Nanocrystalline Si as a Recombination Junction Layer in Perovskite-Si Tandem Solar Cells

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Recombination Junction (RJ)

- Essential to collect charges generated in the top/bottom cells - electrons (from the top cell) recombine with holes (from the bottom cell).
- Usually **ITO** is used, however, there are several disadvantages:
  - Optical losses (reflection and parasitic absorption).
  - Necessitates additional physical vapor deposition (PVD) process between the top and bottom cell fabrication.
  - Contains **indium** - price is volatile in the supply chain and thus the amount of consumption should be as low as possible.
- In this study we replace **ITO** with an in-situ deposited ***(n)* nc-Si:H** by PECVD.
- Study the effect on device performance and contact properties at the RJ, and the evolution of the RJ properties as the *(n)* nc-Si:H thickness is varied.

Tandem Device Structure

Top cell (n-i-p configuration)

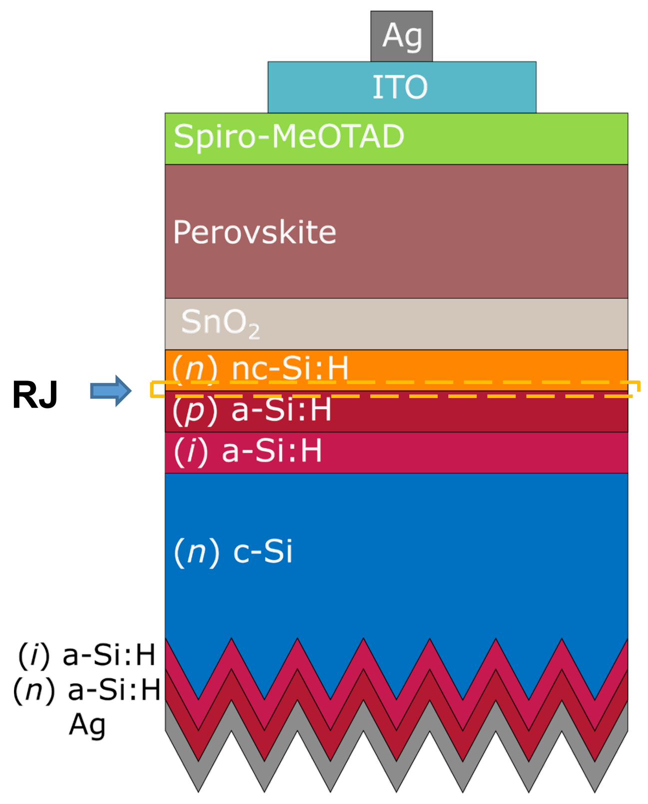
- ITO/Ag (sputtered)
- HTL: doped spiro-MeOTAD (spin-coated)
- Perovskite: $Rb_{0.05}(FA_{0.83}MA_{0.17})_{0.95}PbI_{0.83}Br_{0.17}$ (spin-coated)
- ETL: SnO_2 (spin-coated)

Recombination Junction (RJ) Layer

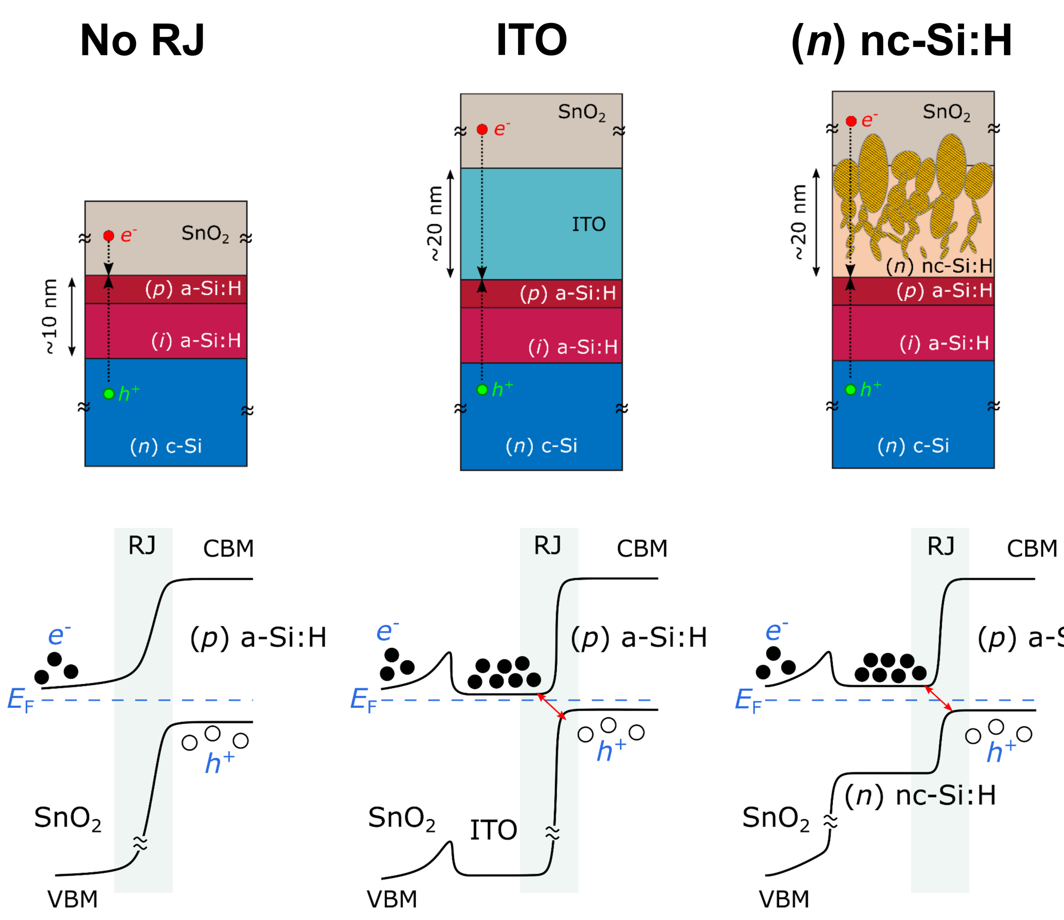
- ***n*-type nanocrystalline Si ((*n*) nc-Si:H) by PECVD**
- **Sputtered ITO**

Bottom Cell (front emitter)

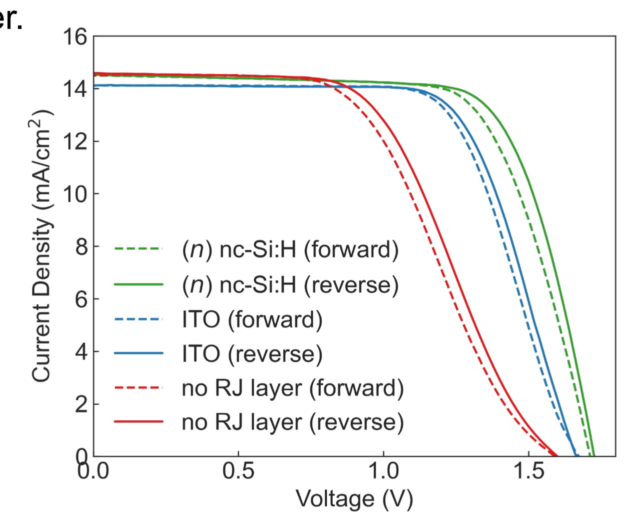
- Silicon heterojunction (SHJ)
- Textured (rear), planar (front)



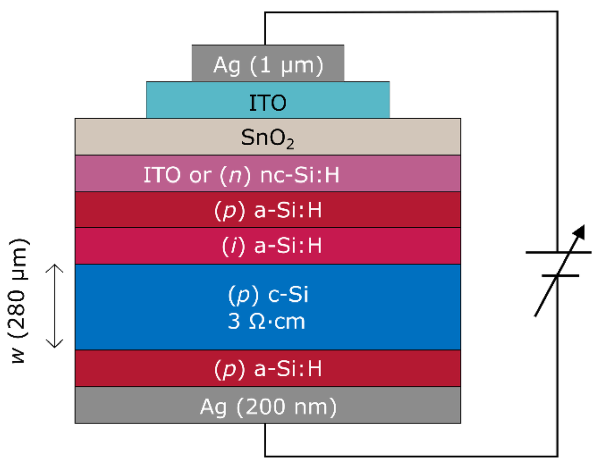
RJ Layer Contact Properties

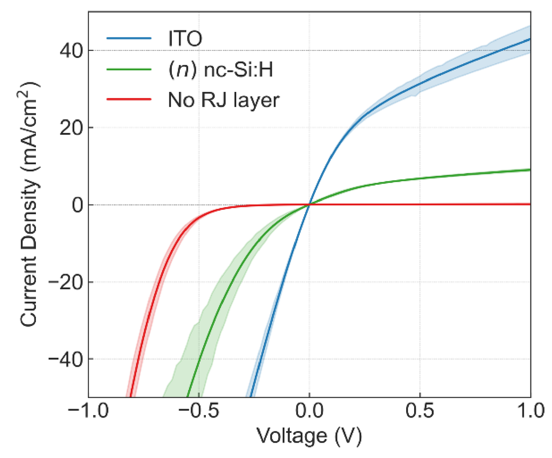


- Investigated various RJs on the solar cell device performance.
- No RJ layer exhibits S-shape due to charge carrier depletion at the SnO_2/(*p*) a-Si:H interface.
- (*n*) nc-Si:H RJ layer exhibits slightly superior J_{SC} than the ITO RJ layer due to reduced interfacial reflection at the RJ layer.



Dark IV through RJ



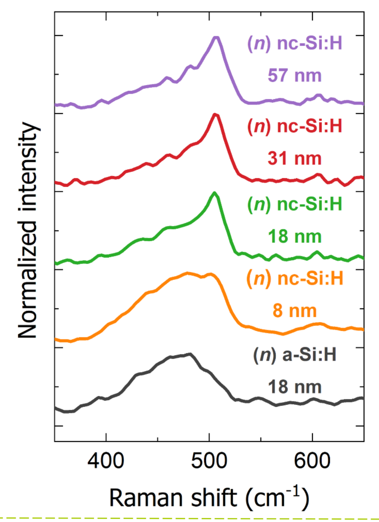


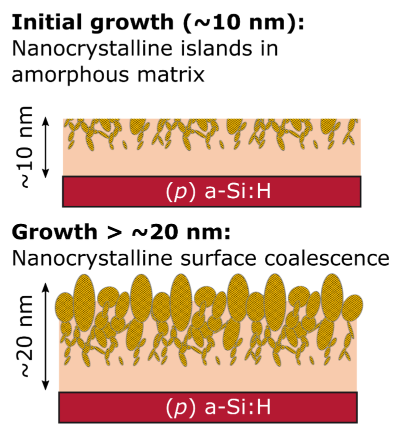
- A test structure was fabricated for characterizing recombination current (electrons supplied from SnO_2, and holes from Si).
- No current should flow in the forward bias for the ideal RJ, whilst reverse bias should exhibit high conductivity.
- No RJ layer results in high resistivity at low voltages (<-0.4 V), explaining the S-shape illuminated IV.
- RJ layer (ITO, (*n*) nc-Si:H) facilitates current flow at low voltages through the RJ.
- ITO RJ layer exhibits significant shunting in the forward bias (reverse bias in the solar cell), possibly causing a lower V_{OC}.

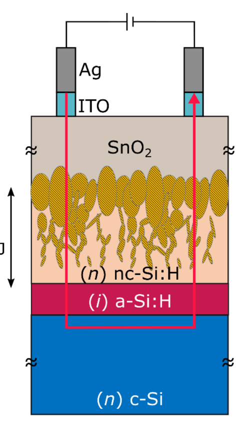
(*n*) nc-Si:H Thickness Dependence

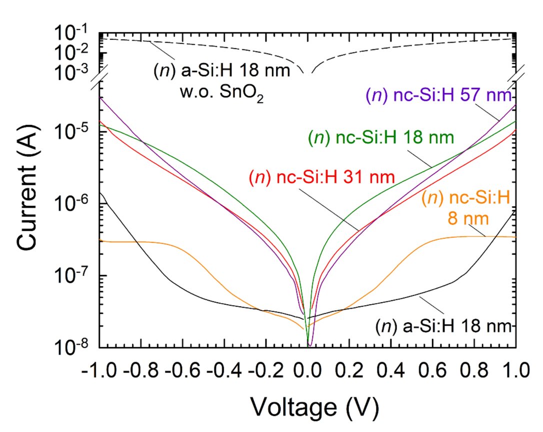
UV (λ=325 nm) Raman Spectroscopy

- Crystallization is identified at ~10 nm, but nc-Si:H layer still exhibits amorphous-rich character.
- Above ~20 nm the layer exhibits nanocrystalline surface coalescence.
- Umishio et al. found that full nanocrystalline surface coalescence can occur at ~15 nm. [1]





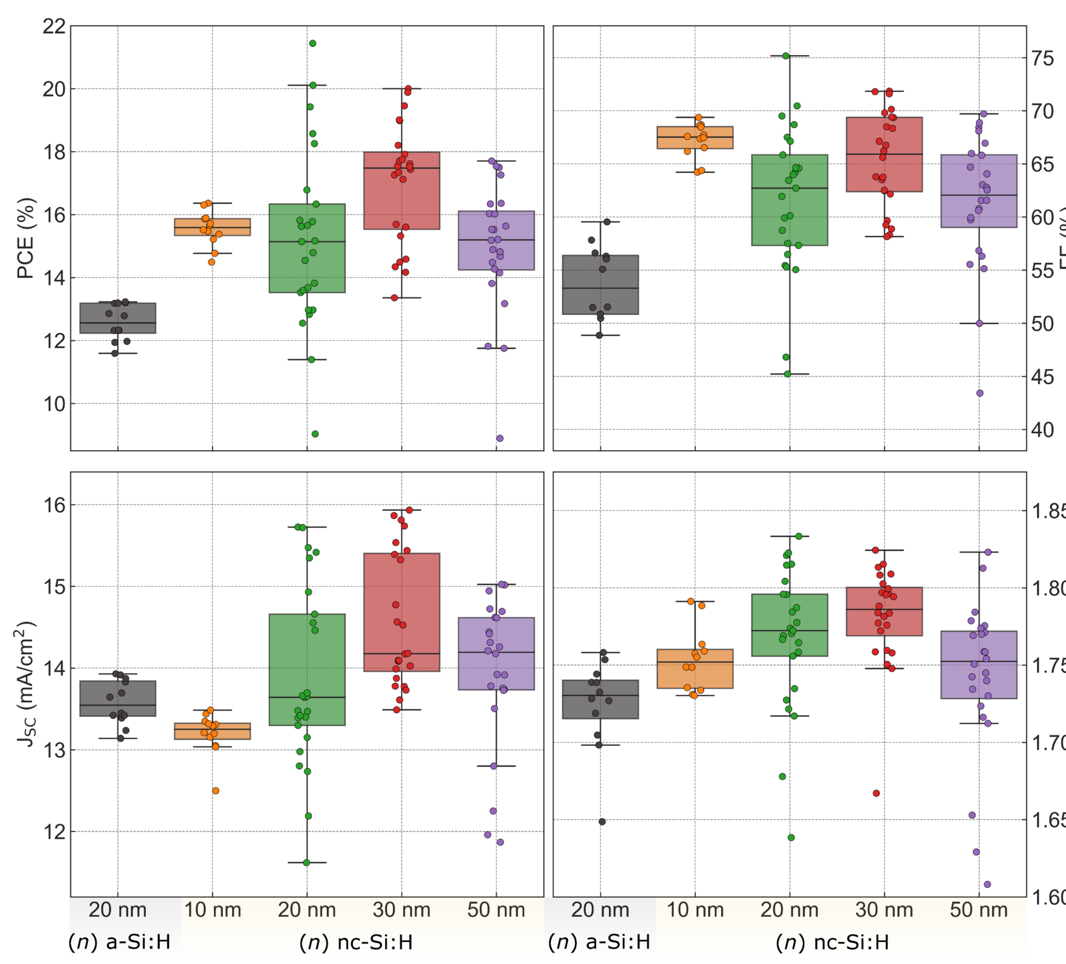




Coplanar Dark I-V Measurement

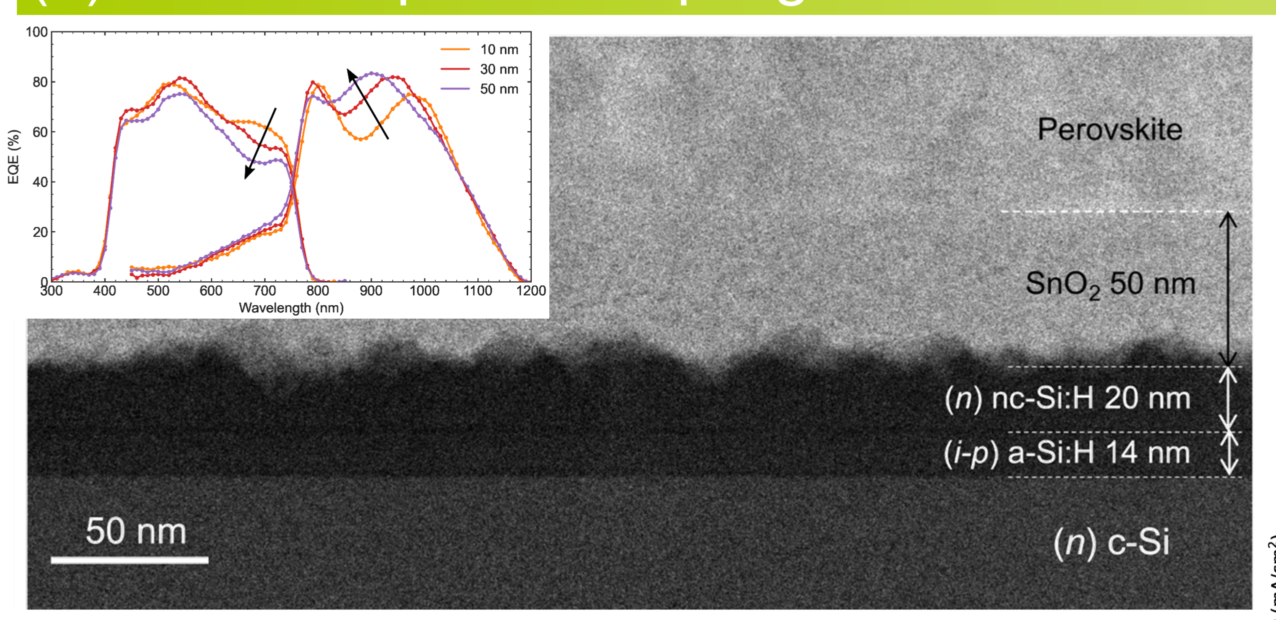
- (*n*) nc-Si:H RJ layer ~10 nm exhibits high contact resistivity and is similar to amorphous Si.
- (*n*) nc-Si:H RJ layer ~20 nm and higher leads to nanocrystalline surface coalescence which results in lower contact resistance.

(*n*) nc-Si:H Thickness– Device Performance



- (*n*) nc-Si:H outperforms (*n*) a-Si:H RJ for any thickness.
- 20-30 nm (*n*) nc-Si:H RJ layer tends to give superior performance.
- We observe a decrease in reflection as (*n*) nc-Si:H increases from 10 nm to 30 nm which results in higher J_{SC}.
- Lower FF, J_{SC} and V_{OC} for ~50 nm due to current mismatch due to J_{SC} limited by the top cell.

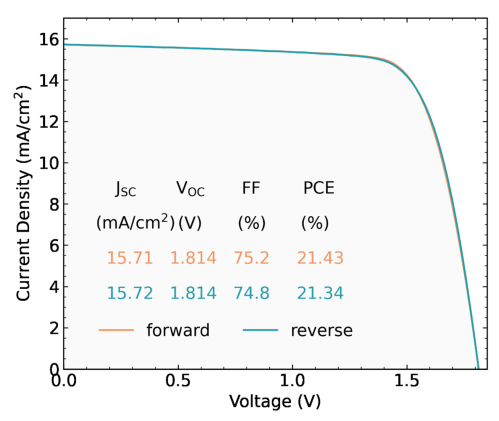
(*n*) nc-Si:H Optical Coupling

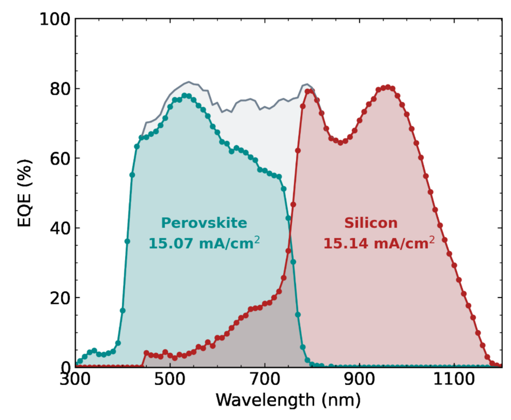


- Scanning TEM revealed a surface roughening (~ 10 nm) of the (*n*) nc-Si:H layer.
- Interfacial mixing layer between (*n*) nc-Si:H and SnO_2 provides a refractive index grading, acting as an optical coupler.
- Perovskite/SnO_2 interface is smooth.

Champion Device Performance – 20 nm RJ layer

- Highest device performance was achieved with a **20 nm (*n*) nc-Si:H RJ layer (~21%).**
- These are unoptimized device for studying the (*n*) nc-Si:H RJ.
- J_{SC} is strongly limited by reflection and parasitic absorption in the thick spiro-MeOTAD layer (~200 nm).
- Device optimization in current configuration has been demonstrated with efficiency >27%. [2]
- See [3] for published results in full.





Conclusion

- (*n*) nc-Si:H RJ performed superior to ITO RJ, non-optimized cells achieved efficiencies of ~21%.
- Interfacial reflection at the RJ can be controlled by varying the (*n*) nc-Si:H thickness.
- nc-Si:H and SnO_2 ETL can provide a refractive index grading, acting as an optical coupler.

References

[1] ***Prog. Photovolt. Res. Appl.***, 2021, **29**, 344–356.
[2] ***Energy Environ. Sci.***, 2021,**14**, 4377-4390.
[3] ***Appl. Mater. Interfaces***, 2022, **14**, 33505–33514.

Acknowledgements

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