Solution-processed perovskite tandems and multi-junction solar cells

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• **Silicon solar panels are cheap!**

• Silicon solar cells account for about **25 to 40 percent** of the total solar panel system cost.

• **Increasing kWh/m²** may be the best pathway to **lower Levelized-Cost of Electricity (LCOE)** in the future.

Cost breakdown of residential PV system (inflation adjusted)  
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Global levelized cost of electricity from utility-scale renewable power generation technologies from 2010 to 2017.  
Copyright – international renewable energy agency (IRENA).
1. Thermalization losses account for $\sim 33\%$
2. All junctions must generate an equal amount of charge-carriers under AM1.5G. ("Current-matching")
3. Gains from lower thermalizations losses must outweigh parasitic absorption from the recombination layers.
4. Added processing complexity

Perovskite Tandems!

- Tandem cells reduce thermalization losses of photons
- Tandem architectures allows us to move beyond the Shockley–Queisser limit
The $\text{FA}_{0.83}\text{Cs}_{0.17}\text{Pb(I}_{1-x}\text{Br}_x\text{)}_3$ perovskite system

**Absorption Onset**

**XRD Pattern**
Thermal stability of FA/Cs system

- Cs is an inorganic non-volatile cation, serving to stabilize α-FAPbI$_3$ “black” phase.

- MAPbI$_3$ degrades to PbI$_2$ and CH$_3$NH$_3$I, which further decompose into volatile compounds: methylamine (CH$_3$NH$_2$), hydroiodic acid (HI).

- (FA,Cs)Pb(I$_{0.8}$Br$_{0.4}$)$_3$ can be heated at 130°C for extended period of time.

2T Monolithic perovskite/c-Si Tandem

- **Sputtered ITO** as recombination layer
- **Atomic Layer Deposition (ALD) SnO₂** acting as “buffer layer” to prevent sputter damage.
- **PCE**: 23.6%
- **V_{OC}**: 1.65V
- **J_{SC}**: 18.1 mA cm⁻²
- **FF**: 79%

• **Sputtered ITO** serves as a temporary DMF solvent barrier, enabling stacking of perovskite/perovskite solar cells

• **PCE:** 17%  \( J_{\text{SC}}: 14.5 \, \text{mA cm}^{-2} \)
  \( V_{\text{OC}}: 1.66 \, \text{V} \quad \text{FF: 70\%} \)

Eperon, Leijtens et al., Science, 2016
Acetonitrile/methylamine solvent system

- **Solution-processable**
- **High evaporation** rate allows for quick crystallization of the perovskite layer
- Solvent-system **does not re-dissolve** underlying layer

ACN/MA Solvent System
- Low viscosity
- Low boiling point
- Rapid crystallization

Noel et al., Energy Environ. Sci., 2017, 10, 145-152
Mechanically Stacking Perovskite

ACN/MA perovskite drop-casted onto the front-cell

Re-dissolution of the undying layer due to solvent penetration
Stacking of perovskite layers
Solution-processed Perovskite Tandems

Solution-processed Perovskite/Perovskite Tandem

Fabricated via spin-coating

Current Density (mA cm$^{-2}$)

- $J_{sc}$: 11.5 mA/cm$^2$
- $Eff$: 15.2 %
- $V_{oc}$: 2.16 V
- $FF$: 0.63

Voltage (V)

Current Density & PCE (mA cm$^{-2}$ & %)

- $V_{mpp}$: 1.72V
- $J_{mpp}$ at 90s: 8.87 mA cm$^{-2}$
- PCE at 90s: 15.2 %

Time (s)
Solution-processed Perovskite Tandems

- **Lead-based perovskites** were used to optimize the recombination interlayer

- Relatively low voltage loss via PEDOT:PSS/ITO NPs recombination layer

- **PCE**: 15.3% JV (15.3 Stabilized)  \( V_{\text{OC}} \): 2.18V  
  \( J_{\text{SC}} \): 11.5 mA cm\(^{-2}\)  
  \( \text{FF} \): 63%
Sn/Pb using ACN/MA Solvent System

- ACN/MA based-solvent can process Sn/Pb mixtures leading to narrow band gap perovskites
- MAPb$_{0.75}$Sn$_{0.25}$I$_3$ resulted in a 1.34 eV band gap
- Narrow band gap PCE reaching 11%

![Graph showing J-V characteristics of a single-junction Sn/Pb solar cell](image)

**MAPb$_{0.75}$Sn$_{0.25}$I$_3$**

- 15% excess metal ions
- Jsc: 21.0 mA/cm$^2$
- Eff: 11.1%
- Voc: 0.82 V
- FF: 0.64

**EQE (%)**

- Wavelength (nm)

**Eg = 1.34 eV**

- hv (eV)

- Tauc
Improving the optoelectronic properties of Sn/Pb

Suppressing the Sn vacancies with excess metals

- Reducing agents (ex: SnF$_2$) have poor solubility in the ACN/MA solvent system
- Excess metal ions improved optoelectronic properties
- Excess metal ions shifted the work function
- Reduction in the “p-type behavior” caused by Sn vacancies
• Proof-of-concept of the first all-perovskite **triple junction**
• Good **mechanical stacking** ability for all three-perovskite junctions
• No apparent **solvent-damage** to the underlayers

• Voltage addition from the added junction, reaching **2.83V**

• Multi-junction solar cells are highly susceptible to **spectral miss-matching**.

• The **Xe peaks** in the IR can cause severe overestimation of PCEs
Scalable Fabrication Methods

Roll-to-roll Processing

Slot die head

Ink

Substrate

Slot die coater
Thank you for your attention!

Questions, comments, suggestions?