6th Annual CdTe Workshop

Surface Photovoltage Spectroscopy: Shining New Light on Back Contacts

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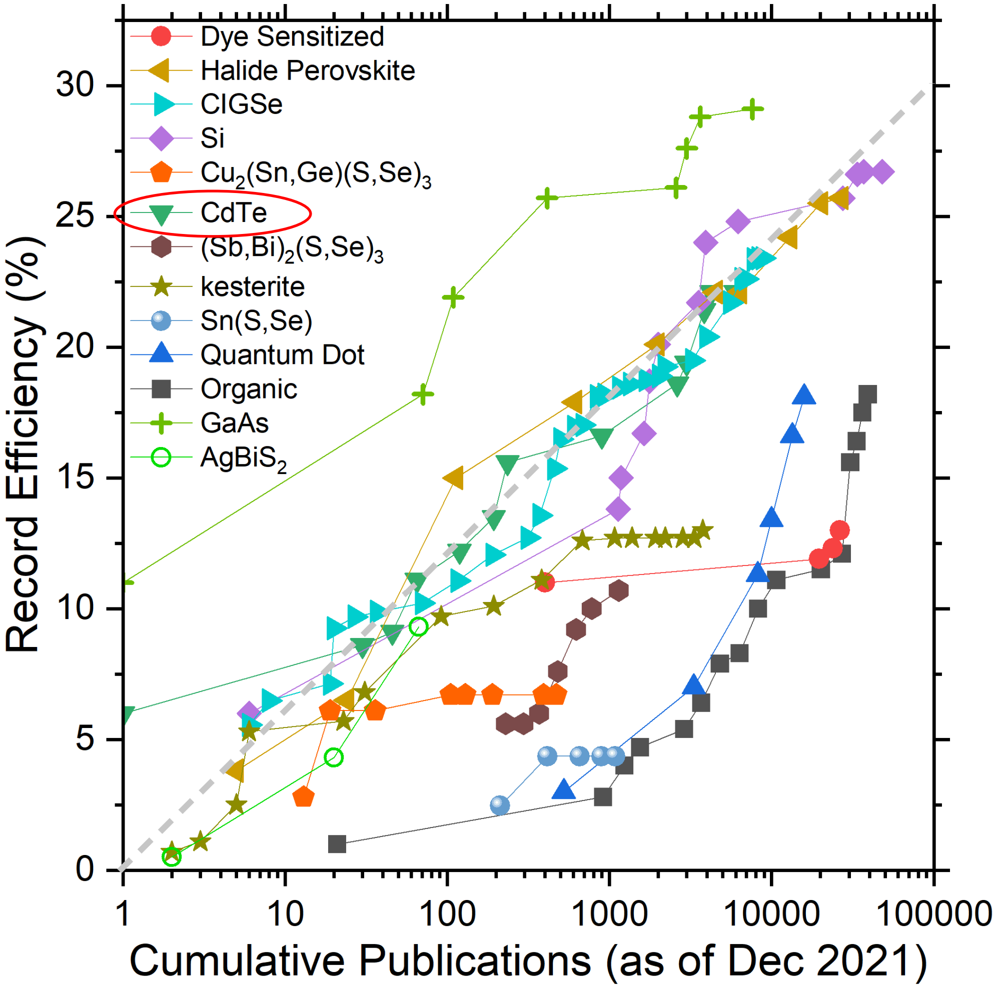
Thank you to CSU, especially Amit Munshi for supplying cells
Thank you to 5N Plus for As-doped Se

Perspective: Efficiency vs Effort PV Technologies



Efficiency vs year hides many factors

Efficiency vs publications: analyze R&D effort it takes to improve different cell technologies.

CdTe, CIGSe, Si, and halide perovskites all fall on same curve!

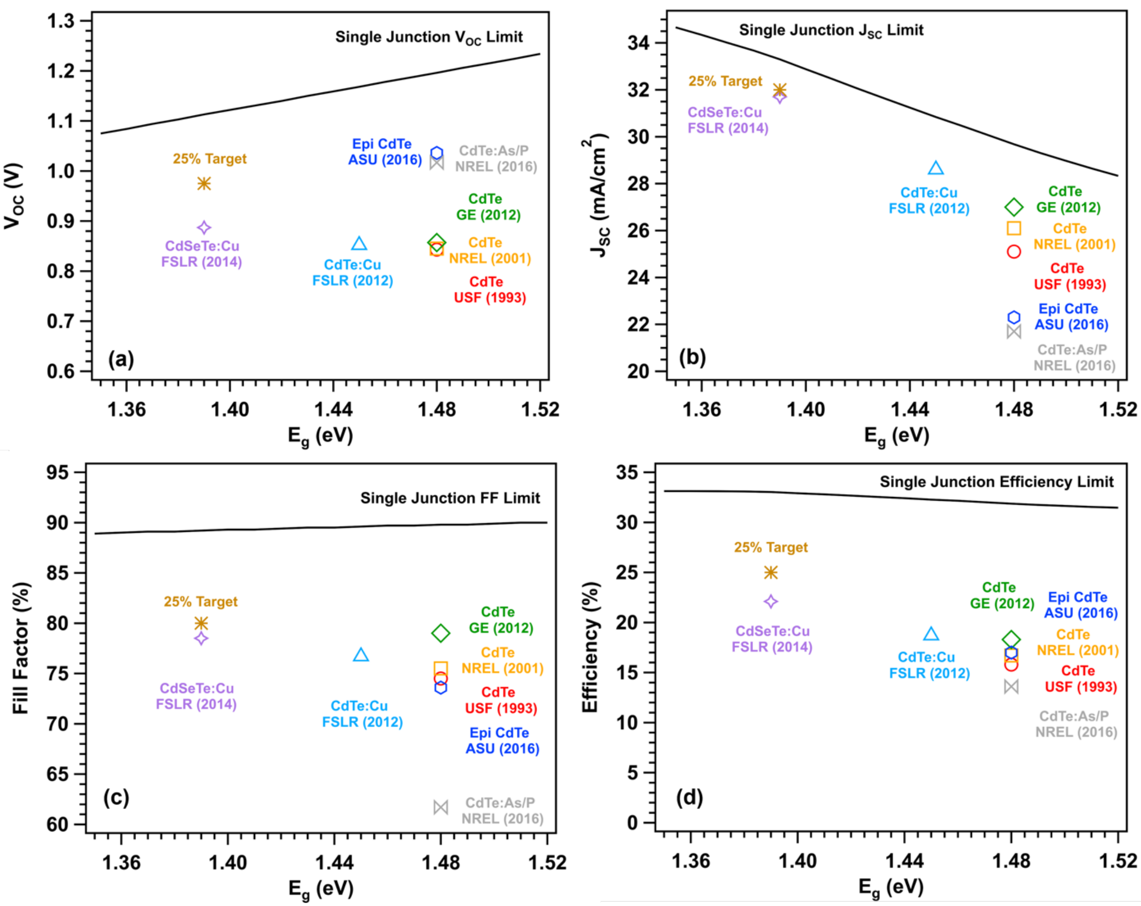
Efficiency is logarithmic with effort (is it all about recombination and V_{oc}?)

Perovskites just had more people publishing

1 paper ≈ 1 grad-student-year of effort ≈ $60,000 - $100,000 ish

Dale & Scarpulla, in review

Path for CdTe: Improve V_{oc} and FF



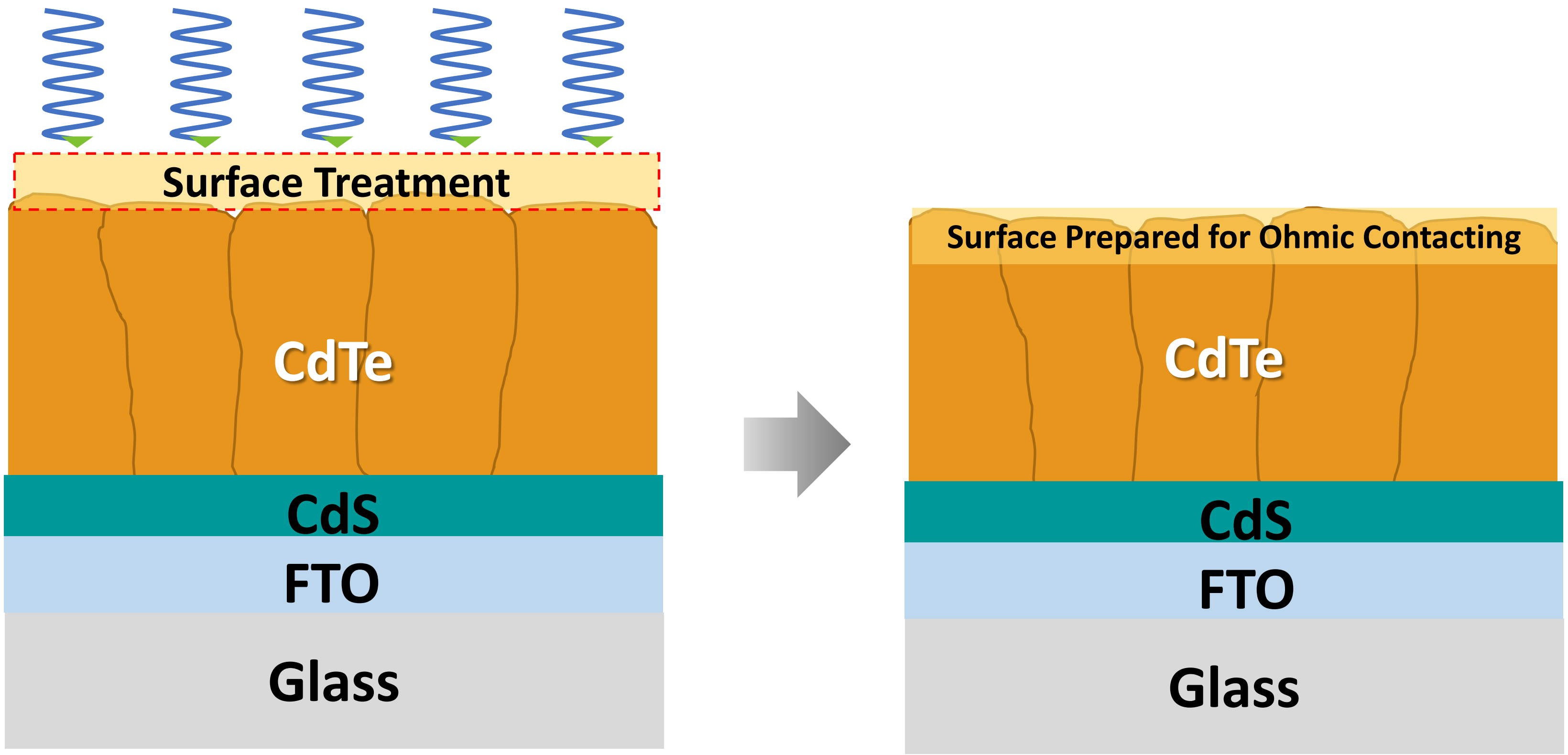
Origins of 900 mV V_{oc} ceiling ?

- Bulk & GB SRH
- Band tails (rad or nonrad rcomb)
- Contact / interface recombination (maybe linked to band bending too)
- Contact carrier selectivity
- Contact V losses (energy offsets, V=IR)

Courtesy of Alex Bothwell. To appear in SEMSC review article

Prior Work: Laser Enhanced Back Contacting

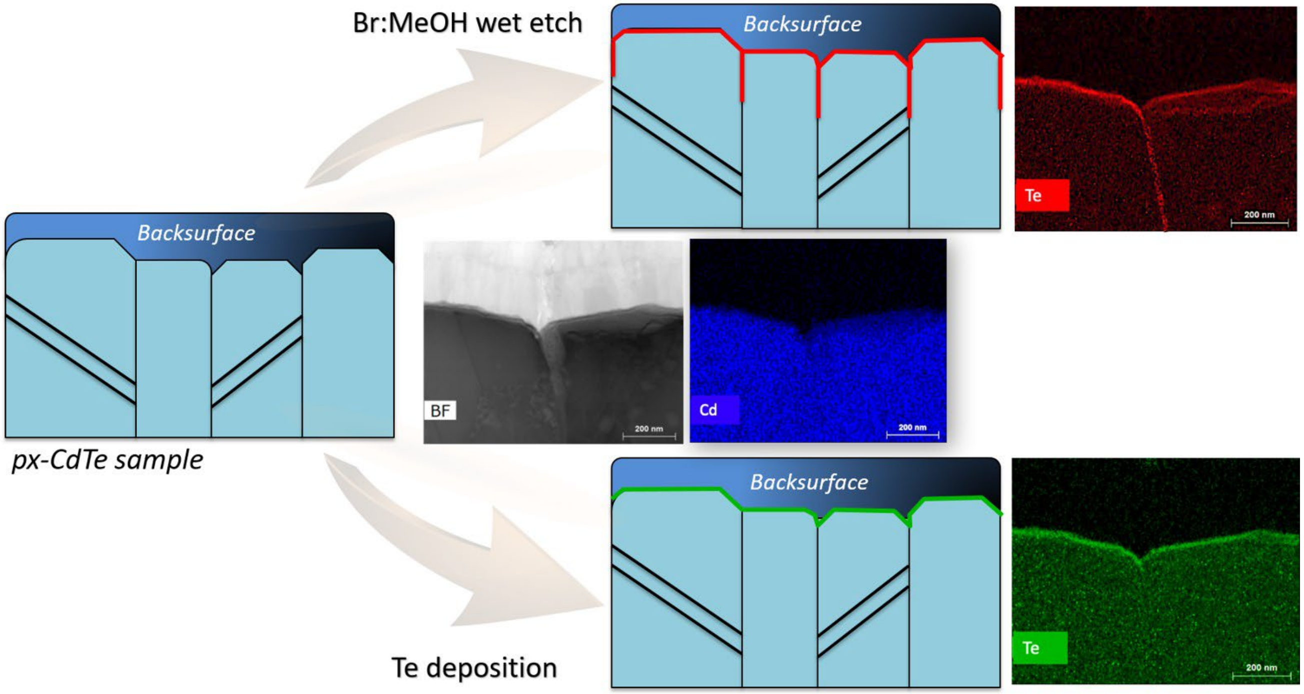
Concept: UV pulsed laser to modify surface



Simonds et al., JAP **116** 013506 (2014)
Simonds et al., APL **104** 141604 (2014)
Simonds, et al., J. Photonics for Energy Review (2014)

This was 10 yrs ago, not saying laser annealing is necessarily a solution now

Prior Work: GBs intersecting Back Contact



- Cd-selective etching leaves elemental Te in GBs (especially CSL boundaries)
- Narrow-gap Te in GB of CdTe limits device efficiency
- Solution: additive back contact processes like Te or ZnTe

Want to Characterize Back Contact Properties

Want: Reversible, hole-selective, low-resistance, bifacial-enabling back contact

• Extract holes at E_{Fp} reversibly	Energy level alignment near V_{oc}
• Reject e-	Upwards band bending (charge) or CB offsets
• Suppress interface recombination	Passivate traps or keep e- away

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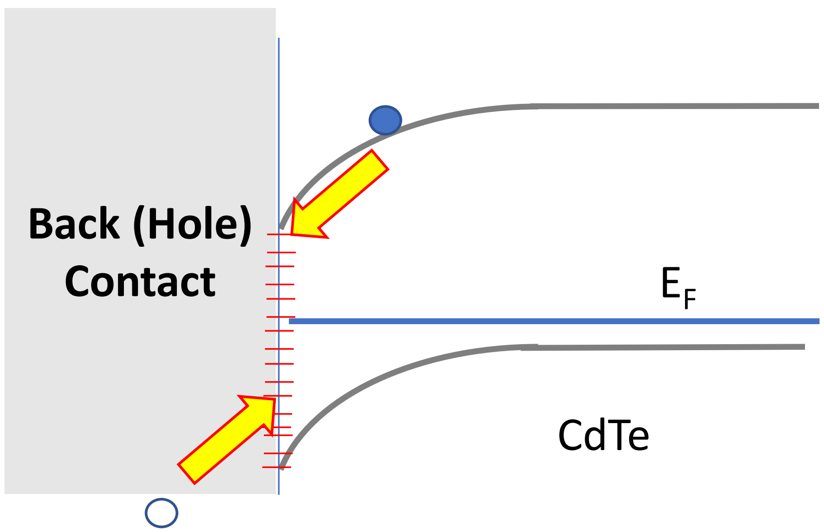


Example of complex back contact situation

Donor-like traps at p-type contact:

- Definitely introduce SRV
- May also cause band bending in 10^{12} /cm^2 range

How to characterize?

Techniques for Advancing Back Contact Understanding

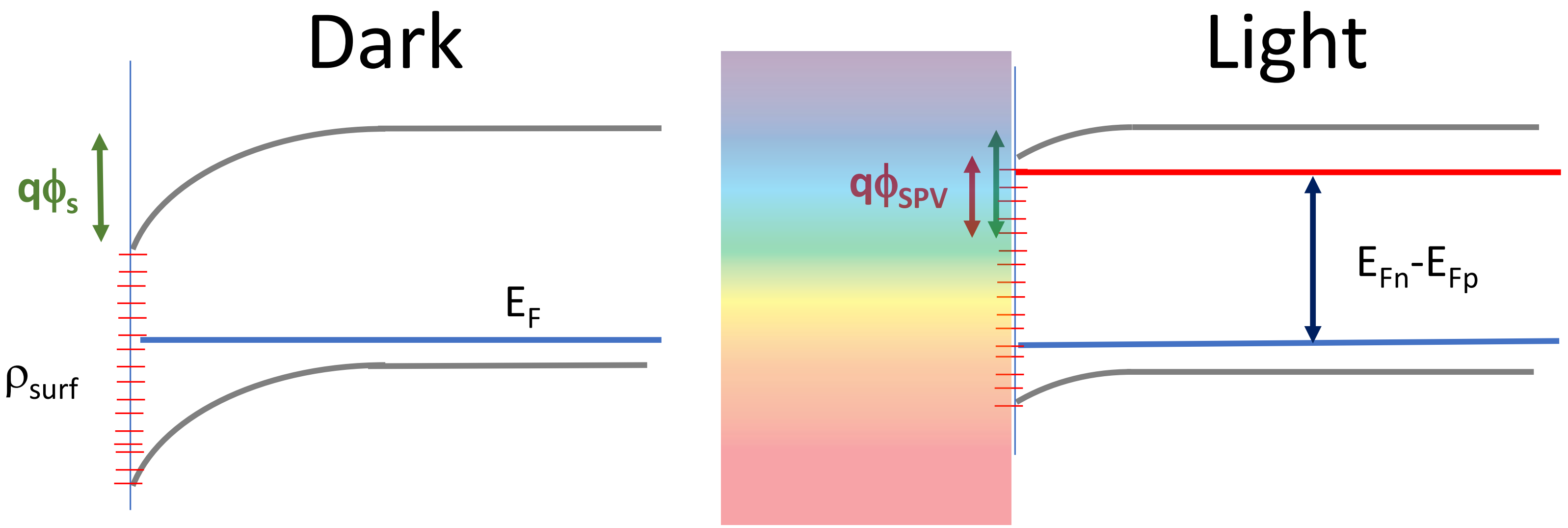
- Want to measure:
  - Band offsets / band bending
  - Surface states’ charge
  - Surface states’ recombination

- Backside IQE: effective surface recombination velocity (SRV)

- TRPL: effective surface recombination velocity (SRV)

- Surface photovoltage (SPV)
  - ✓ Band offsets / band bending
  - ✓ Surface states’ charge
  - ✓ Surface states’ recombination

Surface Photovoltage (SPV)

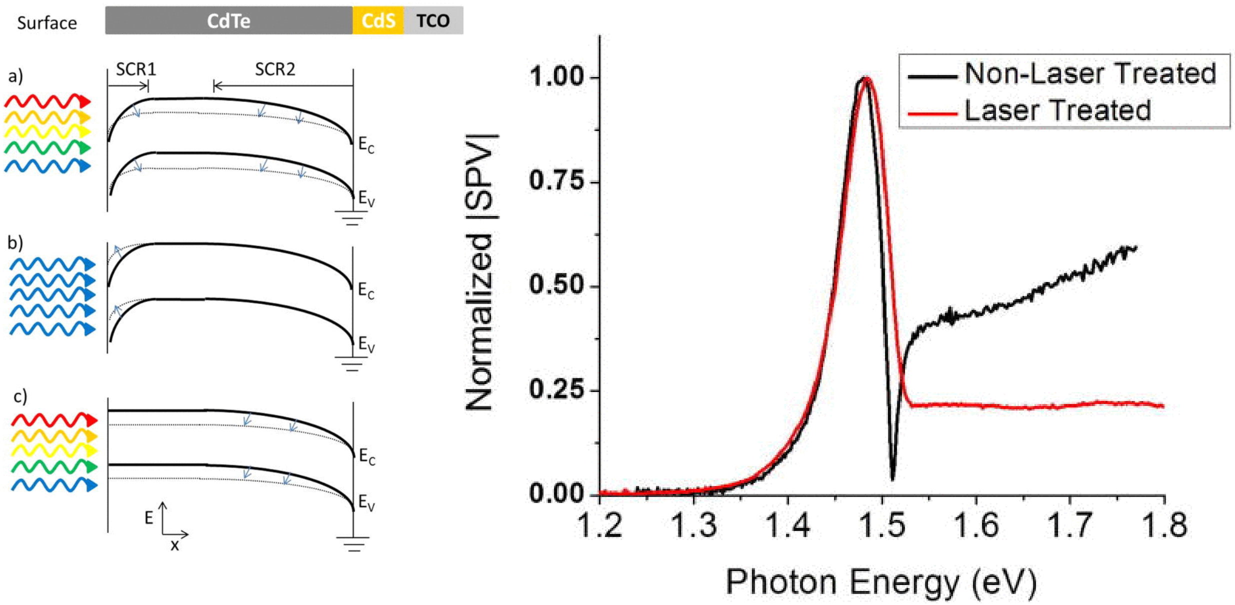


CdTe surface with E_F pinning from traps
ϕ_S = surface built-in voltage

Excess carriers bias surface/bulk junction towards flatband
ϕ_{SPV} magnitude depends on:
ϕ_S, τ_{bulk}, μ_{bulk}, SRV, ρ_{surf}, $I_{light}(\lambda,t)$, …

- SPV: same origin and physics as PV operation. Thus sensitive to all the same factors
- Can be used like IQE, but at V_{oc} rather than J_{sc}
- Adds some orthogonal information to JV, IQE, CV, etc
- Scalable, parallelizable, …

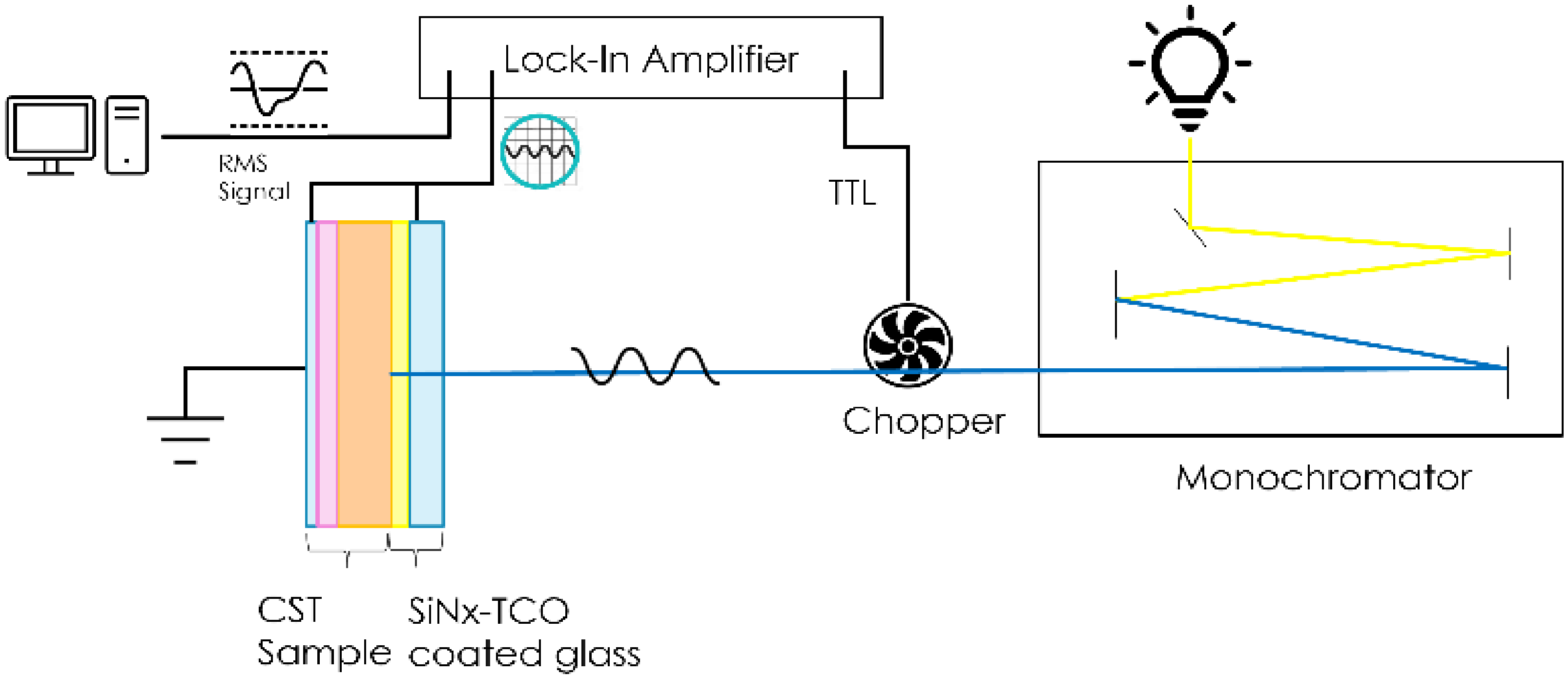
Prior Work: SPV Response to Laser Annealing



- 2014: we used surface photovoltage spectroscopy (SPS) to assess back surfaces
- SPS revealed laser annealing reduced back surface Fermi level pinning
- $h\upsilon = E_g$ probes whole cell; $h\upsilon > E_g$ above gap probes near-surface

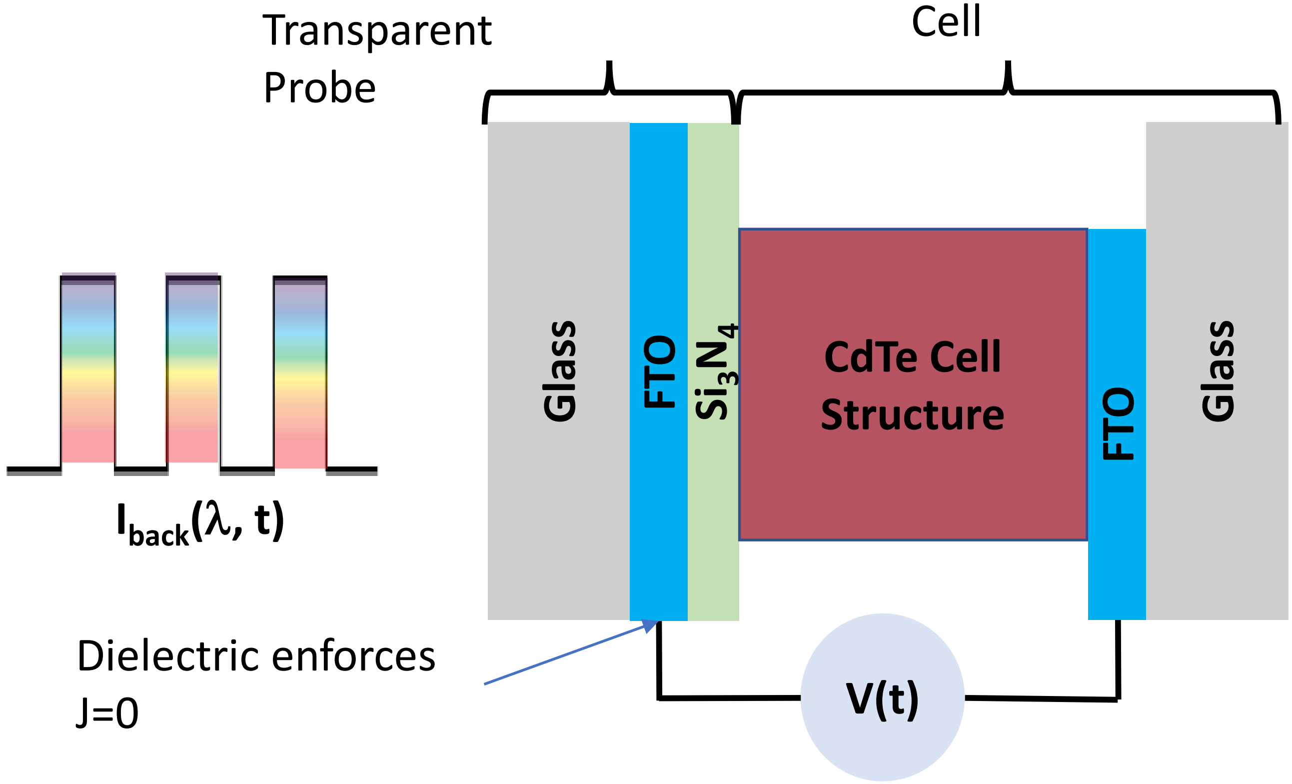
Simonds JAP **117** 225301 (2015)

Current Set-Up



- Chopped monochromatic light (can add other sources and AM1.5 bias light)
- Create MIS structure between cell and SPV/SPS electrode (air or dielectric)
- Vary V and light during experiments
- Many ways to implement

Custom SPV/SPS Electrodes



- Custom electrode – SiN_x on FTO
- Good current blocking, easier alignment than air gap, better coupling
- Can send in light from either side to learn more

SPS Case Studies

Br:MeOH etching test

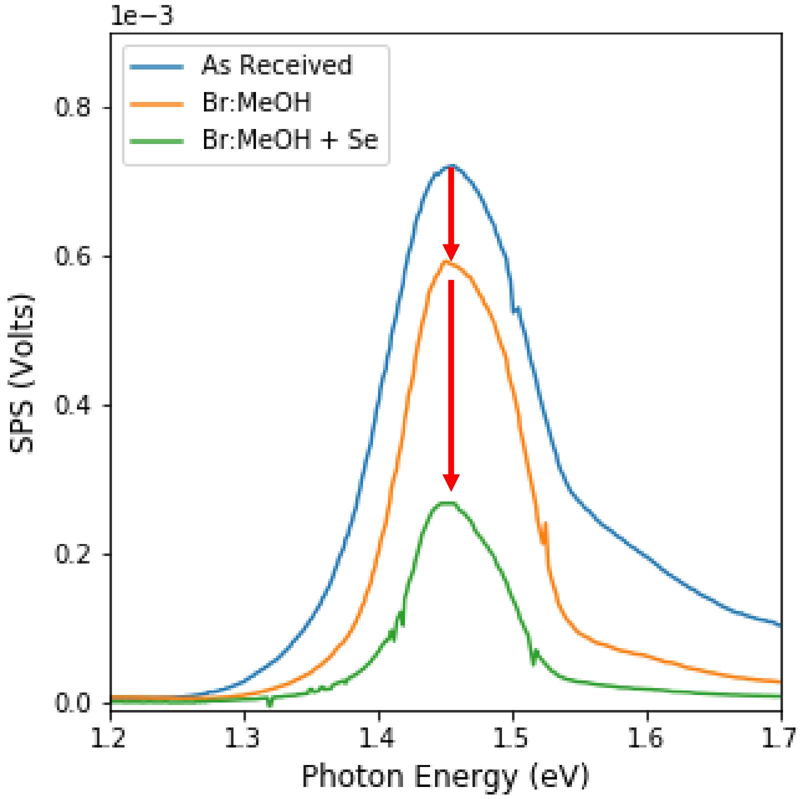
- Br:MeOH etch enhances our backside PL
  Passivation? E_F pinning/band bending?

SPV decreases. Reduced SRV should increase it
∴ Reduction in E_F pinning dominates

Se to replace Te ?

- E_g >1.7 eV, potentially electron reflecting
- Need p-type – tried As doping (5N Plus)
- Too insulating for good IV! As doping didn't work

SPV again decreased
∴ Increase of SRV or decrease in E_F pinning (needs follow-up)



Takeaway: SPV sensitive to surface defect charge in these cases

Thank you to CSU / Amit Munshi for cells and collaboration

SPV: Provides Info Complimentary to TRPL

Reese (2015) SRV from TRPL

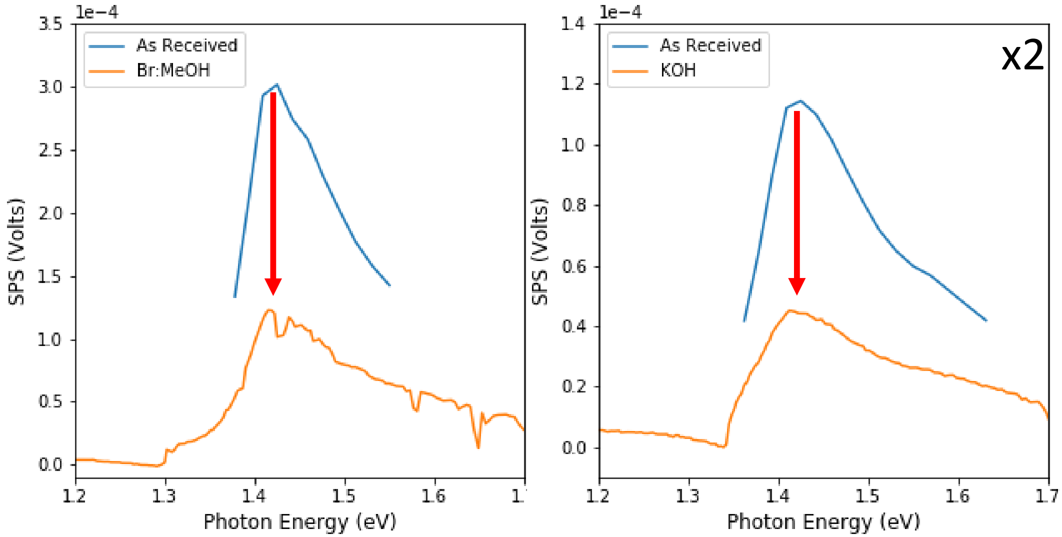
Untreated: 3–15x10^5 cm/s

KOH: 4x10^4 cm/s

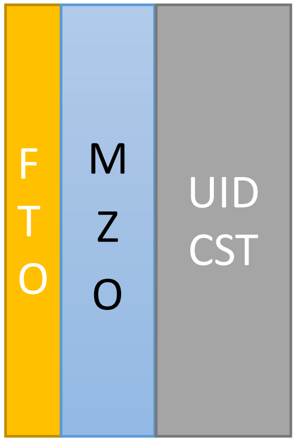
Br-MeOH: 3x10^5 cm/s

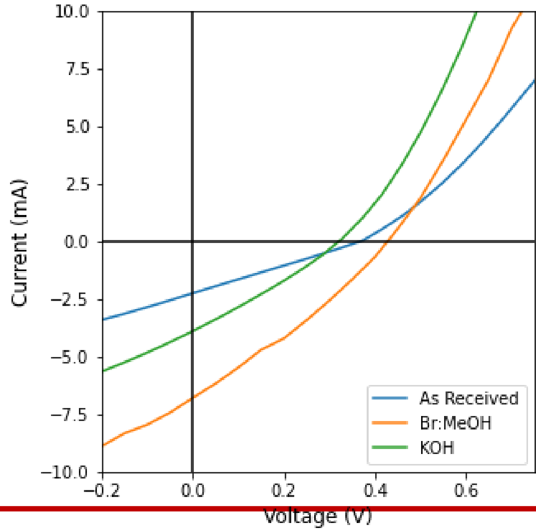
Br:MeOH

KOH



SPS again detects decreases in E_F pinning

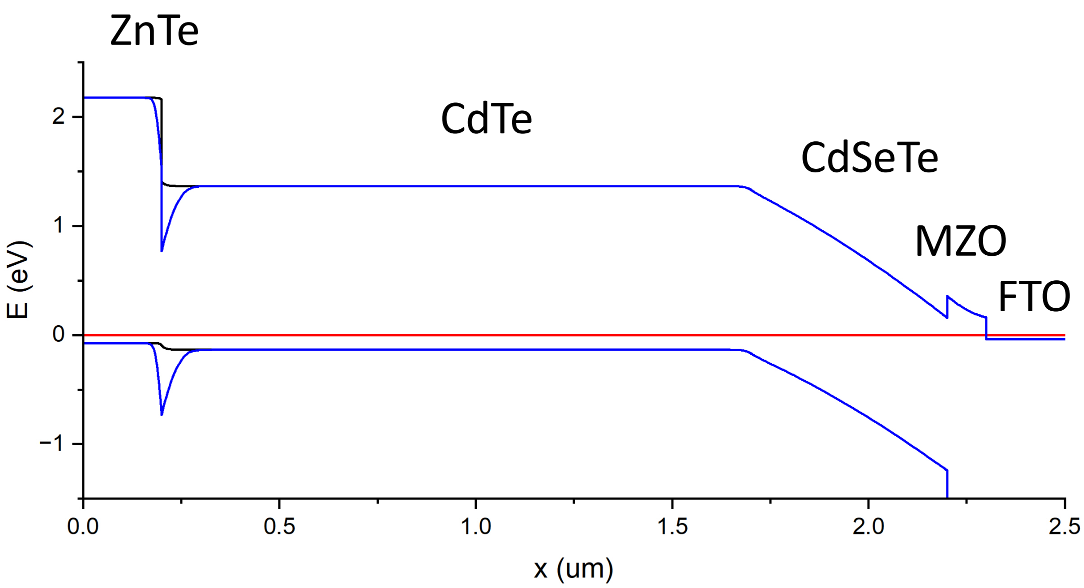


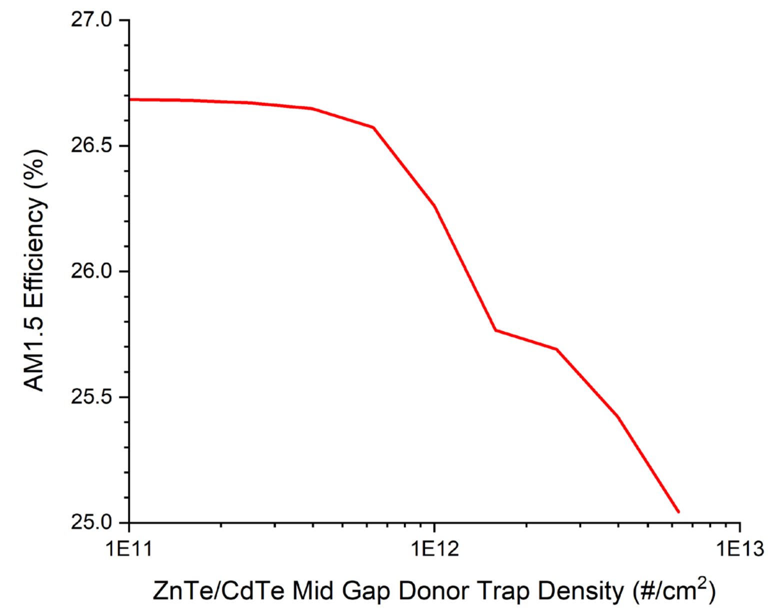


*Why bad IV? Undoped CdSeTe cell

Example: Hypothetical Trap Charge at ZnTe/CdTe Interface

SCAPS Modelling





ZnTe/CdTe interface believed to be NOT passivated

- Treating interface as SRV misses the effect of defect charge; sufficiently-high trap density pins Ef and creates band bending
- As thickness ↓, minority carrier diffusion length ↑, and for bifacial operation, E_f pinning and SRV must decrease

Charge, Band Offsets, and Traps All Matter

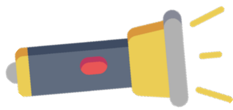
- How are we modeling traps at interfaces and SRV?
  - Boundary condition?
  - Neutral SRH traps?
  - Traps having both charge and capture/emission?
- Effective SRV depends on band bending near traps (BSF in Si)

$$S_{eff} = S_{if} \cdot \exp\left({}^{-q\phi_{if}}\!/_{k_B T}\right)$$

- Combining SPV, TRPL, IV, IQE… with modelling
- Each technique has some linear independence from others, thus combination can decouple parameters

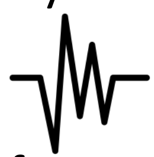
What’s Next?

- Better cells:
  - So far used sub-optimal cells – UID, poor surface quality, aged
  - Need high carrier concentration and bulk lifetime to correlate SPS to Voc
- Bias light:



  - Band bending depends on carrier injection
  - Apply bias light near AM1.5 to study interface near operating conditions
- Temperature dependence

  - SPV signal exponentially dependent on intrinsic carrier concentration
- Monochromatic high intensity – super band gap LED or laser
- Frequency response



  - MHz or GHz LED pulse
  - Sweep several orders of magnitude frequency response
  - Probe trap state lifetimes

Conclusions

- SPV is uniquely suited to evaluate rear contact strategies
  - Easy to set up
  - Probe interface or free surface
  - Measure potential barriers and trap states
- We have shown sensitivity to known effective wet etchants
- We show sensitivity to CdTe/passivation layer interface
- Interfaces affected by SRV, band bending, ultimately by the charge and density of traps
- SPV is complimentary measurement to TRPL to study all parameters which affect interfaces

References

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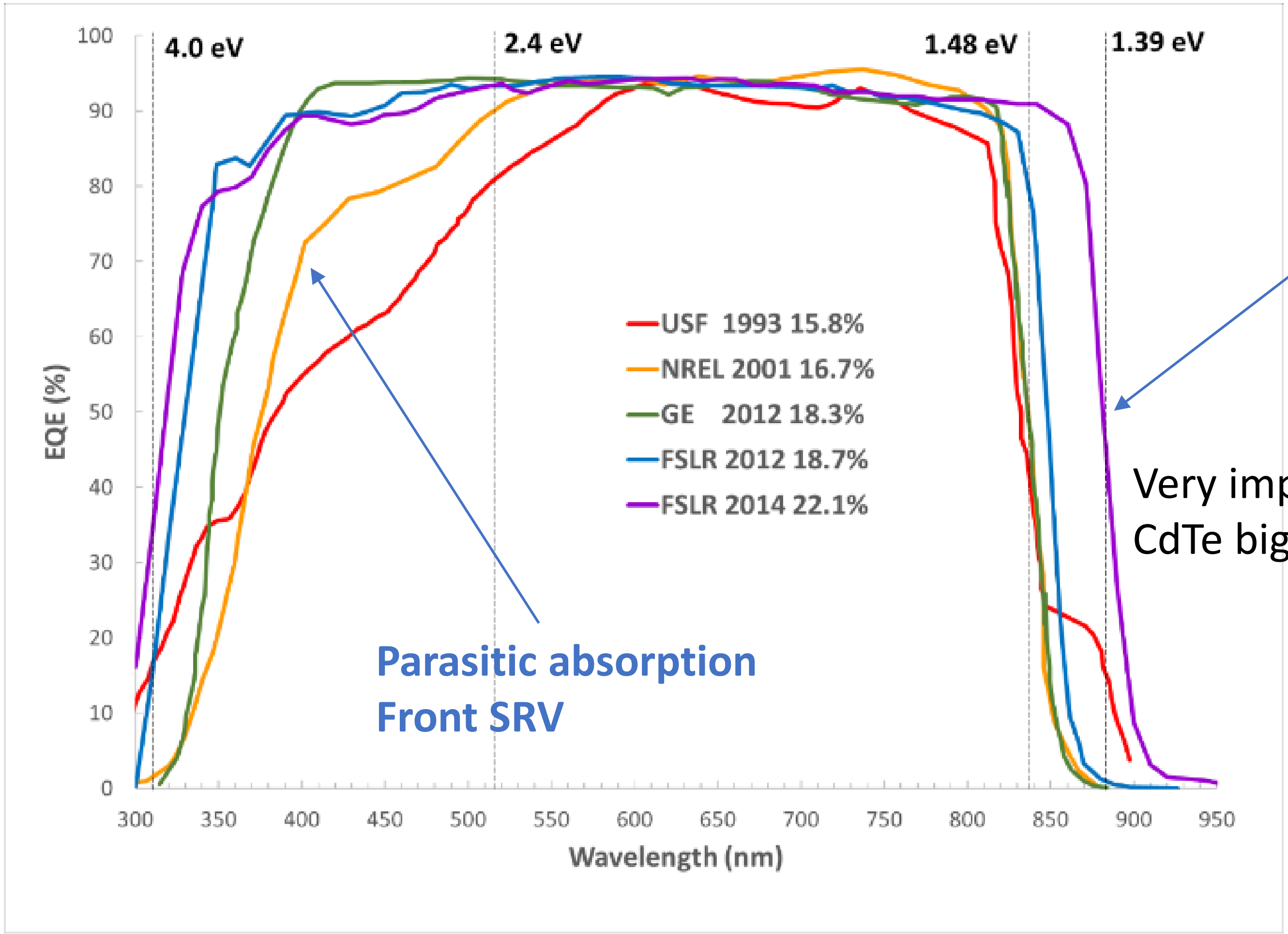
IQE: Great for J_{sc}



Absorption coeff
bulk lifetime

Very important diagnostic, but CdTe biggest challenge is still V_{oc}

Figure; SEMSC Review, forthcoming

Correlating Peak SPV to Recombination Velocity

- IV improvement shows overall positive effect
- But if SRV ↓ SPV should ↑
- Effective SRV dependent on modeling
  - Neutral vs charged defects, number, cross section
- In presence of band bending induced by the traps themselves, SRV is multiplied by an exp(-ϕ/Vth) term

$$S_{eff} = S_{if} \cdot \exp({}^{-q\phi_{if}}/_{k_B T})$$

- Upward bending for e- suppresses effective SRV but downward enhances it
- Br:MeOH/KOH decrease traps → unpin Fermi level → decreasing band bending → decreasing SPV