Fabrication and Characterizations for Efficient CdTe-based Solar Cells at University of Toledo

Deng-Bing Li

10/19/2022

Wright Center for Photovoltaics Innovation and Commercialization (PVIC)

Collins Group

Optical Spectroscopies:
Ellipsometry

Solar Cell Fabrications:
CIGS, CIS

Ellingson Group

Optical Spectroscopies:
PL, TRPL, TA

Device fabrication
Bifacial Solar cell
back contact material

Heben Group

Production and Grid Integration
Instrument Development
Device Fabrication and Characterization

Podraza Group

Optical Spectroscopies:

Ellipsometry

Yan Group

Solar Cell Fabrications
CdTe, Perovskite

DFT Calculations

Electrical Characterizations

Off-Campus Collaborators

Prof. Feng Yan in University of Alabama
Dr. Chuanxiao Xiao and Chunsheng Jiang from NREL
Dr. Jonathan D. Poplawsky and David A. Culler from ORNL

Funding Support

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

NSF

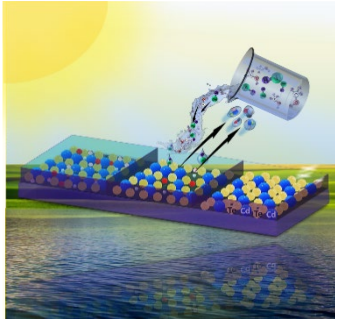
AIR FORCE RESEARCH LABORATORY

Substrate Supply

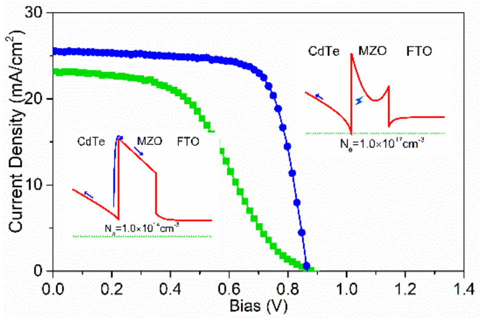
PILKINGTON
NSG Group Flat Glass Business

University of Toledo

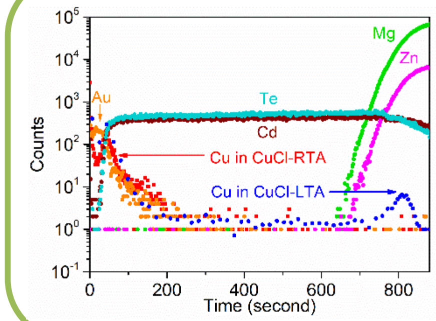
Roadmap for High Efficiency Solar Cells in UT



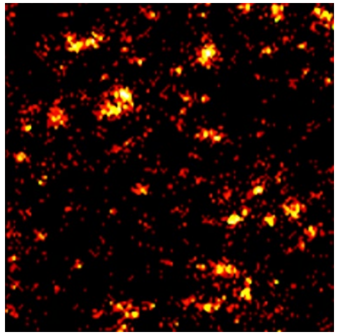
Back Surface Etching-15%
Sol. RRL 3(2019), 1800304



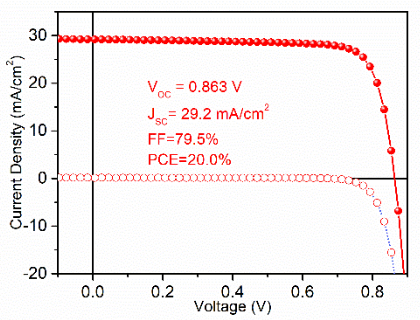
ZMO Conductivity-16.1%
ACS Appl. Energy Mater. 2(2019), 2896–2903
Prog. Photovolt. Res. Appl. 27(2019),1115–1123



Cu Engineering-17.5%
Nano Energy 73 (2020)
ACS Appl. Mater. Interfaces 2021, 13, 38432–38440



Ex-situ GrV Doping-18%, collaborate with Prof. Feng Yan in UA
Nature Energy volume 6(2021), 715–722



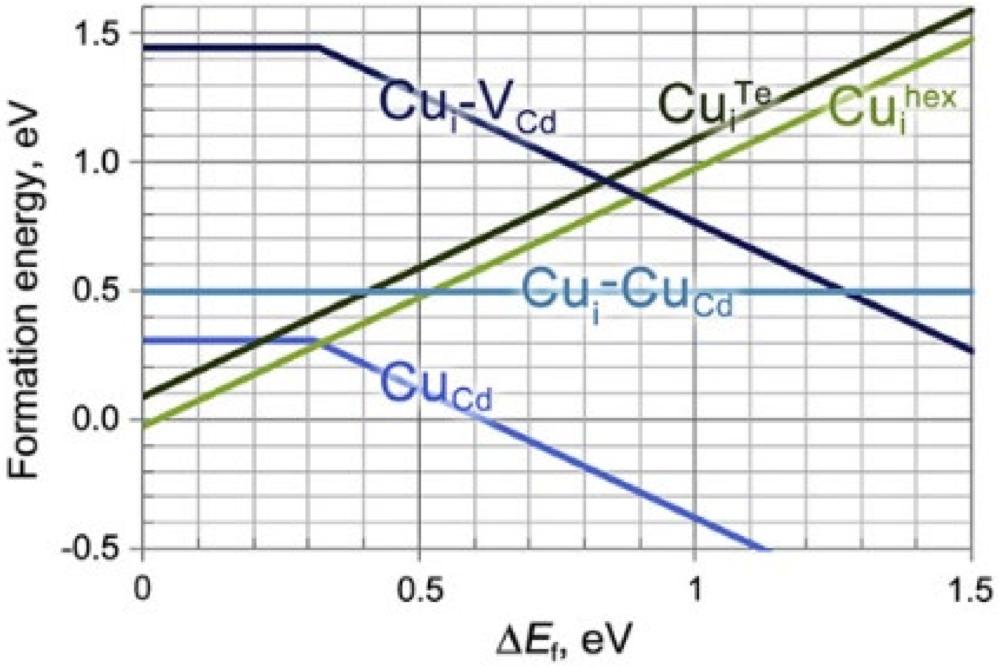
Se incorporation-20%
unpublished

Contents

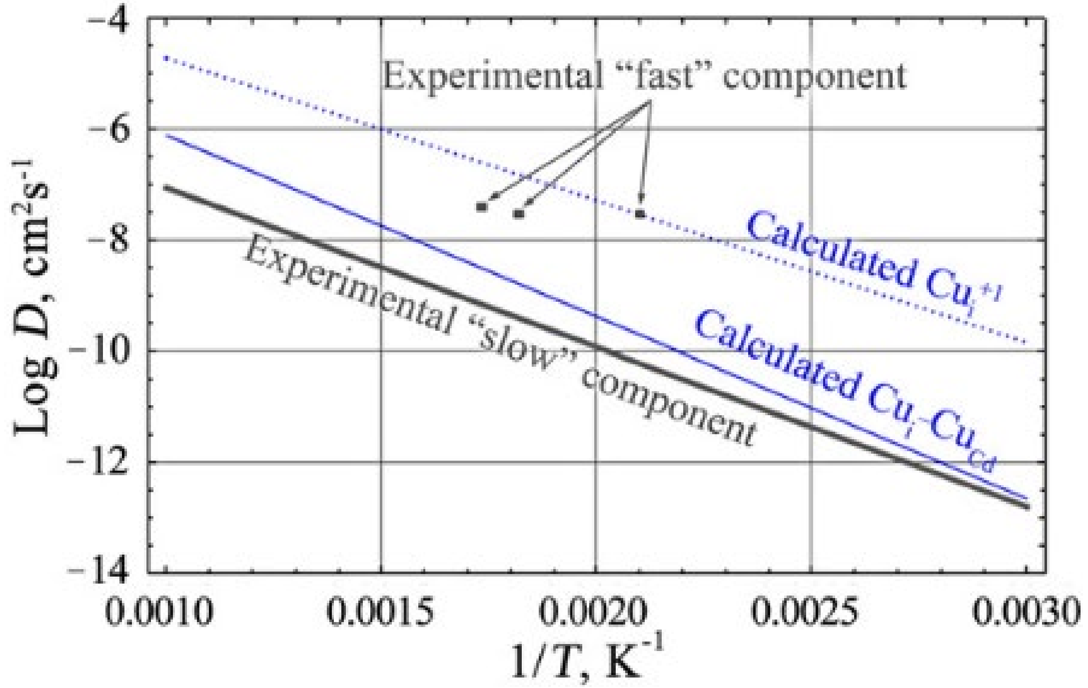
- Cu Engineering
- Se Incorporation
- IGO Emitter Exploration
- Ultra Thin CdSeTe Solar Cells
- Bifacial CdTe Solar Cells
- New Capability in UT

Cu Engineering

Compensatory Defect



High Diffusion Coefficient



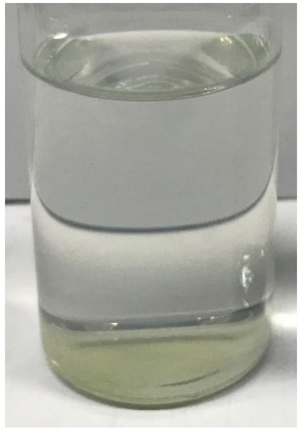
Minimize Cu concentration and optimal distribution

are required to maximize the hole density and device performance in CdTe

S.-H. Wei, et al, Phys. Rev. B 66(2002), 155211 D. Krasikov, et al, Thin Solid Films 535 (2013) 322–325

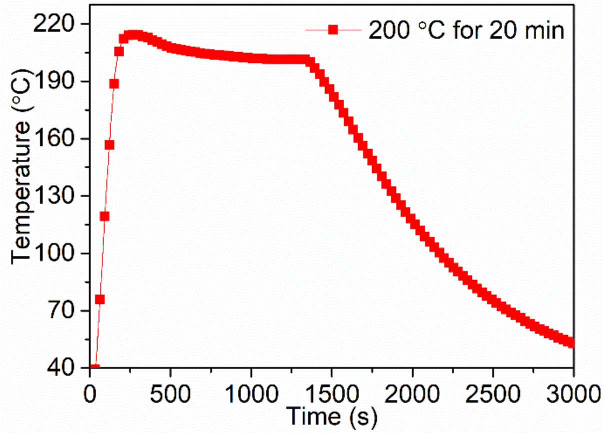
Cu Engineering

CuCl in ET(3.10μg/ml)

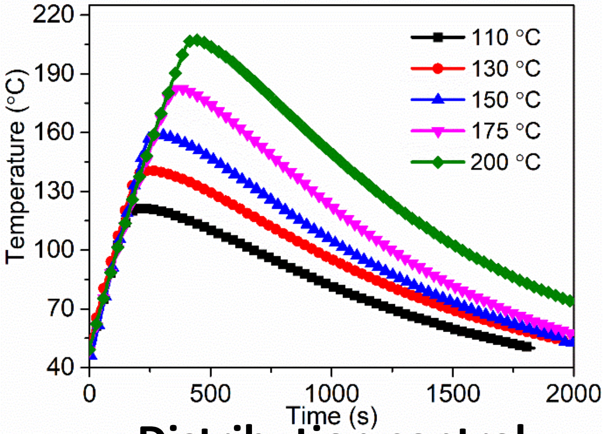


Dosage control

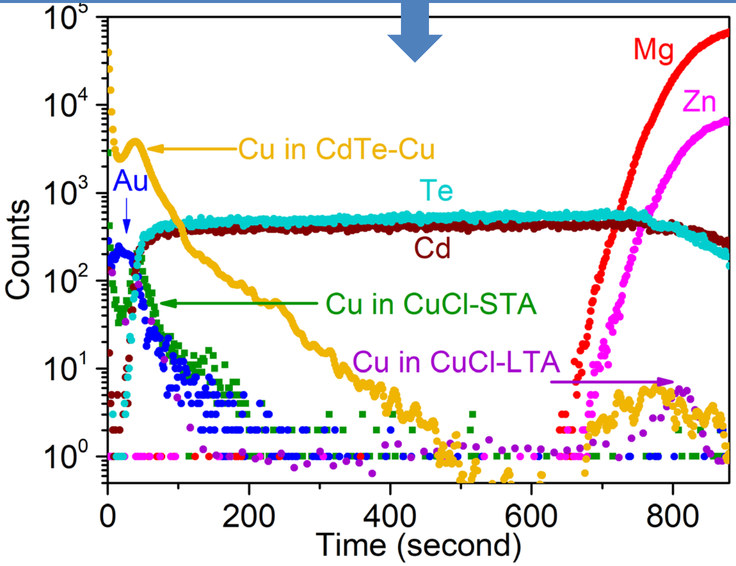
Traditional Cu activation process



Short Thermal Annealing



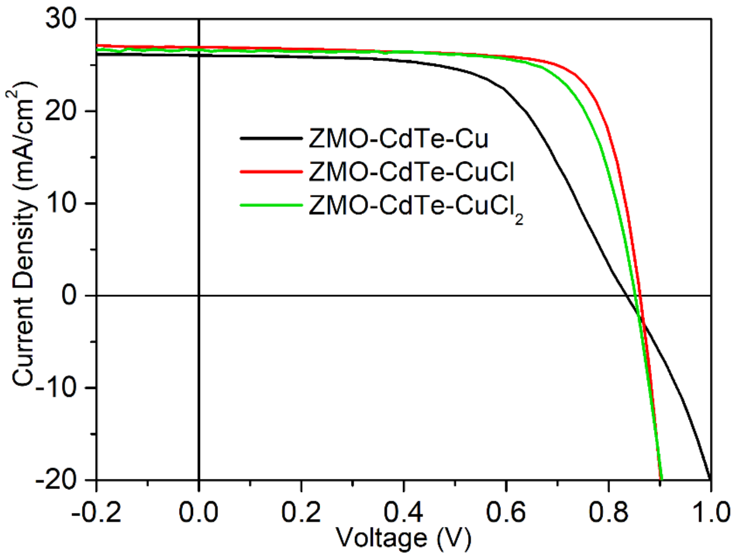
Distribution control

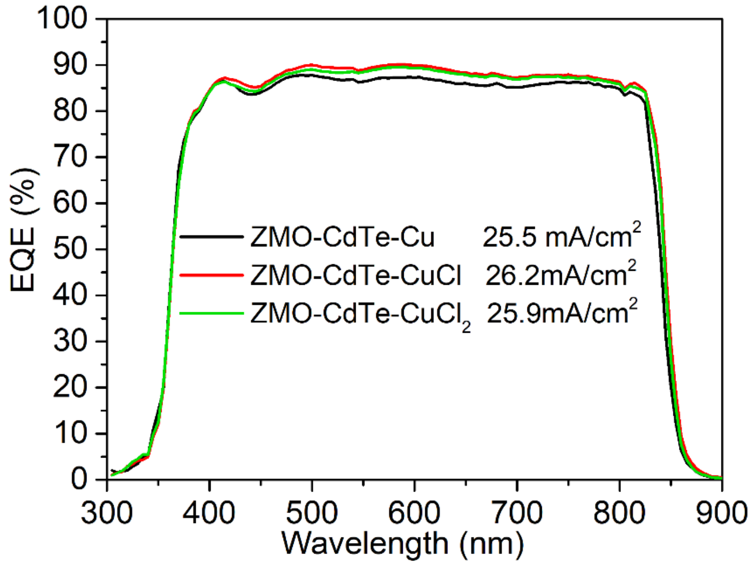


Less Cu dosage:
0.019nm vs. 3-4nm

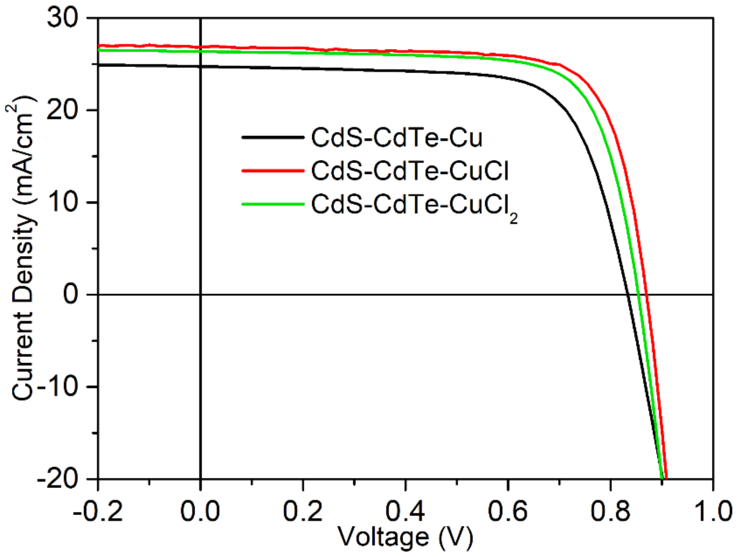
Desired Cu distribution:
less at the front region

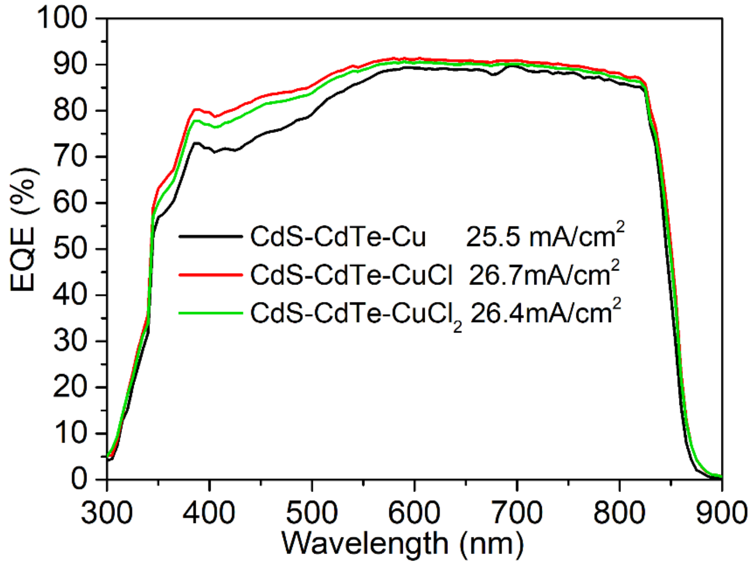
Cu Engineering





With ZMO as buffer layer
17.5% with MgF_2

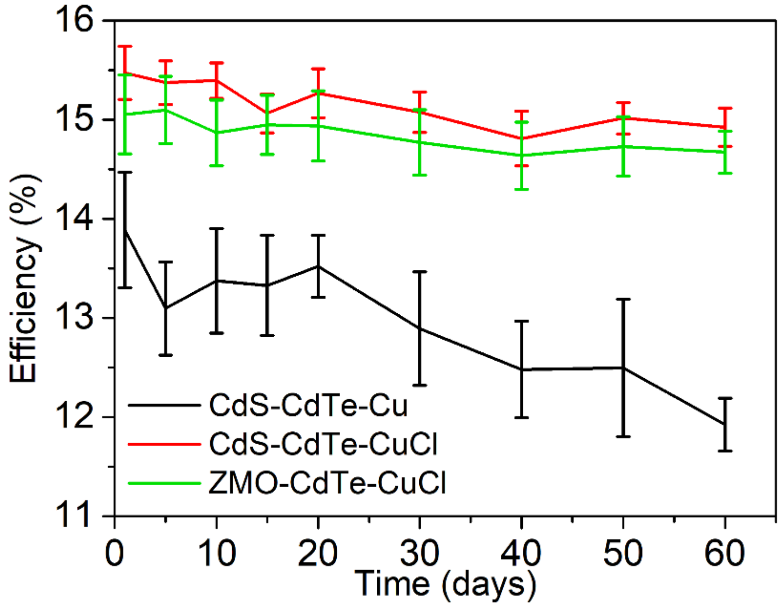


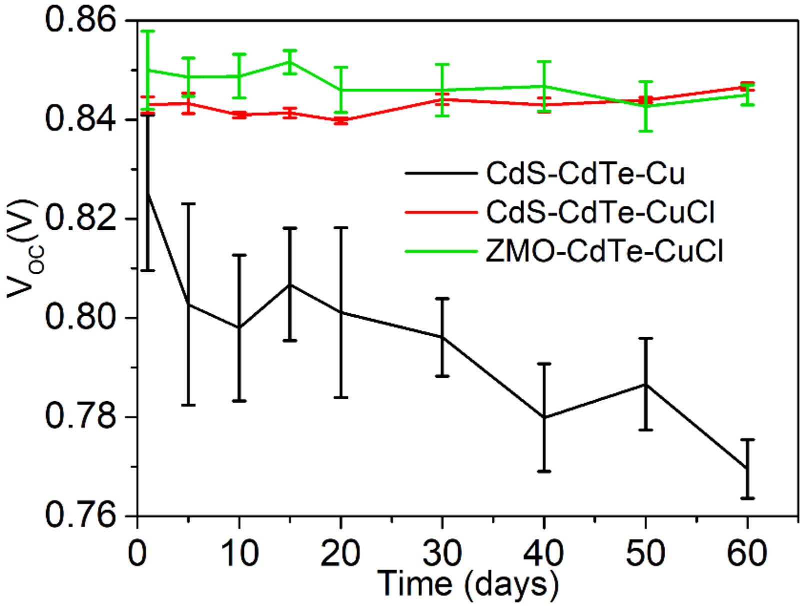


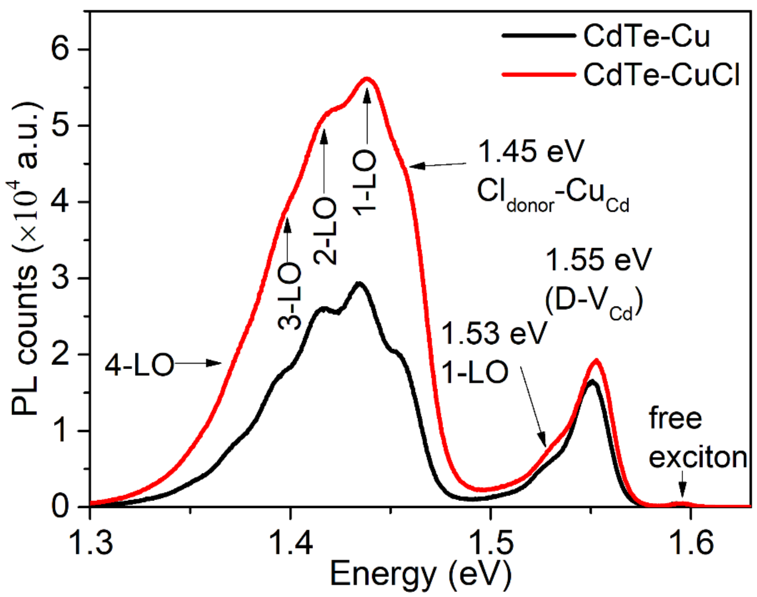
With CdS as buffer layer
17.2% with MgF_2

Cu Engineering

Improved Stability

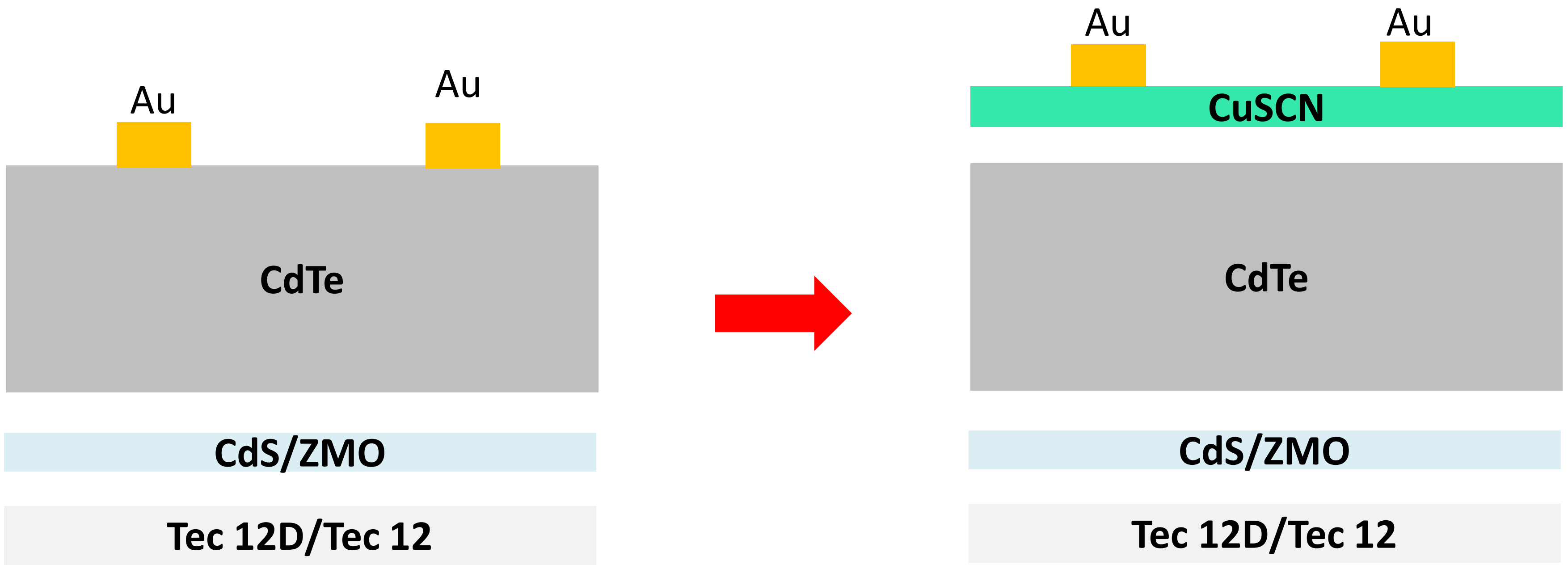






- More substitutional Cu_{Cd} can be observed from low temperature PL spectra and less expected $Cu_i$and other compensatory defects can be expected.
- Higher device stability than traditional can be achieved with this Cu engineering strategy

Cu Engineering



CuCl as dopant

CuSCN as dopant + Hole transport layer

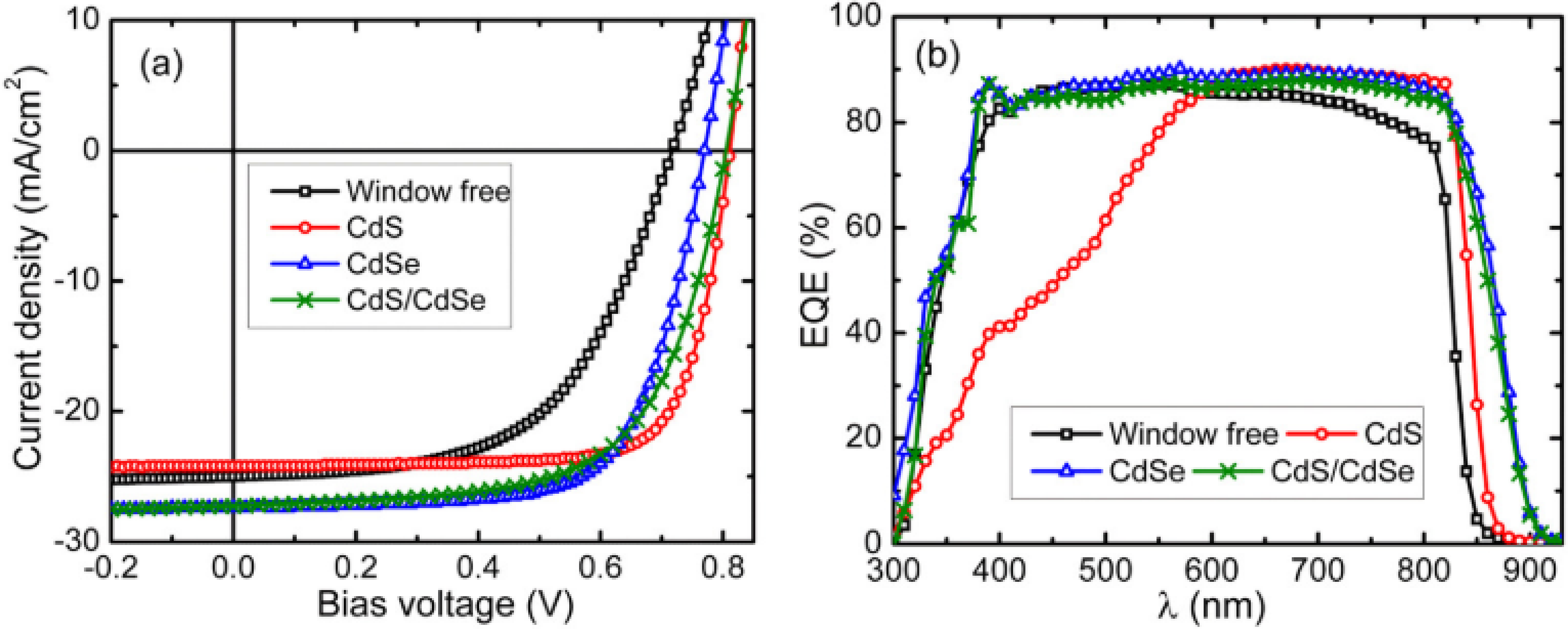
Materials 13(2020), 1991; Prog. Photovolt. Res. Appl. 2019;1–8

Se Incorporation

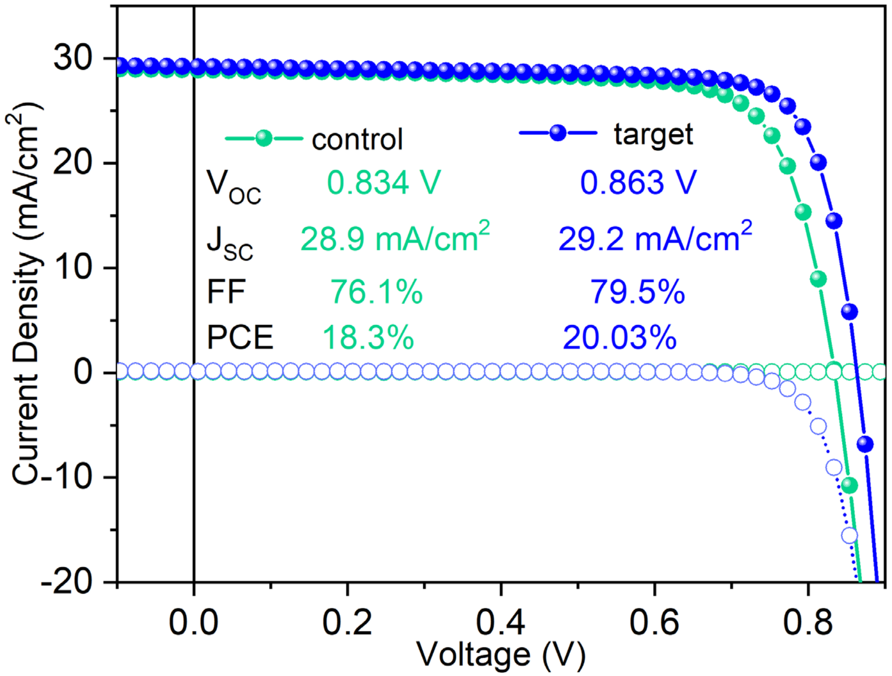
APPLIED PHYSICS LETTERS **105**, 183510 (2014)

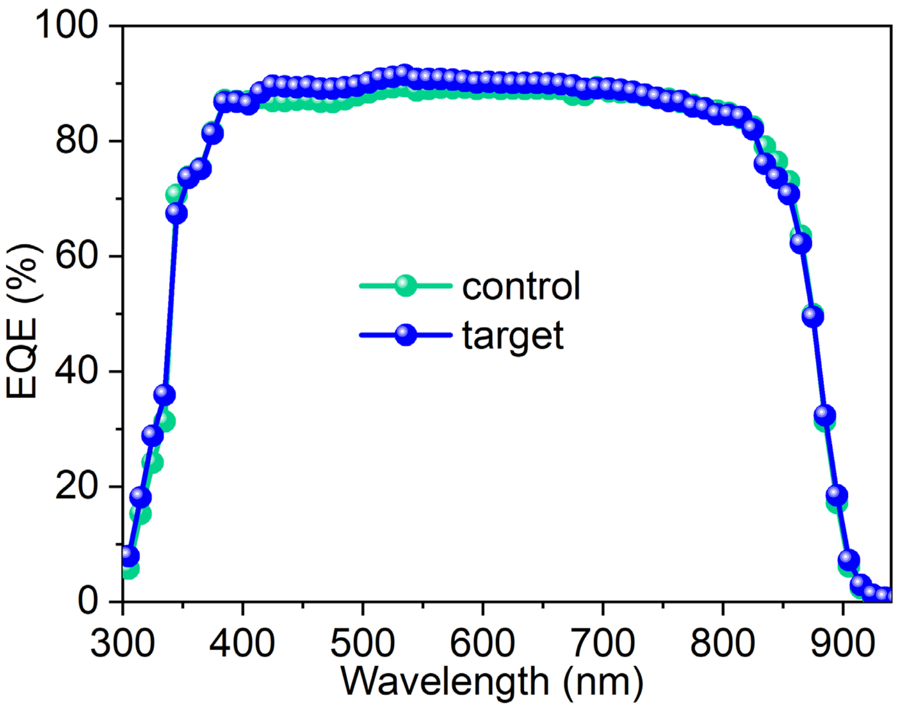
Enhancing the photo-currents of CdTe thin-film solar cells in both short and long wavelength regions

Naba R. Paudel[a] and Yanfa Yan[b]
Department of Physics and Astronomy, and Wright Center for Photovoltaics Innovation and Commercialization, The University of Toledo, Toledo, Ohio 43606, USA



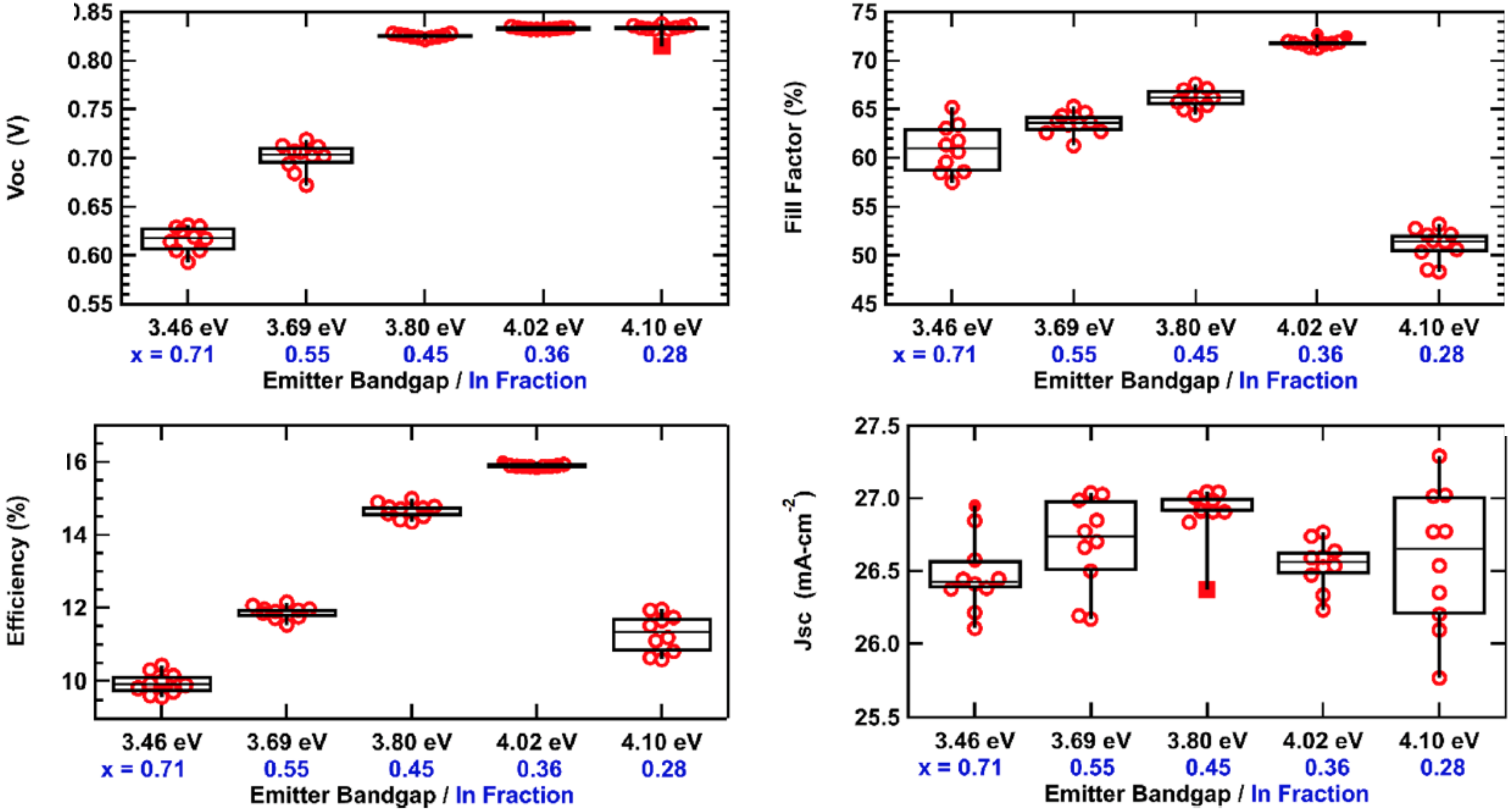
Se Incorporation

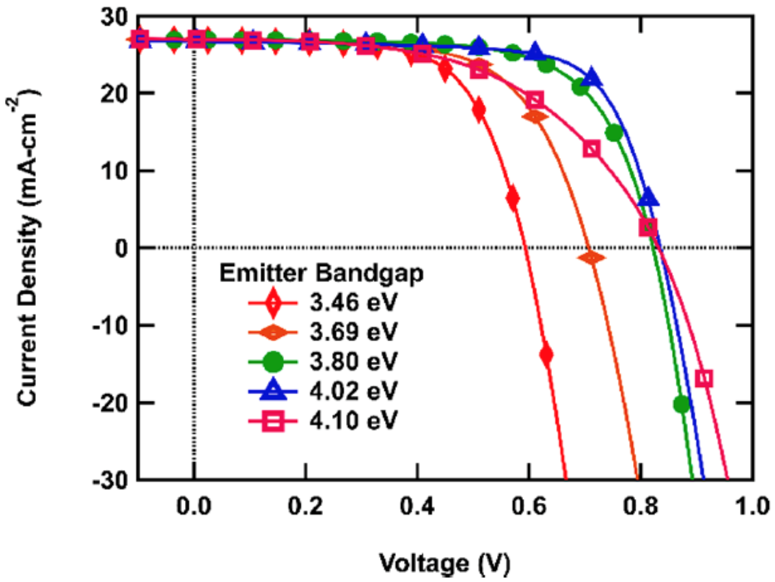


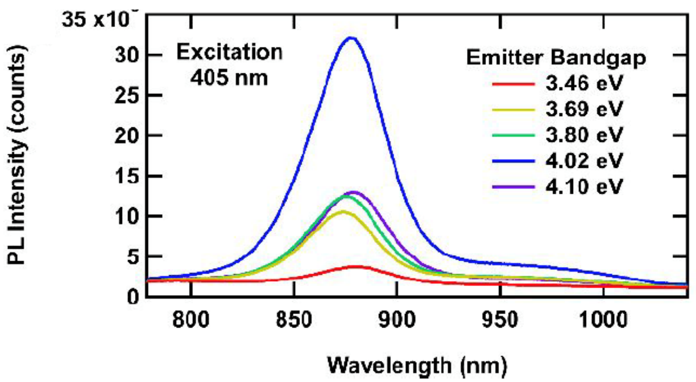


20% PCE was successfully demonstrated with the Cd(Se,Te) region with composition and bandgap gradient.

TEC 10/IGO/CdSe/CdTe/$CuCl_2$/Au



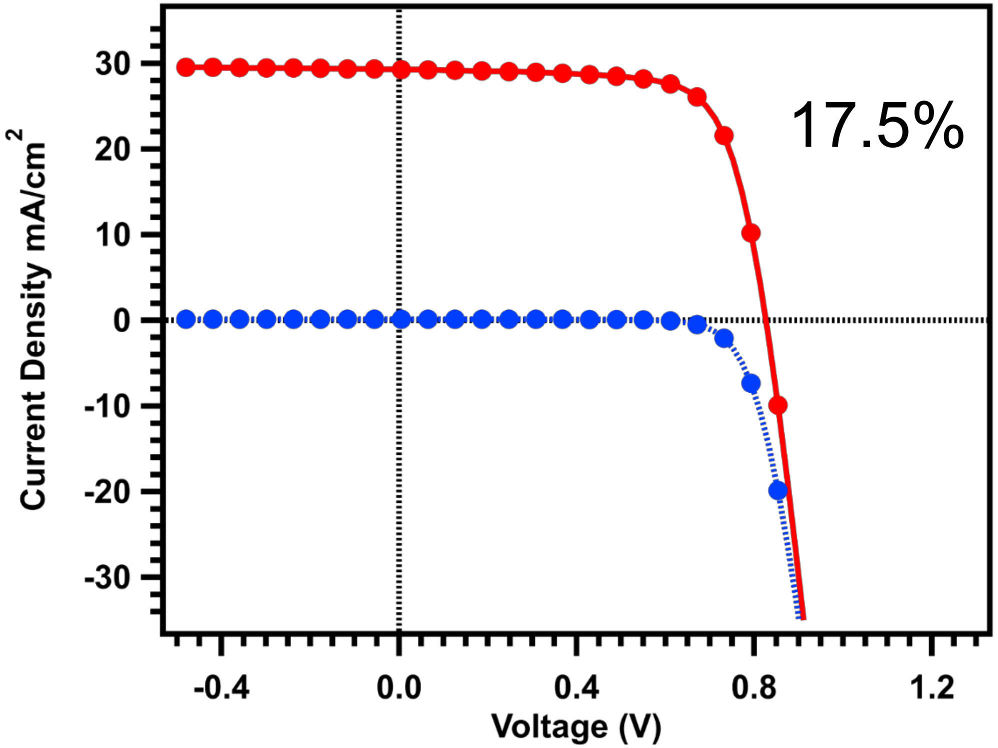




Jamarkattel et al. *ACS Appl. Energy Mater. 2022, 5, 5484−5489*

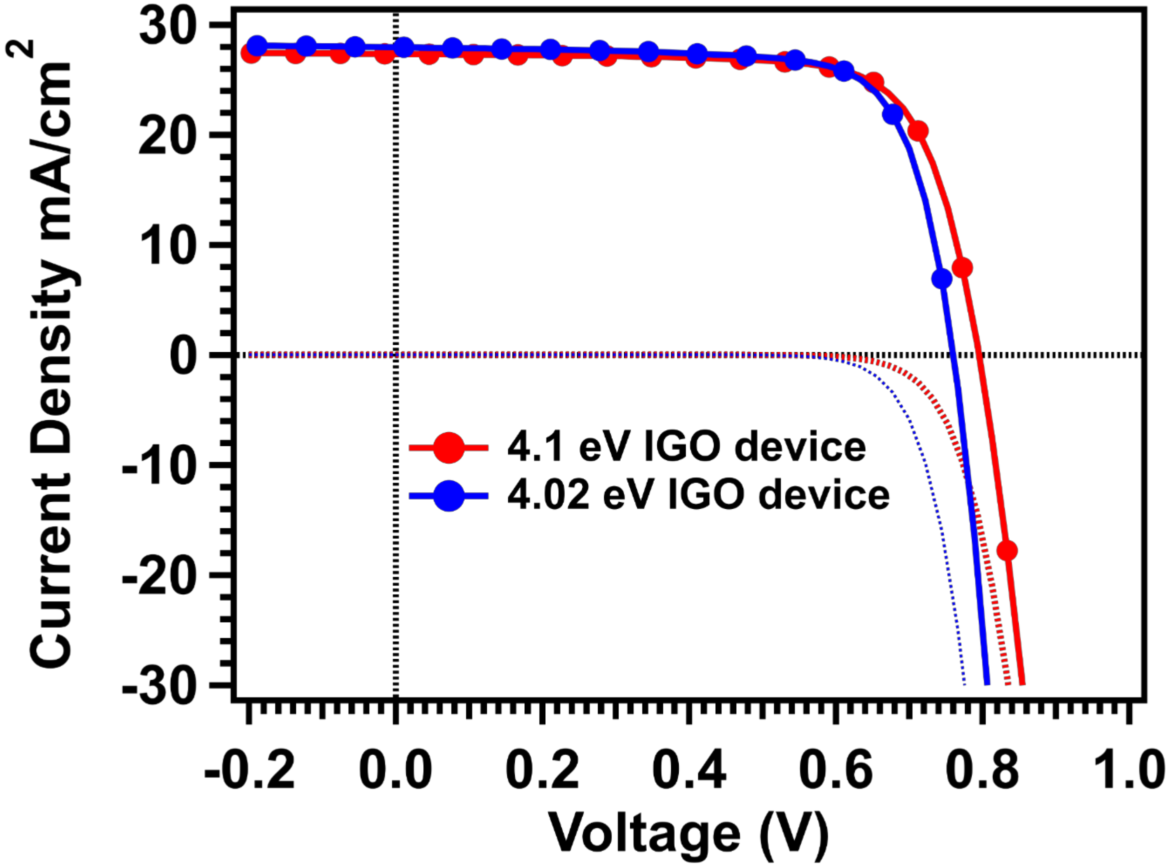
TEC 12/IGO/CdSe/CdTe/$CuCl_2$/Au

Voc: 827 mV
Jsc 29.2 mA/cm^2
FF: 72.3%
PCE = 17.5%



In comparison to MZO, fabrication is less sensitive to P_{O2}

Willow® Glass (100 µm)/ Cd_2SnO_4/IGO/CdSe (90 nm) /CdTe



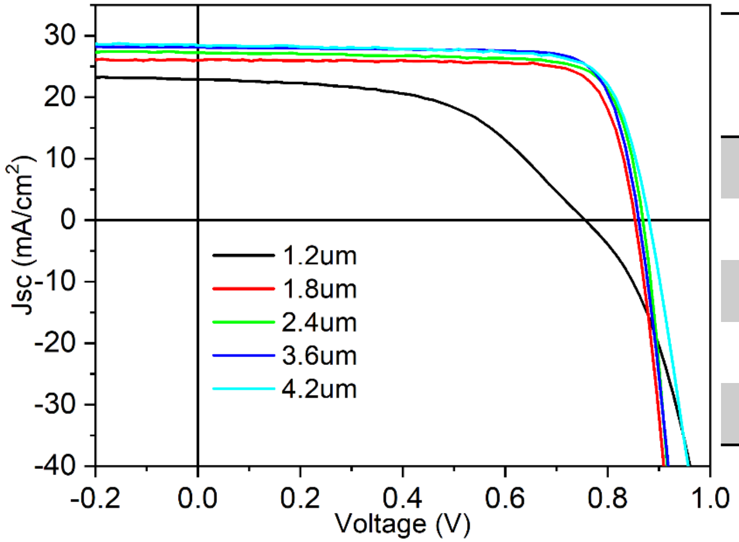
- Larger bandgap of IGO (4.1 eV) is needed for Cd_2SnO_4/IGO/CdSeTe
- May be due to chemistry at Cd_2SnO_4/IGO interface
- 16.1% on Willow is very close to the record*

* 16.4% by Mahabaduge et al, Appl. Phys. Lett. 106, 133501 (2015)

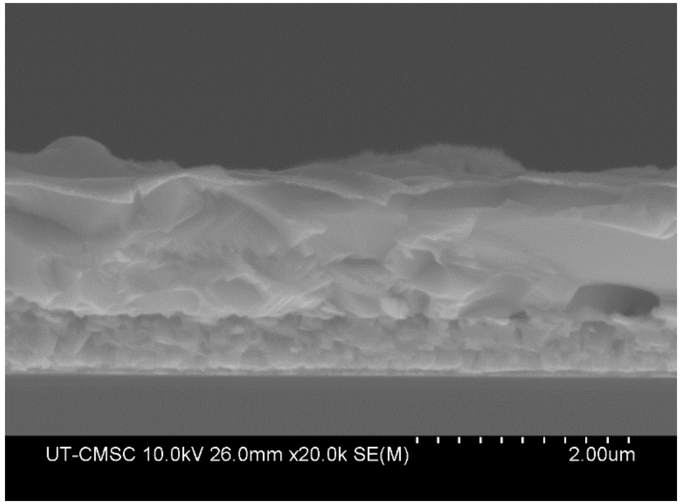
Average/Max PV parameters

Sample	Voc (mV)	Jsc (mAcm ^{2})	FF (%)	PCE (%)
4.02 eV IGO	756/760	27.8/27.9	73.7/74.6	15.5/15.85
4.1 eV IGO	790/795	26.8/27.3	73.5/74.1	15.6/16.13

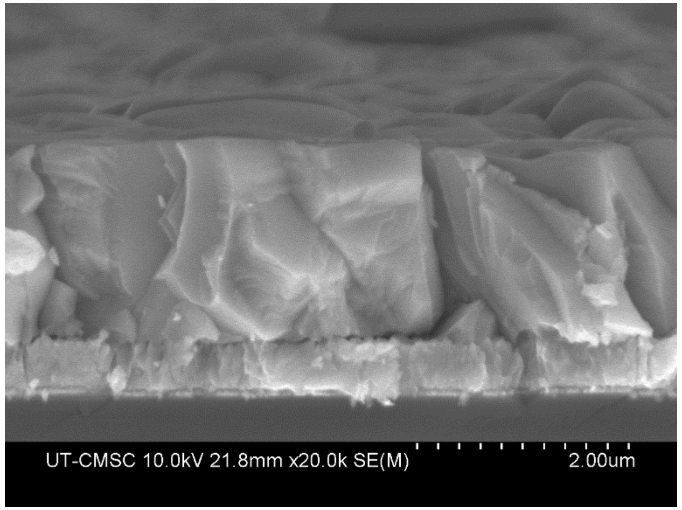
Ultra-thin CdSeTe Solar Cells



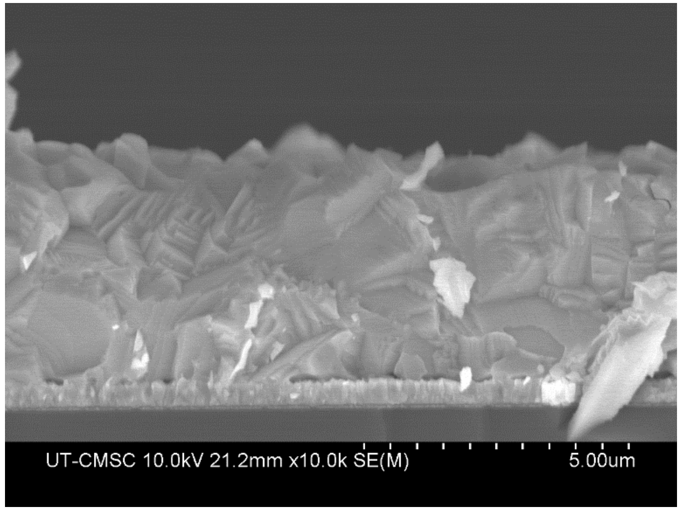
samples	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	PCE (%)	R_S ($\Omega \cdot cm^2$)	R_{SH} ($\Omega \cdot cm^2$)
1.2um	0.756	22.9	53.0	9.18	11.8	556
1.8um	0.853	26.0	80.6	17.9	3.1	2215
2.4um	0.868	27.3	79.9	18.9	2.8	1194
3.6um	0.861	28.2	79.9	19.4	1.3	1760
4.2um	0.881	28.4	76.7	19.2	2.1	1241



1.2μm

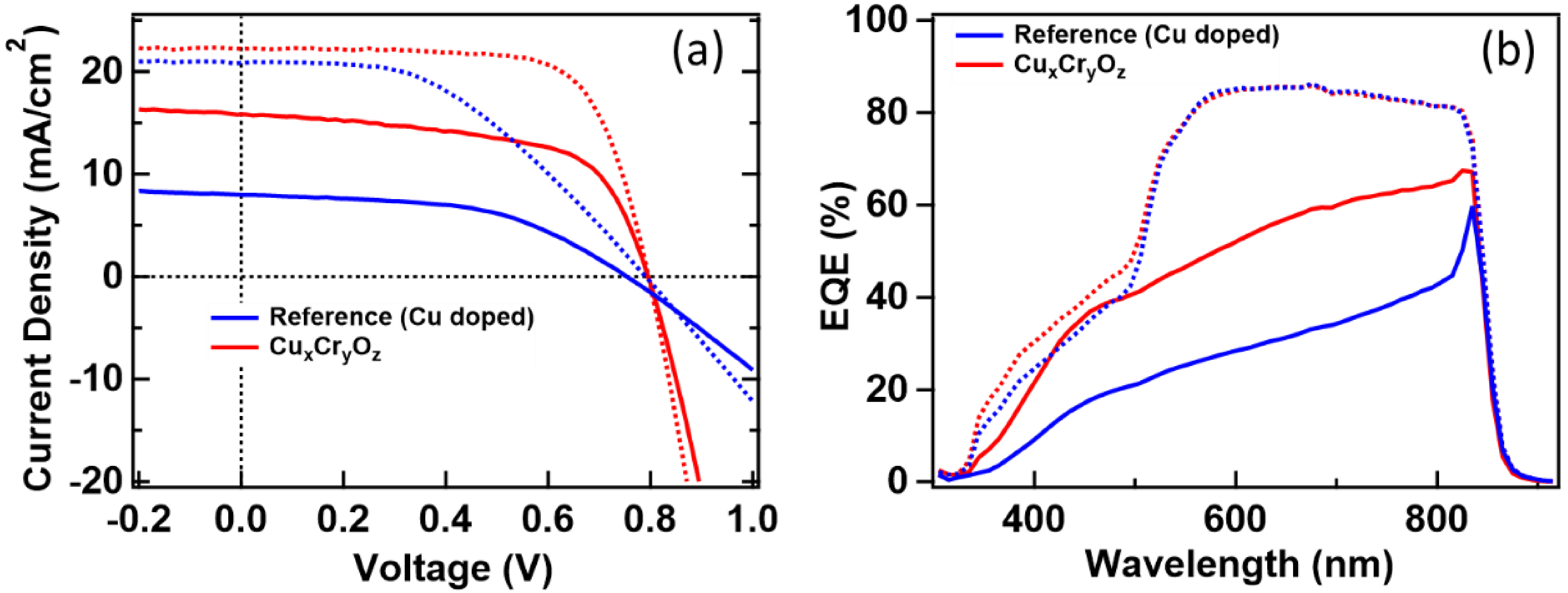


1.8μm



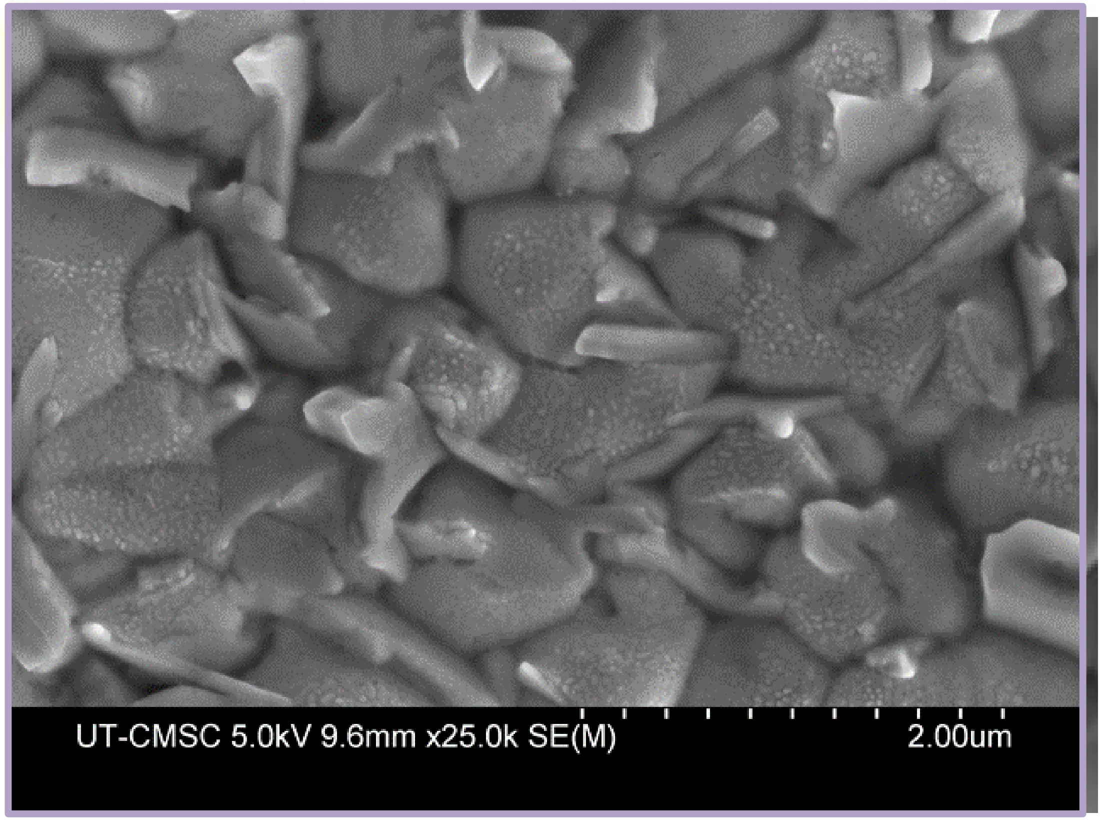
3.6μm

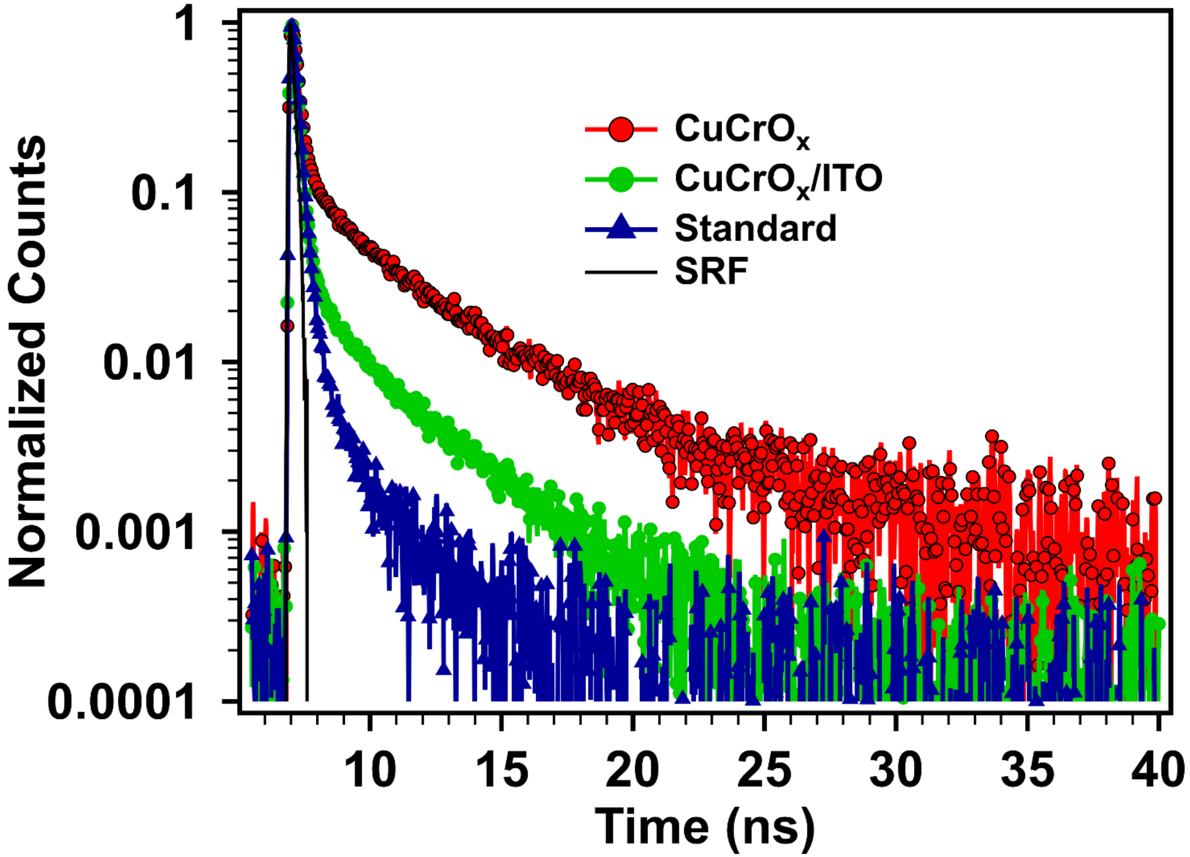
Towards viable bifacial CdTe-based PV: ITO as back electrode



Performance data of bifacial CdTe/CdS solar cells (solid and dotted lines correspond to back and front illumination, respectively). Reference corresponds to a Cu-doped device with ITO contact, and $Cu_xCr_yO_z$ refers to the device with buffer and ITO back contact. (a) J-V characteristics, and (b) EQE.

Bifacial – notes and next steps



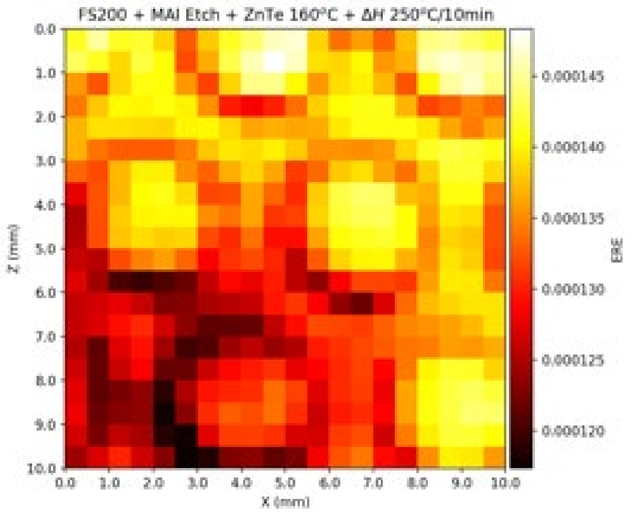


- Identify composition and structure of (CdClOx?) platelets, which correlate with improved back-illuminated performance → material of interest as passivant. Removing platelets w/ HCl etch kills back-side performance.
- Challenges associated with CdSeTe film stack, and achieving simultaneous high PCE and good bifaciality.
- Move to As-doped CST brings new challenges and opportunities (stay tuned).

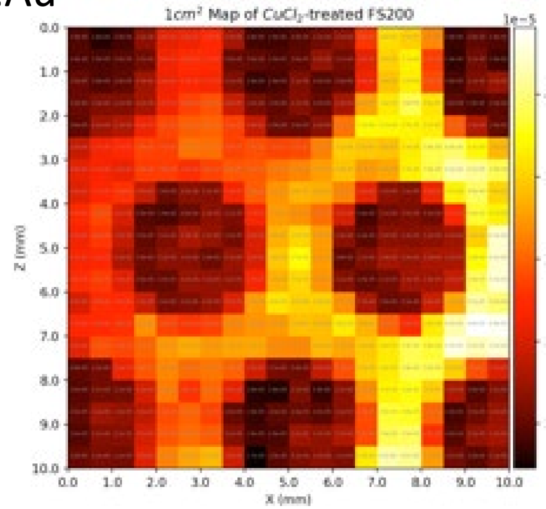
New capability: ERE mapping

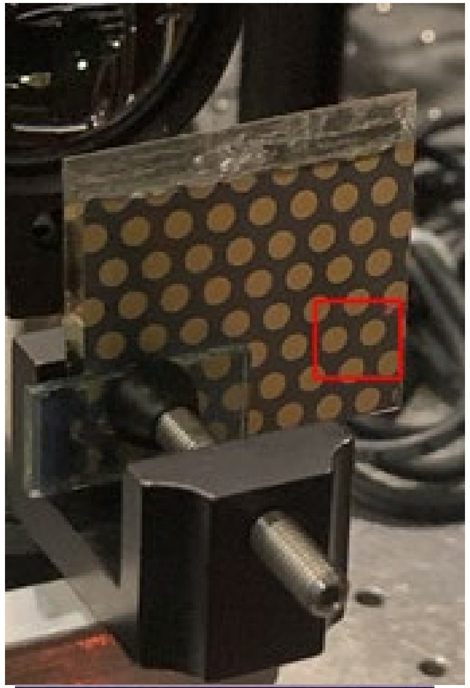
(thanks to ASU for early help: Ohno/Holman/Zhang)

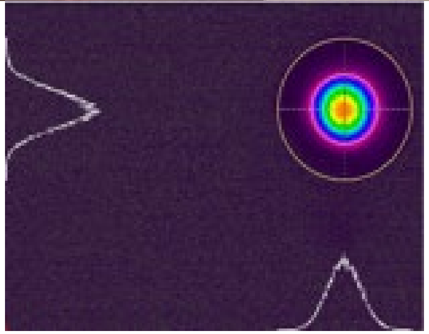
CH_3NH_3I “etch” + Cu:ZnTe



Cu:Au





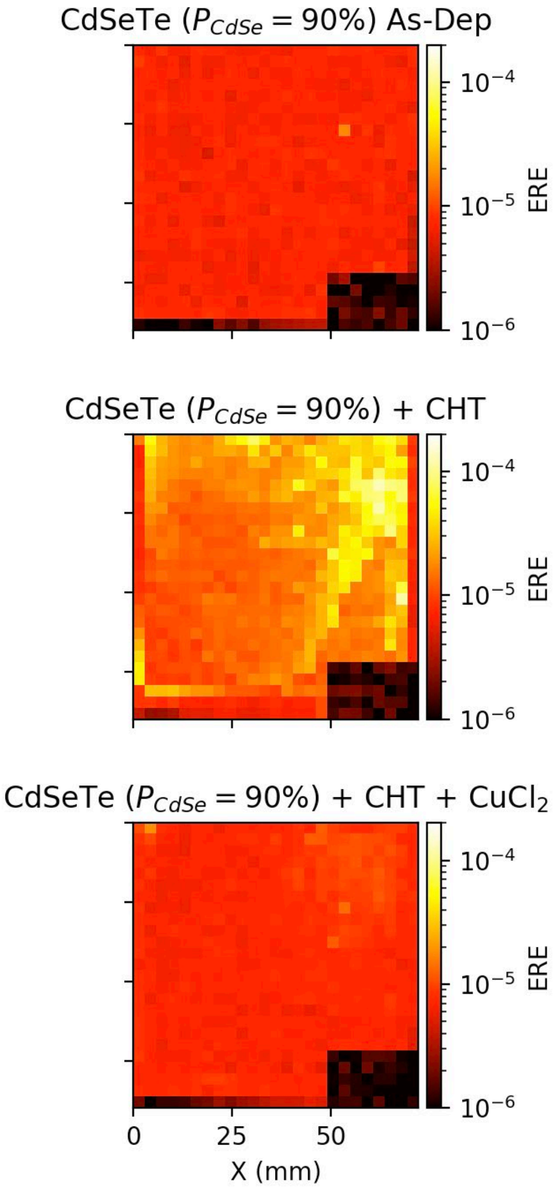


Combinatorial investigations (off-axis co-evap of CdTe /CdSe)

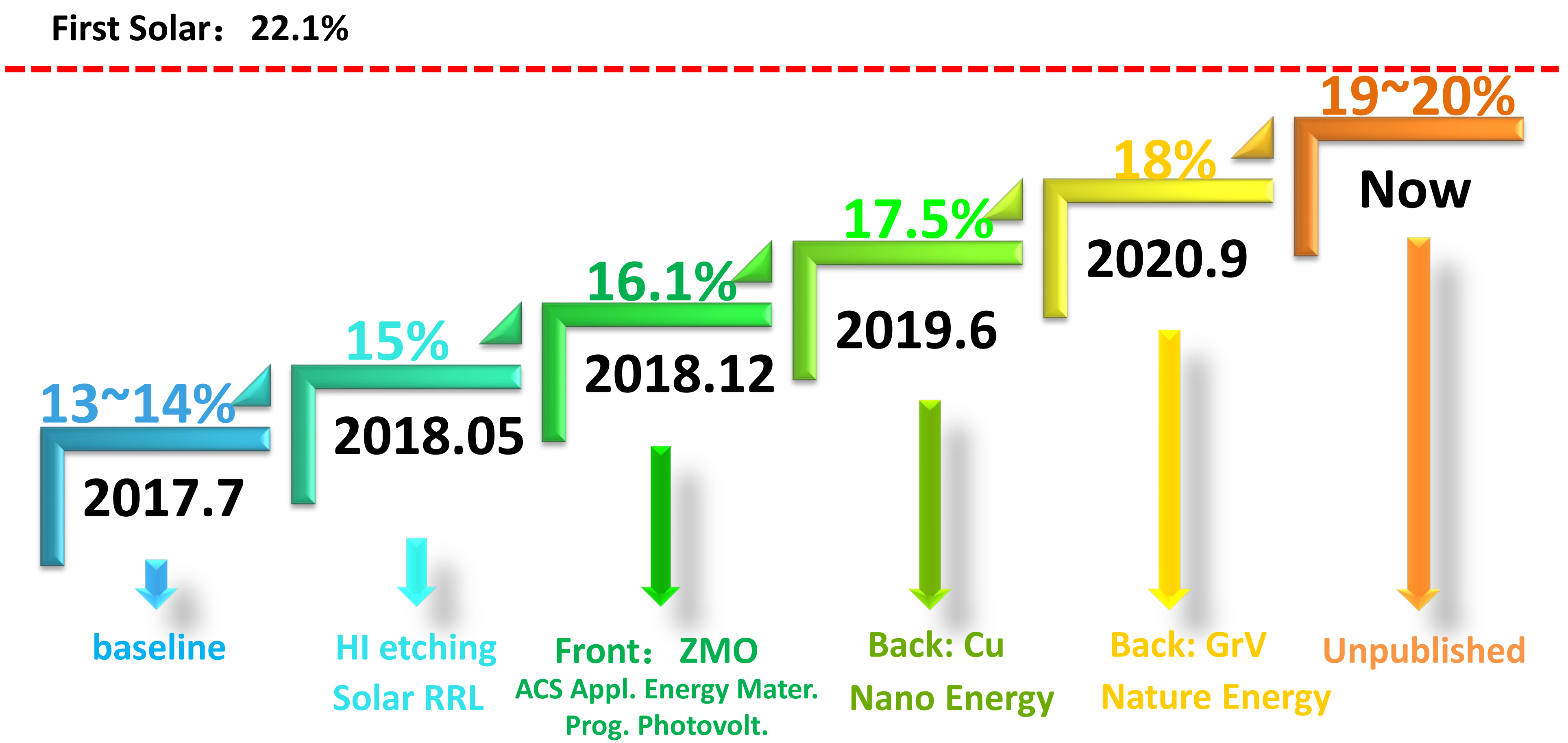
As-Deposited

After $CdCl_2$

After $CuCl_2$



Summary



UT can further improve its contribution to CdTe community and advance the CdTe photovoltaic technolodgy!

Thank You for Your Attention!

Questions?

There are other advances going on at UT and you are encouraged to talk individually to PVIC faculty/students!

Prof Collins: robert.collins@utoledo.edu; Prof. Ellingson: randy.ellingson@utoledo.edu;
Prof. Heben: michael.heben@utoledo.edu; Prof. Podraza: nikolas.podraza@utoledo.edu;
Prof. Yan: yanfa.yan@utoledo.edu.