Progress in Thin Film Photovoltaics: From Nanoscale Innovations to Device Efficiency

Jae Sung Yun
Net zero campus by 2030 (PV 12.2MW)

- Located in Guildford
- ~17K students
- 2021 UK REF Ranking 33/135
- Electrical and Electronic Engineering 6th in the UK
1. Structural Defects in solar cells

2. Perovskite solar cells

3. Widebandgap Perovskites
Part I: Thin Film PV
Silicon vs Thin Film

Silicon solar cell fabrication process

- Silica Sand
- Crystalline Silicon
- Monocrystalline Ingot
- Silicon Wafer
- Solar cell

Long processing time - Energy intensive process

Thin film solar cell fabrication process

- Yellow precursor salt
- White precursor salt
- Organic solvent
- Perovskite liquid formulation
- Incoming coated glass
- Deposit perovskite
- Finished panel with back contact

Low material consumption, suitability for flexible substrates, low temperature processability, and monolithic integration
PV Market

Laser focus world 2020

<10%
Mostly CdTe
Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: NREL, 2018

Polysilicon price reductions:
- From $35/kg to $15/kg.
- Metallization improvements, including silver utilization:
  - From 200 mg/cell to 110 mg/cell.
  - Process engineering and economies of scale.

Move to PERC cell architecture and efficiency improvements.
- Transition to diamond wire.
- Process engineering and economies of scale.

Roadmap for Cz and DW:
- 2% improvement in PERC cell efficiencies by 2020.
- Reduce Ag to 50 mg/cell by 2020.
- Kerfless wafers and realization of the c-Si single junction efficiency potential in mass production.
PV Cost History

Green, SPREE 
seminar (2020)

My PhD 

~ 10c/W
Crystalline Si thin film on Glass (CSG) Technology

Evaporated Si thin film 2-10μm

Closing ceremony, last day in Suntech 2013

Solar Energy Materials and Solar Cells 119, 246-255
Crystalline Si thin film on Glass (CSG) Technology

“NANOSCALE DEFECTS”
Part II: Halide Perovskites

Rise of Halide Polycrystalline Perovskites

MAPbI₃, MAPbBr₃, MAPbIxBr1-x FAPbI₃, CsPbI₃...

High absorption, carrier lifetime, direct bandgap, “defect tolerant” \((10^{15}-10^{16}\text{cm}^{-3})\)
Si/perovskite tandem solar cells >34% (Theoretical efficiency up to 45%)

Perovskite top solar cell
$E_g = 1.6 - 1.8 \text{ eV}$

Si or CIGS bottom solar cell
$E_g = 1.0 - 1.2 \text{ eV}$

Science 2020, 367, 1135.
Wide bandgap phase segregation

MAPb(I_{1-x}Br_x)_3

Phase segregation, band alignment mismatch, poor perovskite quality etc.

*Adv Func. Mater.* 2022;32(12):2110698
Phase Segregation-Hoke Effect

Chem. Sci., 2015, 6, 613
Widebandgap Perovskite
I vs Br

Solubility difference between MAI and MABr

precipitation

Chem. Commun., 2015, 51, 17658

Ionic radius difference

lattice distortion

RSC Adv., 2019, 9, 11151

ACS Appl. Mater. Interfaces 2020, 12, 34, 38376
Microstructural Evaluation of Phase Instability in Large Bandgap Metal Halide Perovskites

Dohyung Kim, Jihoo Lim, Seungmin Lee, Arman Mahboubi Soufiani, Eunyoung Choi, Anton V. Ievlev, Nikolay Borodinov, Yongtao Liu, Olga S. Ovchinnikova, Mahshid Ahmadi, Sean Lim, Pankaj Sharma, Jan Seidel, Jun Hong Noh, and Jae Sung Yun

(a) EQE (%) vs. wavelength (nm)

(b) Voc (V) vs. Bandgap (eV)

ACS nano 15.12 (2021): 20391
Effect of MABr incorporation

(FAPbI$_3$)$_{0.95}$(MAPbBr$_3$)$_{0.05}$

Bandgap ~1.55eV

205 nm

(FAPbI$_3$)$_{0.85}$(MAPbBr$_3$)$_{0.15}$

Bandgap ~1.6eV

256 nm

(FAPbI$_3$)$_{0.70}$(MAPbBr$_3$)$_{0.30}$

Bandgap ~1.75eV

225 nm

(FAPbI$_3$)$_{0.50}$(MAPbBr$_3$)$_{0.50}$

Bandgap ~1.9eV

204 nm
Kelvin probe force microscopy

MABr% ➧
Flat dark grain ➧
Formation of embedded and flat grain with higher work function
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KPFM under illumination

Flat grains -> only responses to 720nm -> likely I rich domain
Nano-IR and HIMS-SIMS

Contacts: Minwoo Lee Moonyong Kim

Pb, I, MA rich
IV curve

**5% Br**
1.55eV

**15% Br**
~1.6eV

**30% Br**
~1.75eV

**50% Br**
~1.9eV

**Hysteresis**
Phase Segregation

Before          After

(a) dark      (b) Light      (c)  (d) dark

1 μm

(f)

Before          After

CPD (mV)

Profile (μm)

Time (min)
Halide Segregation

**Thermal Disorder-Induced Strain and Carrier Localization Activate Reverse Halide Segregation**

Nursultan Mussakhanuly, Arman Mahboubi Soufiani,* Stefano Bernardi, Jianing Gan, Saroj Kumar Bhattacharya, Robert Lee Chin, Harif Muhammad, Milos Dubajic, Angus Gentle, Weijian Chen, Meng Zhang, Michael P. Nielsen, Shujian Huang, John Asbury,* Asaph Widmer-Cooper,* Jae Sung Yun,* and Xiaoqiang Hao*

1. **Light induced strain**
2. **thermal disorder induced strain**

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**30% Br and 1.71eV**
Wide bandgap Perovskites

Multi-functional Surface Treatment against Imperfections and Halide Segregation in Wide-bandgap Perovskite Solar Cells

Nursultan Mussakhaniyev¹, Eunyoung Choi²,³, Robert L. Chin¹, Yihao Wang¹, Jan Seidel¹, Martin A. Green¹, Arman M. Sotfiani⁴, Xiaoqing Hao⁴, Jae S. Yun¹,³

15% Br and 1.67eV

Favourable band bending and uniform \( W_f \) at the interface prevents the funnelling of carriers, thereby, phase segregation
Wide Bandgap Perovskites

Enhanced Hole-Carrier Selectivity in Wide Bandgap Halide Perovskite Photovoltaic Devices for Indoor Internet of Things Applications

Minwoo Lee, Eunyoung Choi, Arman Mahboubi Soufiani, Jihoo Lim, Moonyong Kim, Daniel Chen, Martin Andrew Green, Jan Seidel, Sean Lim, Jincheol Kim, Xincheng Dai, Robert Lee-Chin, Bolin Zheng, Ziv Hameiri, Jongsung Park,* Xiaojing Hao,* and Jae Sung Yun*

40% Br 1.75 eV

Minwoo Lee
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Wide Bandgap Perovskite

**Adjusted Bulk and Interfacial Properties in Highly Stable Semitransparent Perovskite Solar Cells Fabricated by Thermocompression Bonding between Perovskite Layers**

Hee-Yun Jung, Eun Sung Oh, Dong Jun Kim, Hongjae Shim, Wonjong Lee, Soon-Gil Yoon, Jongchul Lim, Jae Sung Yun, Taek-Soo Kim, and Tae-Youl Yang

**23% Br, 1.68 eV**

Large crystal growth, denser interface, reduced trap density
Wide bandgap Perovskite
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Part III: Stability

Carriers need to be extracted fast to avoid interfacial recombination!
FAPbI₃ Perovskite

Synergetic Effect of Aluminum Oxide and Organic Halide Salts on Two-Dimensional Perovskite Layer Formation and Stability Enhancement of Perovskite Solar Cells

Eunyoung Choi, Jin-Won Lee, Miguel Anaya, Alessandro Mirabelli, Hongjae Shim, Joseph Strzalka, Jongchul Lim, Siwon Yun, Milos Dubajic, Jihoo Lim, Jan Seidel, Raphael Edem Agbenyeke, Chang Gyoun Kim, Nam Joong Jeon, Arman Mahboubi Soufiani,* Helen Hejin Park,* and Jae Sung Yun*

Al diffusion into the bulk
Supress loss of OA

Supress lo

a) OAI

b) OAI/AlOx

Surface
Bulk

α-FAPbI₃ δ-phase (OA)₂PbI₄ OA⁺ Al³⁺ I⁻ PbI₂ I₂
Enhancing Stability and Efficiency of Perovskite Solar Cells with a Bilayer Hole Transporting Layer of Nickel Phthalocyanine and Poly(3-Hexylthiophene)

Hyeonwoo Kim, Do Yoon Lee, Jihoo Lim, Jongbeom Kim, Jaewang Park, Jan Seidel, Jae Sung Yun, and Sang Il Seok

Thermal Stability

Excellent thermal stability

Poor thermal stability

$J_{SC} = 24.11 \text{ mA/cm}^2$

$V_{OC} = 1.10 \text{ V}$

FF = 80.6 %

PCE = 21.91 %

$85^\circ \text{C}, 85\% \text{ RH, Encapsulated with PIB, Dark, Ambient air}$

$\text{AM 1.5G, 100 mW/cm}^2, \text{No UV-cut}$
Thermal Stability

High e-field formation

Efficient hole extraction
Summary

Surface passivation suppresses ALD AlOx Stability

Cross-sectional KPFM

Entropy of remixing at high T
Thank you!!

Acknowledgment

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PhD, 2020-2023
Nursultan Mussakhanuly
Any questions?