# Nanoscale Optoelectronic Characterizations of Microstructured Thin-Film Solar Cells


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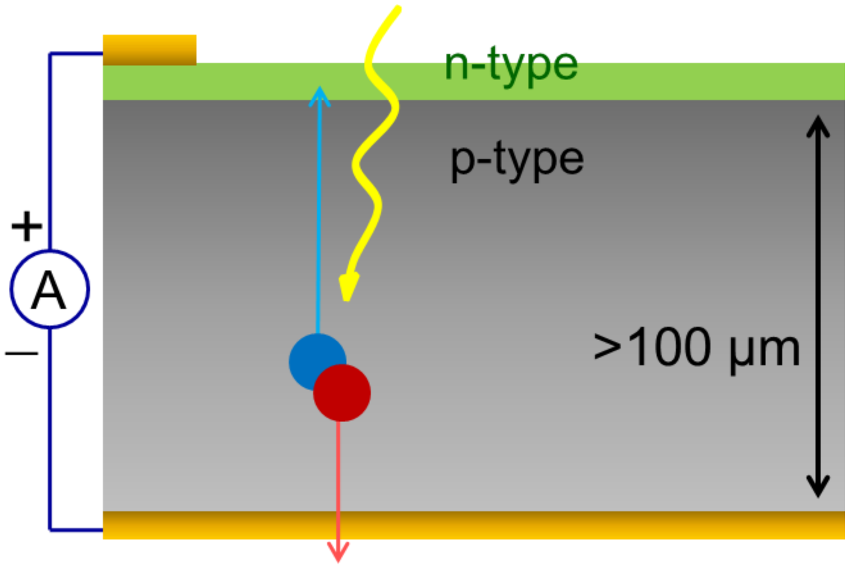
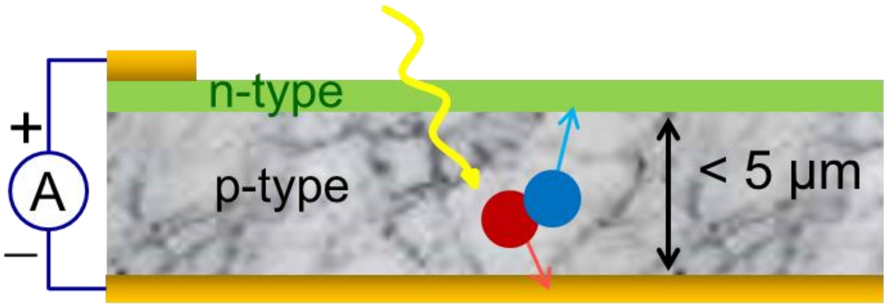
# Thin film PV uses inexpensive materials.

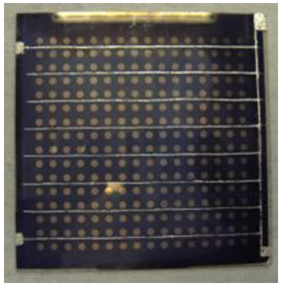



- *c*-Si solar cell
  - Thick (indirect band-gap)
  - High purity (large $L_{n,\,p}$)
  - High efficiency, but expensive

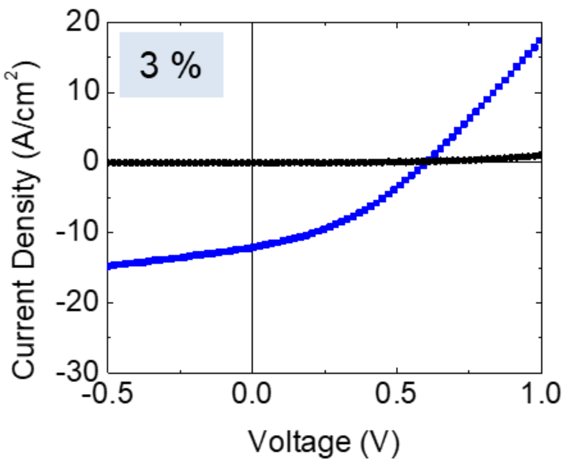
- *px*-CdTe, CIGS, CZTS(Se)
  - Thin (direct band-gap)
  - Highly defective (grains, GBs)
  - Flexible (e.g., metal foil substrate)
  - Relatively high efficiency (→ can be improved more)

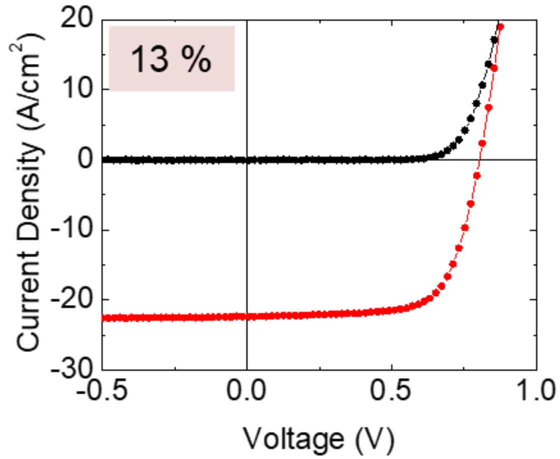
# EQE (1 sun illumination) reflects $J_{sc}$.

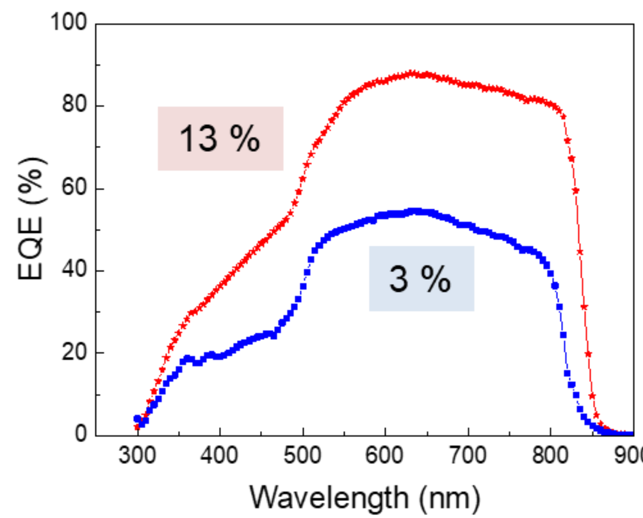


CdTe solar cells fabricated by magnetron sputtering system*

| $\eta$ (%) | $V_{oc}$ (V) | $J_{sc}$ (mA / cm$^2$) | $FF$ (%) | $R_S$ ($\Omega$ cm$^2$) | $R_{SH}$ ($\Omega$ cm$^2$) |
|---|---|---|---|---|---|
| 13.2 | 0.801 | 23.5 | 70 | 3 | 1650 |
| 3.0 | 0.605 | 13.0 | 38 | 20 | 260 |



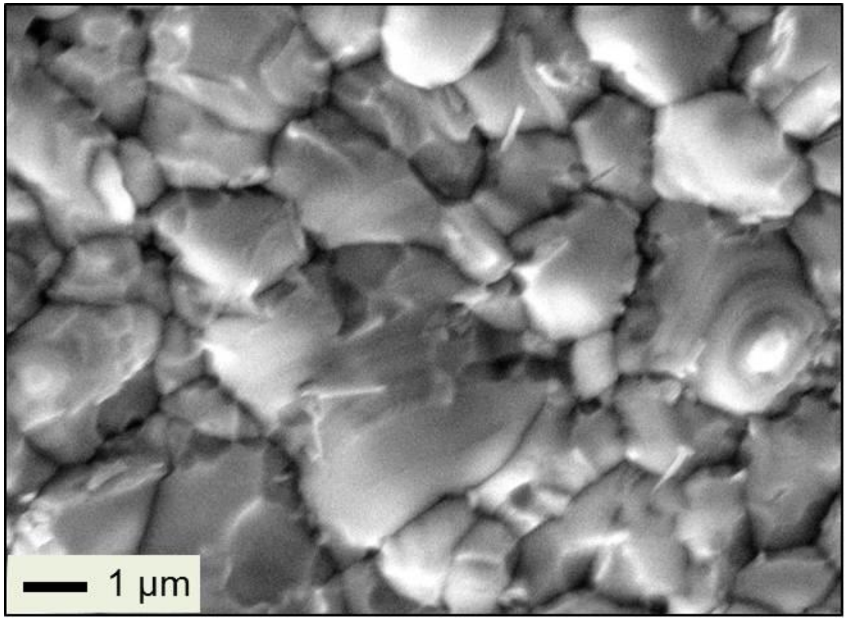



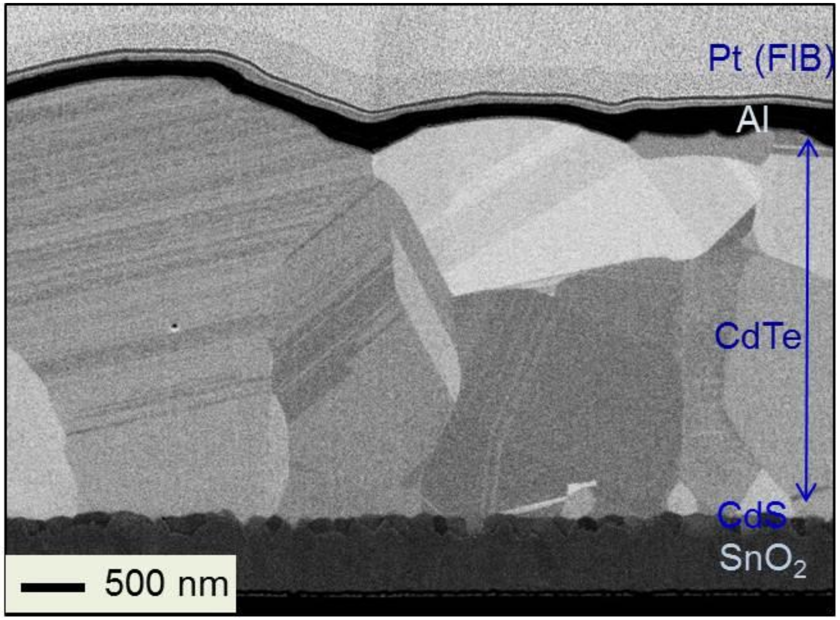

- CdTe absorber of 3 % device is highly resistive.
- EQE analysis shows carrier collection efficiency in each layer and interfaces.

# The microstructure of CdTe is not homogeneous.

top view




cross section




- Comprised of grains (a few µm in size): lots of grain boundaries (GB)
- Local variation of chemical composition, defects
- Inhomogeneous (photo)current

→ impact of GBs on efficiency – mainly unknown

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

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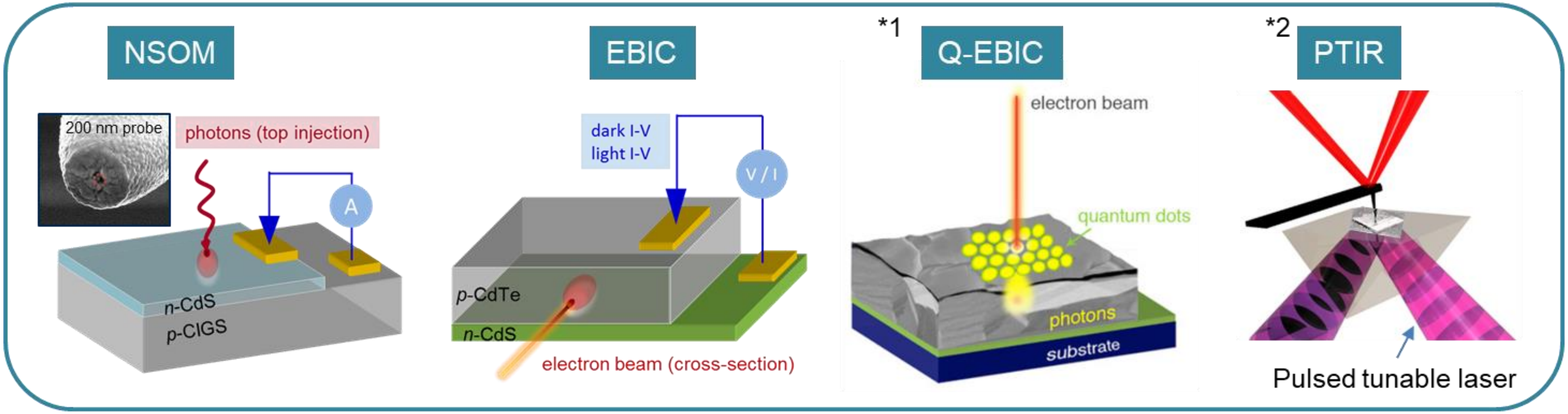
# Techniques for Local PV Characterizations

✓ Local Probe
- Nanocontacts + nanoprobe
- Scanning probes
- Cathodoluminescence
- Photo-thermal induced resonance

✓ Local Excitation
- Electron beam
- Near field optical source
- Ebeam + QD → photons (down-conversion)




✓ Sample prep: plan view / cross-section / wedge / lamella / nanocontacts

✓ Correlation with structural / compositional properties (TEM, EDX, EBSD, XRD)

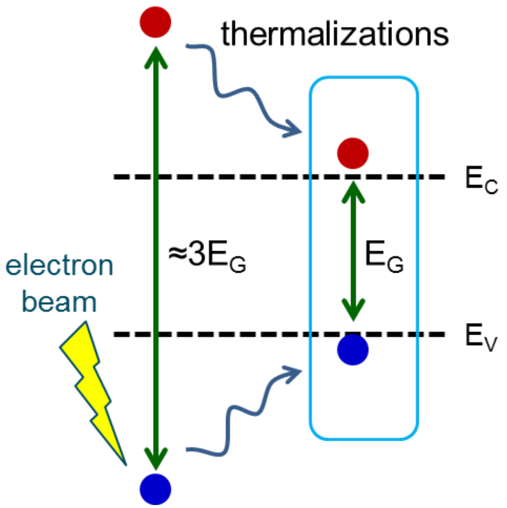
✓ Modelling

*1. H. Yoon *et al.*, AIP Advances (6), 062112, 9 439 (2013)

*2. B. Lahiri *et al.*, Small, 9 439 (2013); Y. Yoon *et al.*, Nanoscale, 9, 7771-7780 (2017)

# Electron beams generate EHPs → EBIC

(1) $I_{beam}$ → generation rate of EHP

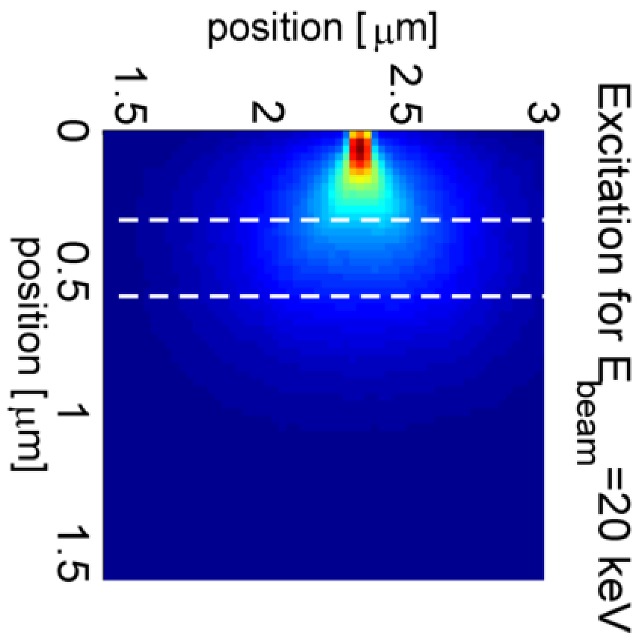



$$(\#\text{ of EHPs}) \approx \frac{(\text{deposited e-beam energy})}{3\times(\text{energy band-gap})}$$

<u>e.g.</u> CdTe: $E_G$=1.5 eV, $V_{beam}$= 10 keV (BSE ≈30 %)

$\Rightarrow$ ≈1600 ehp

(2) $V_{beam}$ → generation bulb size



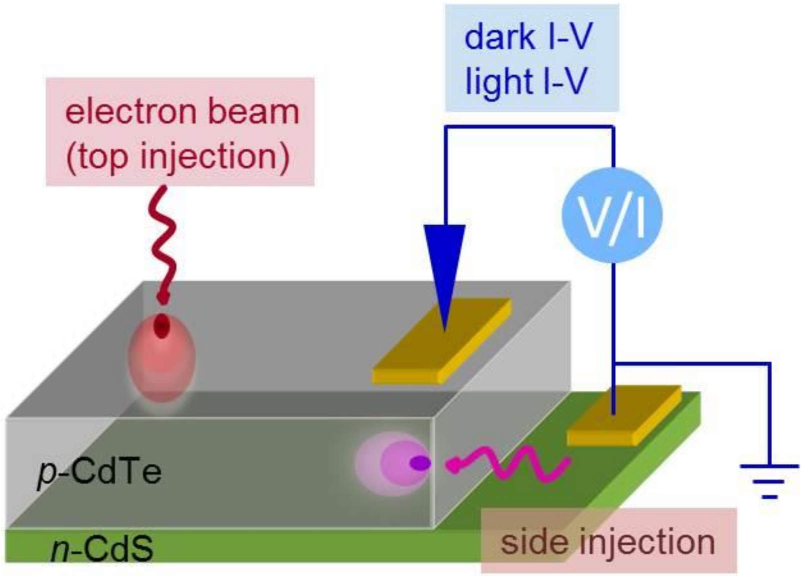

EBIC: Electron Beam Induced Current

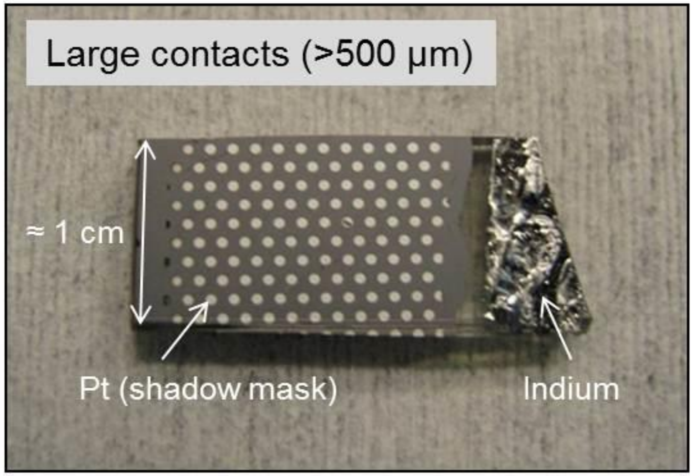
EBIC is an ideal technique for systematic study of local carrier dynamics.

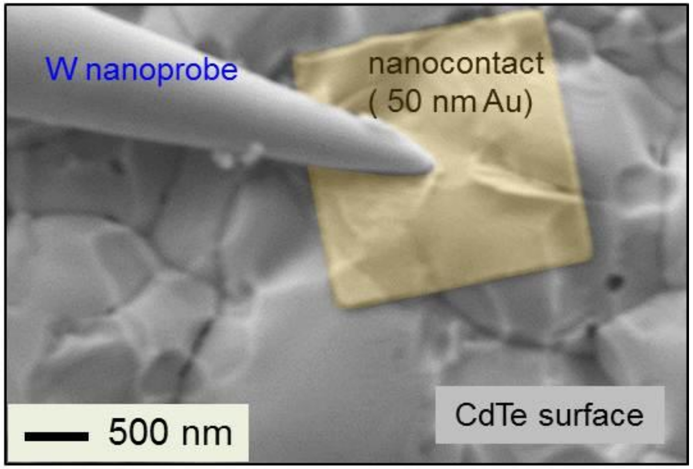


C. Klein, J. Appl. Phys. 39 (4), 2029 (1968)

# EBIC for Grain / Grain Boundary Characterizations

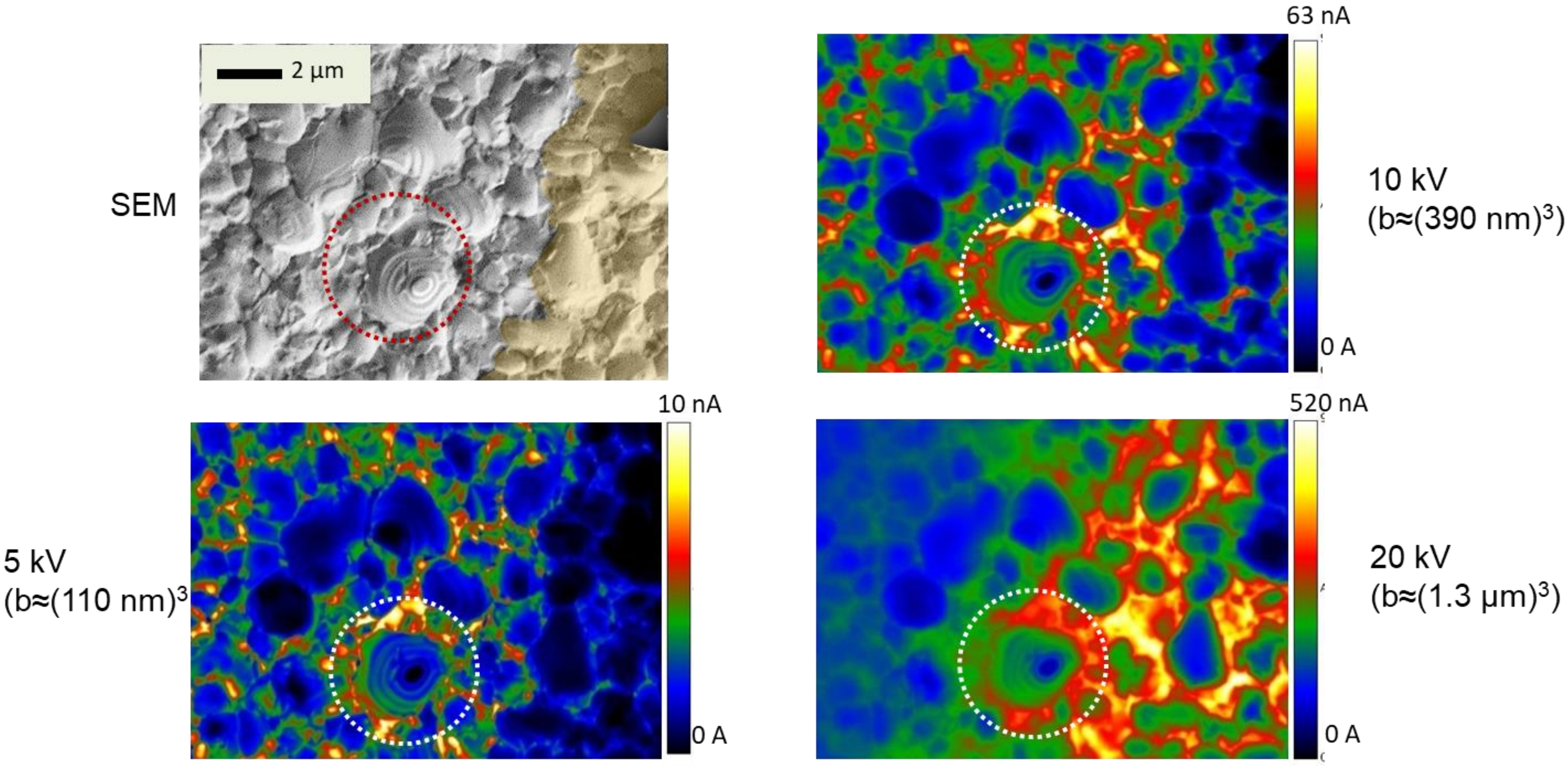


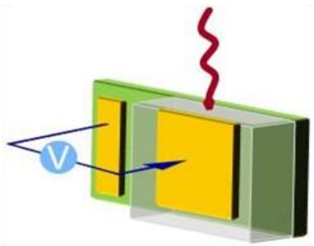

- Injection: top surface, cross-section, wedge
- Local carrier generation
  (bulb size: 110 nm to 1.5 μm in CdTe)
- Nano-contacts at grain boundary / grain bulk
- Probe PV properties of individual grains

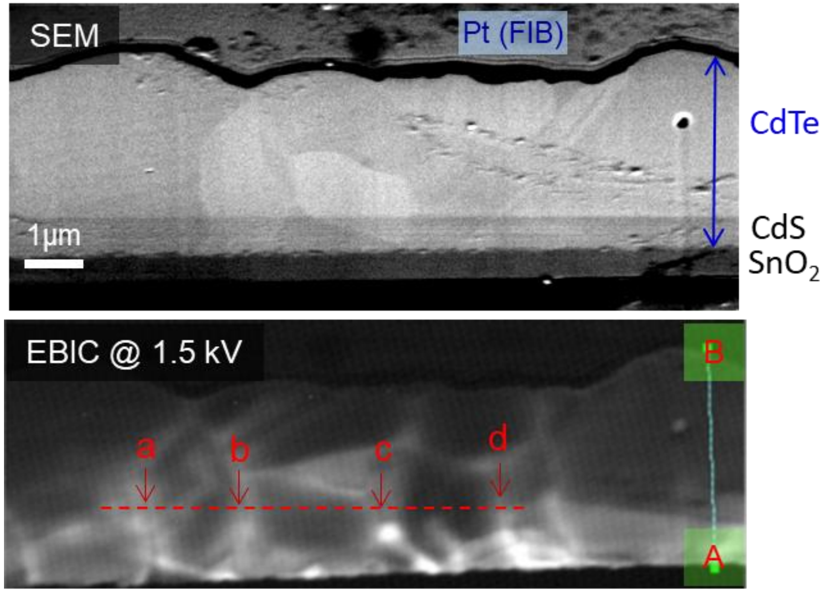
# Spatial resolution < 100 nm with low keV

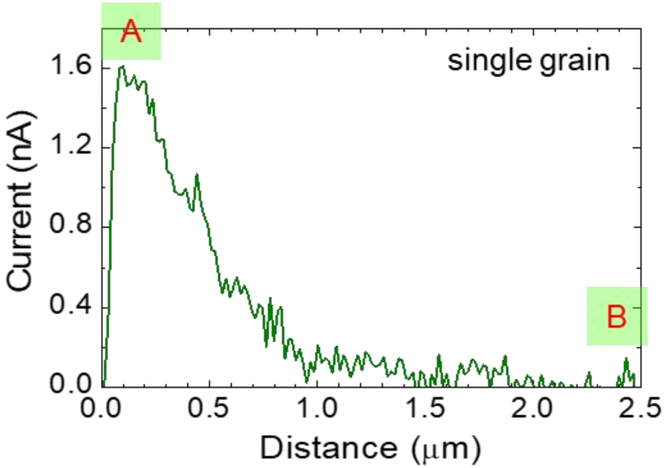


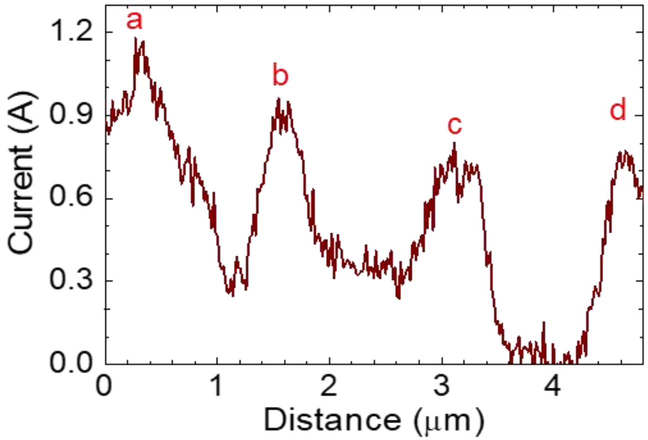

- High keV increases signal-to-noise ratio, but lower the spatial resolution.
- Higher collection at grain boundaries

# Carriers are collected efficiently at GBs in CdTe.






- Smooth surface was prepared by FIB.
- Grain boundaries in CdTe collects carriers more effectively than grain interiors.



Yoon *et al.*, Solar Energy Materials and Solar Cells 117, 499-504 (2013)

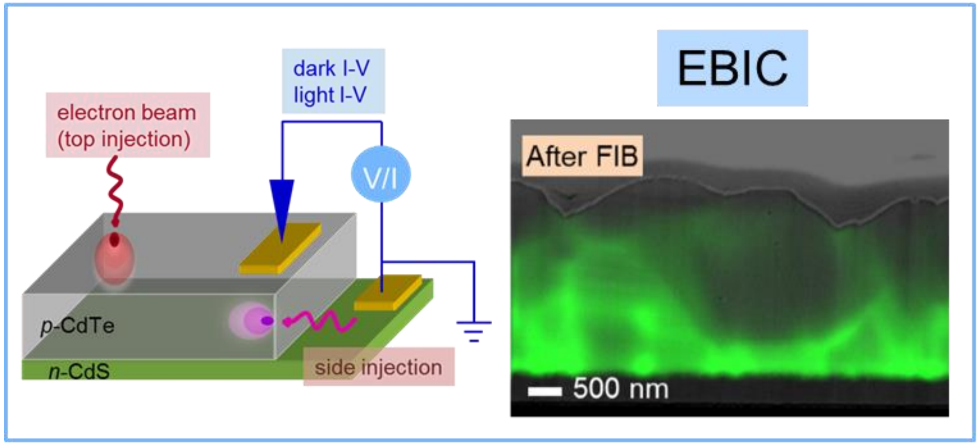
# Summary

✓ Physics of thin film PV is important and exciting.

✓ EBIC allows qualitative AND quantitative characterization of PV materials

- Deconvolution of EBIC signal provides material parameters
- Surface effects in EBIC are strong at the depletion region (and GB?)

✓ In progress: correlating local properties to overall device performance (electrical, optical, chemical, structural properties)



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**Research participants / collaborators**

- CdTe solar cell (U. Toledo)
- CIGS solar cell (U. Toledo)
- CZTS solar cell (DuPont)
- Si solar cells: epi Si, high-efficiency PV (NREL)

Thank you for your attention!


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