Effects of FIB Processing on Local Measurements of Solar Cells

Heayoung P. Yoon

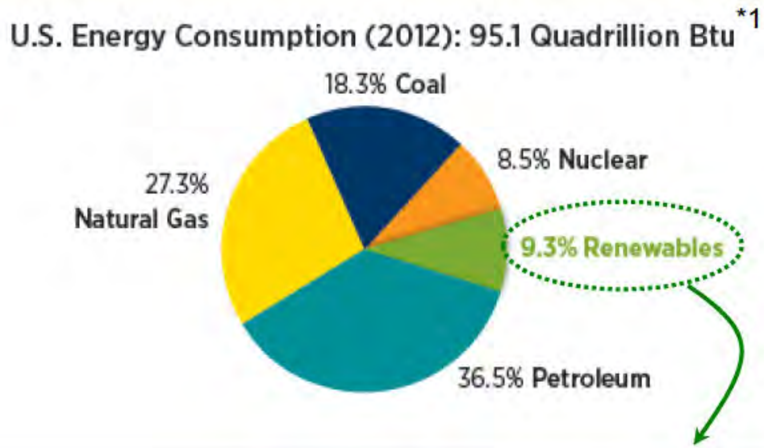
CNST Center for Nanoscale Science & Technology

7th Annual FIB SEM Workshop, Laurel, MD

(February 27, 2014)

NIST National Institute of Standards and Technology • U.S. Department of Commerce

Energy consumption, and renewable capacity



[Q] Size of PV area to cover all US energy consumption?

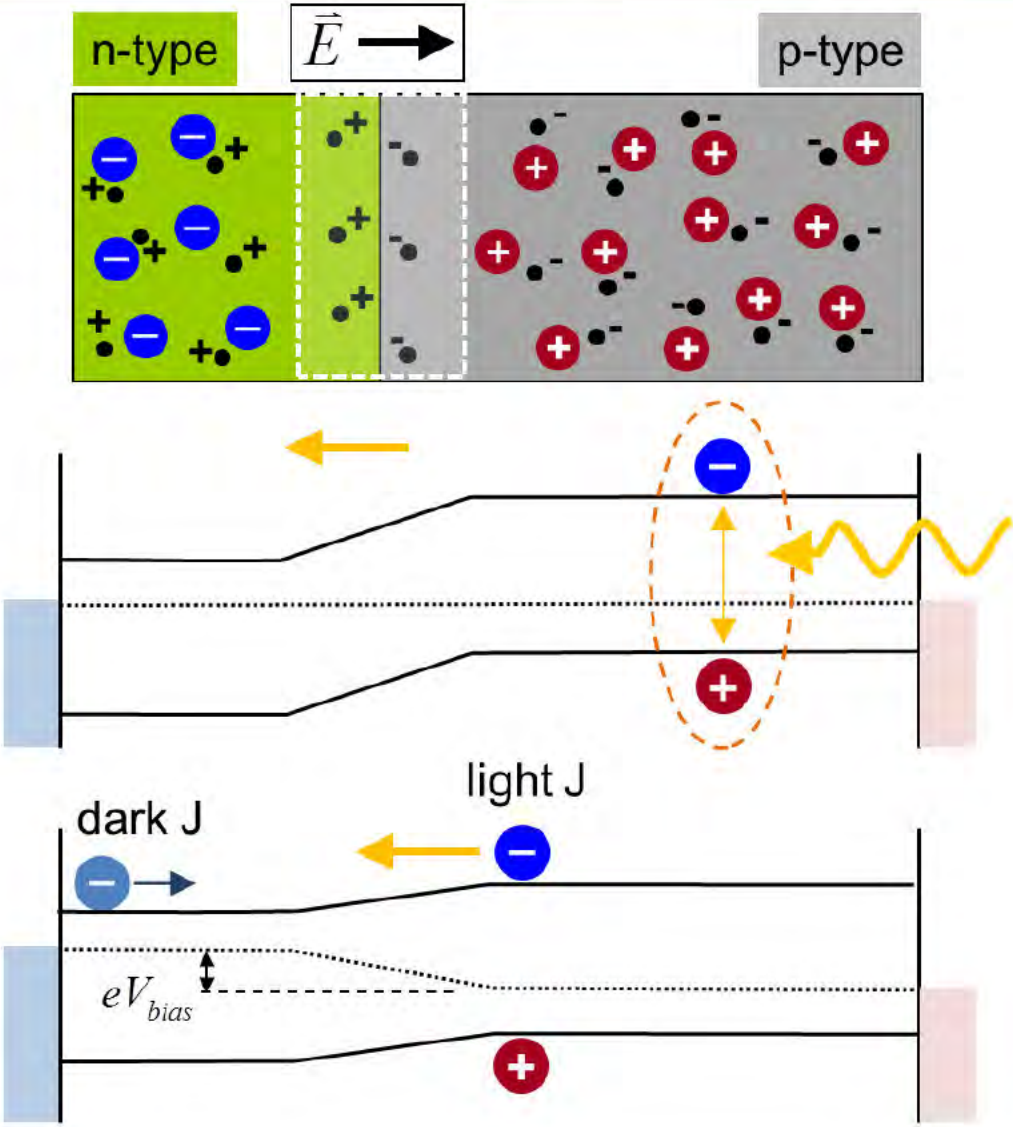
- US Energy consumption rate[*2] $= 3\text{x}10^{12}$ W
- Time-averaged solar energy flux $= 250$ W/m^2
- Best conversion efficiency = 33%

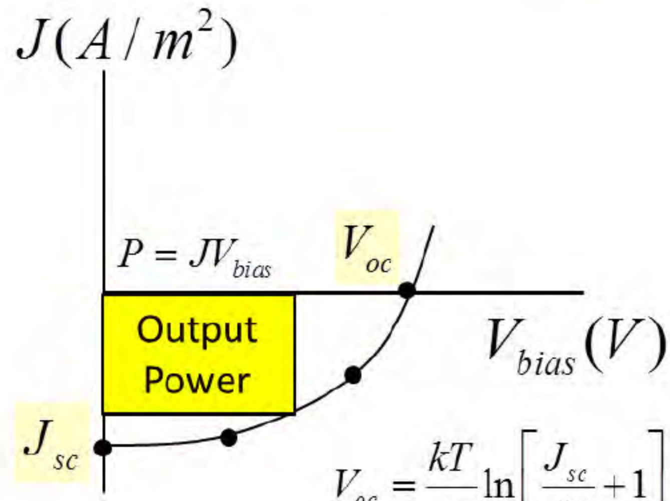
→ Pure PV area of (150 miles)^2

[*2] http://www.eia.gov/forecasts/ieo/index.cfm

[*1] http://www.nrel.gov/docs/fy14osti/60197.pdf (2012 Renewable Energy Data Book)

Extracting photo-carriers with p-n junction





$$V_{oc} = \frac{kT}{q} \ln\left[\frac{J_{sc}}{J_0} + 1\right]$$

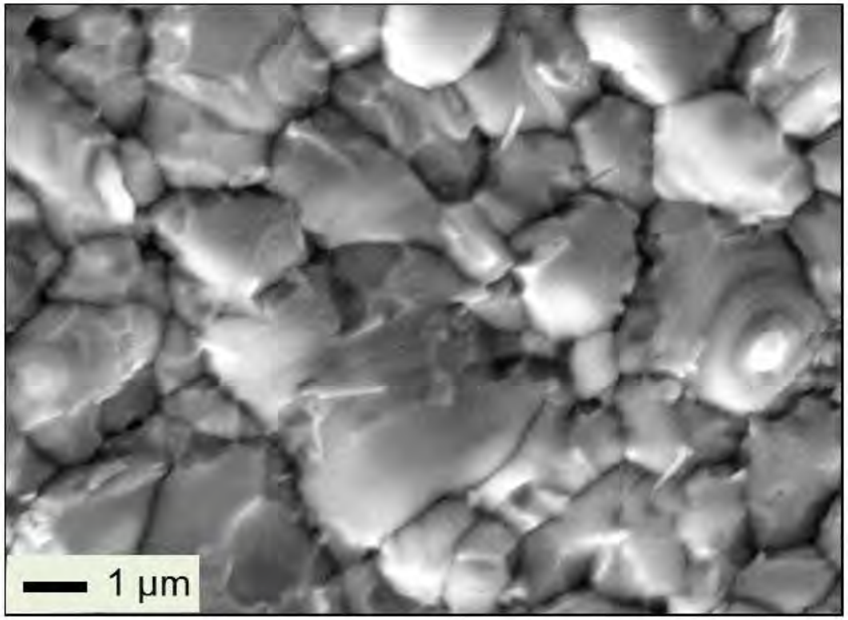
$$\eta = \frac{P_{out}}{P_{in}} = \frac{J_{sc} \times V_{oc} \times F.F.}{P_{in}}$$

η: power conversion efficiency

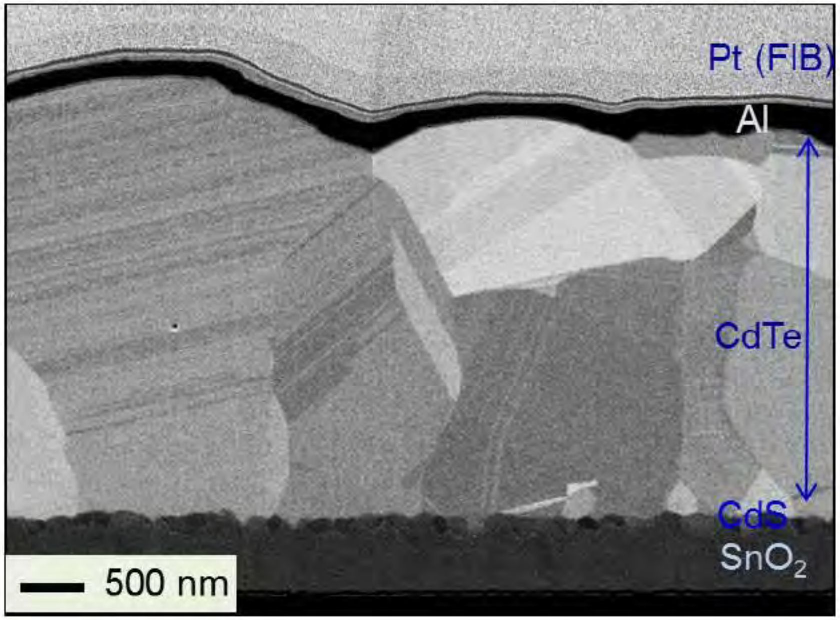
- J_{sc}: short-circuit current
- J_0: dark current
- V_{oc}: open-circuit voltage
- FF: fill factor

Microstructure of thin-film PV: highly defective

top view



cross section

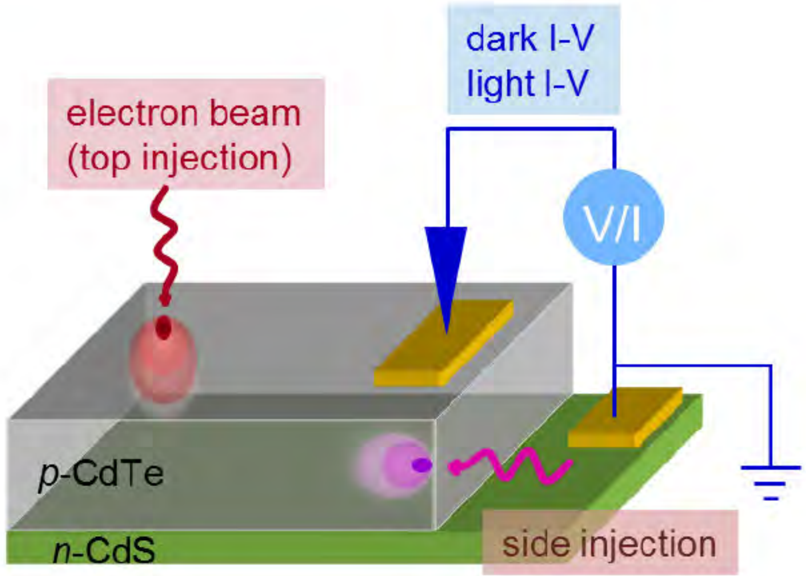


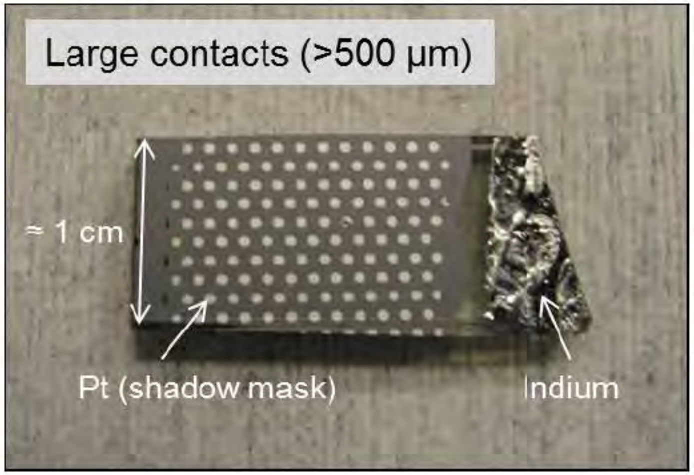
- Comprised of grains (100's nm ~ a few µm): lots of grain boundaries (GBs)
- Local variation of chemical composition / defects

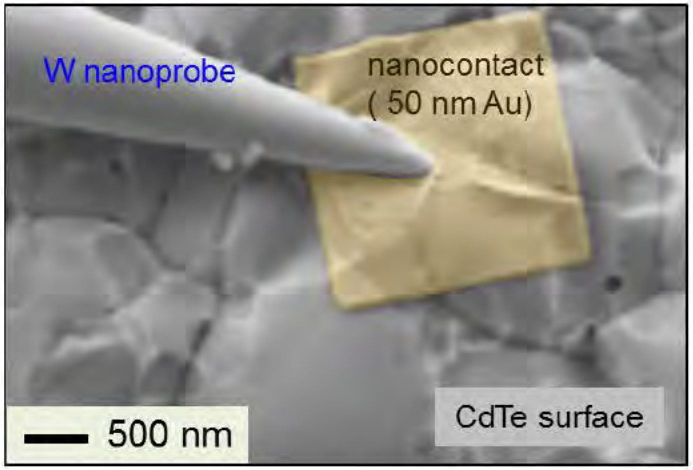
→ impact of grain boundaries on efficiency: mainly unknown

Need for metrology to access properties of individual GB / GI (grain interior)

Electron Beam Induced Current (EBIC)

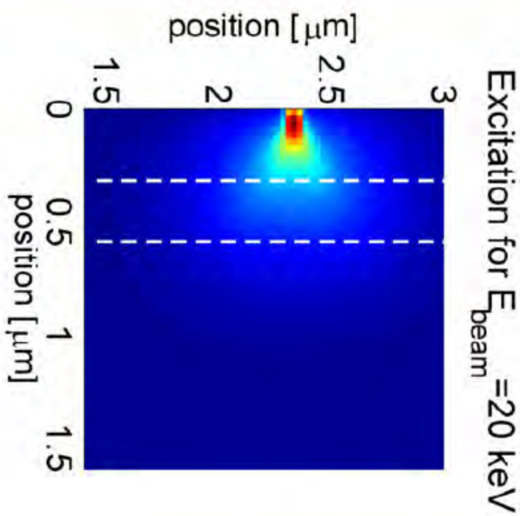


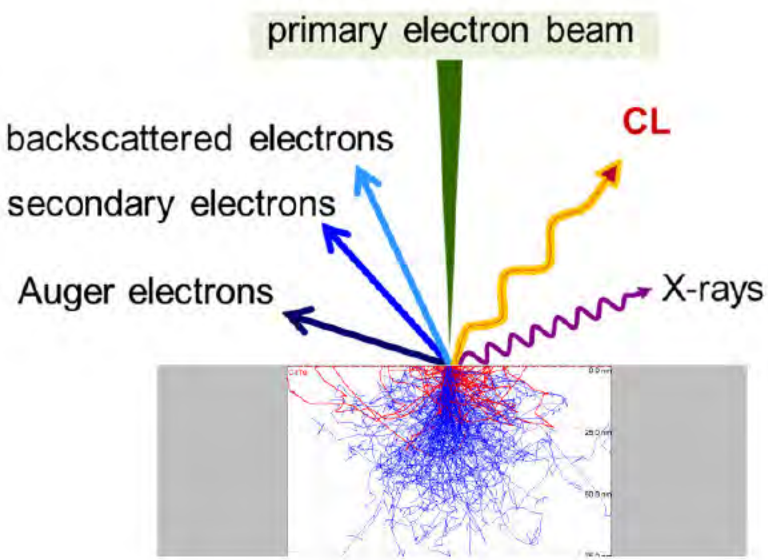


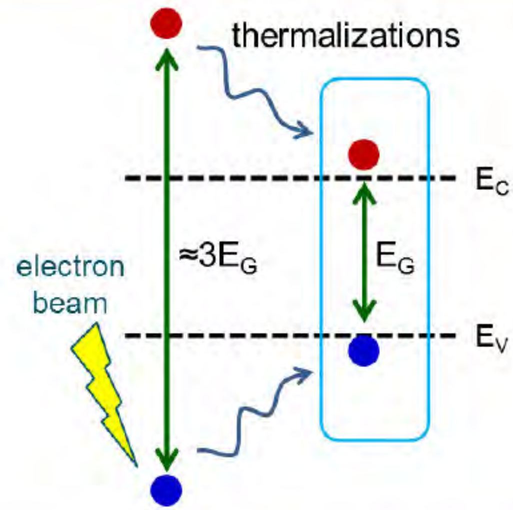


- Local carrier generation with a point injection ((110 nm)^3 at 5 kV, (1.5 µm)^3 at 20 kV in CdTe)
- Beam injection: top surface, cross-section
- Nano-contacts at GBs / GIs
- Probe local PV properties of individual grain / grain boundary

Electron beam generates electron-hole pairs.







$$(\#\text{ of EHPs}) \approx \frac{(\text{deposited e-beam energy})}{3 \times (\text{energy band-gap})}$$

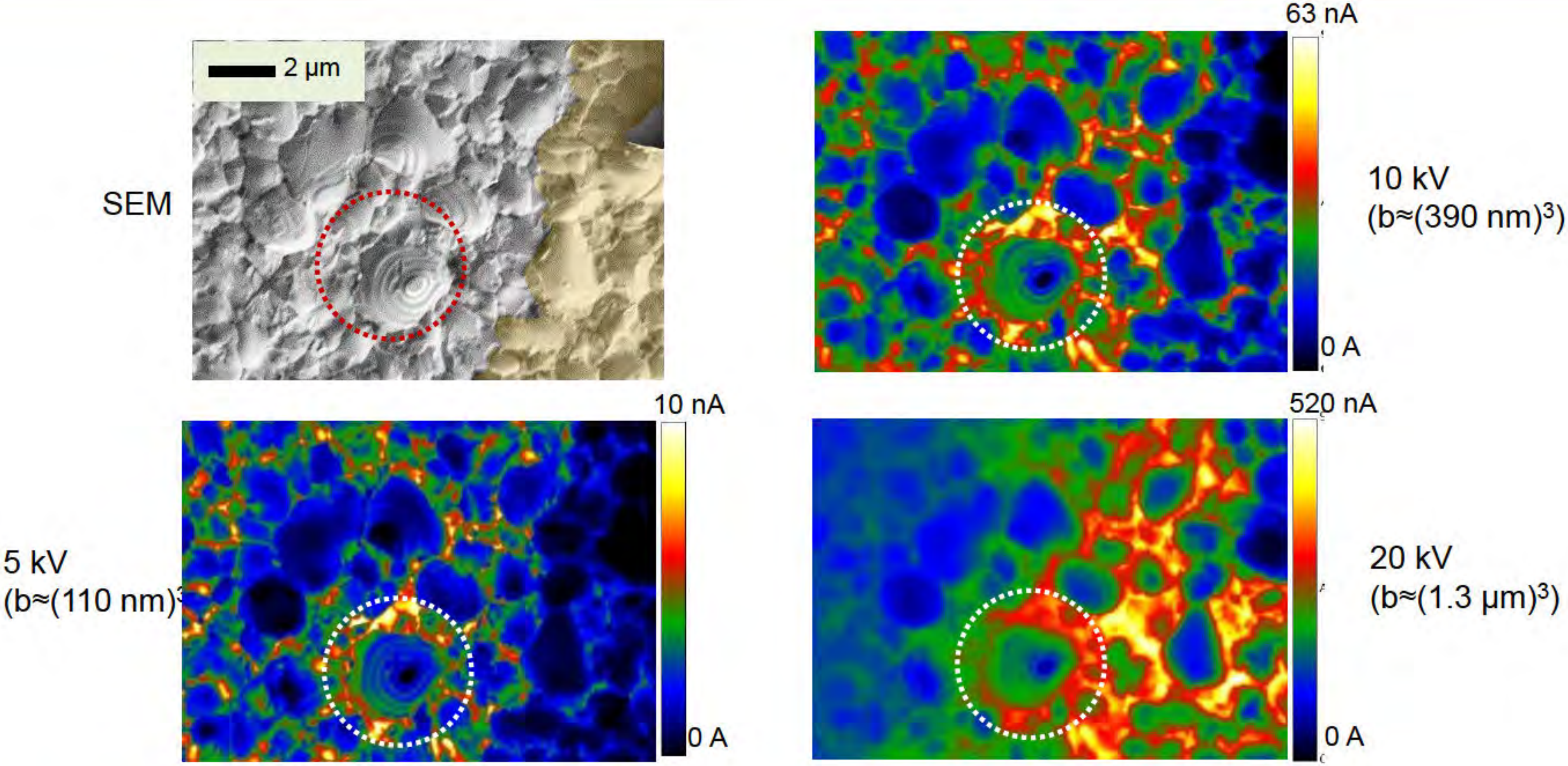
<u>e.g.</u> CdTe: E_G=1.5 eV, Eb=10 keV (BSE ≈30 %)

$\Rightarrow$ ≈1600 ehp

$$(\text{EBIC efficiency}) = \frac{(\text{measured EBIC})}{(\text{beam current})(\#\text{ of EHPs})}$$

C. Klein, J. Appl. Phys. 39 (4), 2029 (1968)

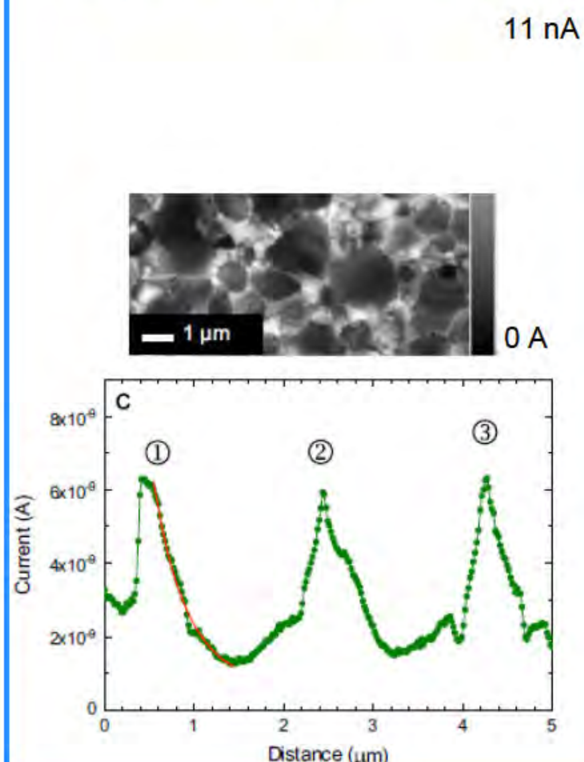
Low keV, high-resolution EBIC



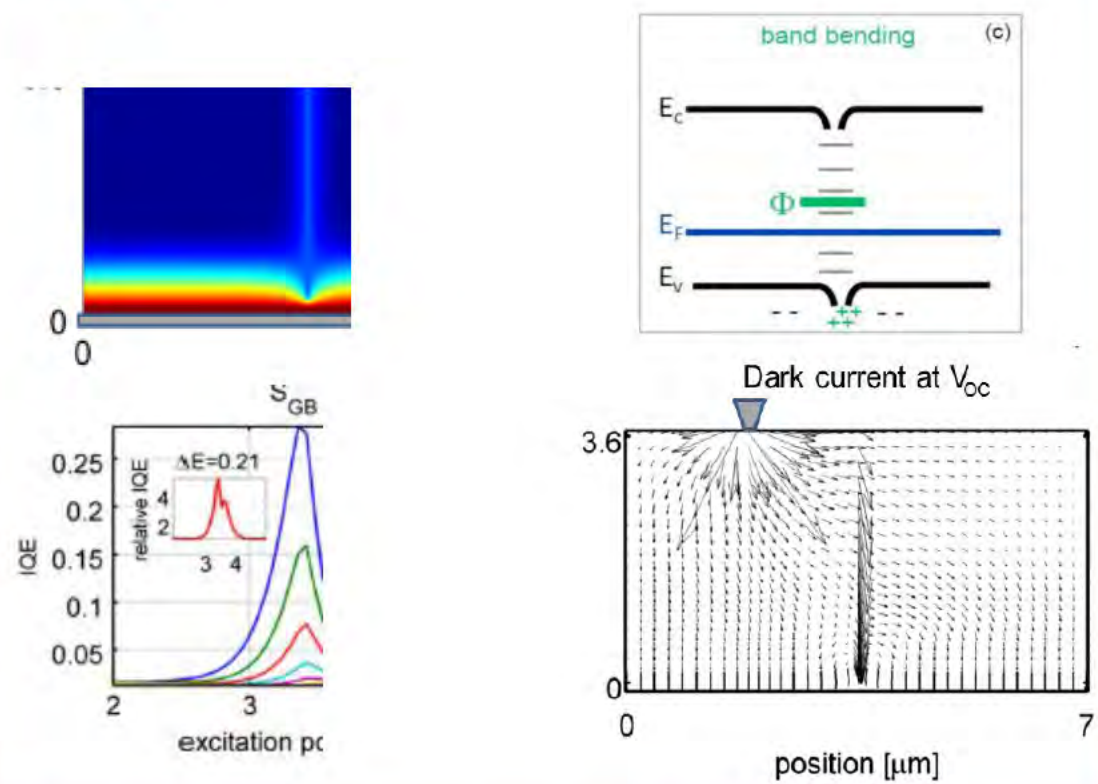
- Current increases as e-h bulb size increases.
- Higher collection at GBs
- Passivated GBs confine and direct carriers (↓ recombination, ↑ IQE).

Modeling explains high carrier collection at GB.

Experiment (3 keV EBIC)



Modeling

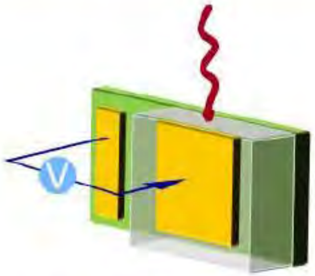


- GBs enhance photo-carrier collection properties (due to the band-bending).
- Model shows high leakage current at V_{oc} near GBs.

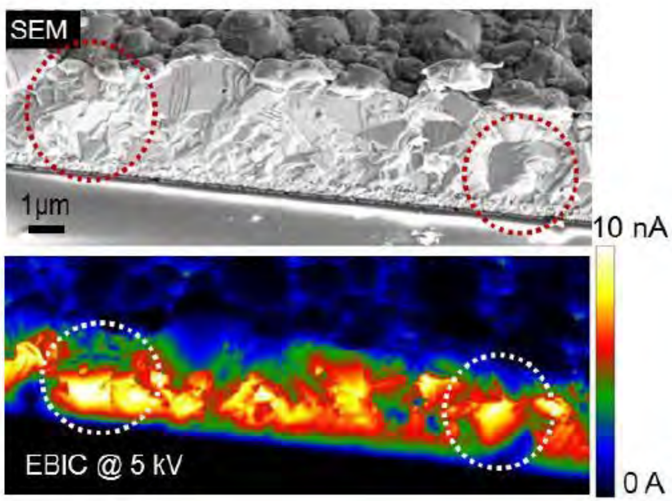
→ Overall impact of GBs: good for low quality PV vs. bad for high quality PV

H. Yoon *et al.*, Solar Energy Mat. and Solar cells, **117**, 499 (2013).

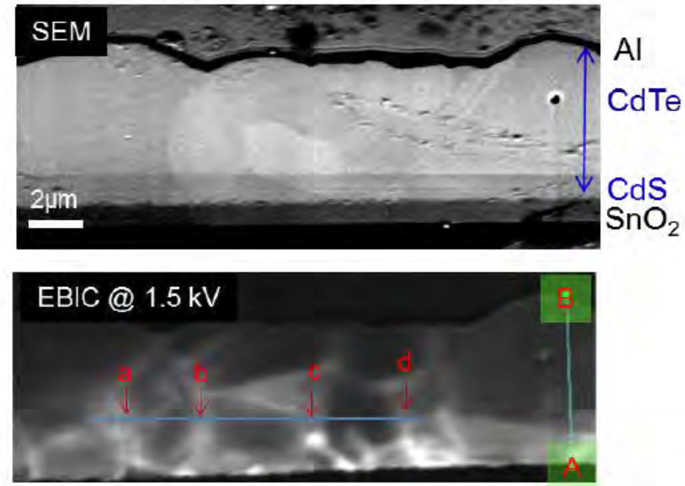
FIB processing creates smooth surface.

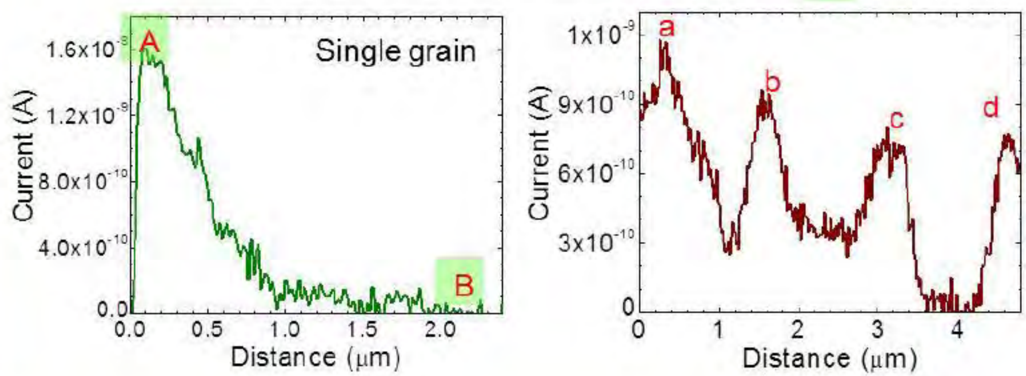


(1) Cleaved device



(2) FIB processed device





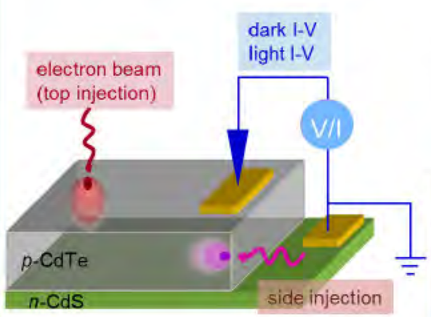
- Higher current at GBs
- GB efficiently serve as 3D contacts collecting minority carriers

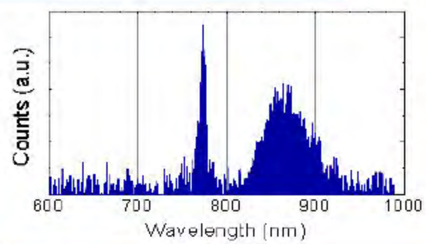
Summary

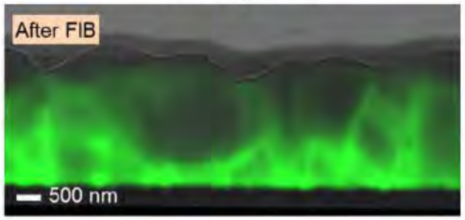
- ✓ Physics of photovoltaic is important and exciting.
- ✓ Low-energy, high-resolution EBIC would be very informative technique for photovoltaic devices.
- ✓ Combination of local detection and local injection for sub-surface microscopy (10 nm to 200 nm scale)

  → electrical, optical, chemical, structural properties

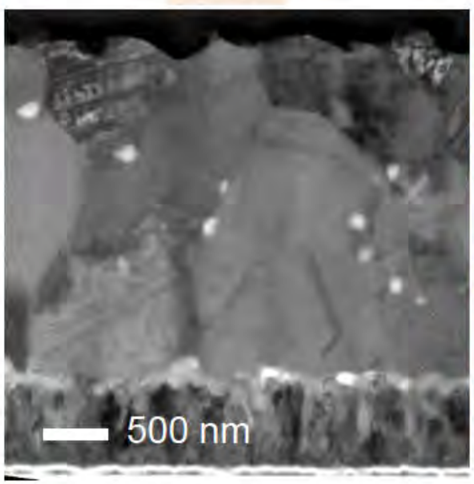
EBIC / cathodoluminescence



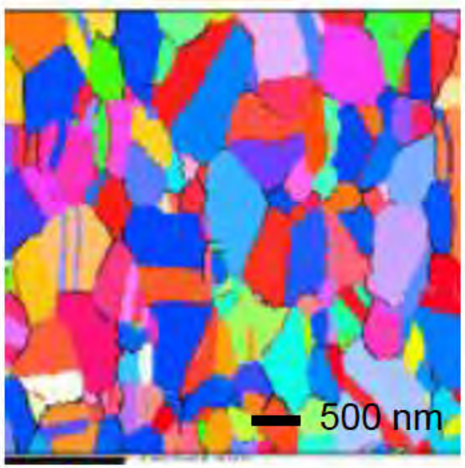




TEM



EBSD



Acknowledgement

Paul Haney
(modeling)

Nikolai Zhitenev
(Group Leader)

Joshua Schumacher
(FIB)

Kerry Siebein
(XRD)

Yohan Yoon
(DLTS)

Alline Myers
(TEM)

Research participants / collaborators

- CdTe solar cell (U. Toledo, GE/First Solar)
- CIGS solar cell (U. Toledo, NRL)
- CZTS solar cell (DuPont)
- Si solar cells: epi Si, high-efficiency PV (NREL)
- Perovskites (U. Nebraska)
- Organic PV

Thank you for your attention!