NATIONAL LABORATORY OF THE ROCKIES

Silicon Cells for Space: Combinatorial Proton Degradation and Recovery Study of p-PERC and n-TOPCon

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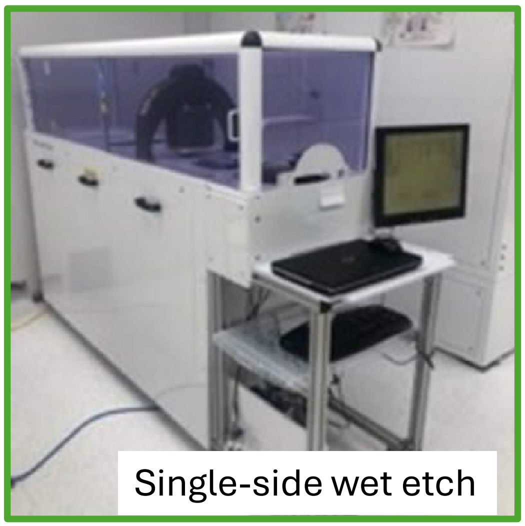
NLR

R&D facilities for silicon processing

Dedicated Silicon Cleanroom – wafer level processing tools


Automated wet bench


4-tube diffusion furnace


Single-side wet etch


3-tube low-pressure CVD and PECVD furnace

10-Chamber PECVD Cluster Tool

Gases:

SiH_4
BF_3
B_2H_6
PH_3
GeH_4
NH_3
CF_4
SF_6
C_2H_6
H_2
N_2
Ar

- Atomic Layer Deposition (ALD)
- Laser processing
- Metal deposition (evap, e-beam, screen printing)

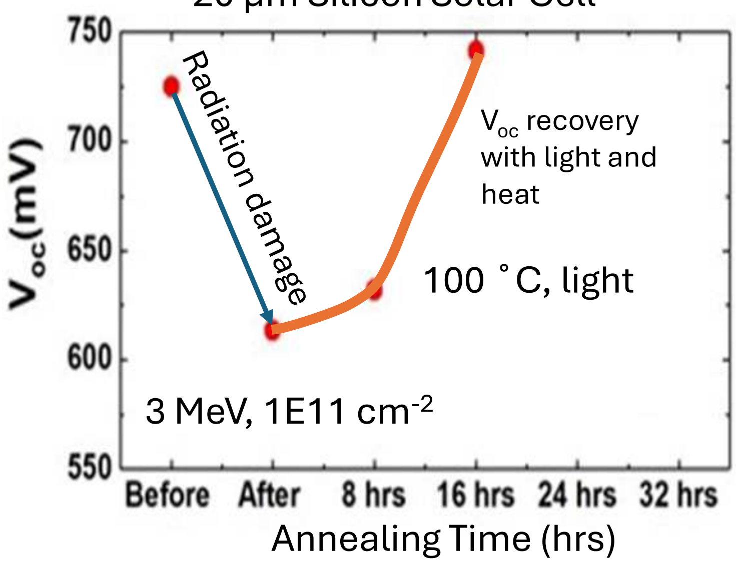
NLR -processed thin c-Si cells for space applications

Silicon for Space Applications

- Use p-type wafers
- Use Si:Ga wafers
- Thin the wafers to ~ < 30 μm
- Diffuse hydrogen into cell

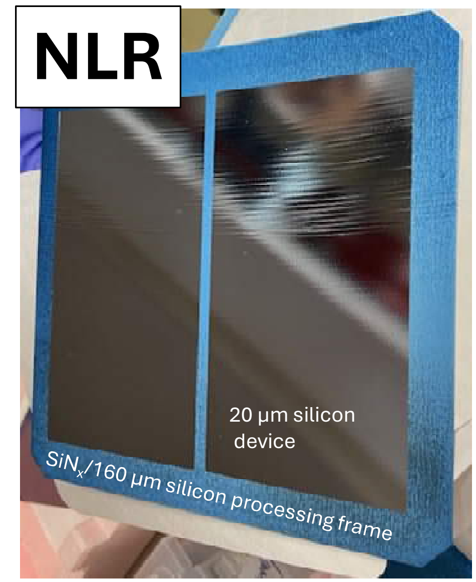
- Radiation degrades cells
- Voltage recovers after light and heat annealing

20 μm Silicon Solar Cell



Gurimaskaya et al. 2023

Commercial p-type solar cell thinned to 20 μm with Si-frame left for processing support



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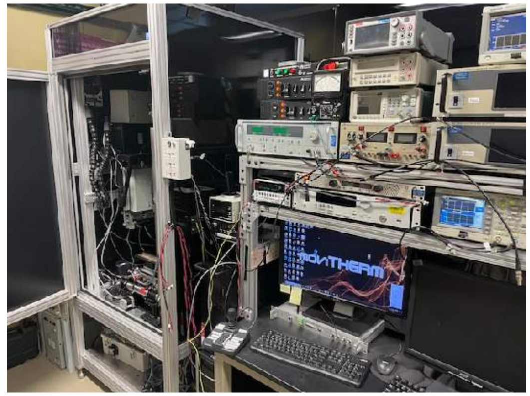
Characterization Equipment

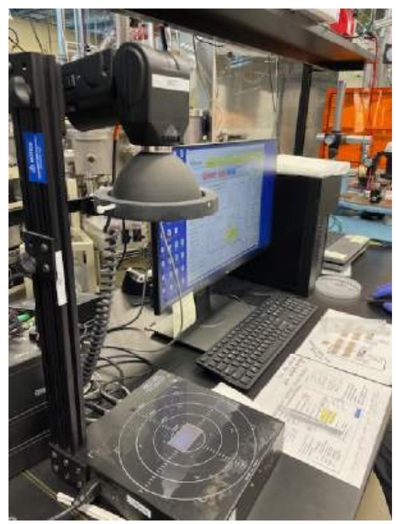
Electron Spin Resonance

Photo-, Electro-luminescence Imaging



Proton Radiation Combinatorial Beamline

Silicon carrier lifetime



<u>Other Characterization Techniques</u>

- Sinton lifetime/SunsVoc
- DC and Flash JV
- Contact resistivity
- Quantum Efficiency
- Ellipsometry
- Dark Lock-in Thermography
- Raman Spectroscopy
- UV-Vis-IR spectrometers
- Capacitance (C/V, C/f DLTS, Photocapacitance)
- Photothermal deflection spectroscopy
- SEM – FIB, EDX, EBD,EBIC, CL
- STEM – EDX, EELS, 4D Scan
- XRD
- Auger, X-ray, UV photoelectron spec
- SIMS (dynamic, TOFS)
- Rutherford backscattering
- Hydrogen Effusion
- FTIR

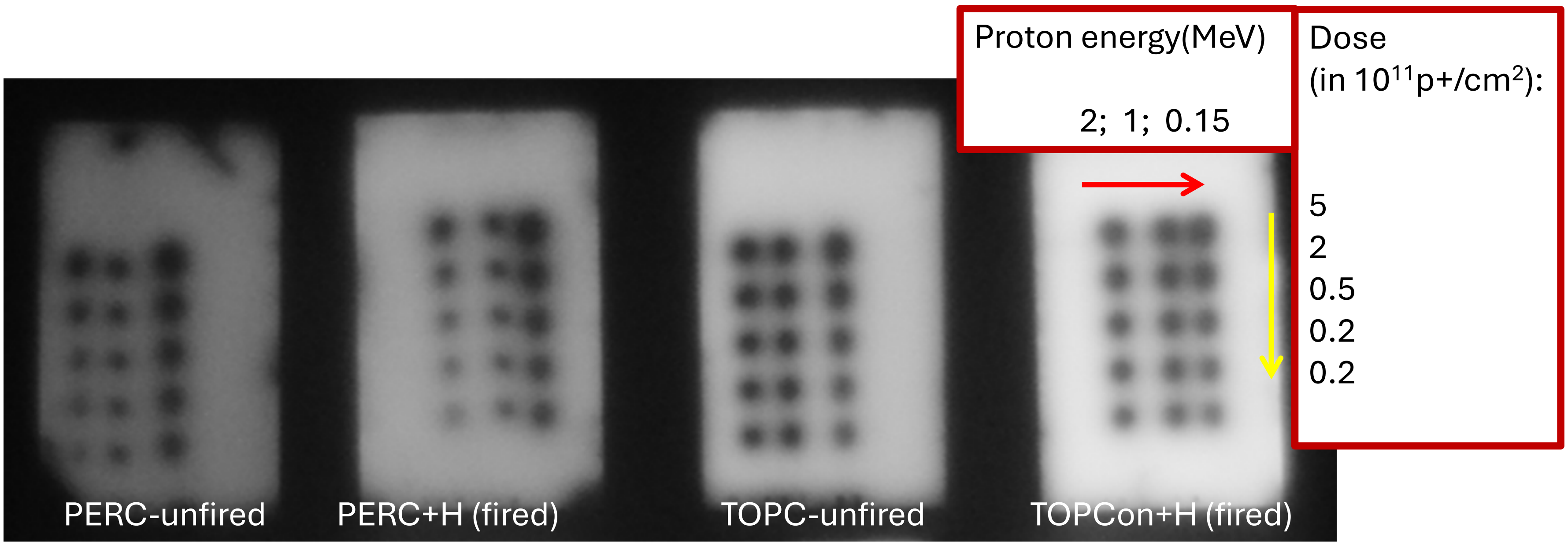
<u>Modeling</u>

- Device (Quokka3)
- Module (SunSolve)
- Physics (COMSOL)
- Radiation damage (SRIM)

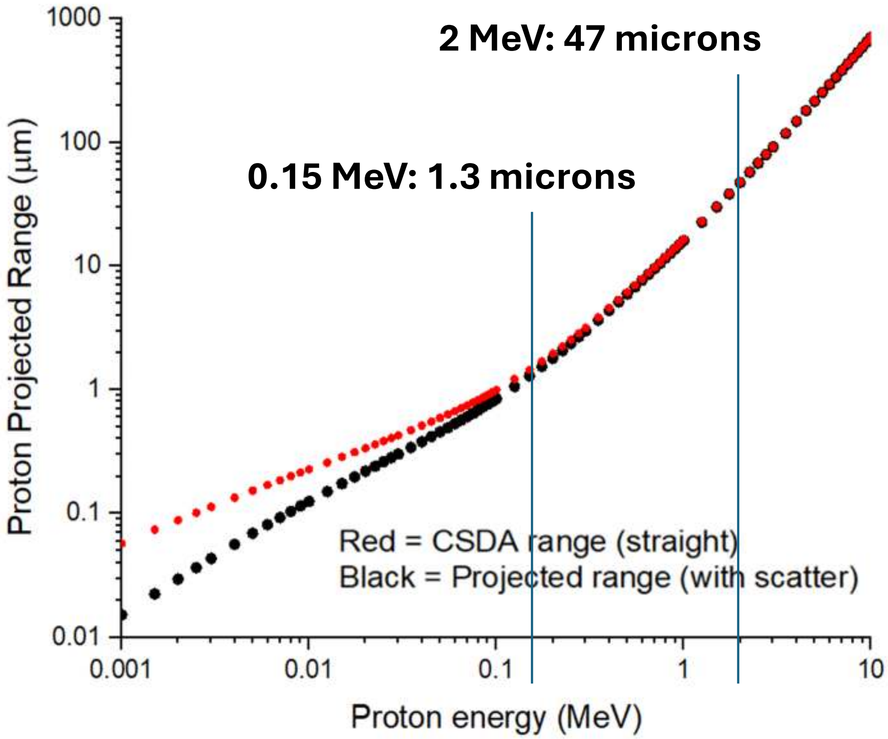
Terrestrial cells tested for space applications

Ga-doped p-PERC, and P-doped n-TOPCon cells:

Proton exposure in RBS with different energies and doses
Focus on 0.15 MeV (1.3 µm proton range in Si) and 2 MeV (47 µm range)



Proton damage is dominant in Si space cells.
Protons that end their ranges in Si, matter most:
vacancy defects are produced by the low-energy protons.



PERC –like cell (130 – 200 microns thick)

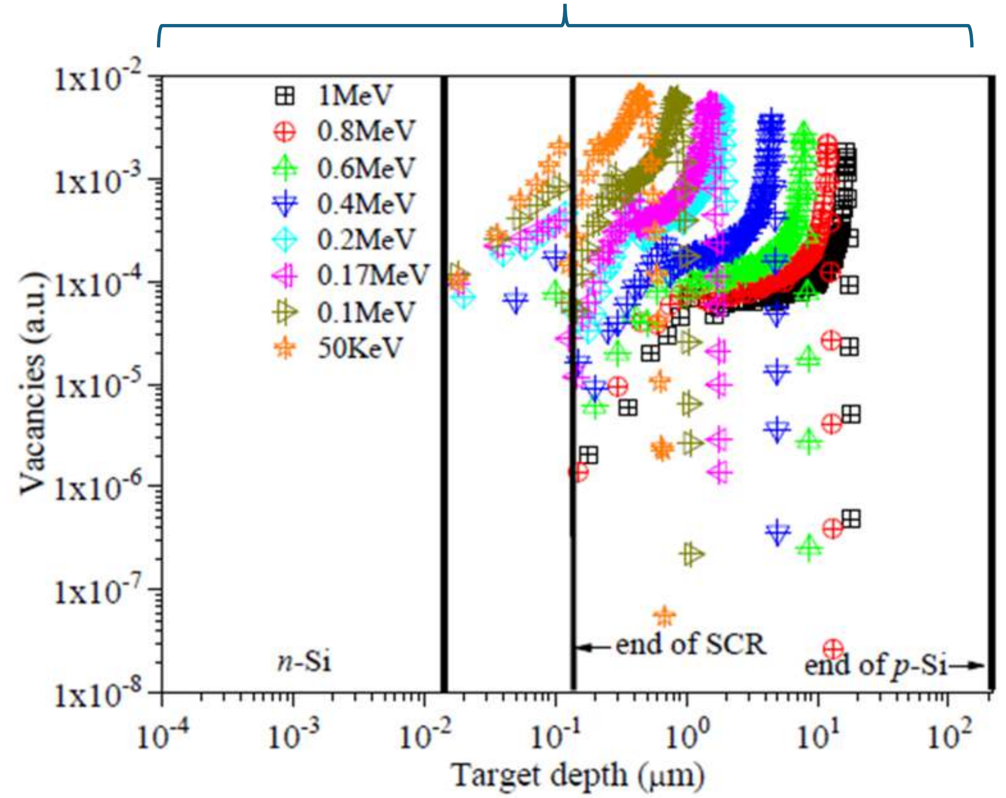
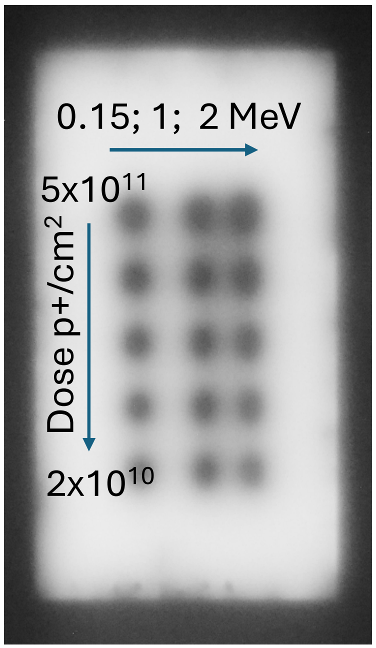


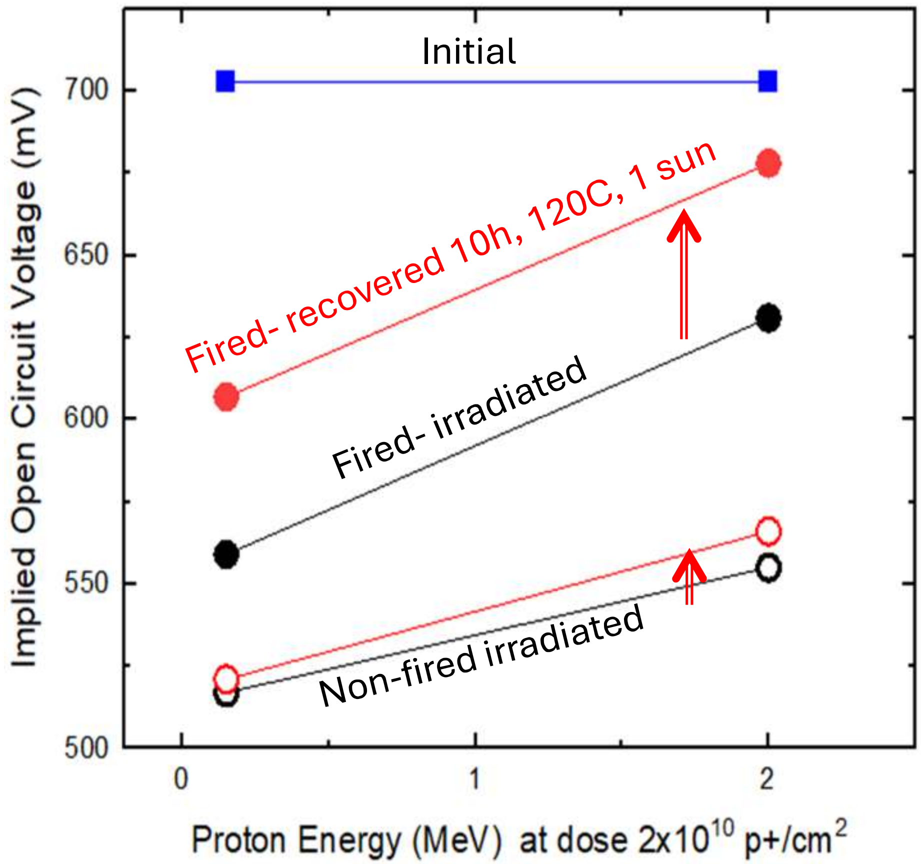
Fig. 6. Vacancies distribution for different proton energies.

P. Song et al., Infrared Physics & Technology 2022

Commercial Ga-doped PERC “blue cells” (non-metallized):
Degradation by 0.15 MeV and 2 MeV protons, dose $2x10^{10}$ p+/cm^2

Photoluminescence

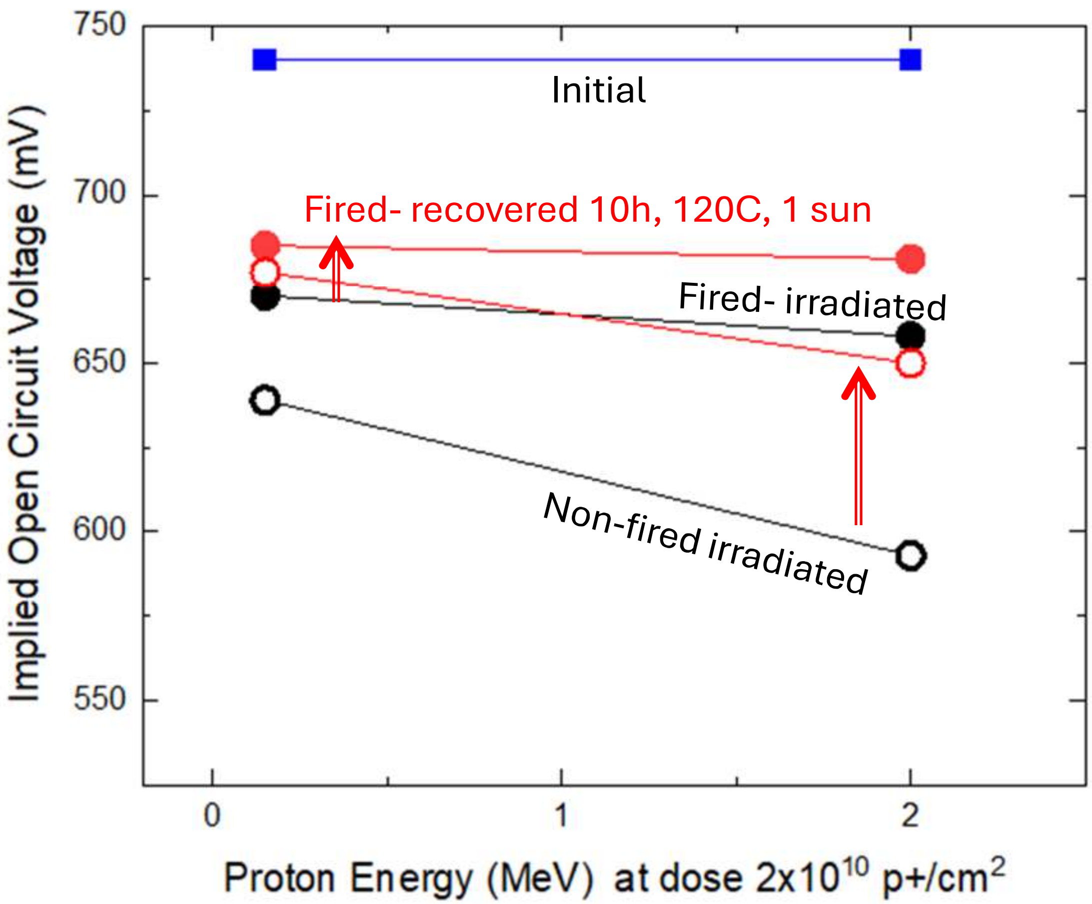




PERC cell degradation and thermal recovery (12h at 120C, 1 sun):

1. Much stronger degradation at 0.15 MeV, likely damage shallow emitter and it’s passivated interface.
2. Stronger degradation in non-fired (non-hydrogenated) PERC cells.
3. Recovery much more pronounced in fired cells, suggesting effect of H in thermal recovery under 1 sun.

Commercial Phosphorus-doped TOPCon "blue cells" (non-metallized):
Degradation by 0.15 MeV and 2 MeV protons, dose $2x10^{10}$ p+/cm^2

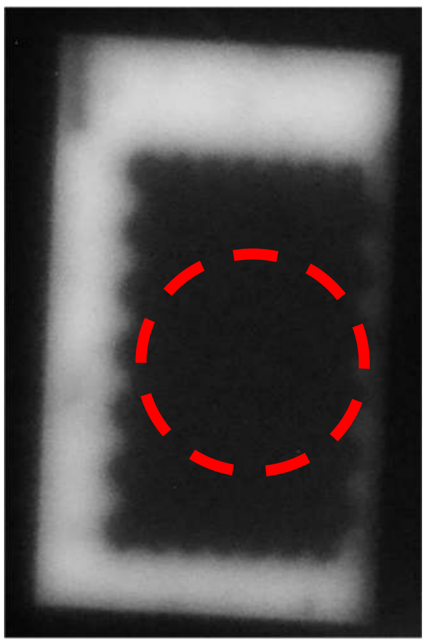


TOPCon cell degradation and thermal recovery (12h at 120C, 1 sun):

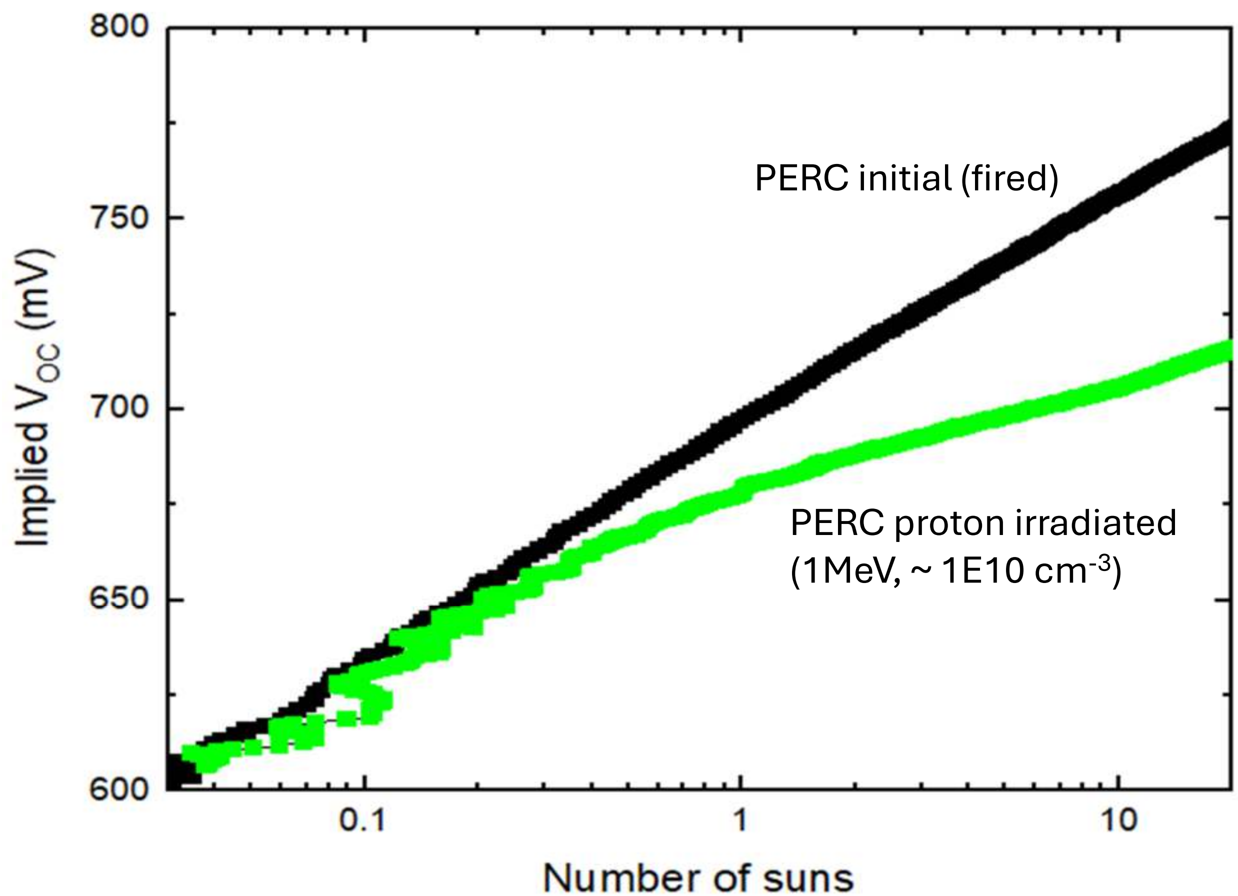
1. Weaker degradation at 0.15 MeV, likely due to ~ 1-micron thick Boron-emitter.
2. Stronger degradation in non-fired (non-hydrogenated) TOPCon cells.
3. Recovery more pronounced in un-fired cells but fired cells still retain higher voltage after recovery.

Large area proton irradiation study on fired PERC cell:

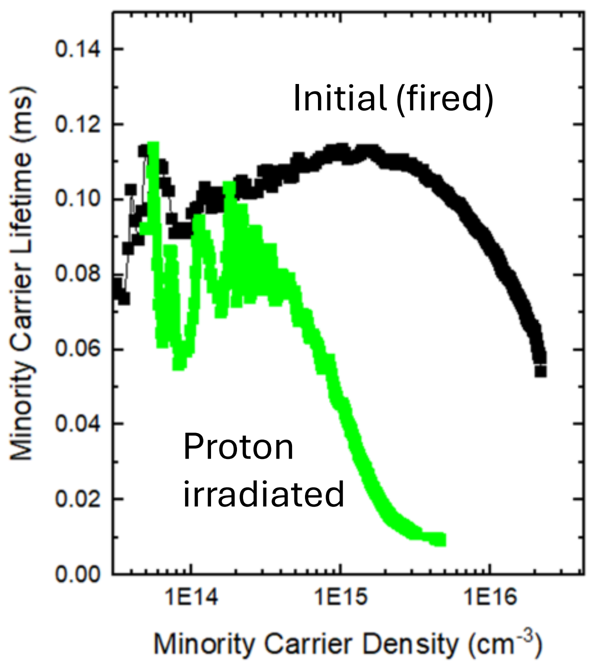
Implied V_{OC} drops significantly at high light intensities > 1 sun:
Evidence of relatively shallow defect or interface damage



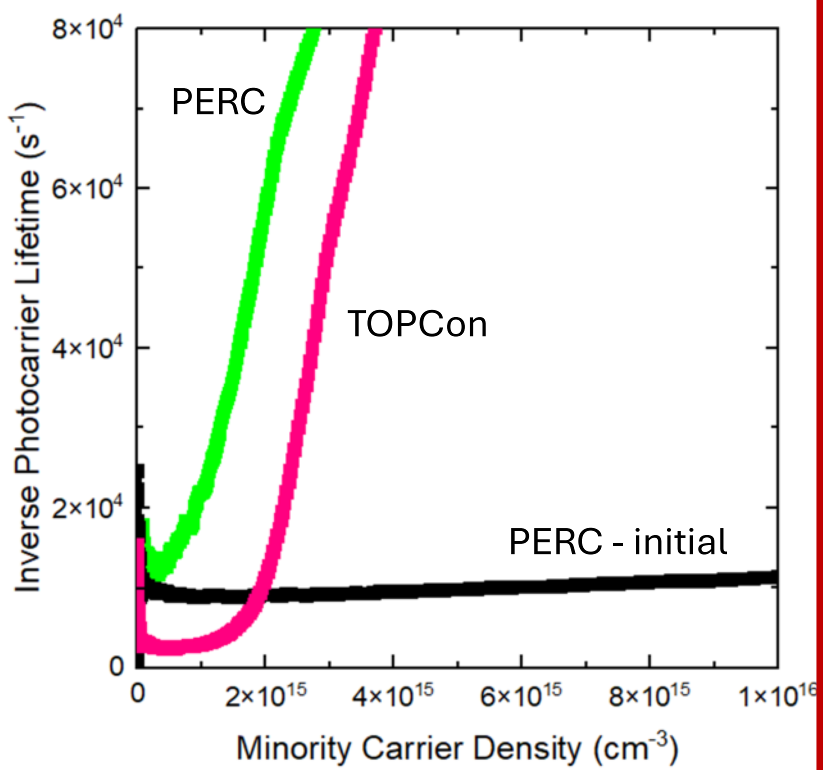
- Large area proton exposure on 3x5 cm^2 PERC cell coupon
- Measurement with Sinton WCT-120 carrier lifetime tester



Lifetime data consistent with divacancy defect ~ 0.21 eV below the conduction band of Si



Sudden drop in lifetime at injection > 1E15 cm^{-3} in PERC cell

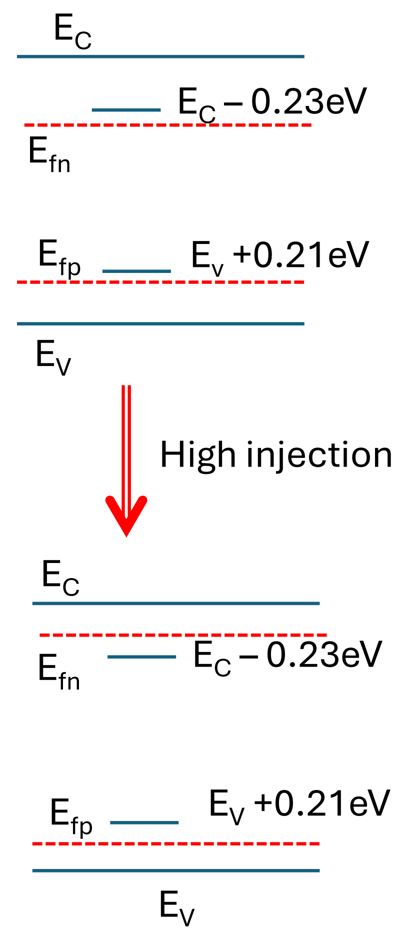


Lifetime drop at injection > 1E15 cm^{-3} in PERC cell

In TOPCon cell, at > 2E cm^{-3}

Bulk, not interface defect.

At high injection (> 0.5 suns), the divacancy defect changes from trap to recombination center in p-type Si



Conclusions

- Monochromatic, tunable proton irradiation at NLR is well suited for degradation-recovery combinatorial studies relevant to LOE. – Welcome to collaborate!
- PERC and TOPCon cells degrade and recover differently:
  - PERC cell sees more damage by low energy 0.15 MeV protons
  - TOPCon cell behaves opposite
  - In both PERC and TOPCon, hydrogenation (firing) reduces damage and enhances thermal recovery at 1 sun.
- Cell degradation for PERC and TOPCon especially pronounced at high injection levels, consistent with divacancy defect with relatively shallow both donor and acceptor levels

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