10th Tartu Hydogen Days

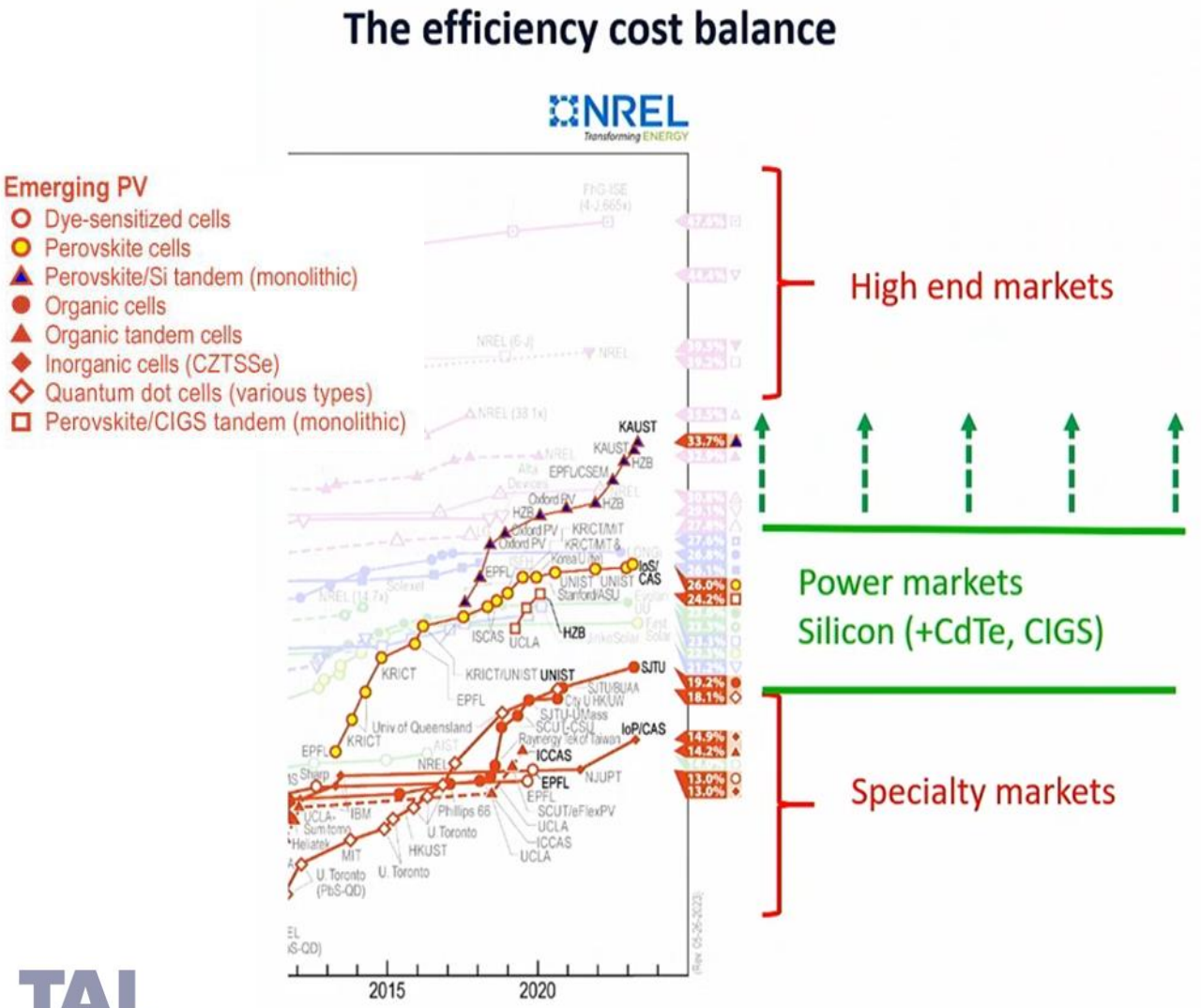
Sb_2S_2 õhukesekilelised päikesepatareid-materjalide arendusest rakenduseni

Ilona Oja Acik

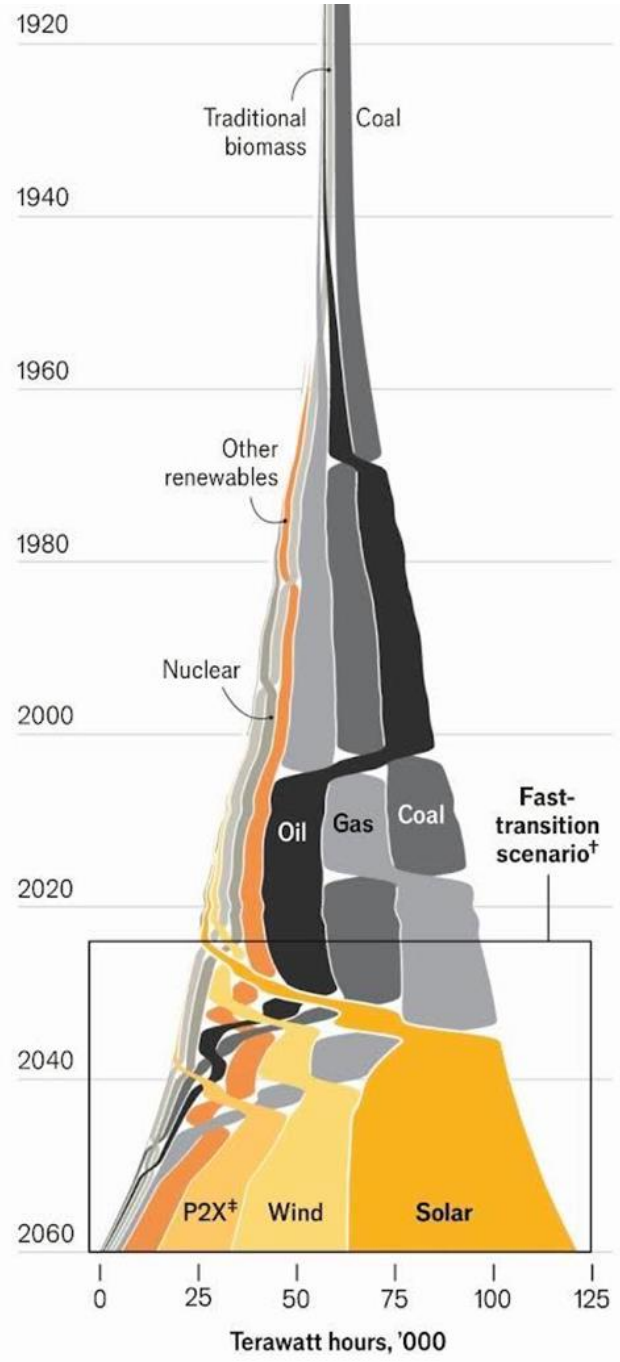
Õhukesekileliste energiamaterjalide teaduslabor

Tallinna Tehnikaülikool

Introduction

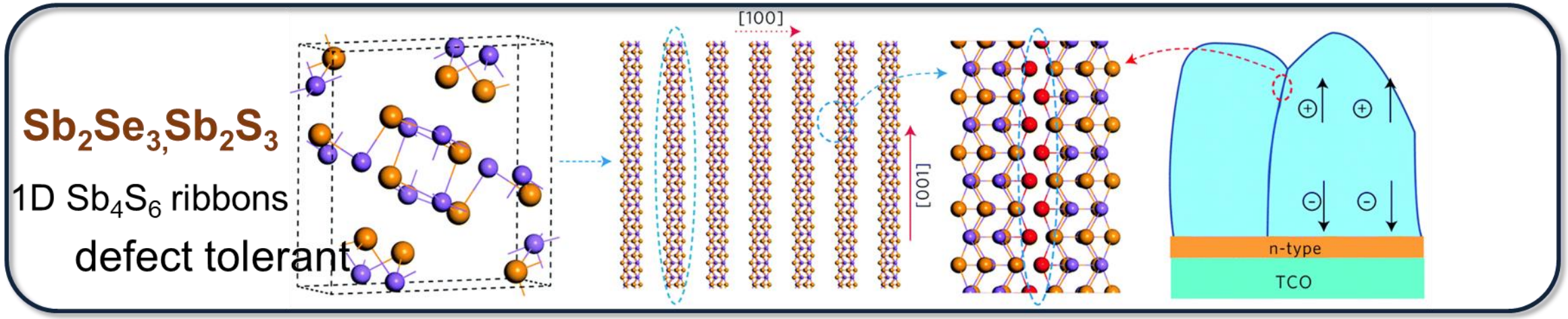


Rutger Schlatmann, presentation EU-PVSEC, 2024



The Economist, The Sun Maschines, 06 21 2024

The Choice for Antimony- Based Chalcogenide



From: Y. Zhou *et al, "Thin film Sb_2Se_3 photovoltaics."* Nat. Phot., 2015, 9, 409.

Sb_2S_3 structure consists of quasi 1D $(Sb_4S_6)_n$ ribbons.
Covalent bonding is dominant within ribbon.
Van der Wales forces between the ribbons.

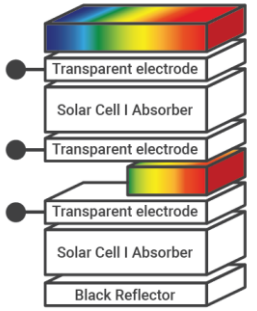
$Sb_2(S,Se)_3$

- Se, Sb abundant in nature
- α >10^5 at 450 nm
- E_g ~ 1.1–1.7 eV
- Record PCE ~11 %

Sb_2S_3

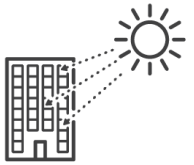
- S, Sb abundant in nature
- α ~ 1.8*10^5 at 450 nm
- E_g ~1.7 eV
- Record PCE ~8.2% (1,5 AM)
- Record I-PCE ~20% (1000 lux, LED (3000K)
- Layer thickness 50-300 nm

Tandem Solar Cell



Bifacial Solar Cell

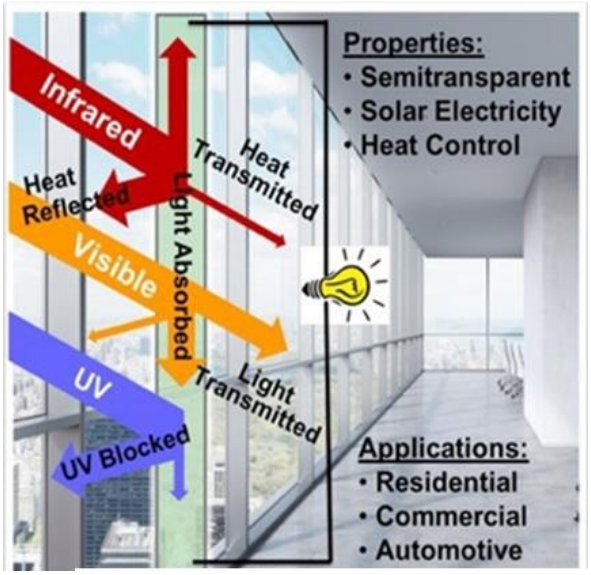
Semi-transparet BiPV



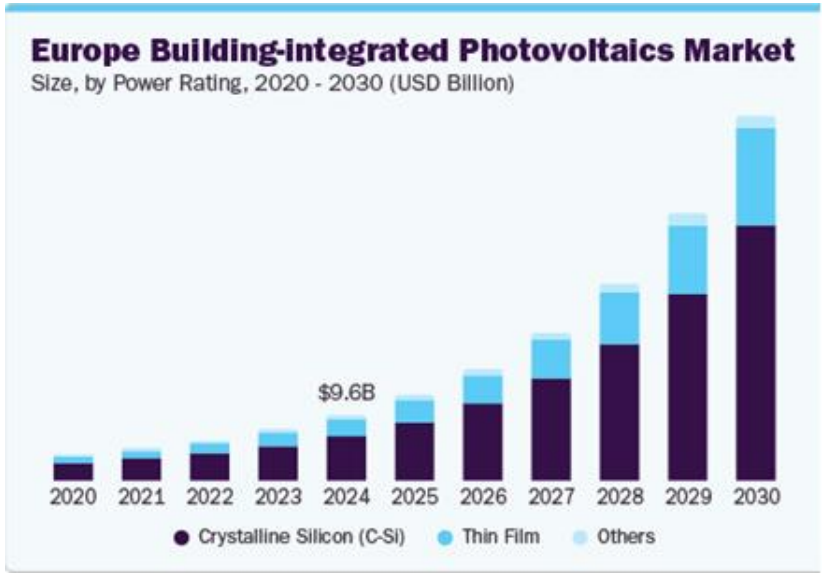
PV Powered IoT

Prospective applications of Sb_2S_3 absorber solar cells

Solar windows

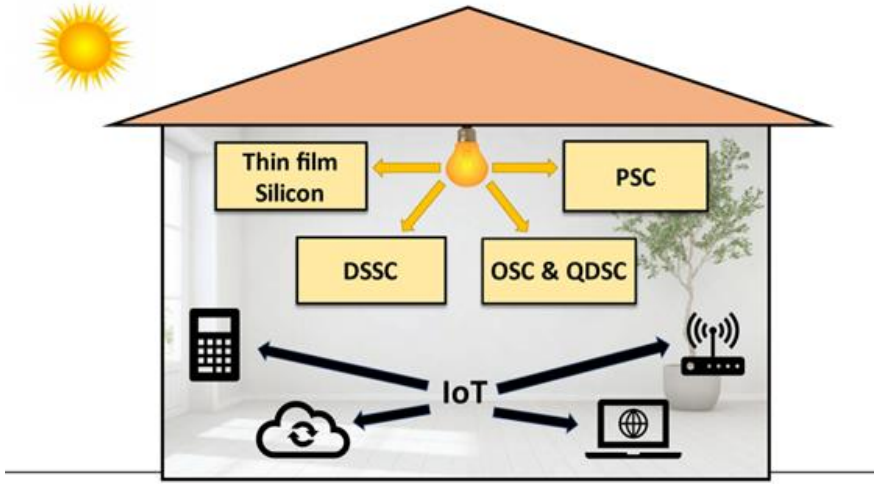


Sun et al., Joule, 2, 2018, 1816

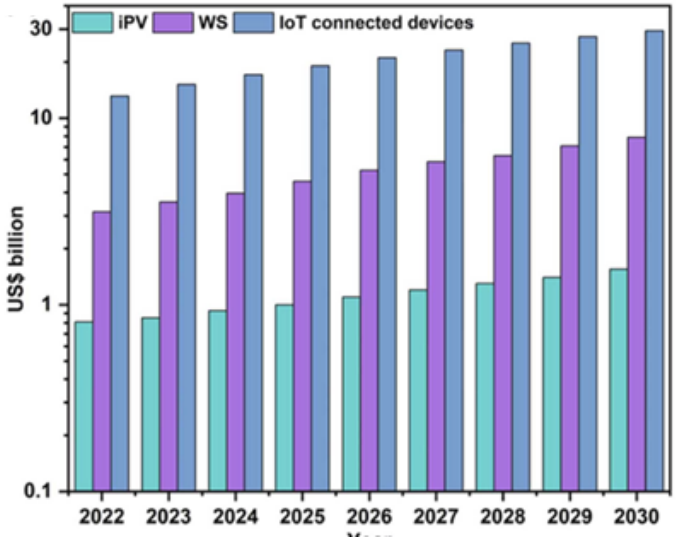


Grand View Research, Europe Building-integrated Photovoltaics Market, 2025–2030 (accessed 7 October 2026)

Indoor PV (IPV)



S. Mishra En. Advances, 1 (2022) 11, 761

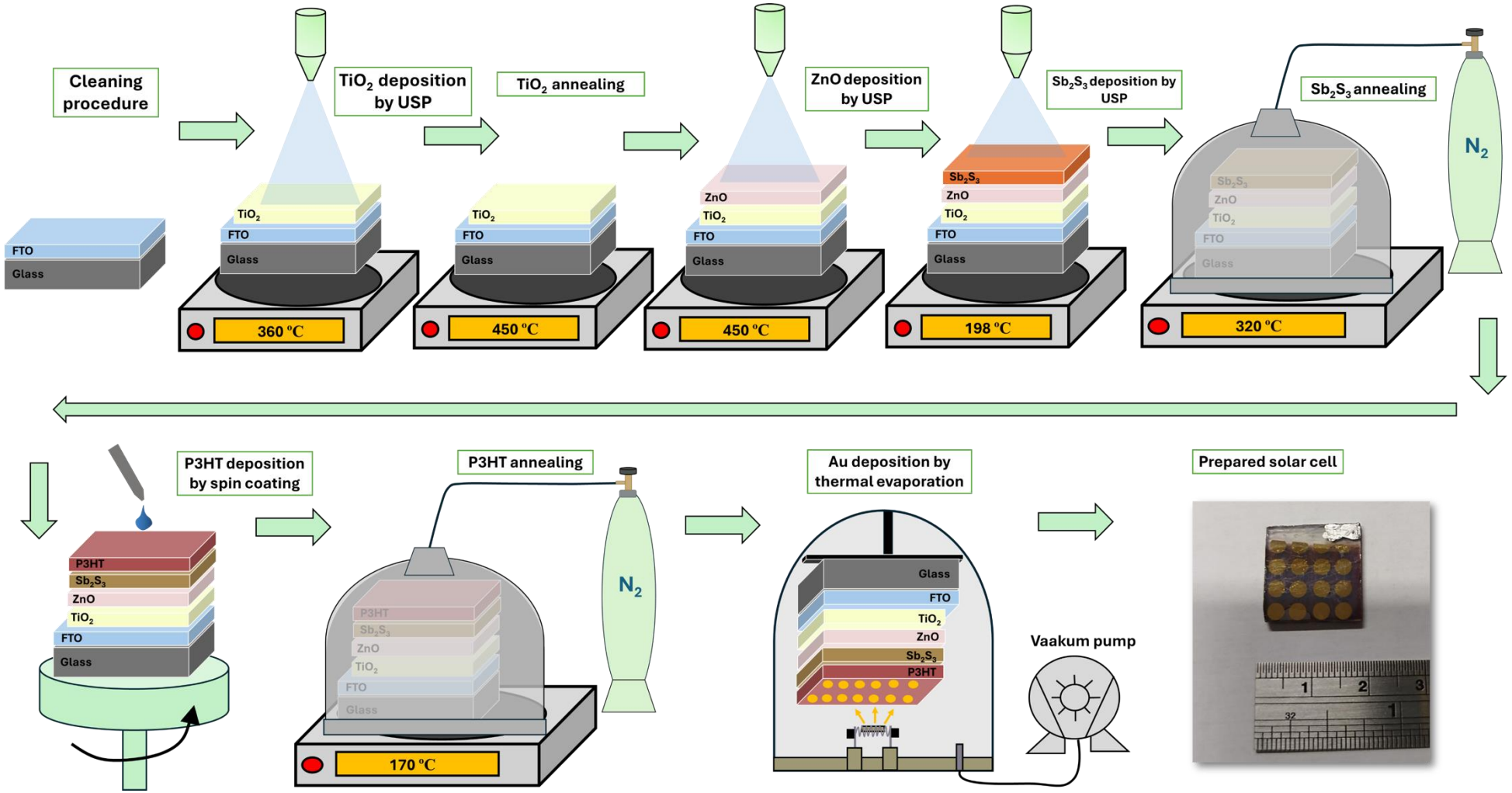


Chakraborty et al., Nano Energy, 128 (2024), 109932

- Solar windows combine electricity generation with daylight transmission.
- Europe's BIPV market is forecast to grow by 33.8% annually in 2025–2030, including roofs, façades and windows.
- Indoor PV harvests ambient light to power low-energy sensors and IoT devices.
- Sb_2S_3, with a bandgap of approximately 1.7 eV, is a promising absorber for solar windows and indoor PV.

TAL TECH

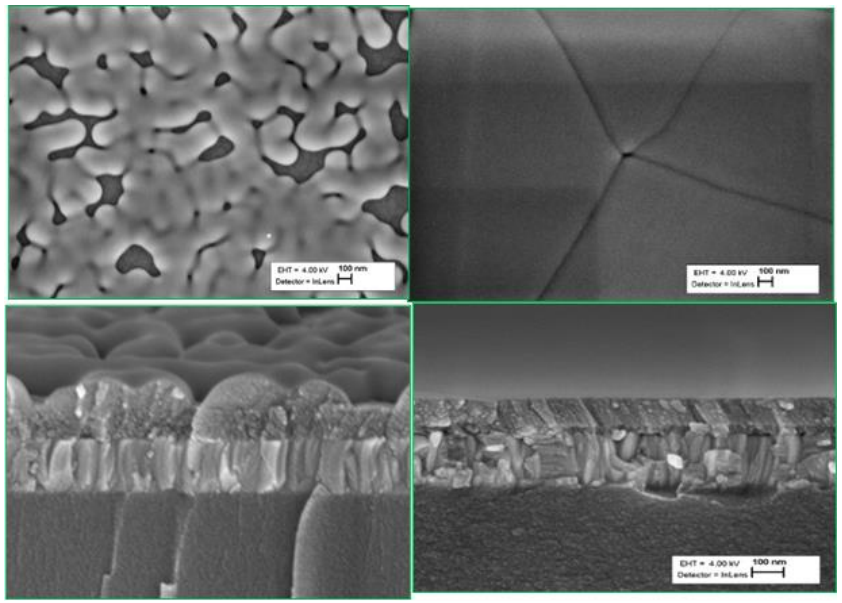
Fabrication of Sb_2S_3 thin film solar cells



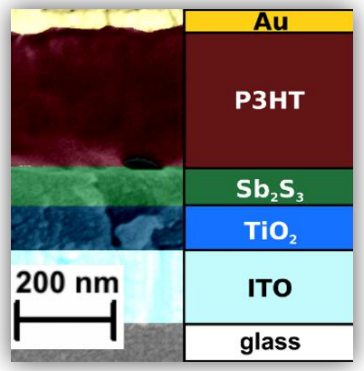
Sb_2S_3 solar cells: film formation and device performance

Two-step absorber fabrication

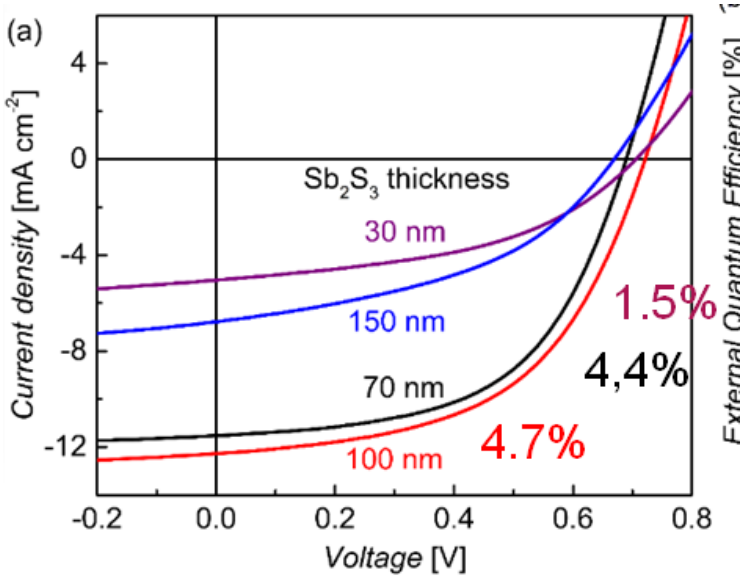
Deposition: 185 °C, air Annealing: 270 °C, N_2



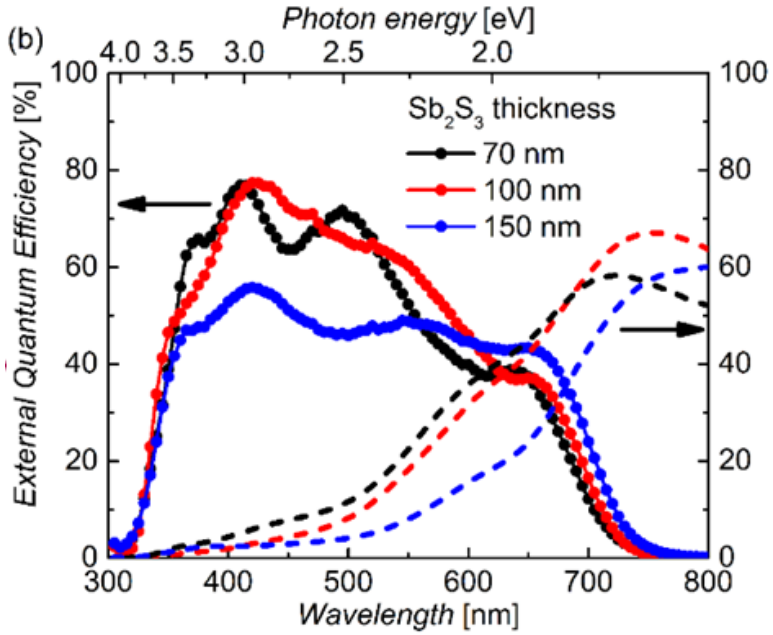
Amorphous Sb_2S_3 Crystalline Sb_2S_3



Absorber thickness and device performance

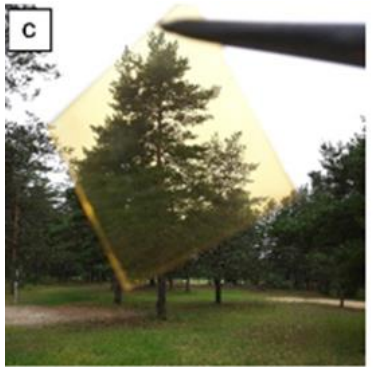


J–V curves under AM1.5G, 100 mW cm^{-2}



EQE (solid) and transmittance (dashed)

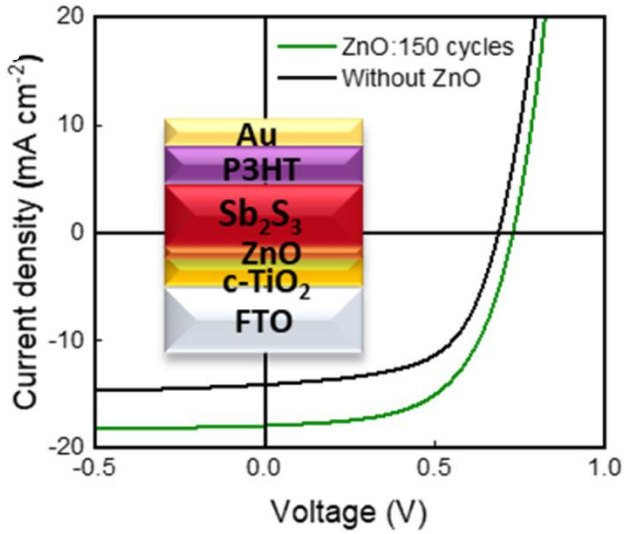
Dense continuous film, grain size ≈ 10 µm
Glass/ITO/TiO_2/100 nm Sb_2S_3 → Average transmittance (AVT) of 24 % w/o back contact

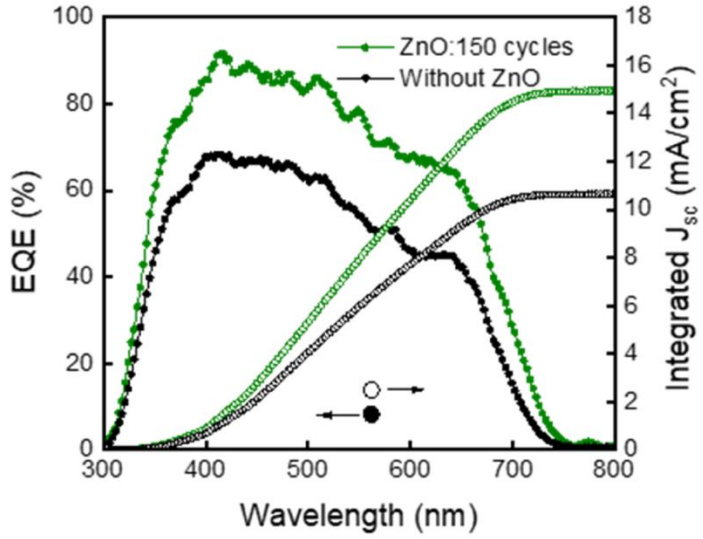


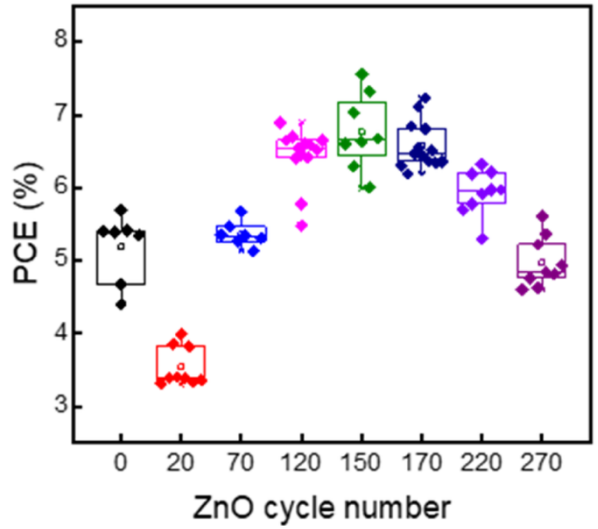
Semitransparency

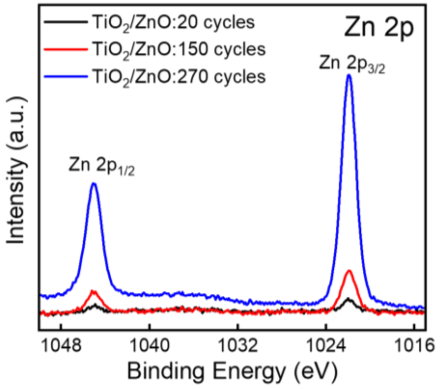
Eensalu et al., Beilstein J. Nanotechnol. 10, 198–210; 2019, 10, 2396

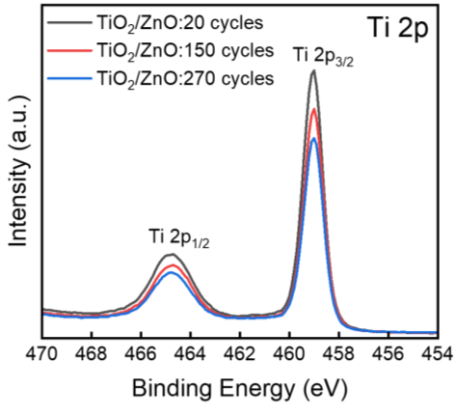
Engineering the ETL/absorber interface: $TiO_2/ZnO/Sb_2S_3$



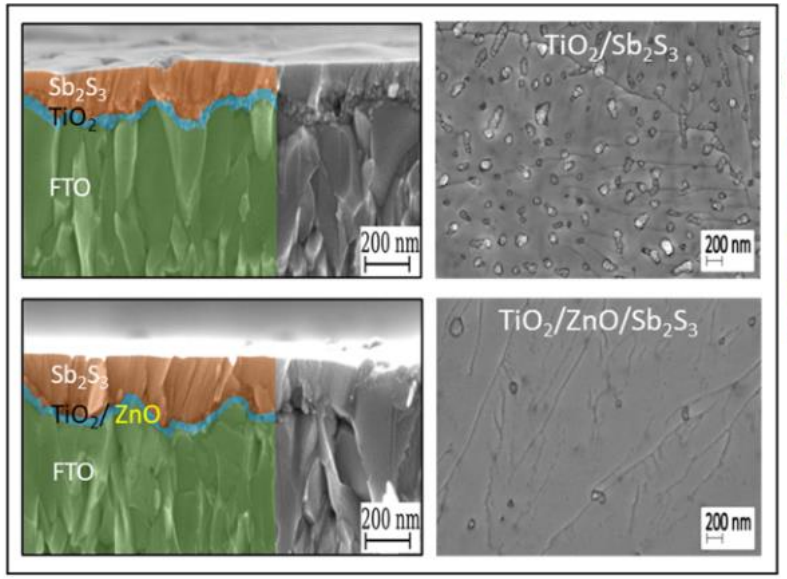


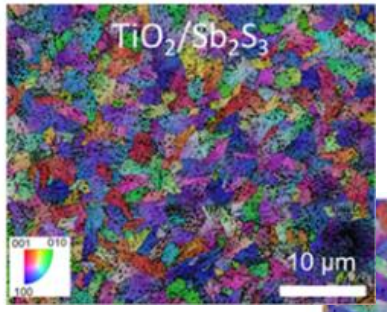






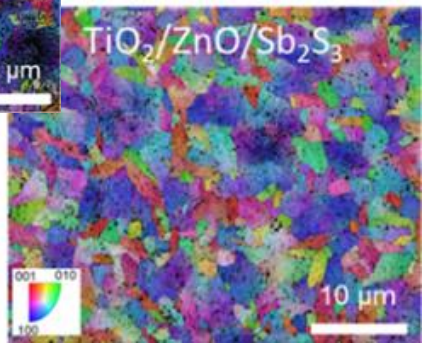
Absorber morphology: without / with ZnO





0.9 µm

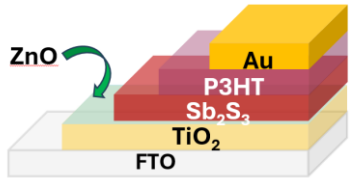
1.4 µm

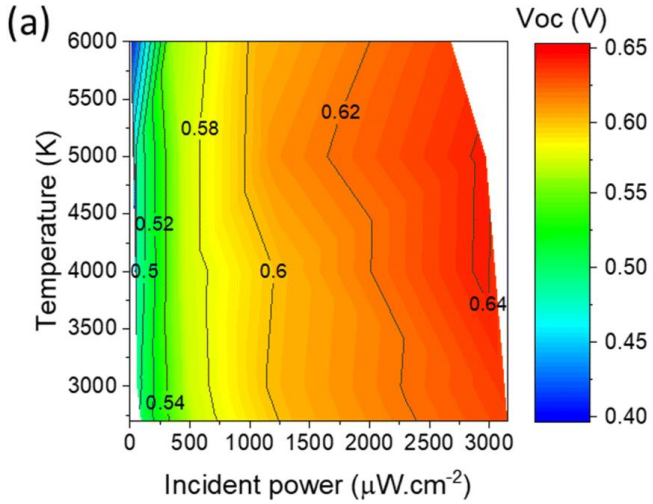


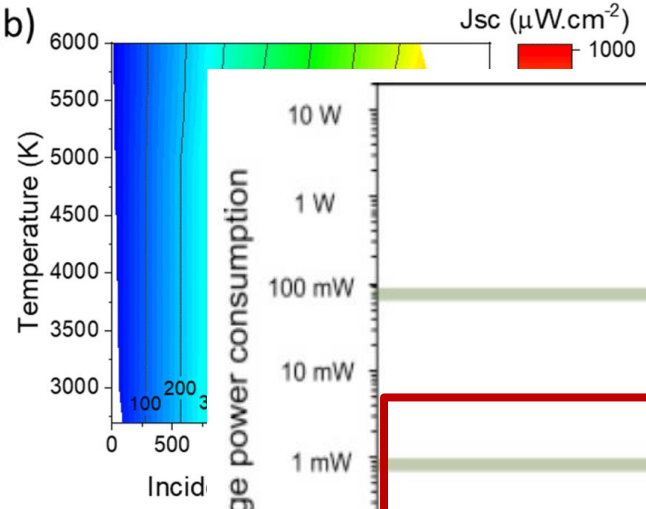
TAL TECH

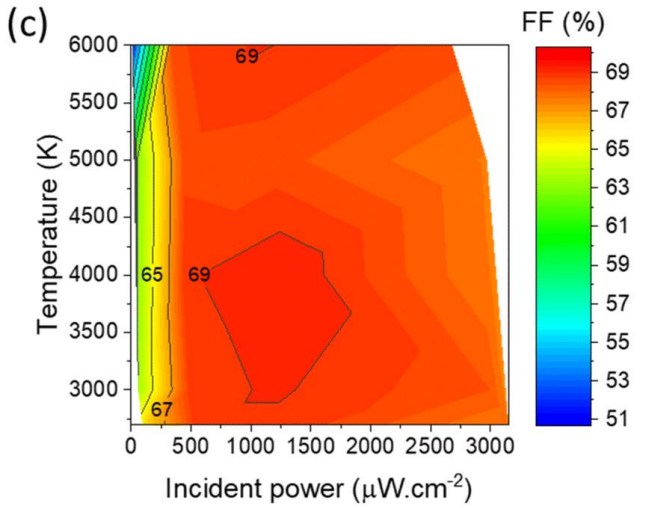
Hussien et al., J. Mater. Chem. A 13 (2025), 37215–3723

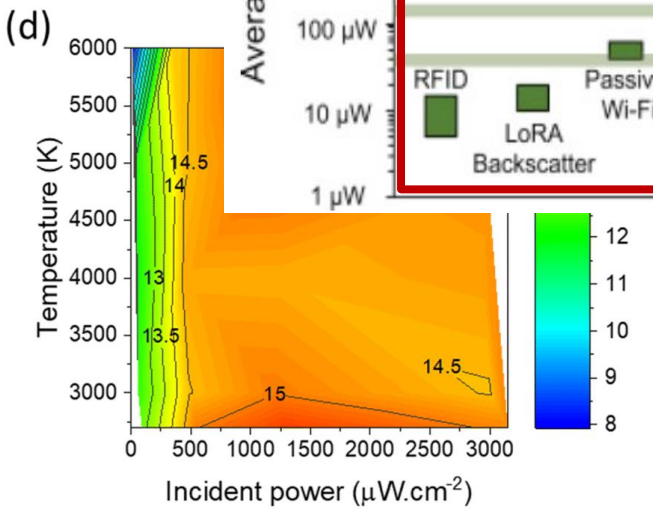
Engineering the ETL/absorber interface- IPV application

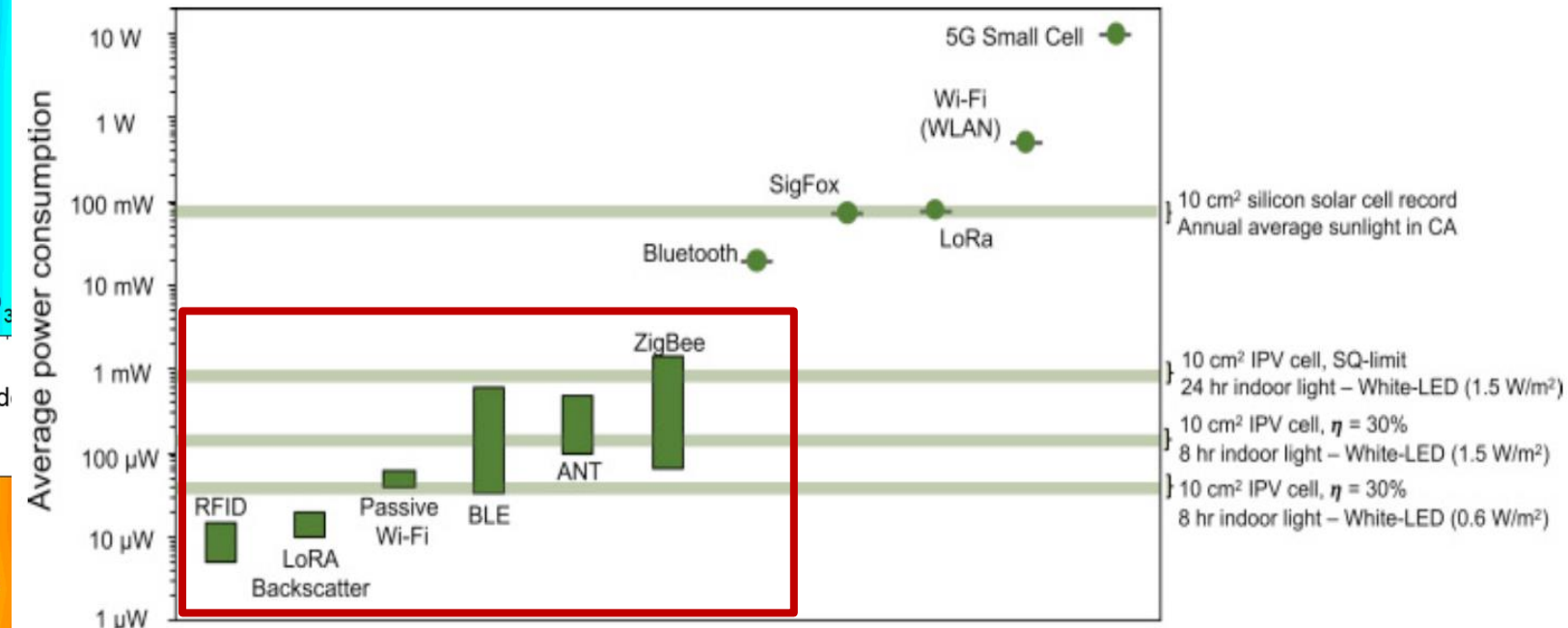












IPV with power output in the 0.1 - 4.0mW range.

feasibility of integrating IPV in IoT nodes: to activate & read commercial Sensors

TAL TECH

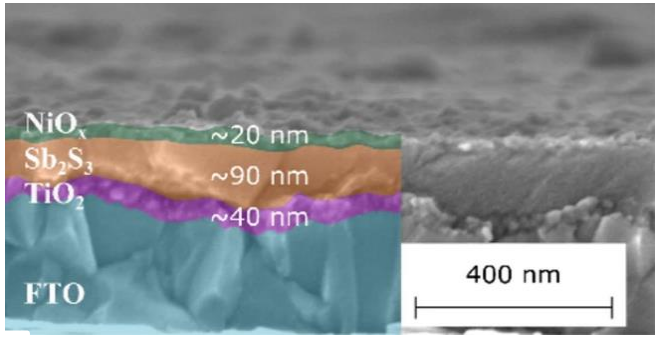
Indoor characterisations are realised using a Keithley 6430 source meter and a G2V Pico solar simulator controlled with a self-developed script (Z. Jehl Li-Kao, UPC) allowing to adjust the spectrum to match that of LED light sources of various temperatures.

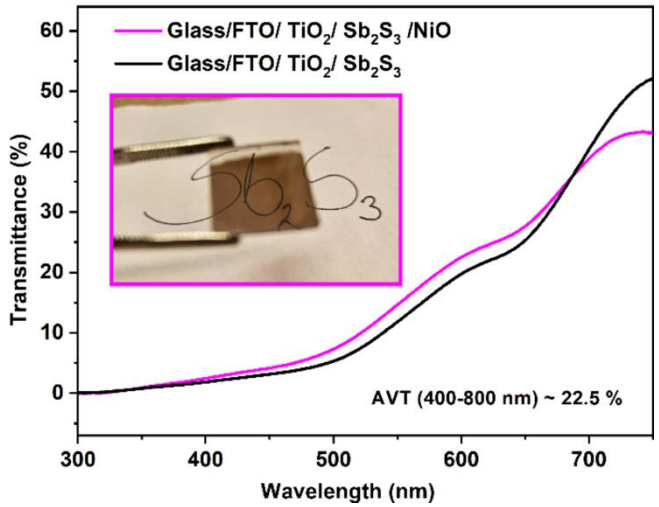
Hussien et al., J. Mater. Chem. A, 2025, 13, 37215-37231

Semitransparent Sb_2S_3 Solar Cells

Inorganic hole transport layer: NiO_x

Glass/FTO/TiO_2/Sb_2S_3/NiOx/Au





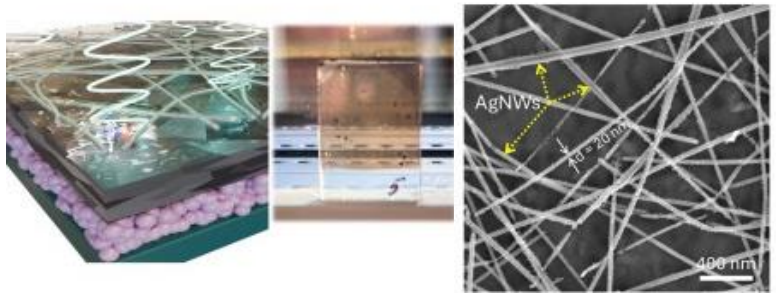
AVT ≈ 22% (stack without Au)

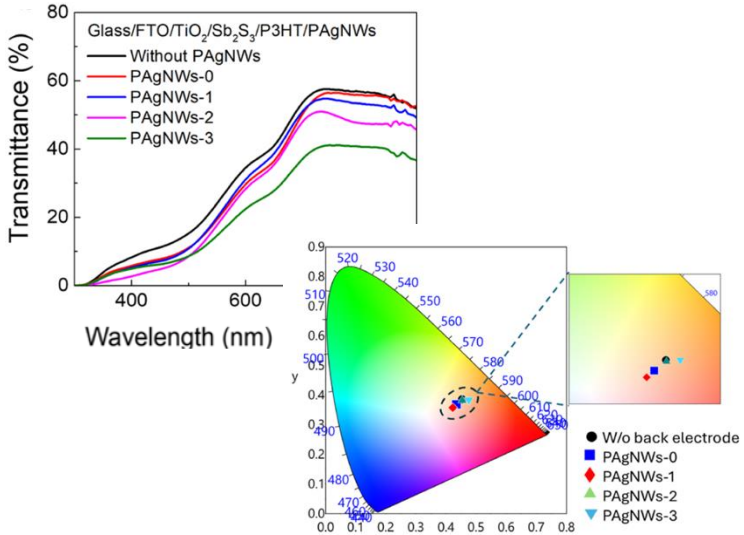
PCE: 2.68% (with Au)

Pareek et al, Sci. Rep. 15, 1468 (2025)

Transparent electrode: AgNWs

Glass/FTO/TiO_2/Sb_2S_3/P3HT/PAgNWs



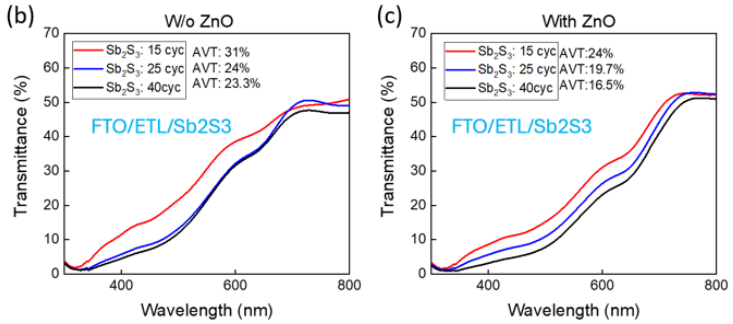


CIE 1931 standard

AVT: 20-26% **PCE: 2.1%**

Nguyen et al, ACS Appl. Mater. Interfaces 18, 33981(2026)

Optimizing layer thickness: Sb_2S_3



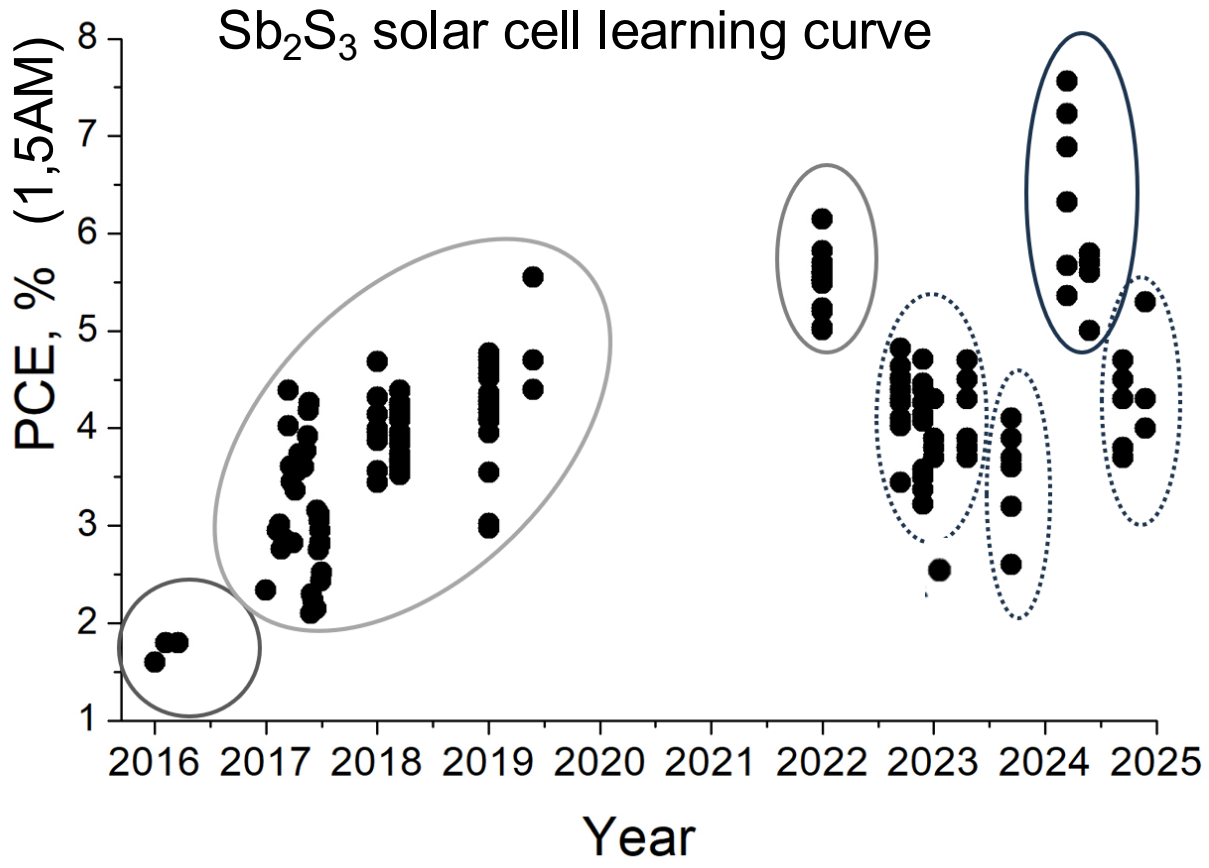
Devices	d (nm)[a]	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	PCE (%)
Without ZnO	60	675	8.6	56	3.25
Without ZnO	75	703	9.5	50	3.37
With ZnO	60	756	8.9	57	3.85
With ZnO	75	736	9.4	54	3.71

[a] Absorber thickness

Hussien et al, ACS Appl. Mater. Interfaces, submitted

Summary and Outlook

Antimony chalcogenides, including Sb_2S_3 are promoising photovoltaic materials with potential for use in thin film semitransparent solar cells and indoor photovoltaics.



Materials and devices

Absorber engineering
Interface engineering
All-inorganic solar cells

Applications

Indoor PV
Semitransparent PV
Artificial synapses

TAL TECH

ACKNOWLEDGEMENTS

THANK YOU FOR YOUR ATTENTION!

TK210; TK210U8 Estonian Ministry of Education and Research project, Center of Excellence in Sustainable Green Hydrogen and Energy Technologies (2024-2030)

PRG2676 All inorganic semi-transparent thin film solar cells for solar windows and indoor photovoltaics (2025-2029)

PSG689 Bismuth Chalcogenide Thin-Film Disruptive Green Solar Technology for Next Generation Photovoltaics (2021–2025)

H2020 ERA Chair Emerging next generation photovoltaics, 5GSOLAR (2020-2026)

H2020 COST Action (European Cooperation in Science and Technology), CA21148 Research and International Networking project, Emerging Inorganic Chalcogenides for Photovoltaics (RENEW-PV) (2021-2026)

HORIZON TMA MSCA Staff Exchanges, Solar Cells-Inspired Inorganic Semiconductor Synaptic Systems for Low Energy Edge Computing and Visual Learning (SOLIS) (2025-2029)

CET Partnership, MOB3PRT2 Sustainable Antimony Chalcogenide Thin-Film TAndem Solar Technology (2024-2026)

CET Partnership, **MOB3PRT17** Sustainable chalcogenide thin films for low power photovoltaics (ENPOWER) (2025-2027)