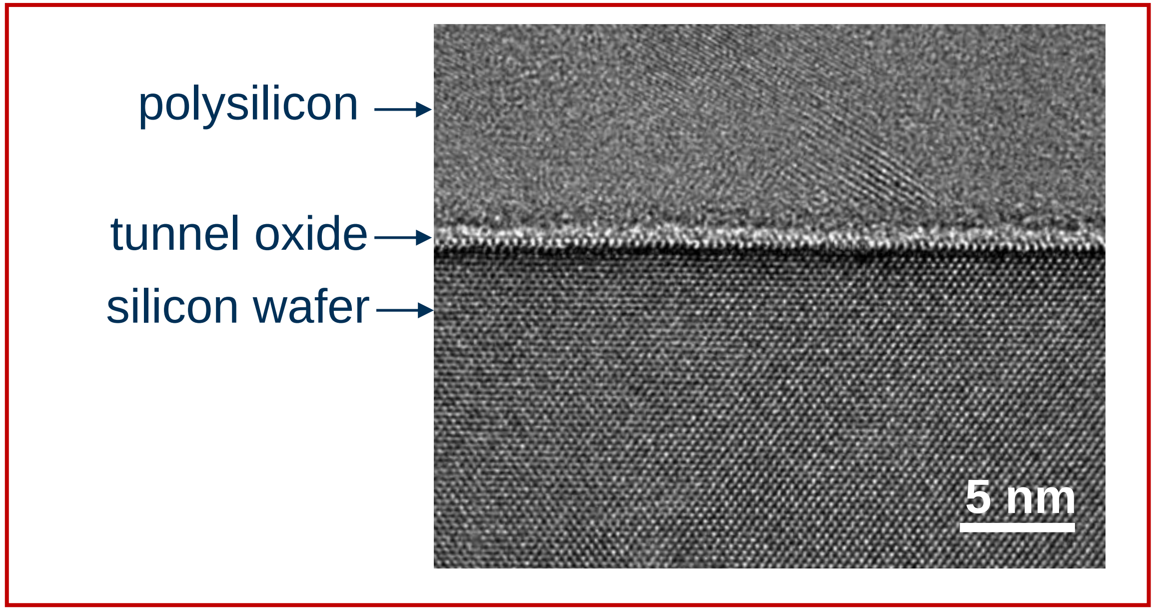
TEM Image of Tunnel Oxide Passivating Contact



High-resolution transmission electron microscopy (TEM) image



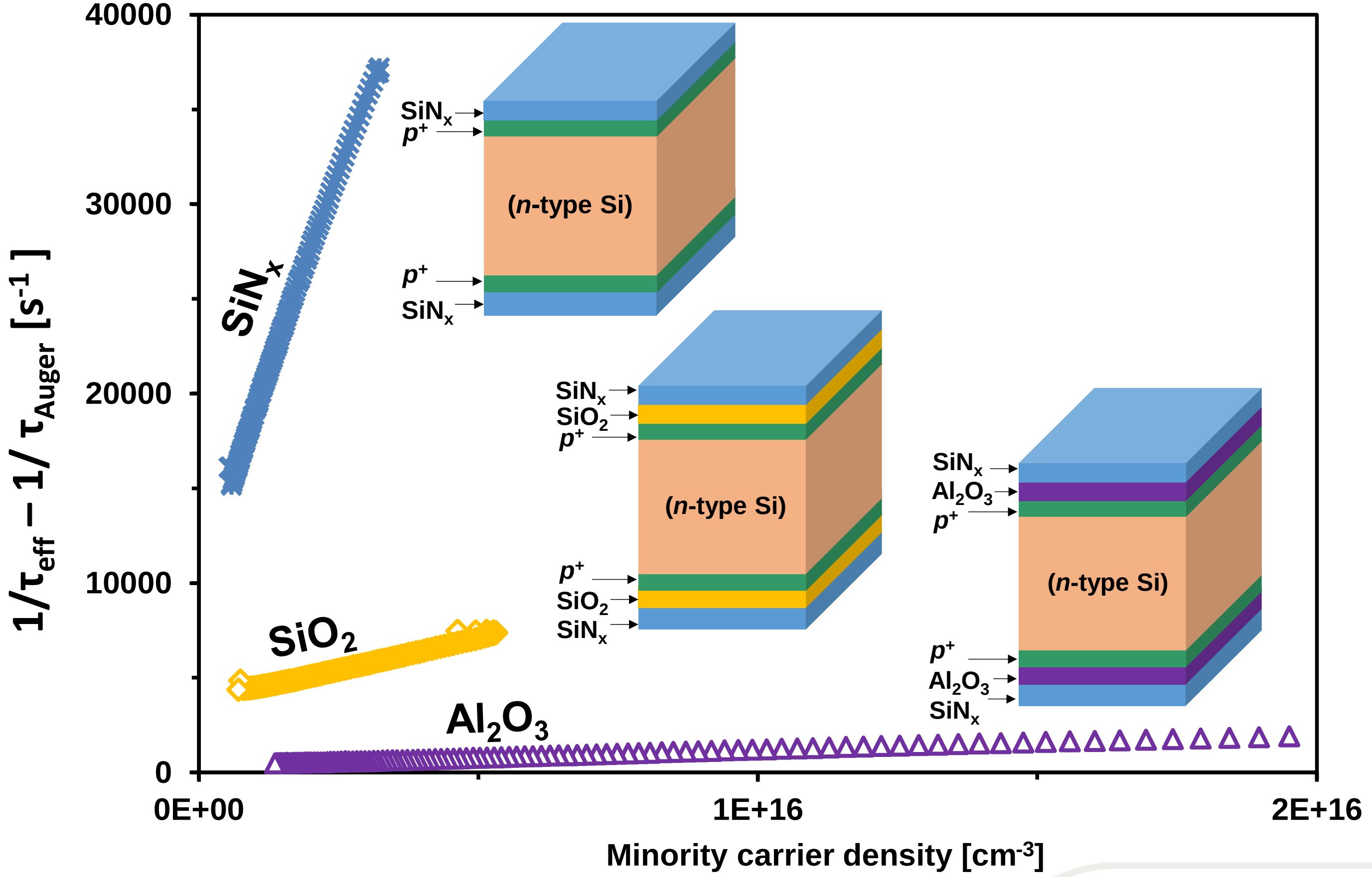
Characterization Technique to Quantify Carrier Recombination

Quasi-steady-state photoconductance (QSSPC)

$$\frac{1}{\tau_{eff}} - \frac{1}{\tau_{Auger}} = \frac{1}{\tau_{SRH}} + 2\frac{J_{0e}(N_d + \Delta n)}{q n_i^2 W}$$

τ_{eff}: measured effective excess carrier lifetime,
τ_{Auger}: intrinsic Auger lifetime
τ_{SRH}: SRH defect related bulk lifetime,
J_{oe}: emitter saturation current density,
W: wafer thickness,
Δn: excess carrier density,
q: elementary charge,
n_i: intrinsic carrier concentration,
N_d: bulk doping level.

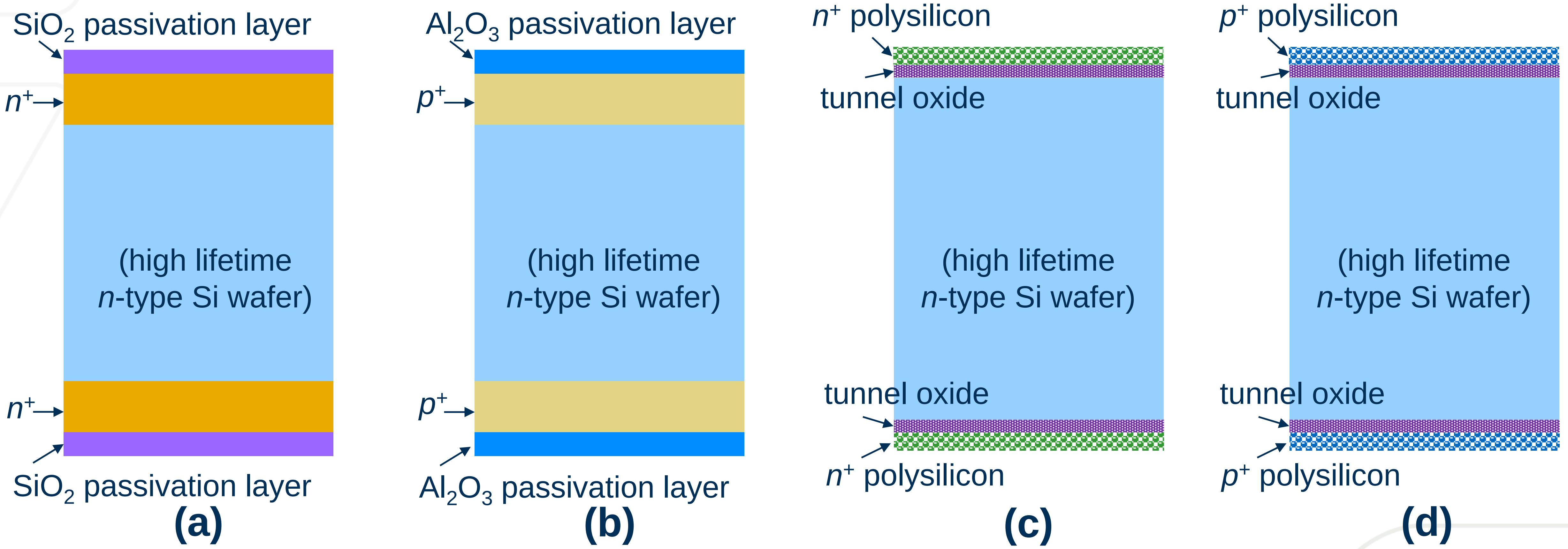
Lifetime measurement on the same p^+ emitter



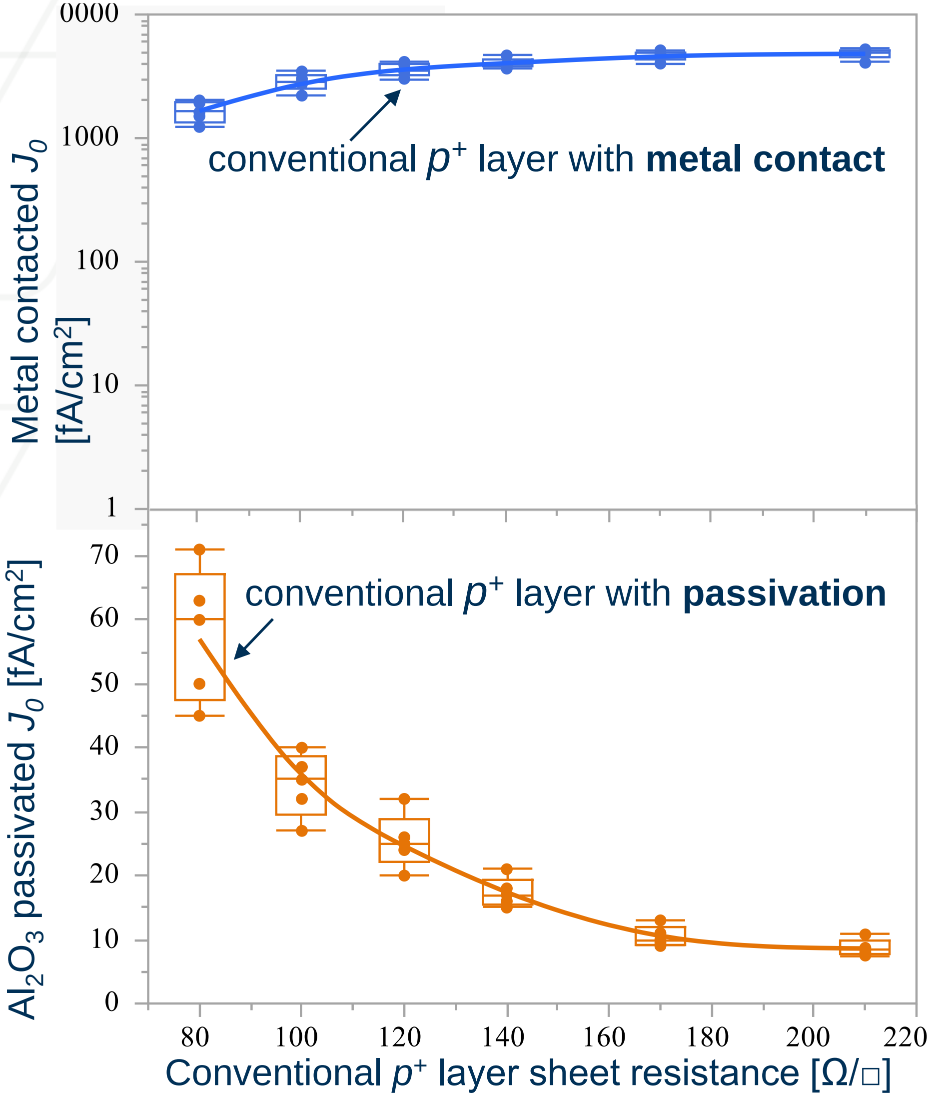
R. A. Sinton and A. Cuevas, *Appl. Phys. Lett.*, vol. 69, no. 17, 1996.

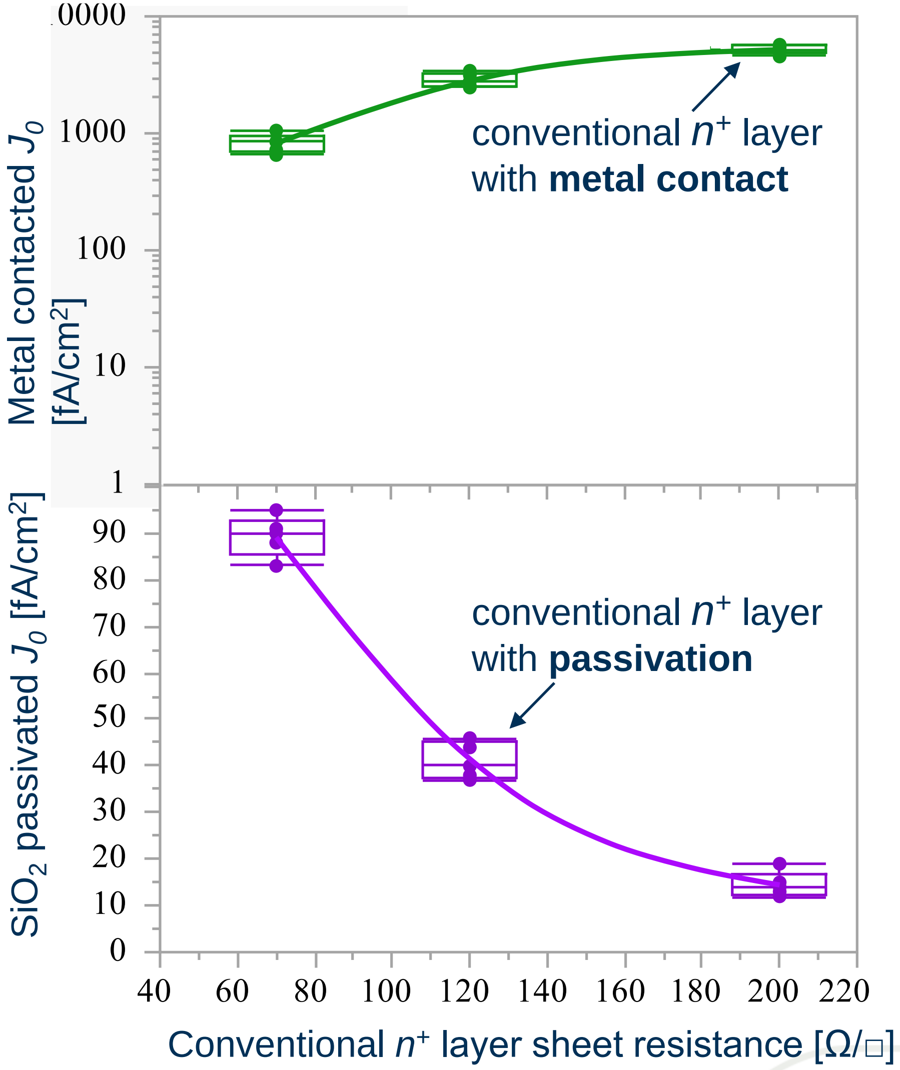
Sample Structures for Comparing Conventional n^+ and p^+ Layers with *n*-type and *p*-type Tunnel Oxide Passivating Contact

With passivation layer to measure J_0 ---- without metal



J_0 of Conventional n^+ and p^+ Layers





Sheet resistance (ohm per square) is the resistance of a square piece of a thin material. Higher sheet resistance typically indicates lower doping level, and then lower recombination.

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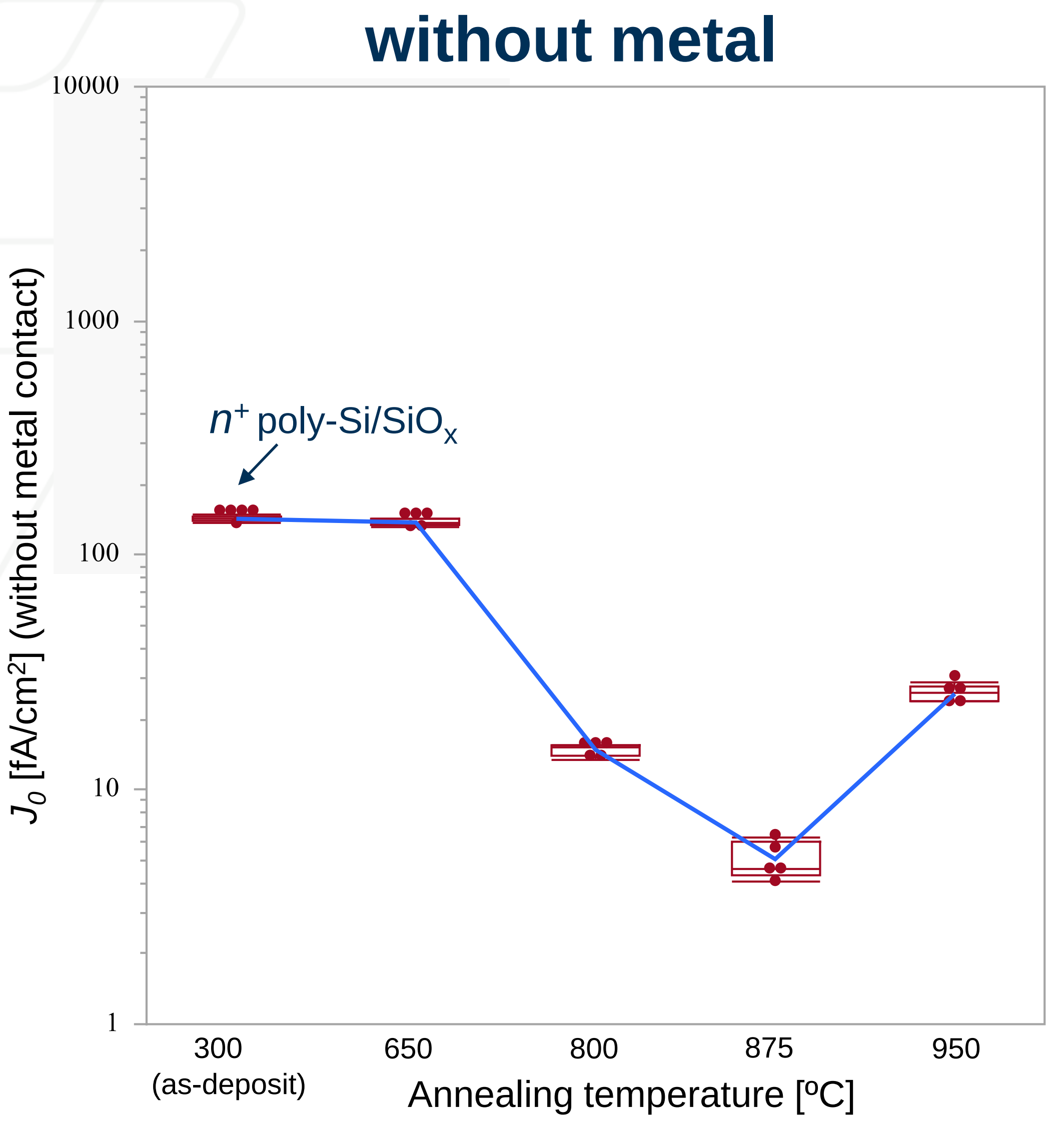
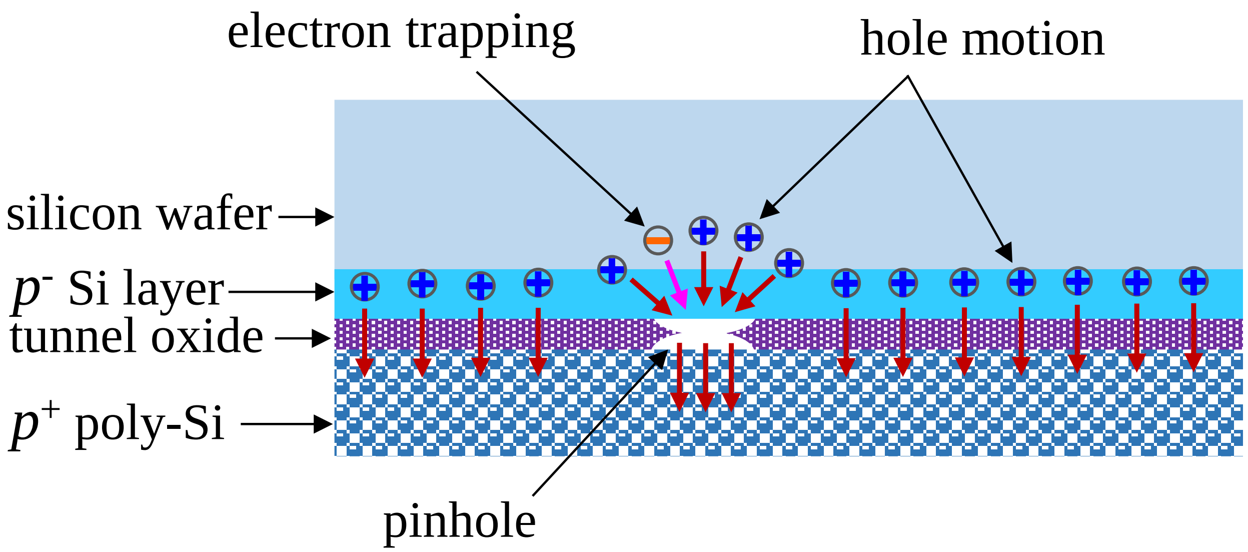
J_0 of *n*-type Tunnel Oxide Passivating Contact



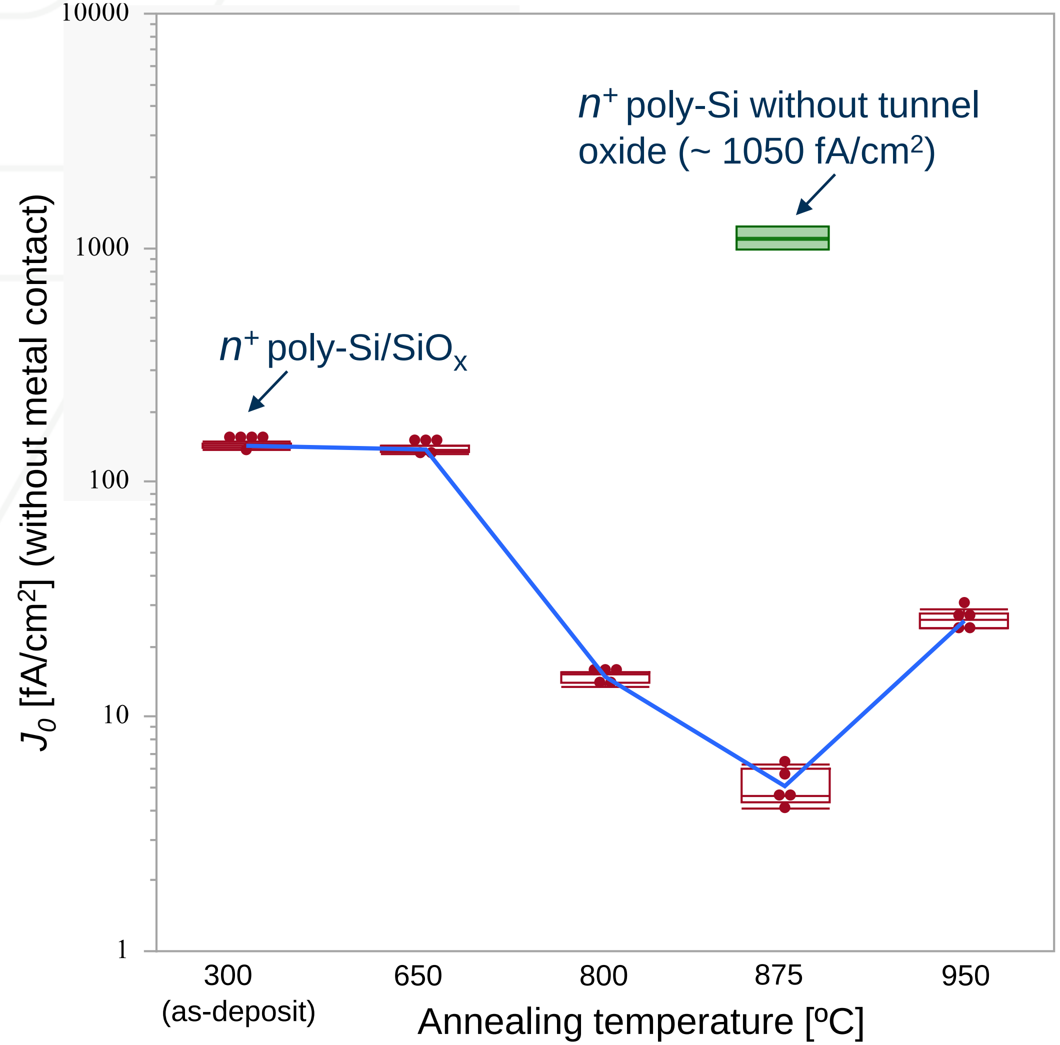


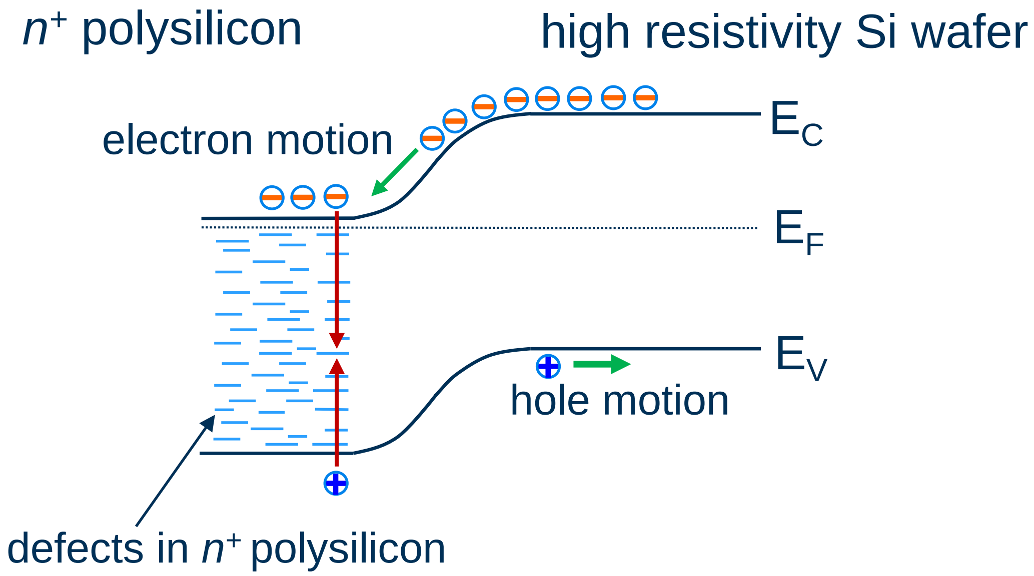
- Excessive dopant in-diffusion → increasing Auger recombination.
- High pinhole density → increasing Shockley-Read-Hall recombination (polysilicon is defect-rich material).

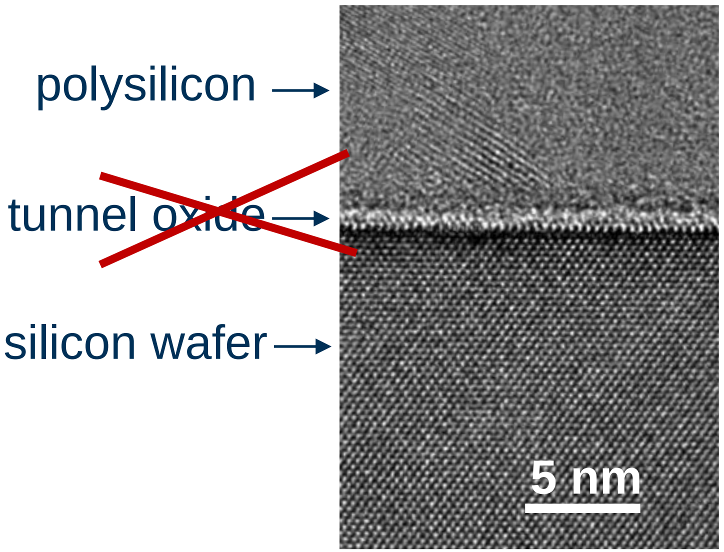
Peibst, R., *et al.*, *Solar Energy Materials and Solar Cells* 158 (2016): 60-67.

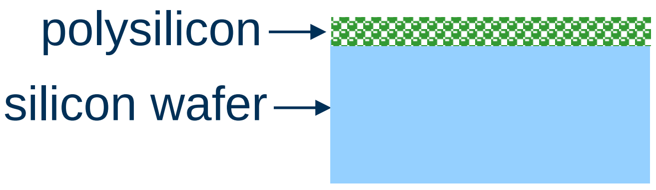
Prominence of Tunnel Oxide Layer

without metal









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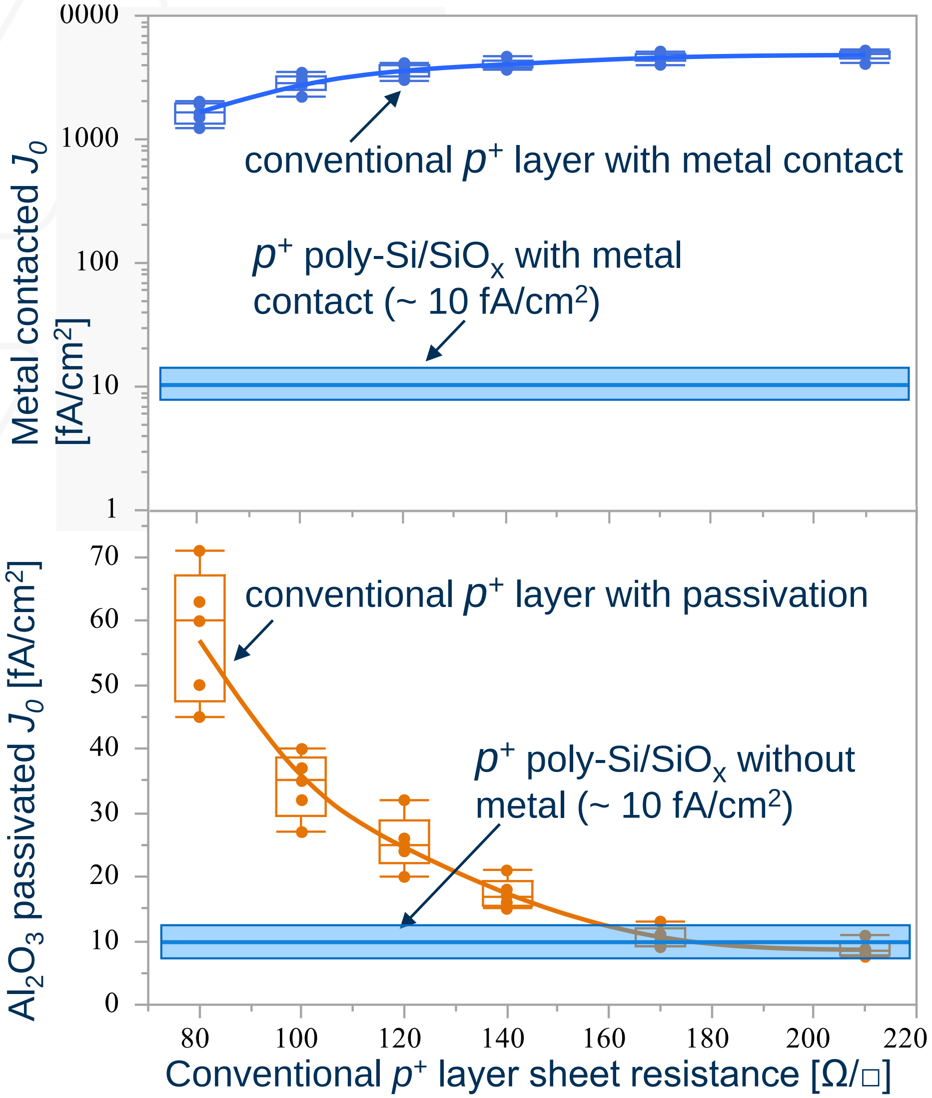
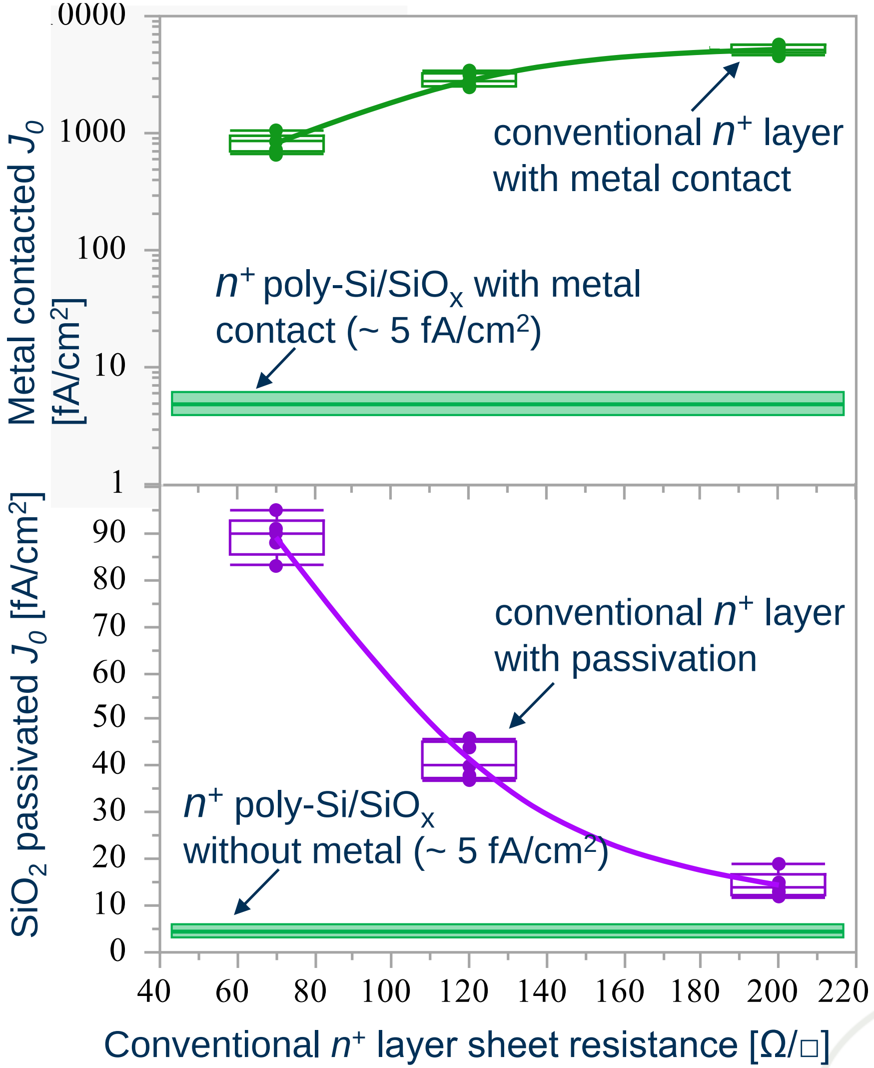
Comparison Conventional n^+ and p^+ Layers with *n*-type and *p*-type Tunnel Oxide Passivating Contact





Conclusion

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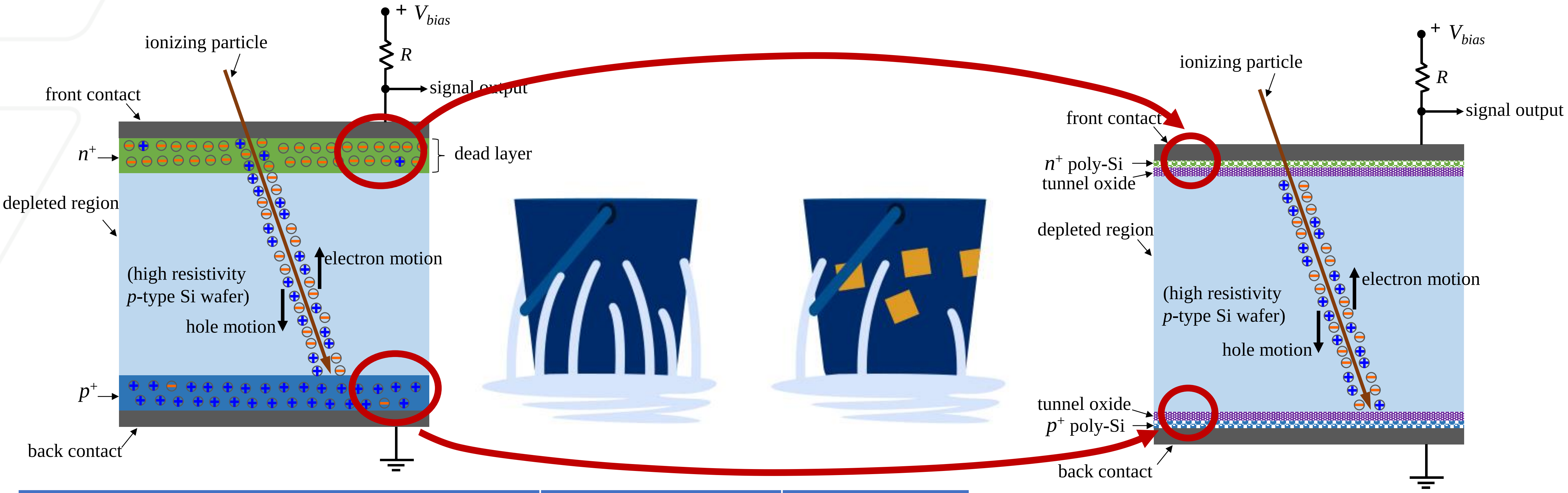
J_0 [fA/cm²]	With passivation	With Metal
Conventional n^+ layer	15 ~ 90	800 ~ 6000
n-type tunnel oxide Passivating contact	~5	~5



J_0 [fA/cm²]	With passivation	With Metal
Conventional p^+ layer	10 ~ 70	1500 ~ 6000
p-type tunnel oxide Passivating contact	~10	~10

Image courtesy: Andar Software

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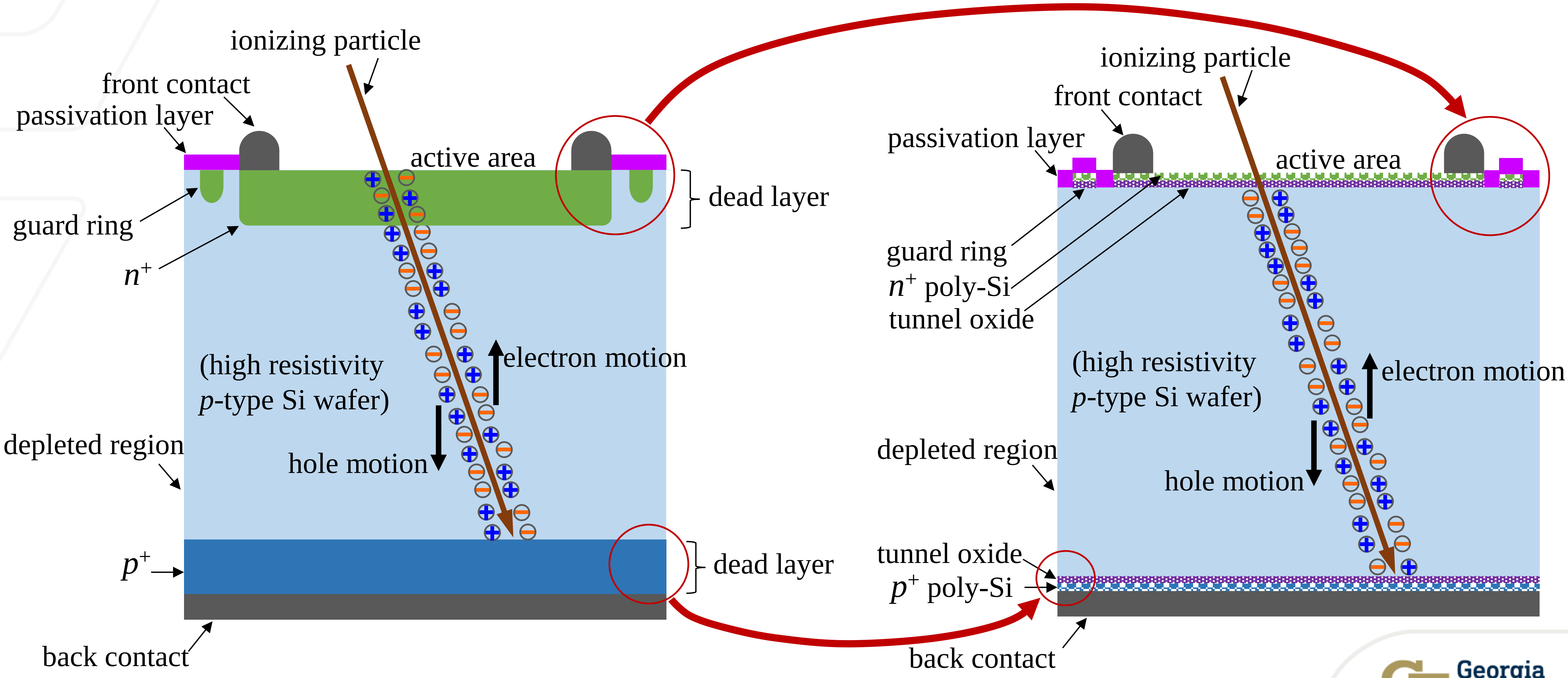
Outlook


ionizing particle
front contact
passivation layer
active area
dead layer
guard ring
n^+
(high resistivity
p-type Si wafer)
electron motion
hole motion
depleted region
p^+
dead layer
back contact
ionizing particle
front contact
passivation layer
active area
guard ring
n^+ poly-Si
tunnel oxide
(high resistivity
p-type Si wafer)
electron motion
depleted region
hole motion
tunnel oxide
p^+ poly-Si
back contact

Acknowledgement

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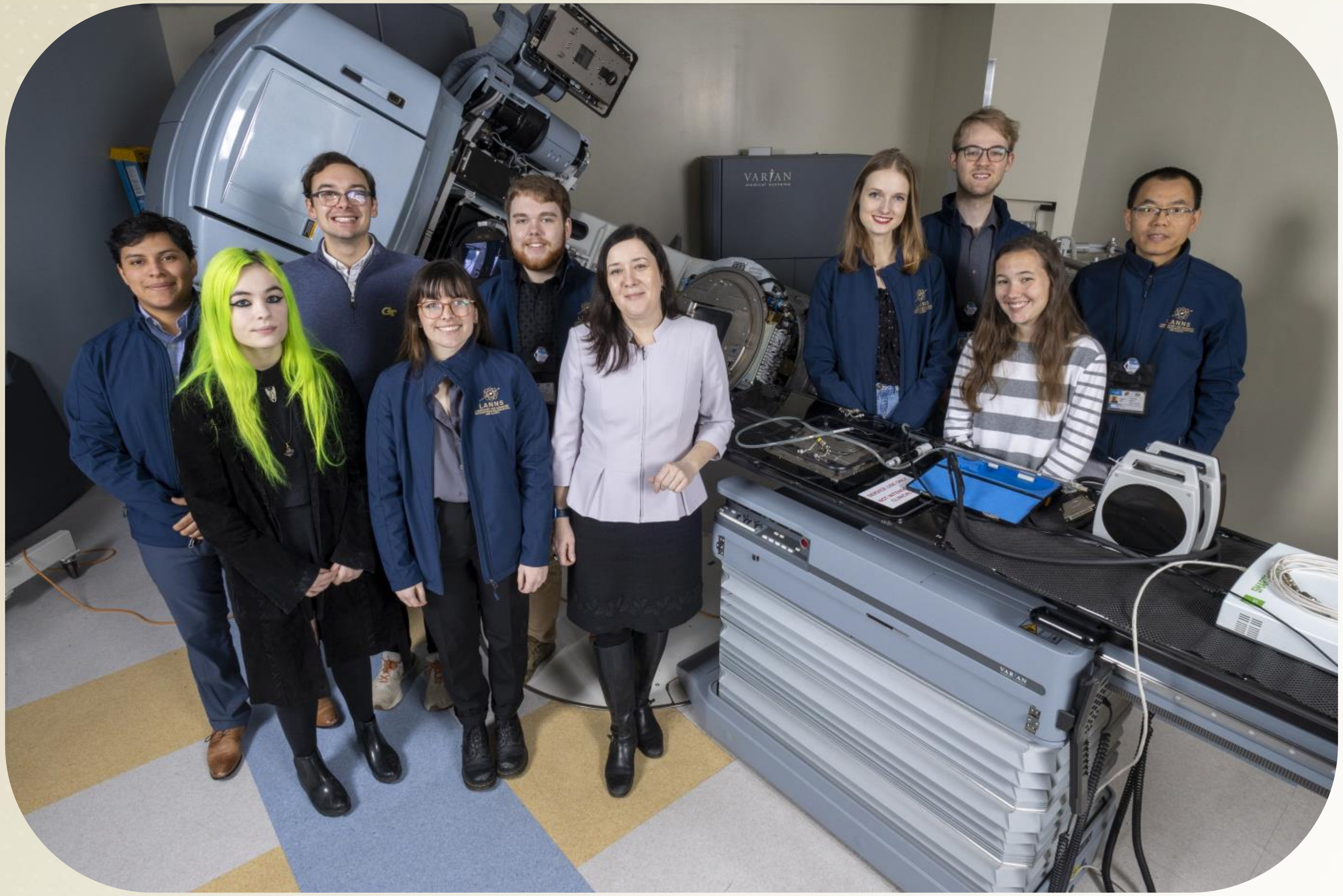
Thank you



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