Outline

- Indoor light harvesting
- Markets and applications of indoor PV
- Photovoltaic technologies
- Test conditions: indoor vs outdoor
- Strategies for high indoor efficiencies
- Indoor perovskite solar cells
- Challenges and perspectives
Photovoltaics for indoor light harvesting

**OUTDOORS**
- Solar farms (MWs)
- Building-integrated

**INDOORS**
Harvesting of artificial light inside buildings
- Product-integrated (μW-mW)

✓ Improvement in buildings’ **sustainability**
✓ Reduction of **battery** usage
✓ **Portability**
• Market rise associated with **lowering of consumers products’ cost**
• **Fastest growth** among alternative small volume PV markets
Applications of indoor PV

- **Consumer** electronics
- Healthcare and **biomedical** devices
- Building-integrated and indoor appliances
- **Communication** technologies
- WSN and RFID
- Sensors for the **Internet of Things**
Photovoltaic technologies

First Generation
Crystalline silicon solar cells

Second Generation
Thin film solar cells

Third Generation
DSSC, OPV, perovskite, multi-junctions

Crystalline Silicon cells
Mono-crystalline cells
Efficiency: 18%~25.6%
Multi-crystalline cells
Efficiency: 17%~20.8%

Thin film solar cells
CdTe cells
Efficiency: 18.3%~22.1%
Amorphous silicon cells
Efficiency: 13.4%
CIGS cells
Efficiency: 20.4%~22.6%

Multi-junction cells
Efficiency: ~45%


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Photovoltaic technologies – 3rd generation

DYE-SENSITISED SOLAR CELLS (DSSC)

- Photosensitive organic dye
- Efficiency: 12.3%

ORGANIC PHOTOVOLTAICS (OPV)

- Donor/acceptor system of polymers and small molecules
- Efficiency: 17.4%

PEROVSKITE SOLAR CELLS (PSC)

- Hybrid organic inorganic perovskite crystalline absorber
- Efficiency: 25.2%

http://www.nrel.gov/ncpv/images/efficiency_chart.jpg
Photovoltaic technologies – 3rd generation

**DYE-SENSITISED SOLAR CELLS (DSSC)**
- Photosensitive **organic dye**
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**ORGANIC PHOTOVOLTAICS (OPV)**
- Donor/acceptor system of polymers and small molecules
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**PEROVSKITE SOLAR CELLS (PSC)**
- Hybrid organic inorganic **perovskite crystals**
- Efficiency: 25.2%

- Low-cost
- Printability
- Flexibility
- Colour-tunable, semi-transparent

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PV performance evolution @STC

PEROVSKITE SOLAR CELLS*

3.8% (2009) → 25.2% (2019)

*performance at 1 sun (1000 W/m²)

...what happens in indoor conditions?
Outdoor vs Indoor

**STANDARD TEST CONDITIONS**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>25 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>Air mass</td>
<td>1.5</td>
</tr>
</tbody>
</table>

~100 klx

**INDOOR ILLUMINATION**

- Low light: 50 lx
- Living room: 200 lx
- Office: 500 lx
- Supermarket: 1000 lx


Different optimization of indoor PV compared to outdoor cells!
Strategies for highly efficient indoor PV

❖ Bandgap engineering

- Eg opt. @AM1.5G = 1.1 eV
- Eg opt. @Indoor = 1.9 eV

Compositional tuning of perovskite:

- Eg increase 1.6 eV -> 1.8 eV
- PCE increase 30% -> 36%
Strategies for highly efficient indoor PV

❖ Suppression of charge recombination

- Minimization of dark currents by insertion of compact, defect-free transport layers

\[ \text{TiO}_2 \text{ electron transporting layer (ETL)} \]

Vapour-deposited (ALD) film: PCE > 10%

Solution-processed (SG) film: PCE < 1%

Strategies for highly efficient indoor PV

- **Suppression of charge recombination**

  - Minimization of trap-mediated recombination by **morphological control** of the active layer

  [Graph and images showing the process of charge recombination suppression]

Strategies for highly efficient indoor PV

❖ Light absorption and charge transport

- Dilution of electrolyte increases transparency (light absorption) of DSSC
- Increase in active layer thickness improves photogeneration in amorphous Si

Indoor perovskite solar cells

**Composite SnO$_2$/MgO ETL for rigid PSCs**

- MgO interlayer **blocks recombination** (insulating thin layer)
- **Reduces ETL roughness** and defects at interface

![Current Density vs Voltage Graph](image)

26.9% @ 400lx
25.0% @ 200lx

![Diagram of Solar Cell](image)

- ITO/SnO$_2$
- MgO
- PVK
- SpiroMeOTAD
- Au

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Indoor perovskite solar cells

Flexible PSCs on R2R-coated ultrathin glass

- Optimal optical, electrical, surface properties and bendability of flexible glass

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Indoor perovskite solar cells

Flexible PSCs on R2R-coated ultrathin glass

- Enhancement of electron lifetime and charge extraction with **mesoporous scaffold**
- Suppression of **leakage currents**
Progress of indoor PV

Ref [20] Theoretical efficiency limit 46% for fluorescent light

Indoor PCE (%)

Published year


OPV
DSSC
III-V SC
PVSC
Progress of indoor PV - flexible

Perovskite solar cells on R2R-coated flexible glass

Maximum Power Density [μW cm⁻²] vs. Illuminance [lx]

- a-Si FL
- GaAs FL
- DSSC FL
- DSSC LED
- OPV FL
- OPV LED
- PSC LED

21-23%
Challenges & perspectives

- Big margin of efficiency improvement for indoor PV (theoretical max. 50-60%, depending on type of lamp)
Challenges & perspectives

- Low-cost **printing techniques**
- Replacement of expensive and rare materials
- Predicted **increasing production volumes**
Challenges & perspectives

- Milder operating conditions indoor vs outdoor
- Efficient encapsulation methods
- Compositional engineering and material optimisation for stable indoor PV
Conclusions – how to choose the best indoor PV?

**Functionality**
(Transparency, colour, flexibility, weight, easy integration)

**Efficiency**
(STC, indoor low lighting e.g. CFL and LED lamps, 200-1000 lx)

**Stability and environmental impact**
(Toxic elements content, green solvents, lifetime in indoors)

**Cost and commercialization**
(Market readiness, production volumes, cost of raw materials and processes)
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Thanks for your attention!