Junction Evolution During Fabrication of CdS/CdTe Thin–film PV Solar Cells

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NREL/PR-520-49387



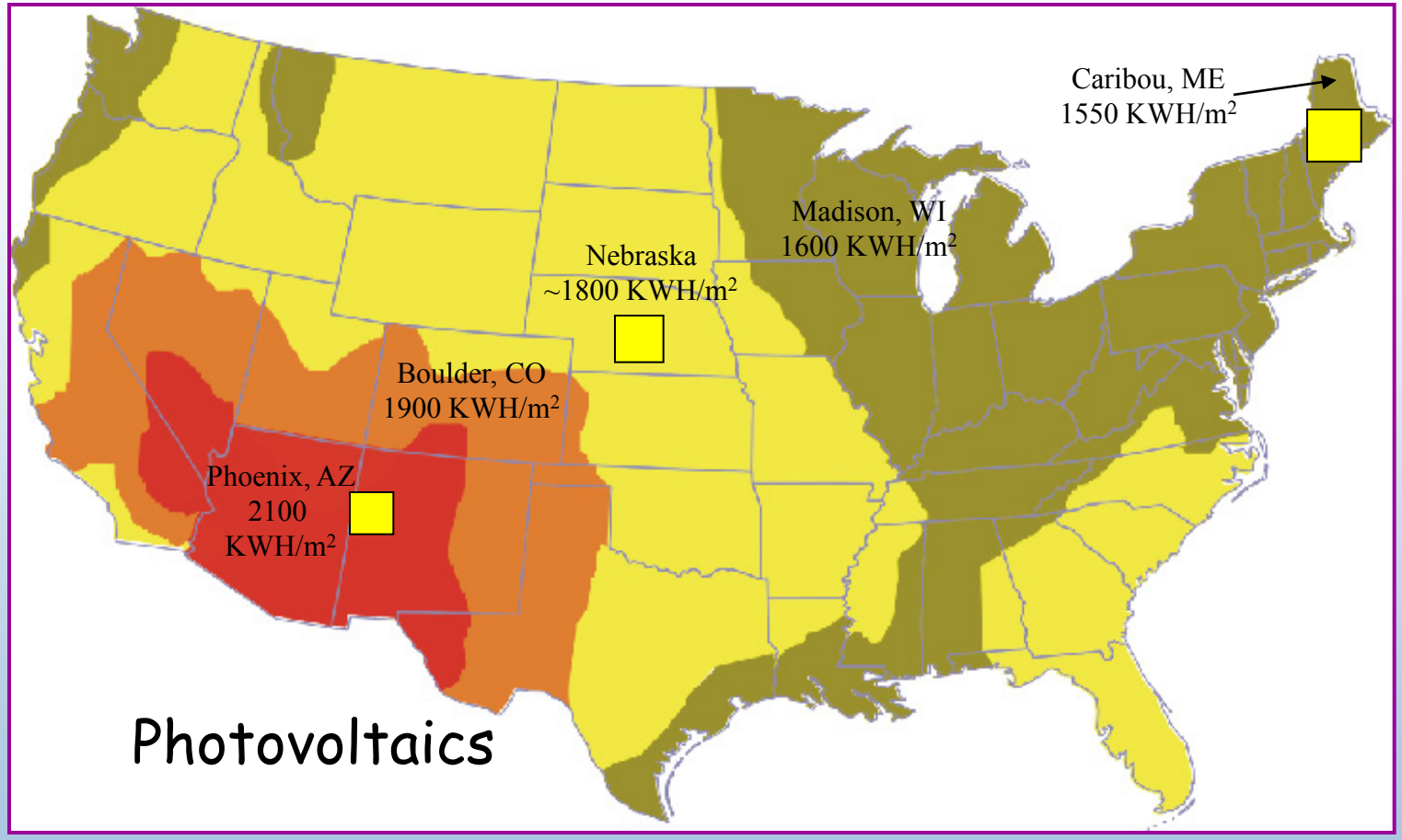
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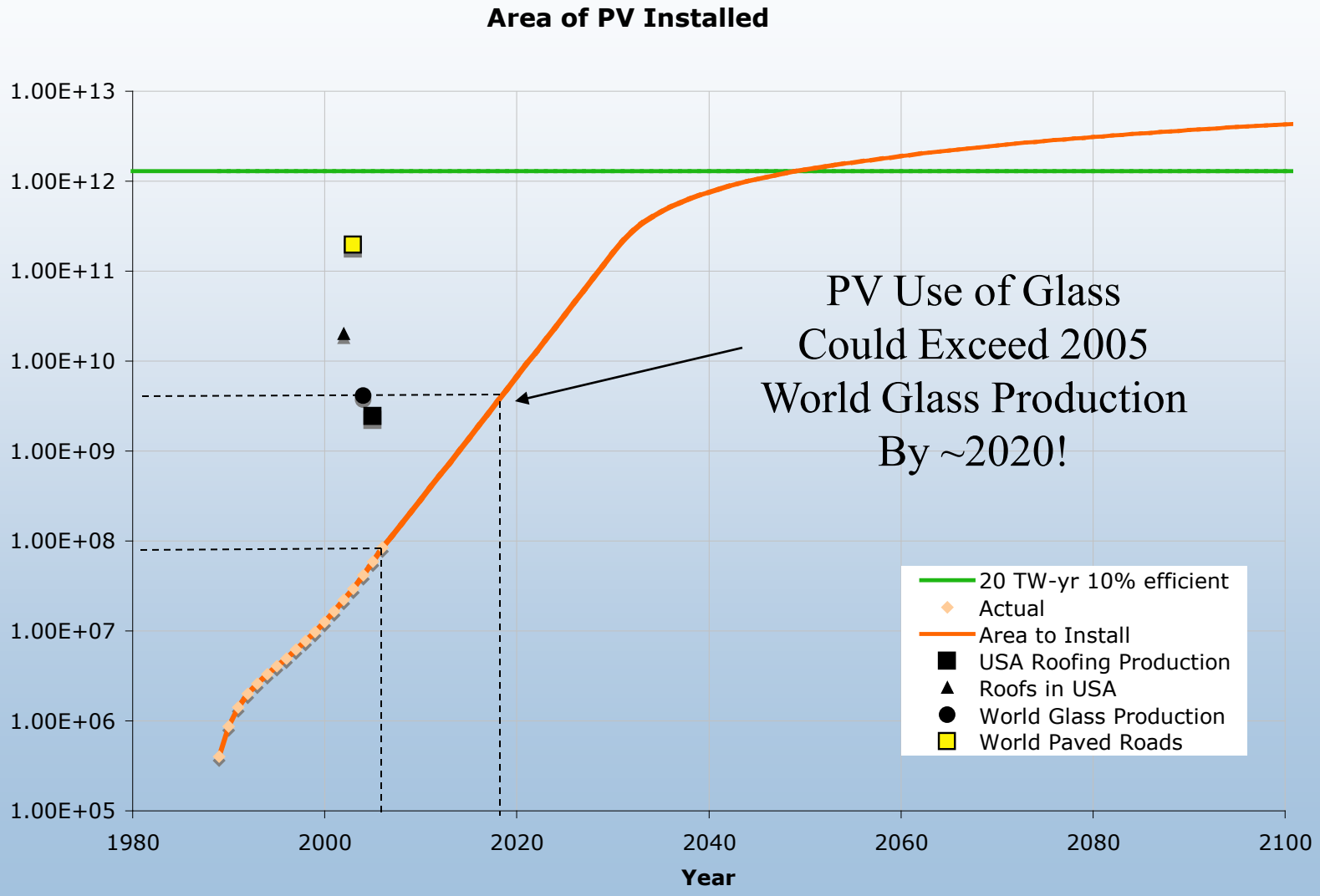
Solar Land Area Requirements For 2004 US Electricity Requirements



Sources: K. Zweibel, "PV Past the Tipping Point" (www.nrel.gov/ncpv/thin_film)
PVWATTS Calculator, Version 1 (http://rredc.nrel.gov/solar/codes_algs/PVWATTS/)

Note:
Munich, Germany
~1100 KWH/m2

Example - Size of PV Market for Commercial Glass



Source: Brent Nelson, NREL

Some CIGS-alloy, CdTe, & a-Si Laboratory Cell NREL-Confirmed Record Efficiencies

Area (cm^2)	Area (cm^2)	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	Efficiency (%)	Comments
CIGSe	0.410	0.697	35.1	79.52	20.0	CIGSe/CdS/Cell NREL, 3-stage process
CIGSe	0.402	0.67	35.1	78.78	18.5	CIGSe/ZnS (O,OH) NREL, Nakada et al
CIGS	0.409	0.83	20.9	69.13	12.0	Cu(In,Ga)S_2/CdS Dhere, FSEC
CIAS	–	0.621	36.0	75.50	16.9	Cu(In,Al)Se_2/CdS IEC, Eg = 1.15eV
CdTe	1.03	0.845	25.9	75.51	16.7	CTO/ZTO/CdS/CdTe NREL, CSS
CdTe	–	0.814	23.56	73.25	14.0	ZnO/CdS/CdTe/Metal U. of Toledo, sputtered
a-Si	-	-	-	73.25	12.1	United Solar, Stabilized Efficiency

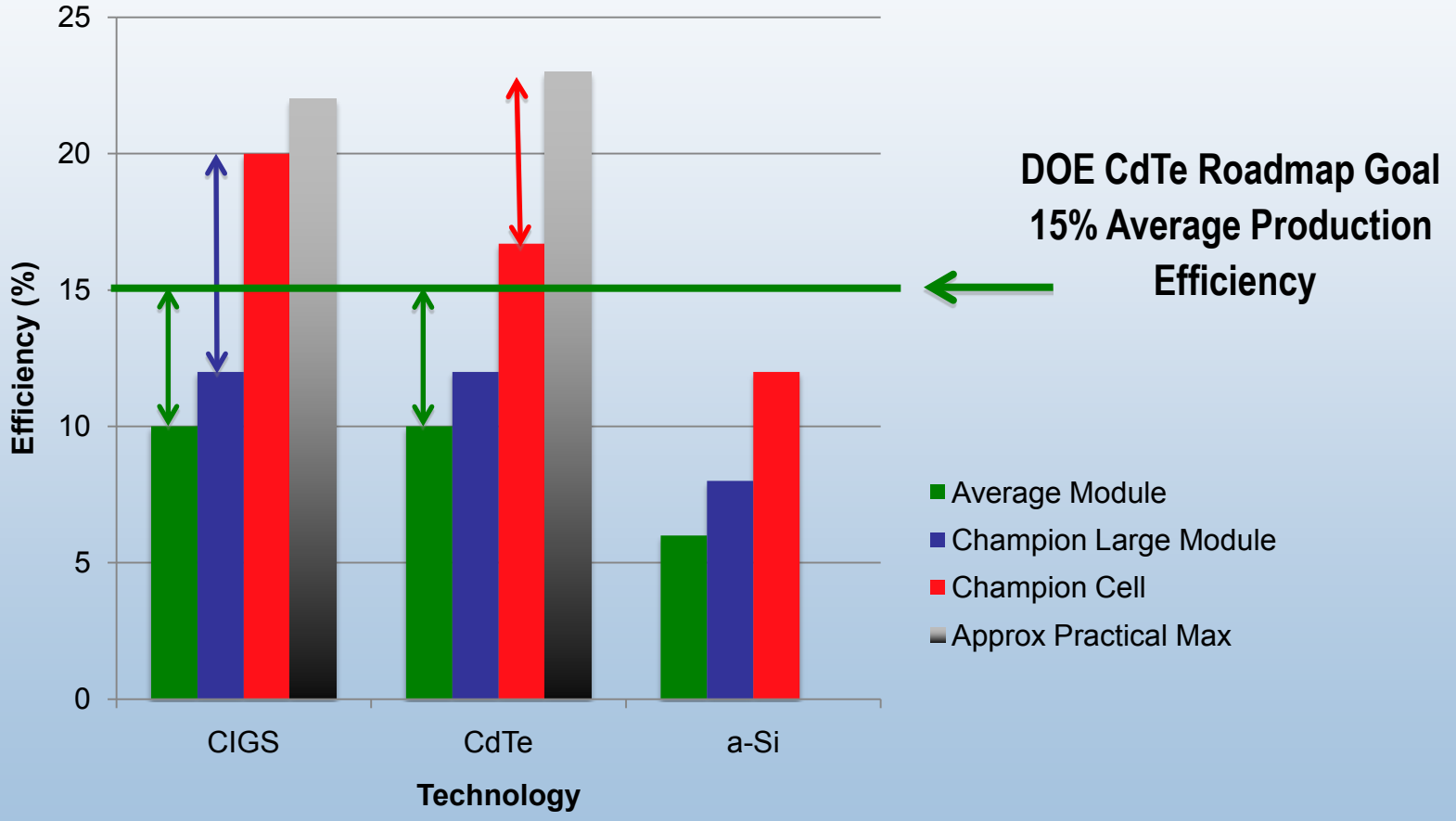
Sources: Updated from R. Noufi and K. Zweibel, Proc. 4th WCPEC, Waikola, Hawaii, 5/2006, Photon International, October 2004

Polycrystalline Thin Film PV Modules (Standard conditions, Aperture-area, *NREL Confirmed) Ranked by Power

Company	Device	Aperture (cm^2)	Efficiency*(%)	Power (W)	Date
Miasole	CIGS	9762	13.6-13.8	-	4/10
Global Solar	CIGS	8390	10.2*	88.9	8/02
First Solar	CdTe	6623	12.6*	84.4	8/08
Wurth Solar	CIGS	6500	13.0	84.6	6/04
United Solar	a-Si	4519	7.9*	35.7	6/97
Shell Solar	CIGSS	3626	12.8*	46.5	3/03
Showa Shell	CIGS	3459	13.5	-	8/02

Sources: Updated From R. Noufi and K. Zweibel, Proc. 4th WCPEC, Waikola, Hawaii, 5/2006, Photon International October 2004,

Goal
Increase Average Production Module Efficiency



Present Strengths of Each Thin-film PV Technology

	Demonstrated Efficiency	Perceived Production Advantage	Perceived Materials Abundance/ Low Toxicity
a-Si			Strength
CdTe		Strength	
CIS	Strength		

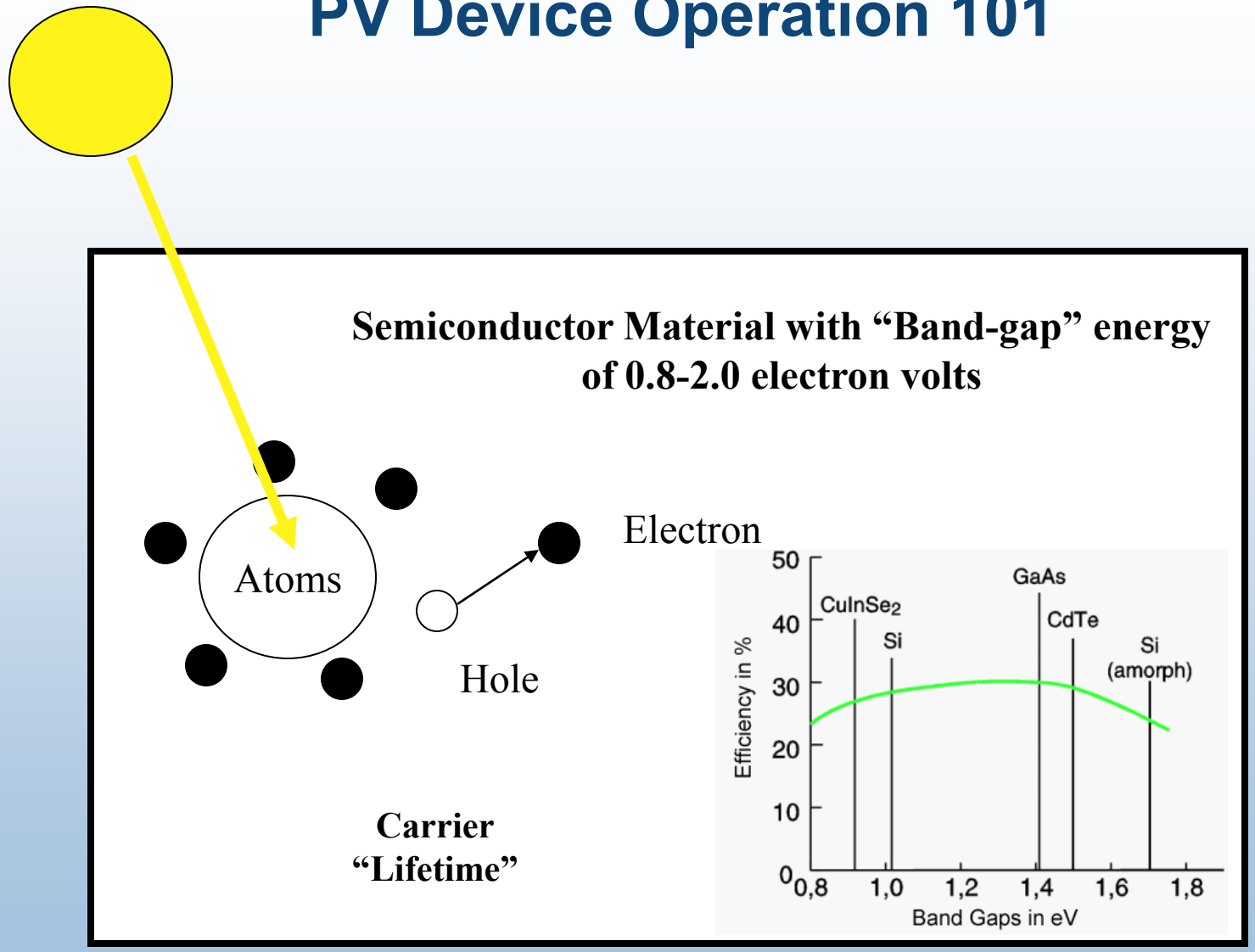
Thoughts:

Each technology has different advantages

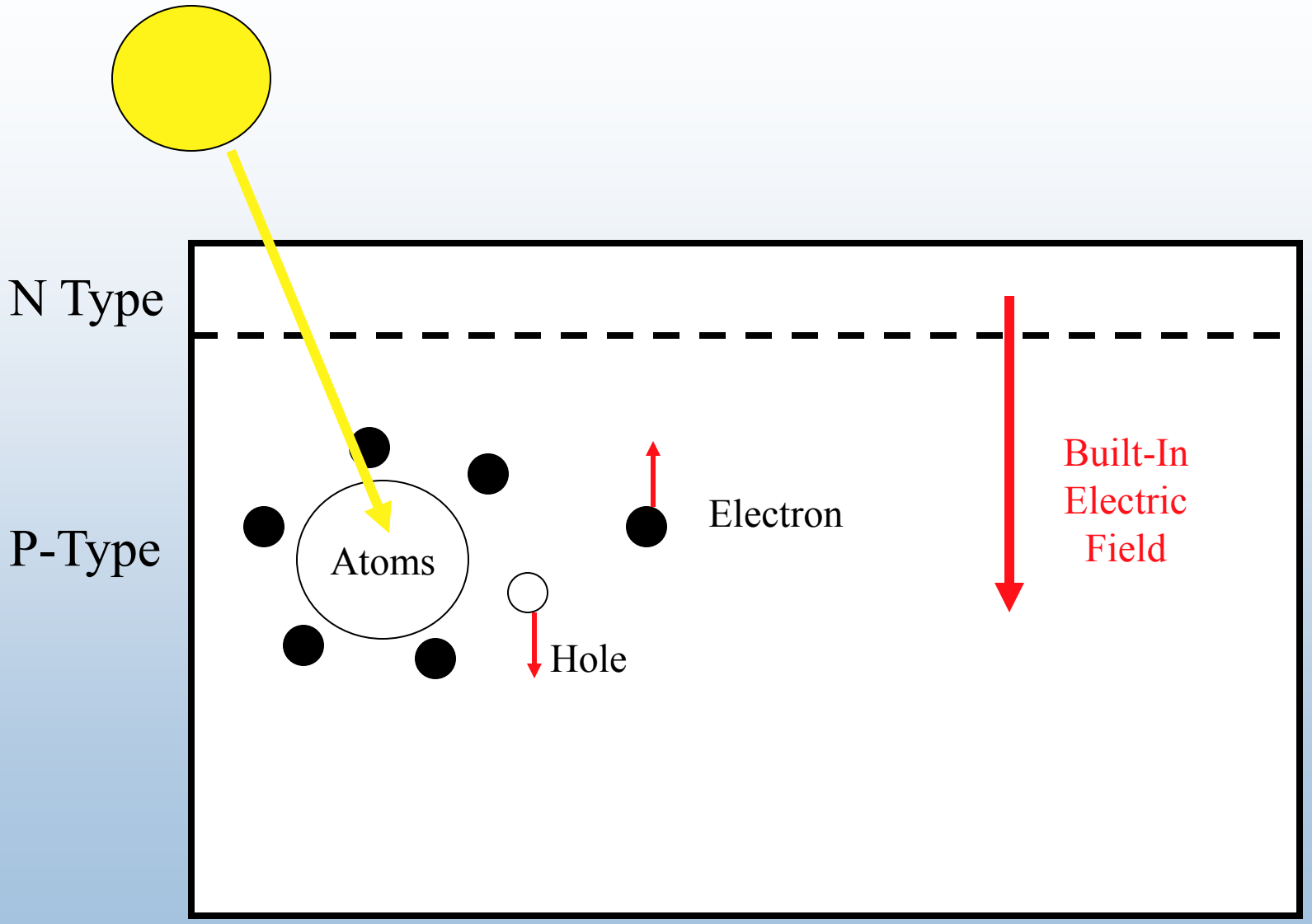
Its not clear which (if any) advantage will yield a long-term product advantage

This situation could remain true for many years!

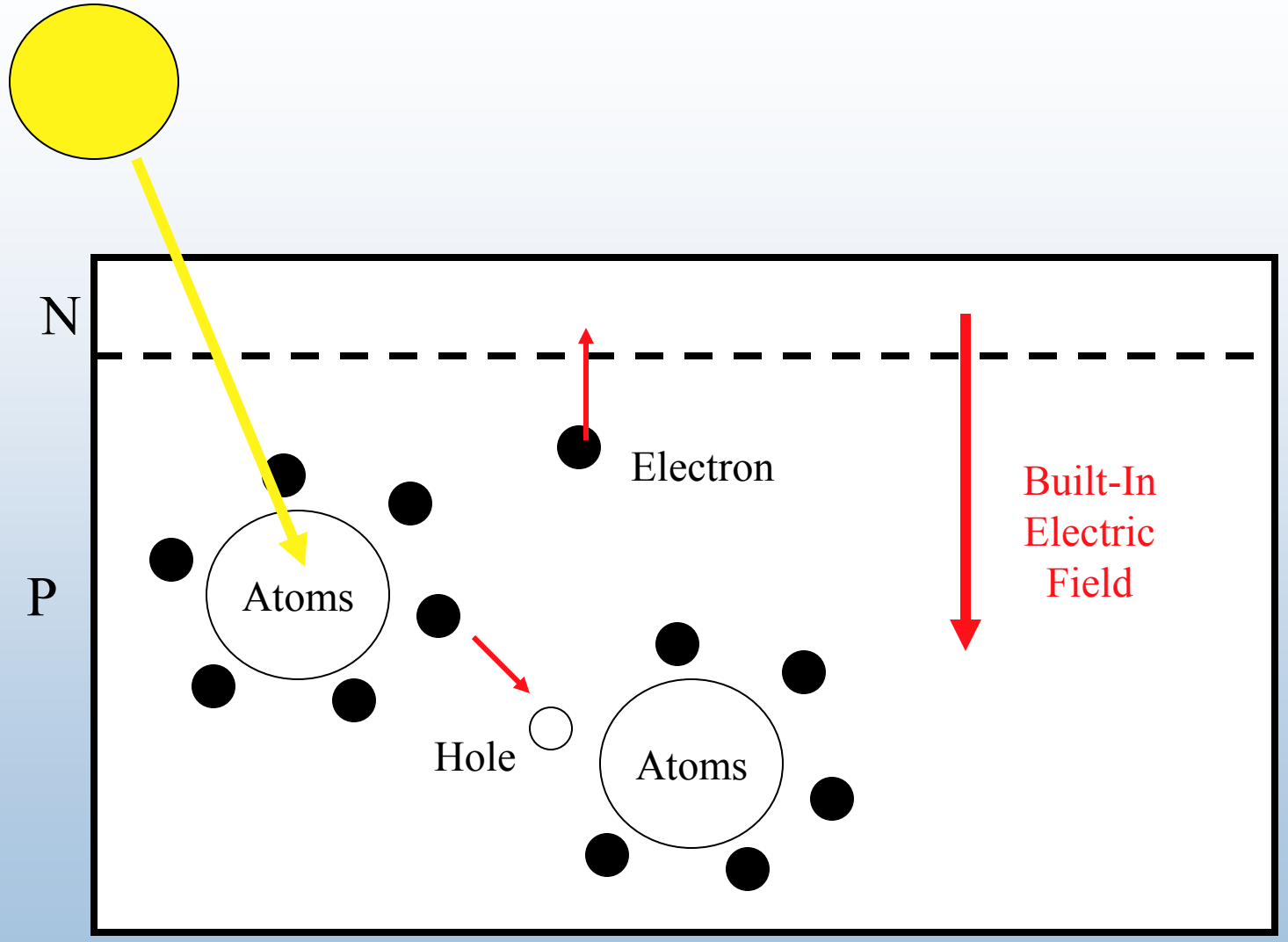
How Do These Things Work?
PV Device Operation 101



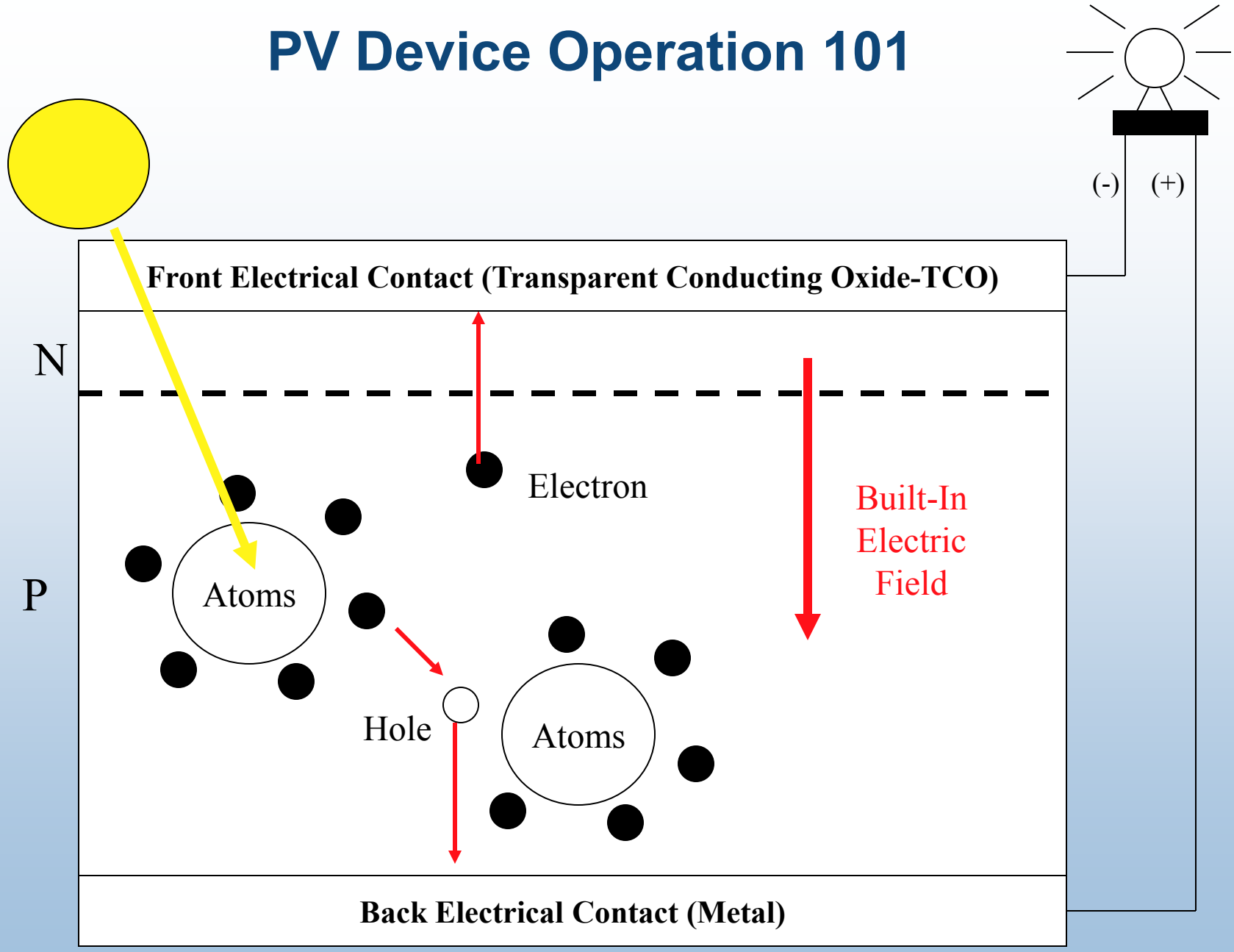
PV Device Operation 101



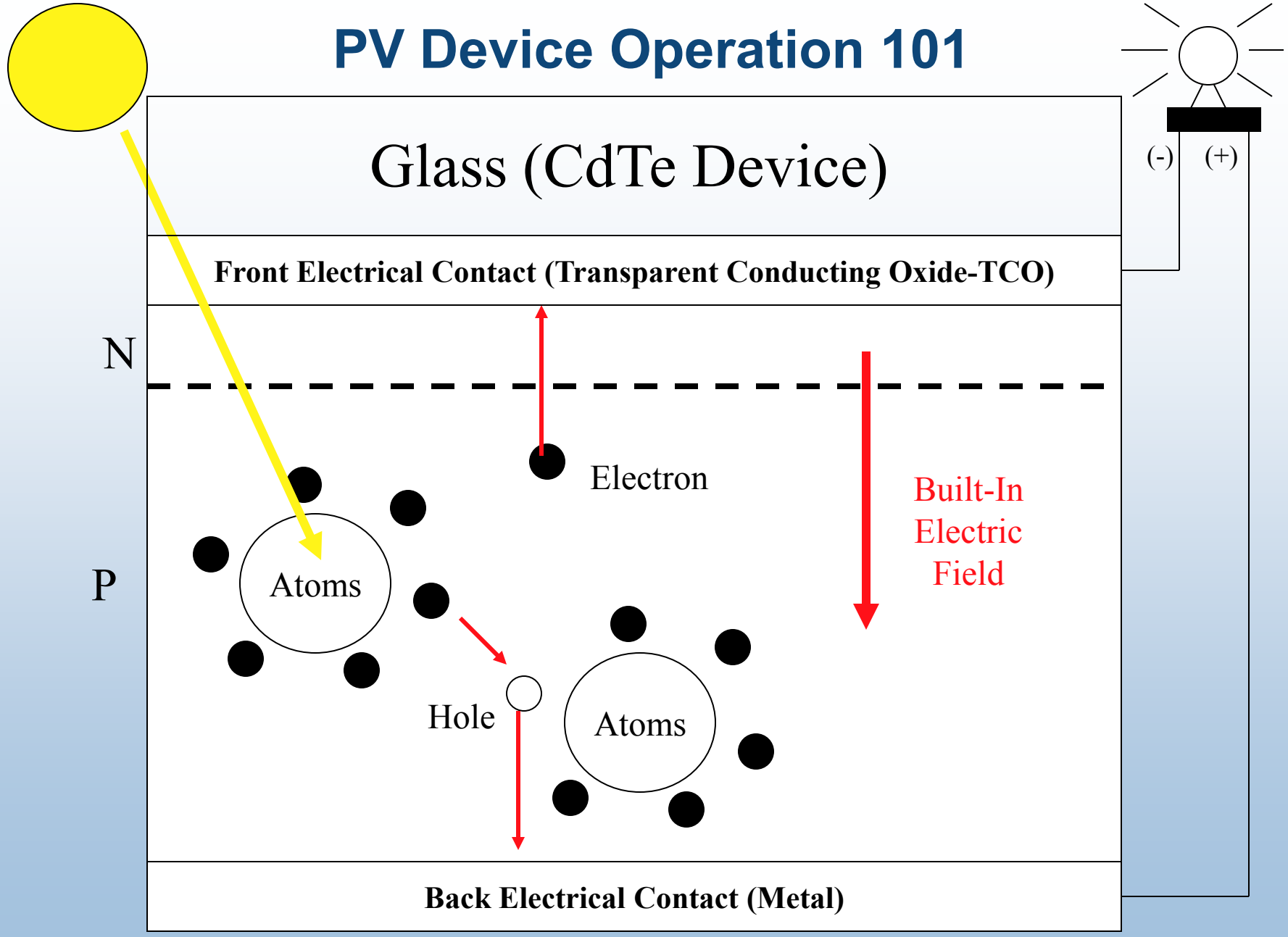
PV Device Operation 101



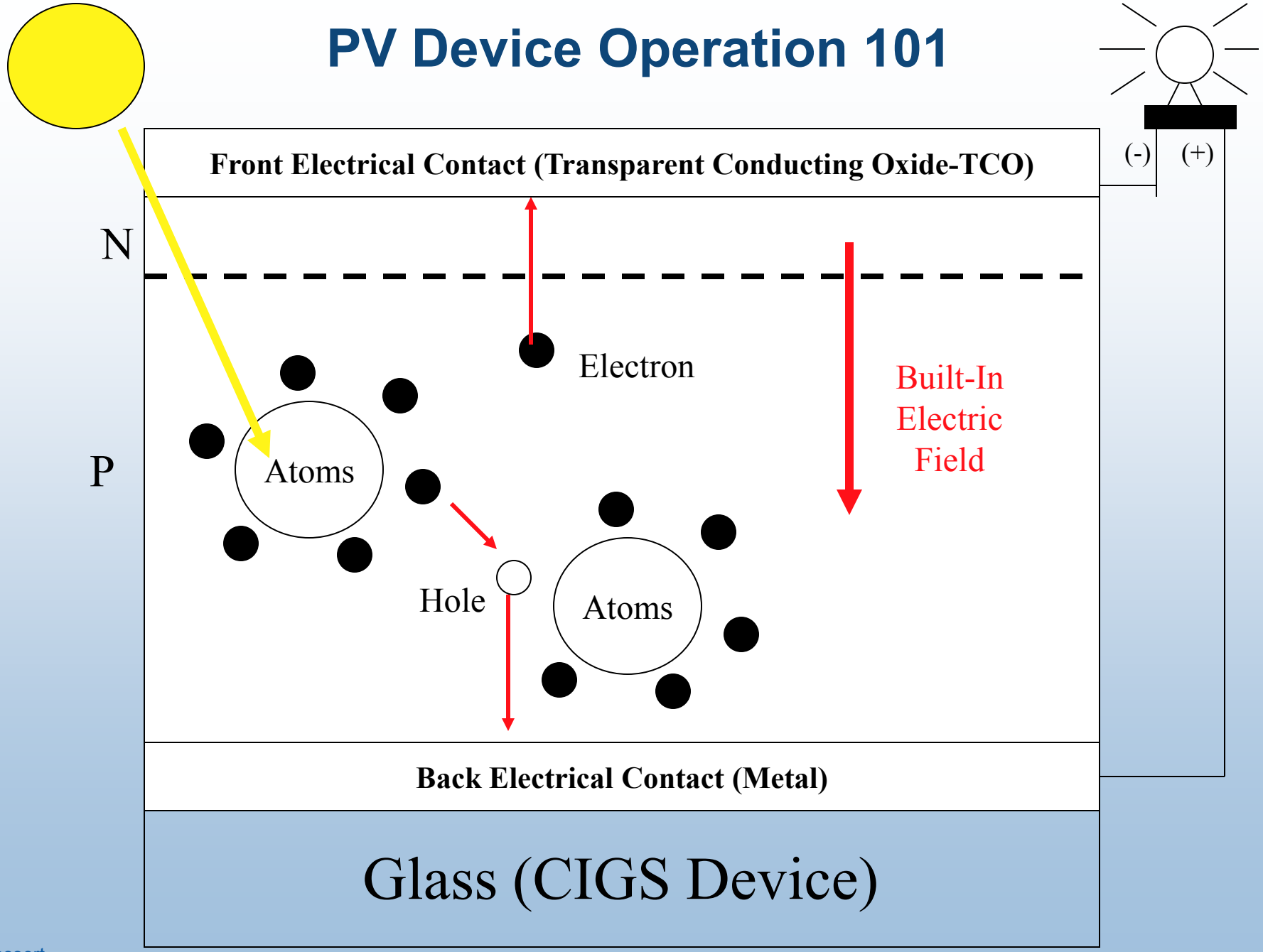
PV Device Operation 101



PV Device Operation 101

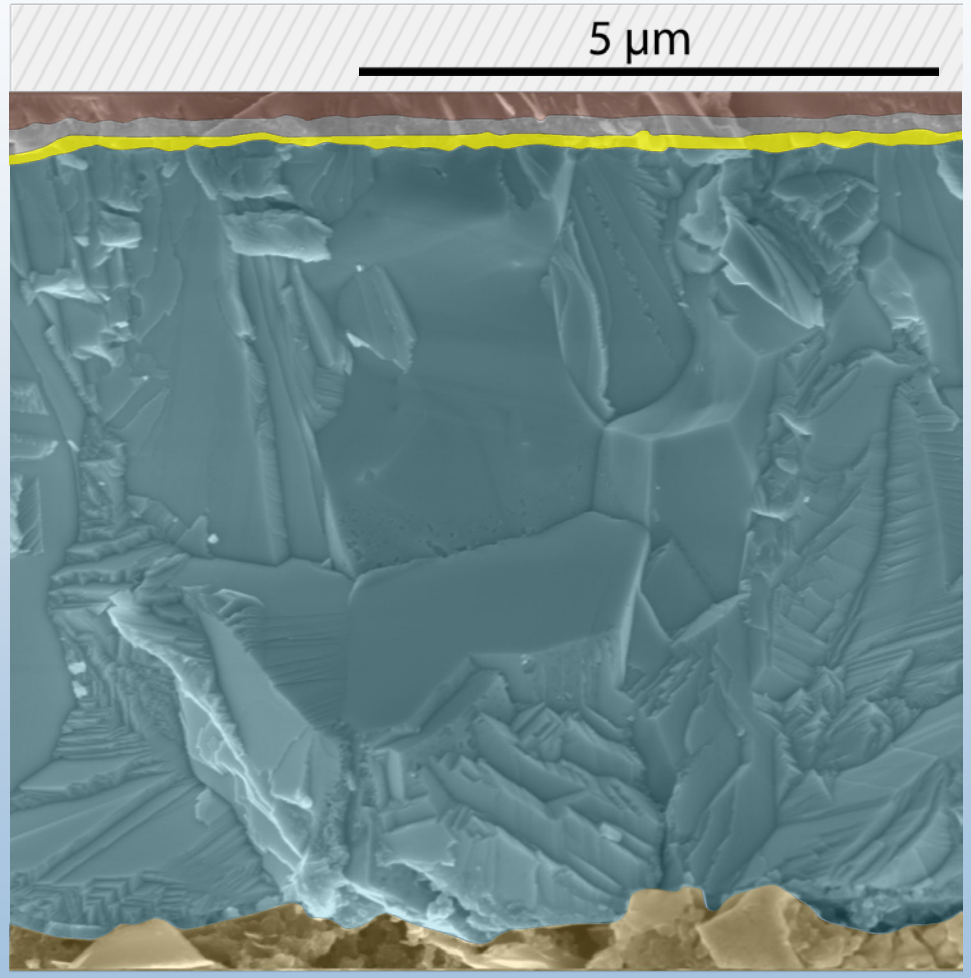


PV Device Operation 101



Thin Film CdTe Solar Cells

$\eta = 16.7\%$
(NREL)



Glass

TCO

CdS (600-2000 Å)

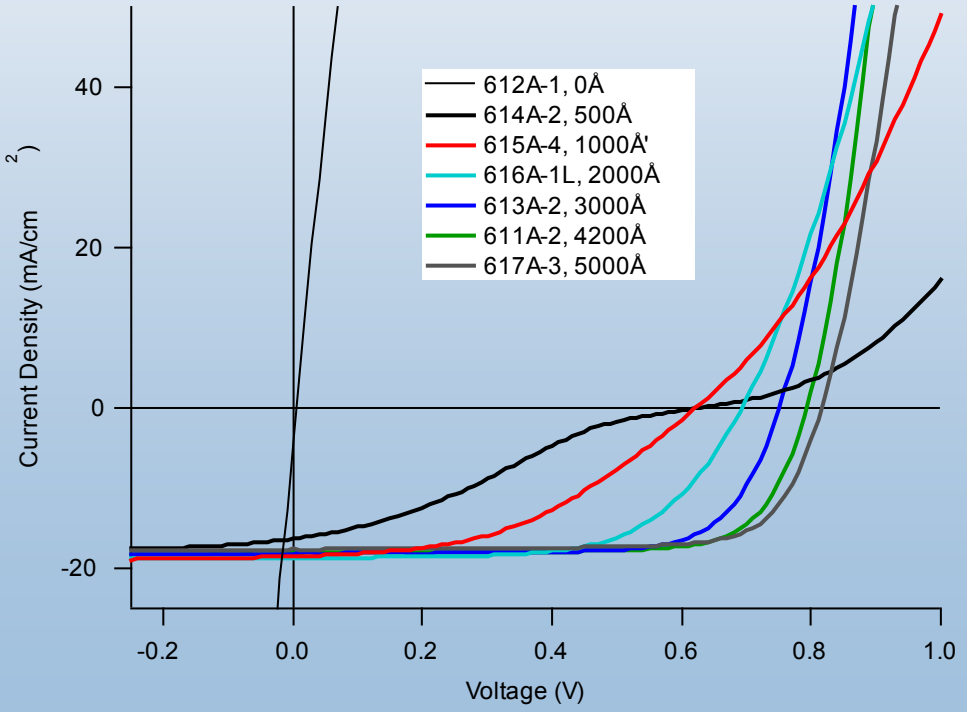
CdTe
2-8 µm

Cu-Containing Interface
(Paste, Pretreatments, ZnTe:Cu) + Metals

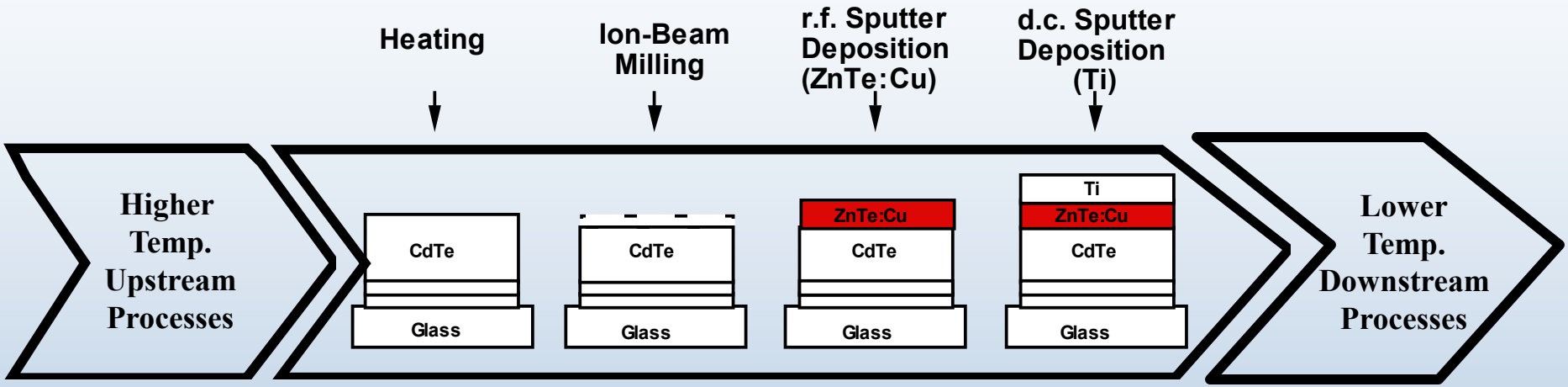
How do CdTe Thin-Film PV Junctions Form??

What this really means:

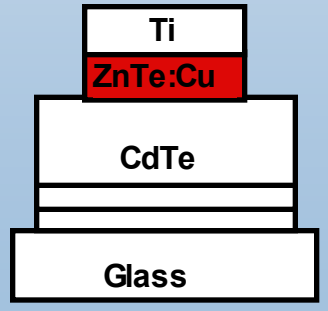
How do we get the electric field to form in the device at the correct location and strength -- without destroying the minority-carrier lifetime?



The ZnTe:Cu/Ti Contact Process
(All-Dry, High-Temperature [~300°C])



Photolithography



<u>Some Research Advantages</u>

Precise control of junction performance

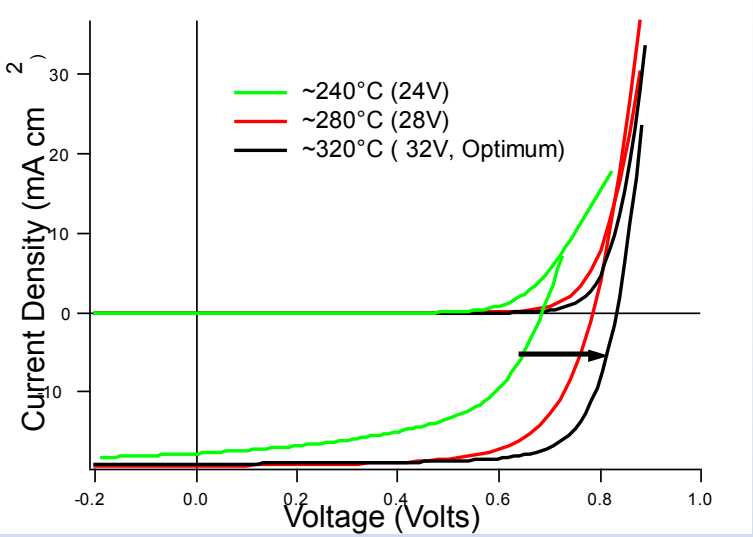
High device stability

Can achieve very low Cu incorporation

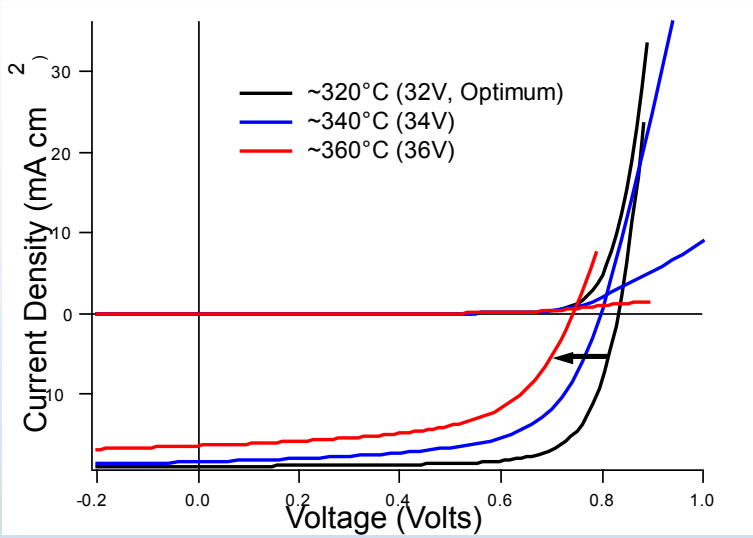
Easy to make large, identical sample sets

Some Insight from Past Studies

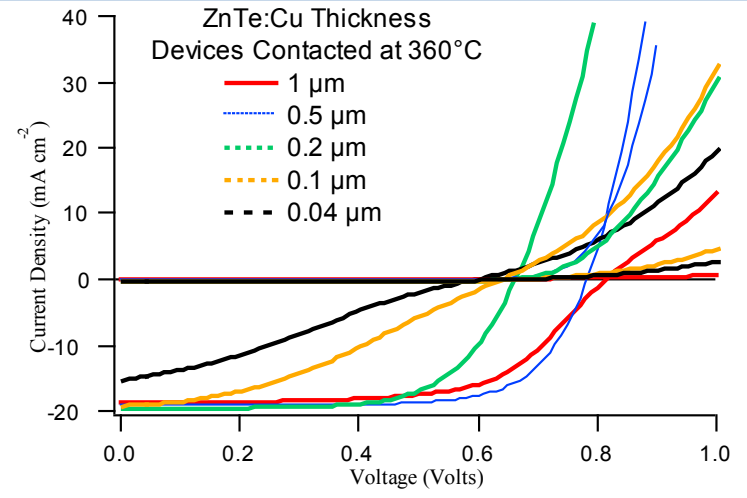
Cu Diffusion Less Than Optimum



Cu Diffusion Greater Than Optimum



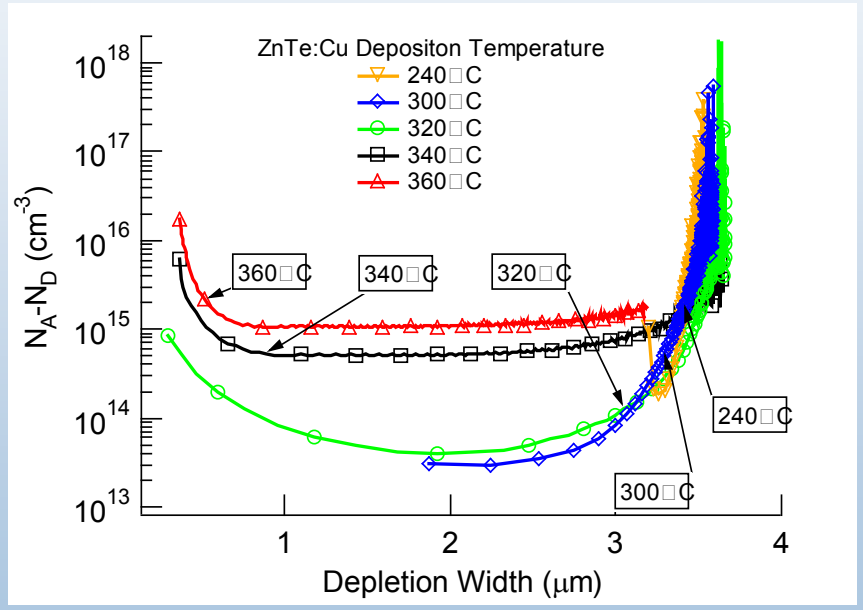
Effect of Contacting Temperature



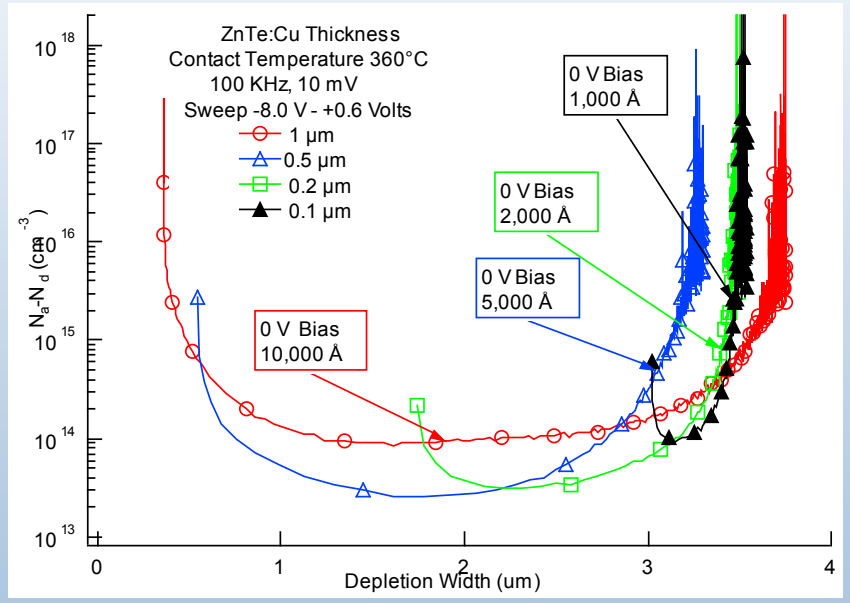
Effect of ZnTe:Cu Thickness

Comparison of Profiling C-V Analysis

Vary Contact Temperature



Vary ZnTe:Cu Thickness

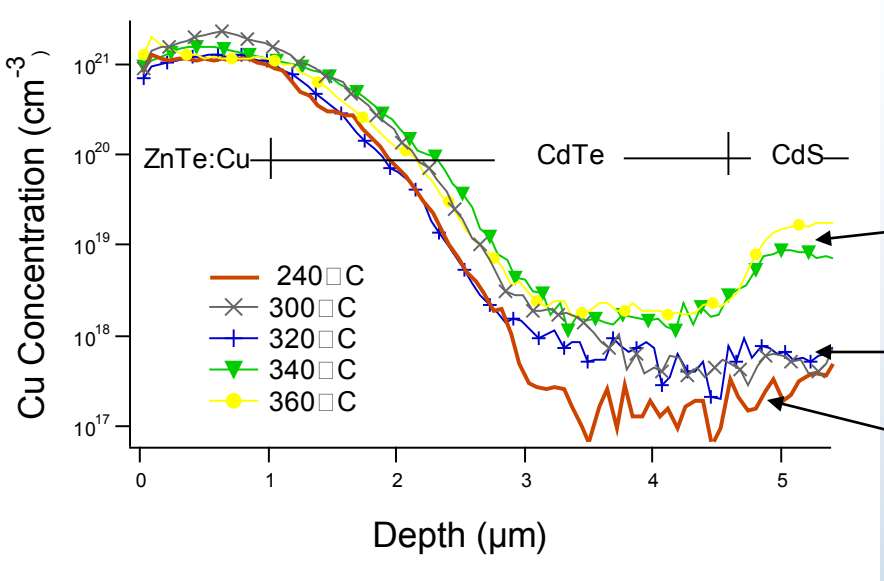


(100 kHz, 10 mV, -8.0 to +0.6 Sweep)

T.A. Gessert, S. Smith, T. Moriatry, M. Young, S. Asher, S. Johnston, A. Duda, C. DeHart
Proc. 31st. IEEE Photovoltaics Specialists Conf. (IEEE, Piscataway, NJ, 2005), pp. 291-294

T.A. Gessert, S. Asher, S. Johnston, A. Duda, M.R. Young, T. Moriarty,
Proc. 4th World Conf. on PV Energy Convr. (IEEE, Piscataway, NJ, 2006) pp. 432-435

Some Insight from Past Studies



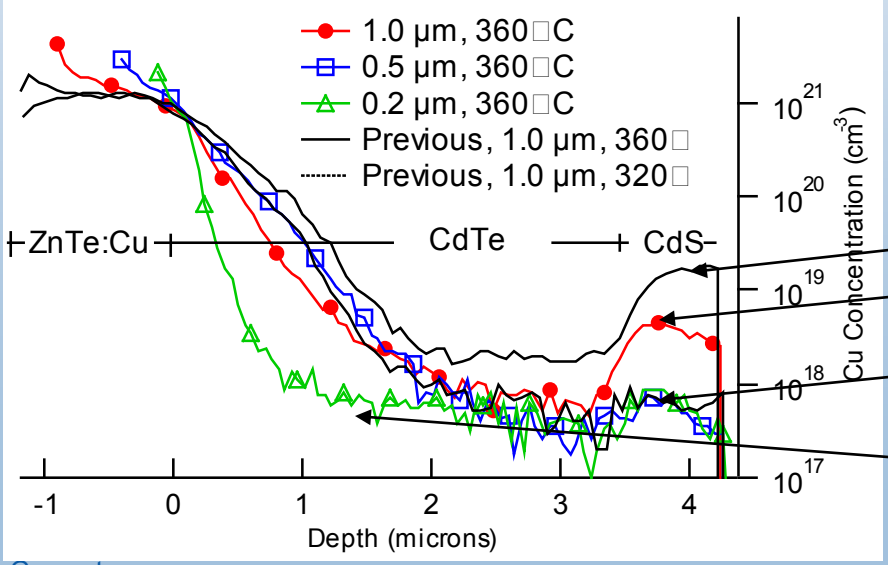
Vary Contact Temperature

Excessive Cu

Optimum Cu

Insufficient Cu

High-Resolution Compositional Depth-Profiling Secondary Ion Mass Spectrometry Analysis (SIMS)



Vary Contact Thickness

Excessive Cu

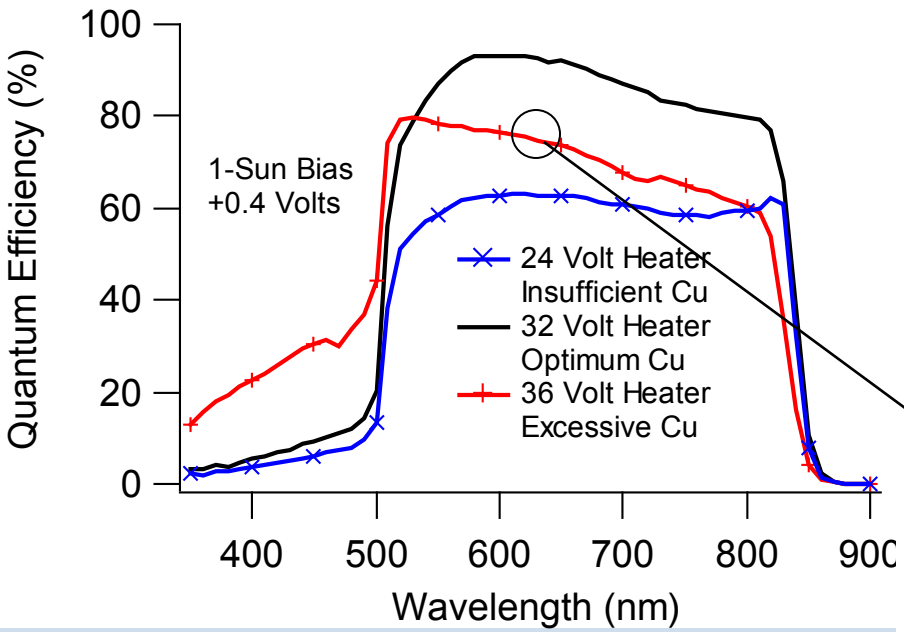
??

Optimum Cu

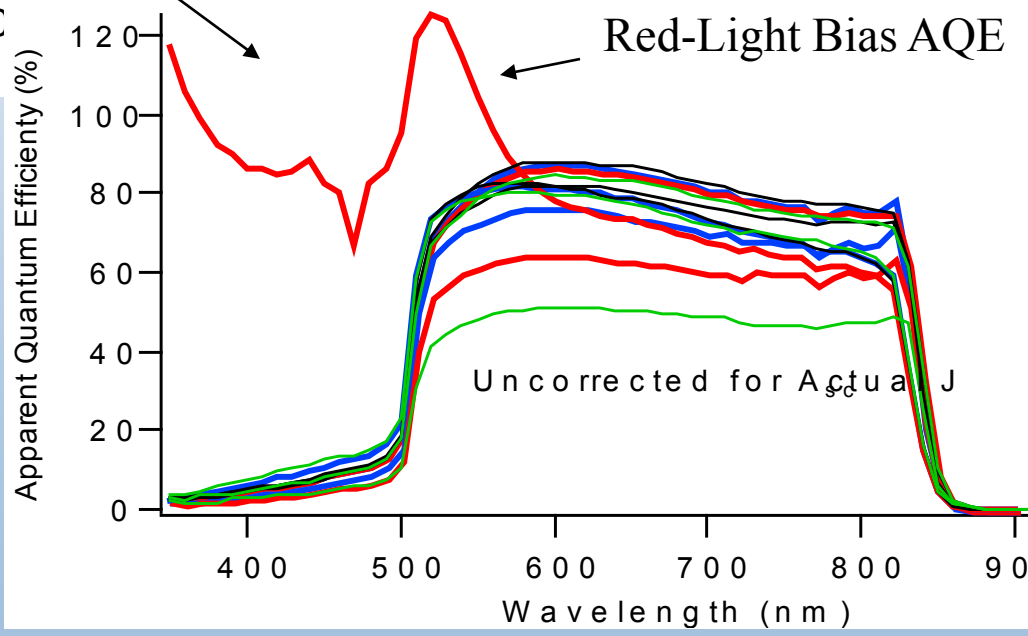
Insufficient Cu

T.A. Gessert, W.K. Metzger, P. Dippo, S.E. Asher, R.G. Dhere, M.R. Young, Thin Solid Films, 517, 2370-2373 (2009)

Light and Voltage-Dependent Quantum Efficiency



Red-Light Bias QE Confirms Photoconductive CdS Only For "Excessive" Cu Devices

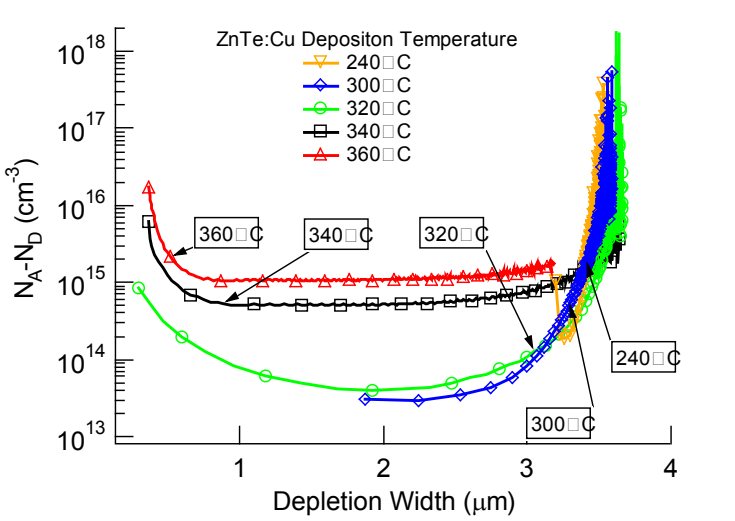


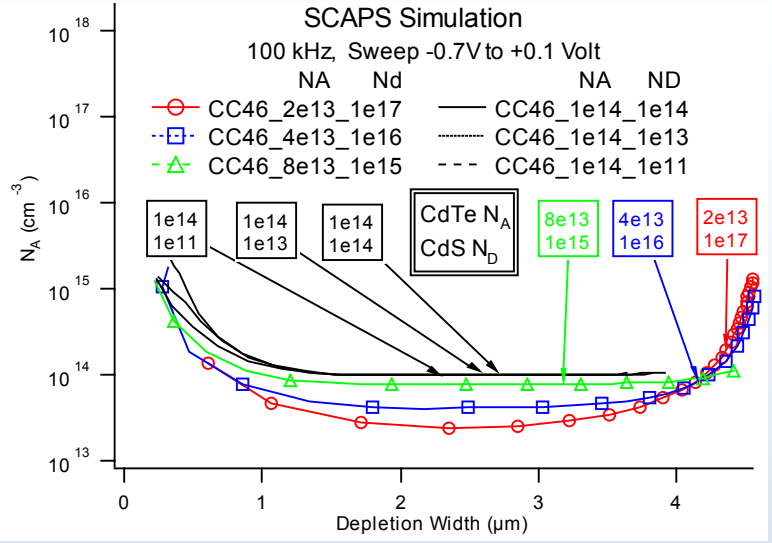
QE Comparison Suggests Narrowing Junction for Excessive Cu Devices

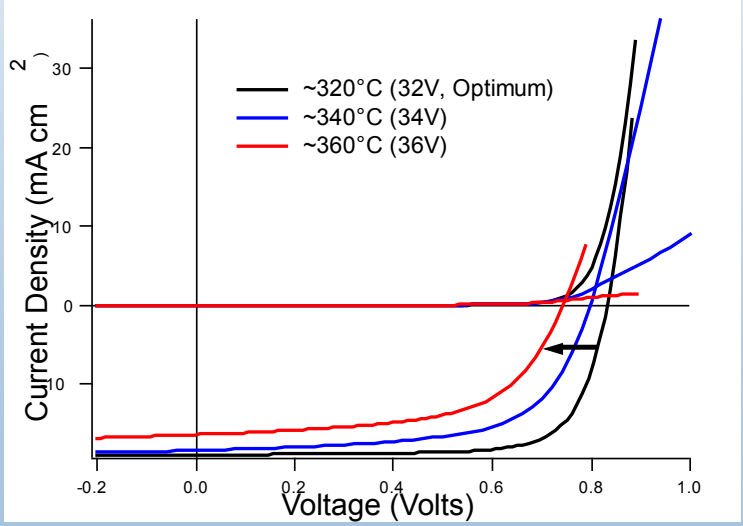
T.A. Gessert, W.K. Metzger, S.E. Asher, M.R. Young, S. Johnston, R. Dhere, T. Moriarty, A. Duda
Proc. 33rd Photovoltaics Specialists Conf. (IEEE, Piscataway, NJ, 2008) Manuscript No. 14.

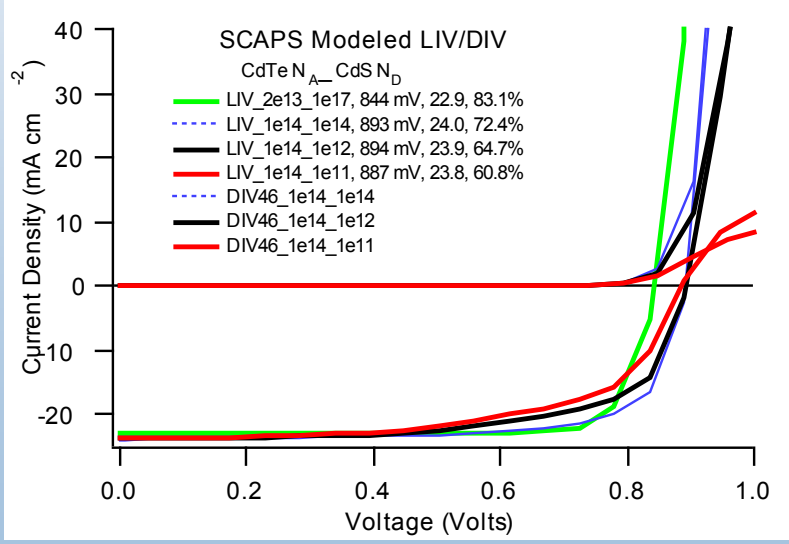
SCAPS1D Simulation

4th World Conf. PV Energy Conversion, pp. 432-435





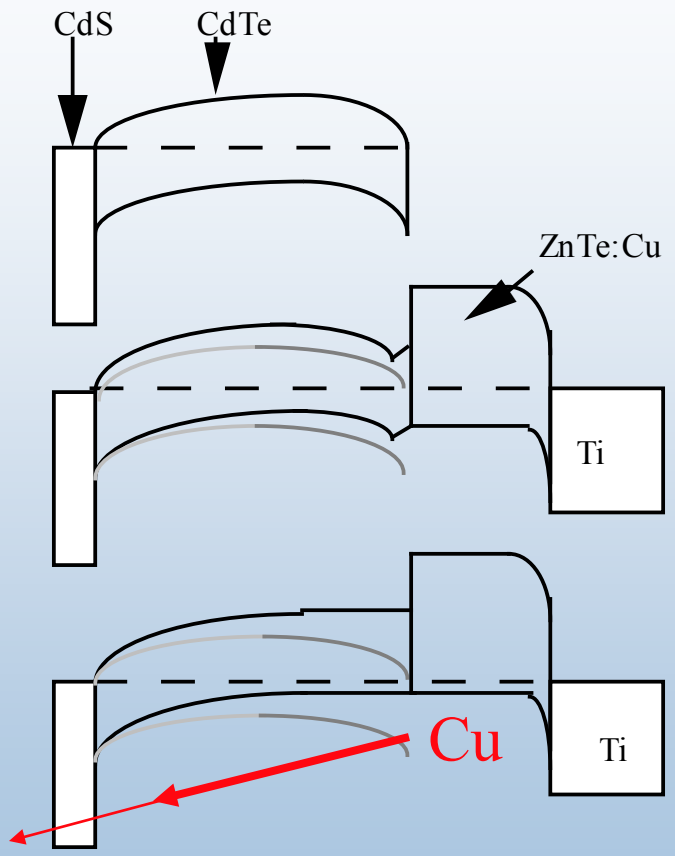




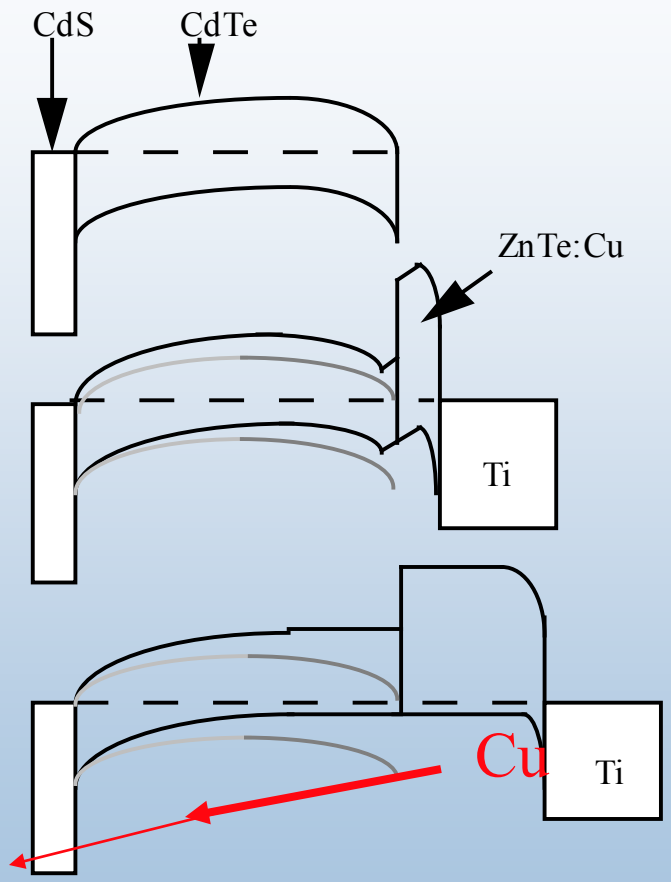
T.A. Gessert, S. Asher, S. Johnston, A. Duda, M.R. Young, T. Moriarty,
Proc. 4th World Conf. on PV Energy Convr. (IEEE, Piscataway, NJ, 2006) pp. 432-435

Some Insight from Past Studies

Constant Thickness ~0.5 µm
Vary ZnTe:Cu Temperature



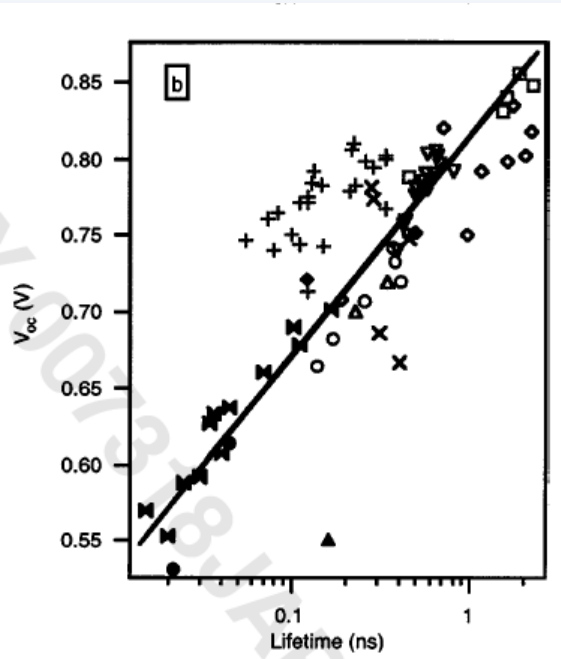
Constant Temperature ~300°C
Vary ZnTe:Cu Thickness



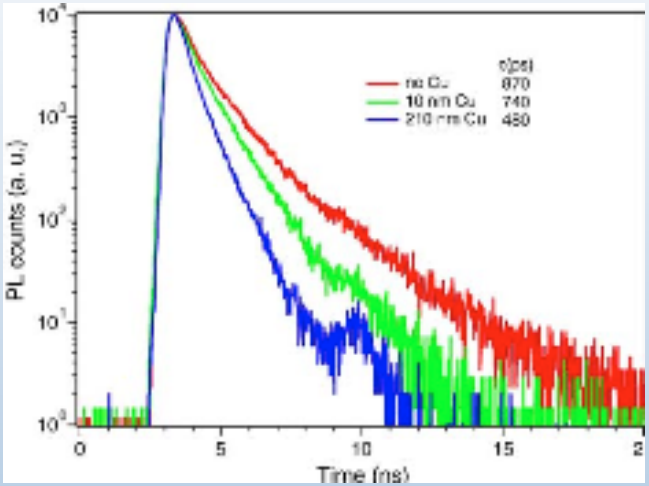
But…Assumes Minority Carrier Lifetime Does Not Change

T.A. Gessert, M.J. Romero, S. Johnston, B. Keys, and P. Dippo
Proc. 29th IEEE Photovoltaics Specialists Conf. (Piscataway, NJ, 2002) pp. 535-538

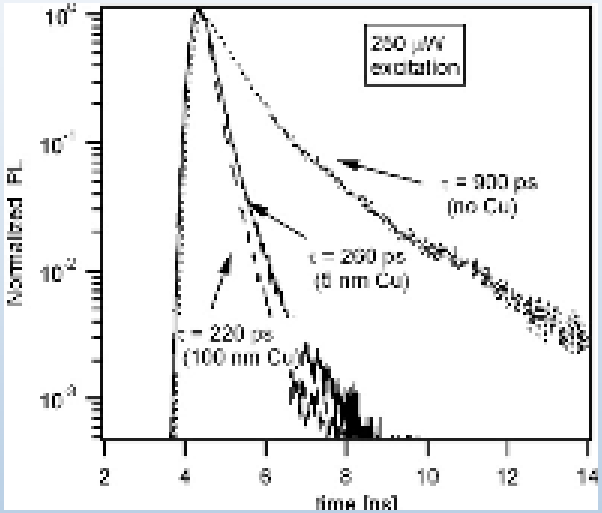
Previous TRPL studies indicate minority carrier lifetime decreases with Cu



Metzger, Albin, Levi, Sheldon, Li, Keyes, Ahrenkeil, JAP 94(6) (2003)



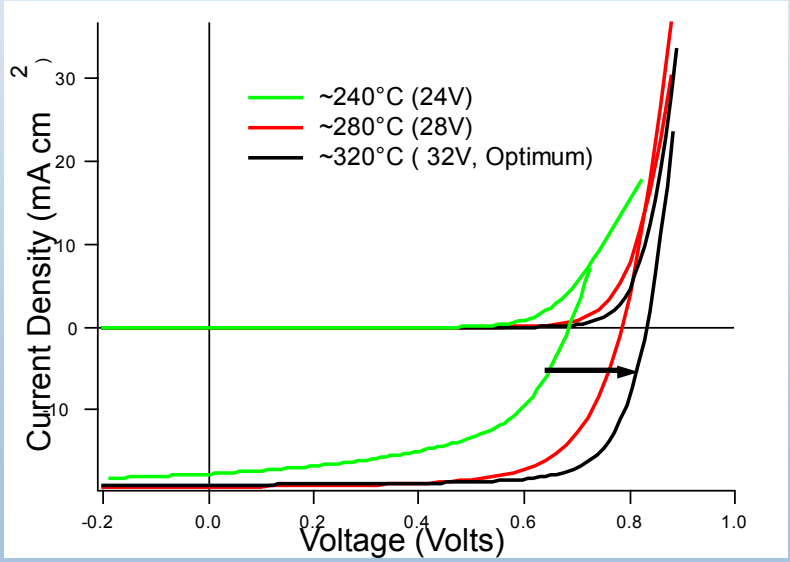
Wu, Zhou, Duda, Yan, Teeter, Asher, Metzger, Demtsu, Wei, Noufi, TSF, 515, 5798 (2007)

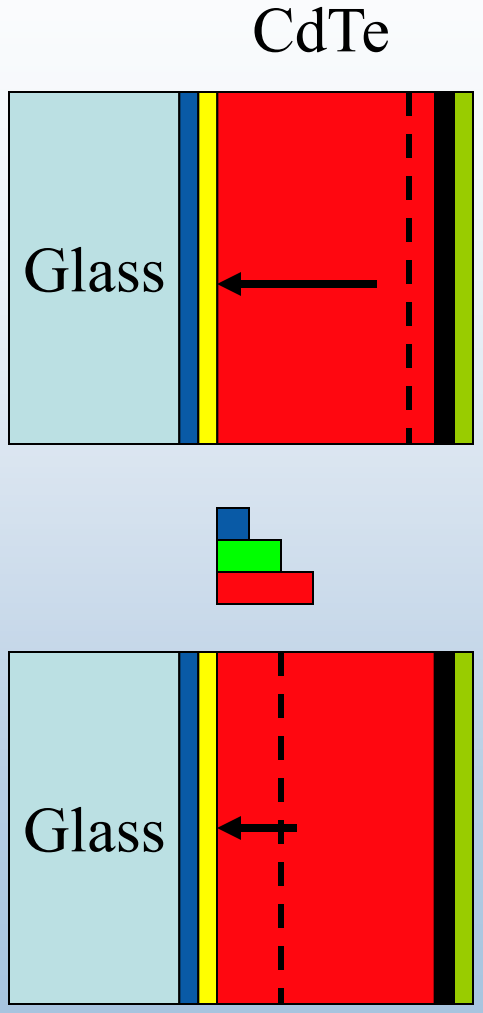


Demtsu, Albin, Sites, Metzger, Duda, TSF, 516 p. 2251 (2008)

Question

If both carrier lifetime and space charge width decreases with Cu incorporation, why does voltage-dependant collection decrease?



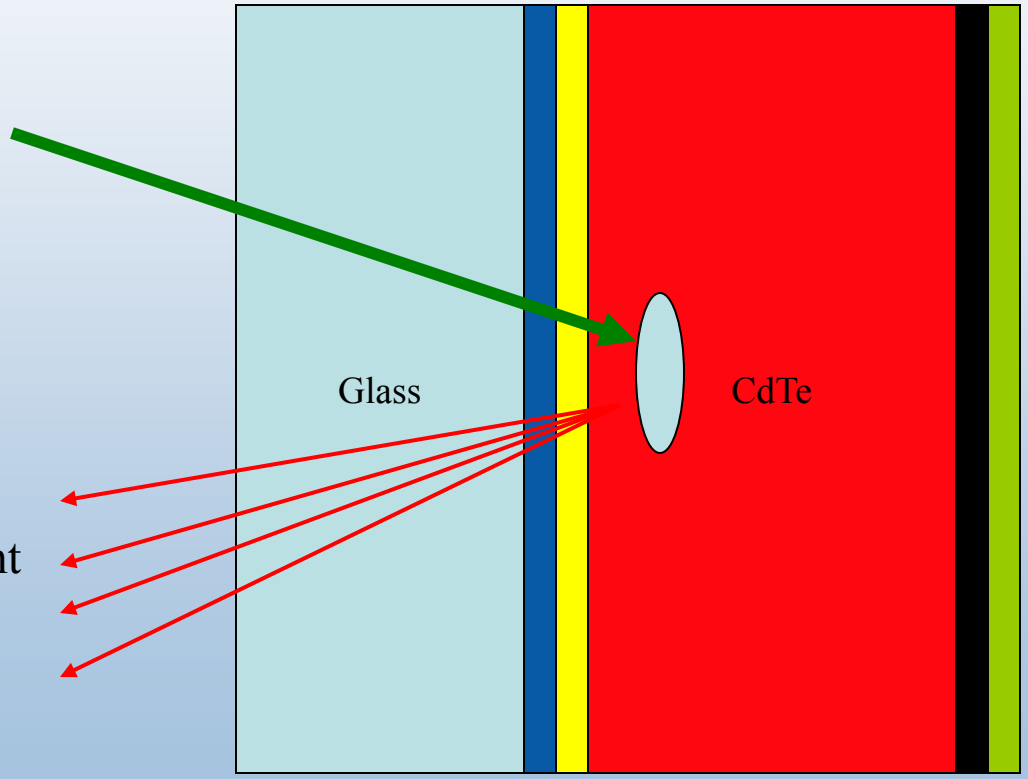


Time Resolved Photoluinescence (TRPL)

650 nm Excitation

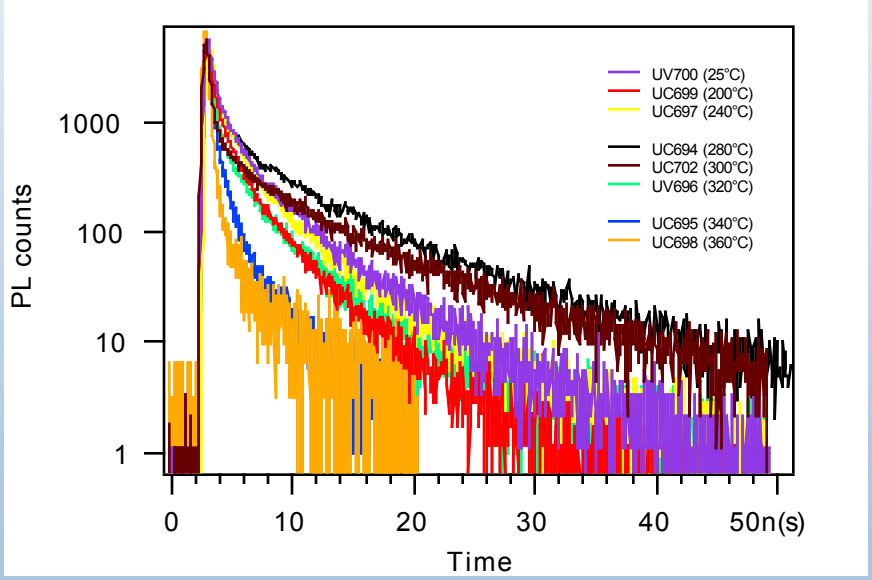
Two Power Levels
250 μW and 2500 μW

820 nm PL Measurement
Room Temperature

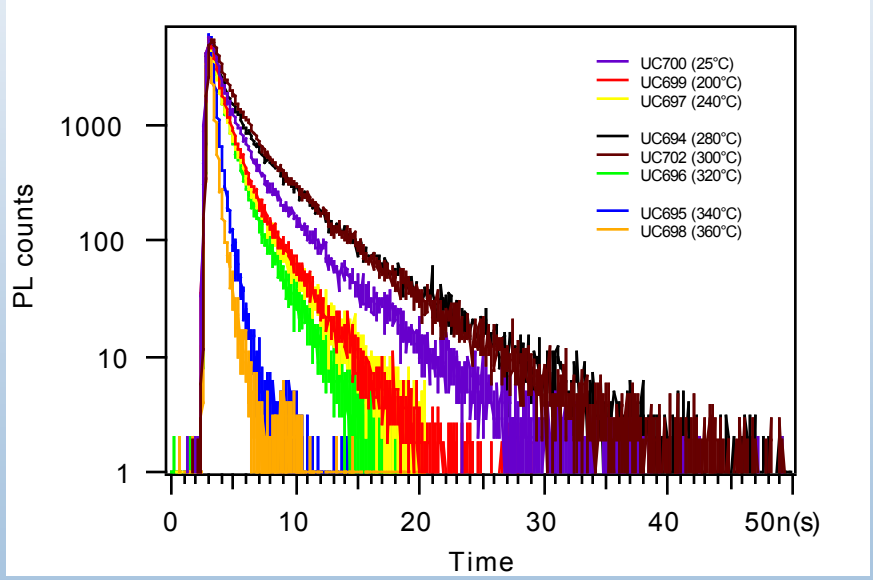


TRPL Study of Cu Diffusion and Contact Temperature

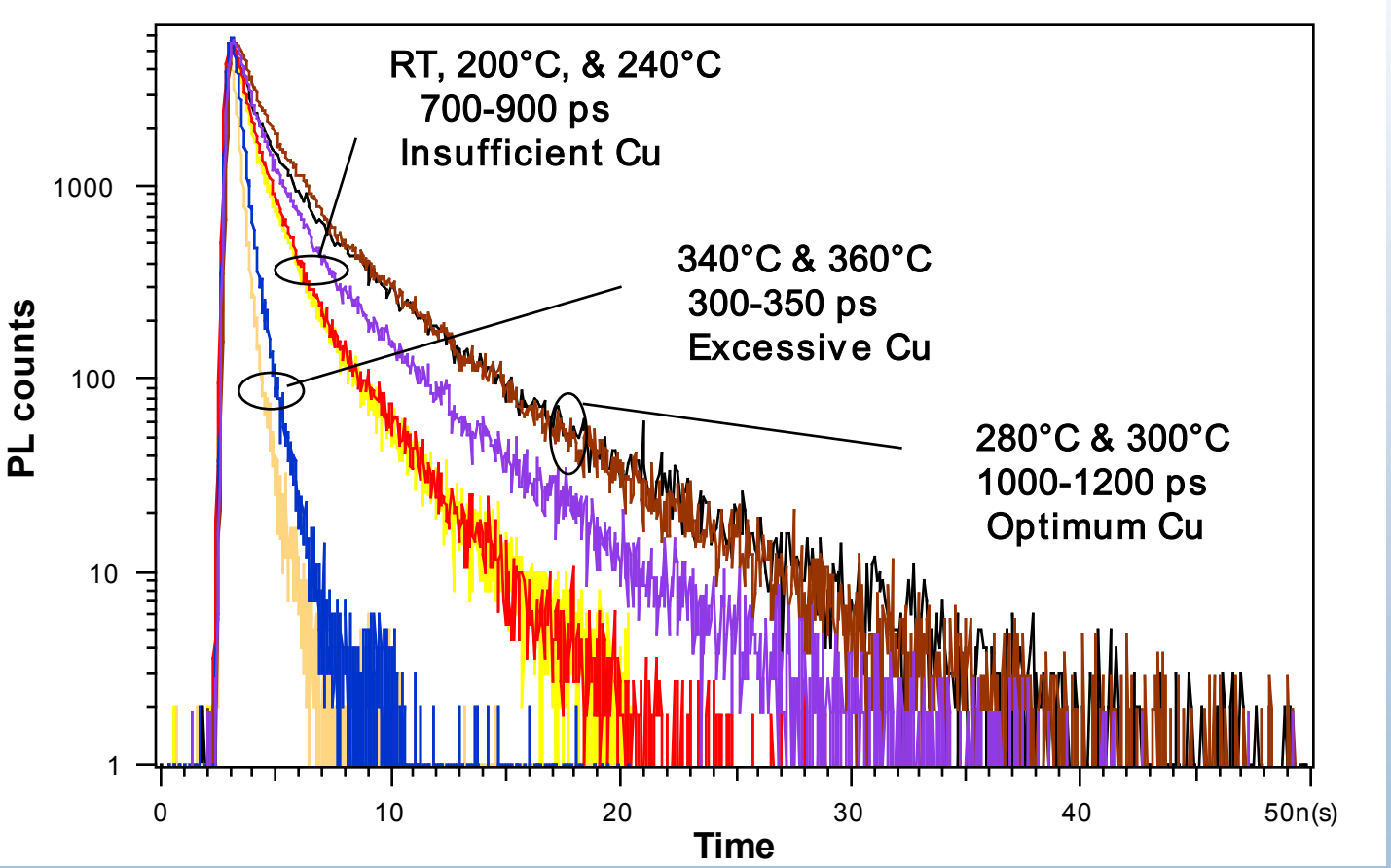
250 µW Power



2500 µW Power

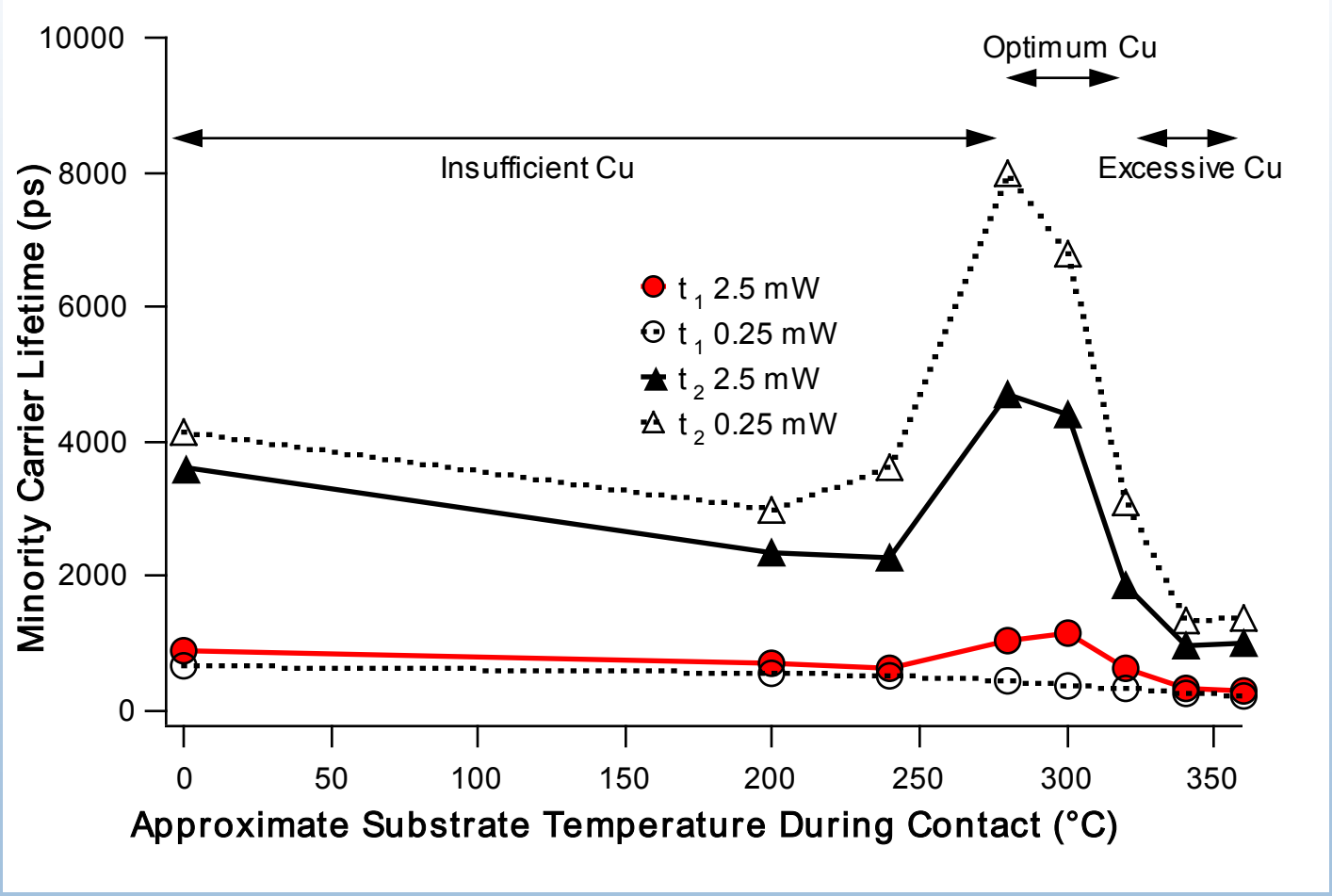


TRPL Study of Cu Diffusion and Contact Temperature (2500 µW Power)



T.A. Gessert, W.K. Metzger, P. Dippo, S.E. Asher, R.G. Dhere, M.R. Young, Thin Solid Films, 517, 2370-2373 (2009)

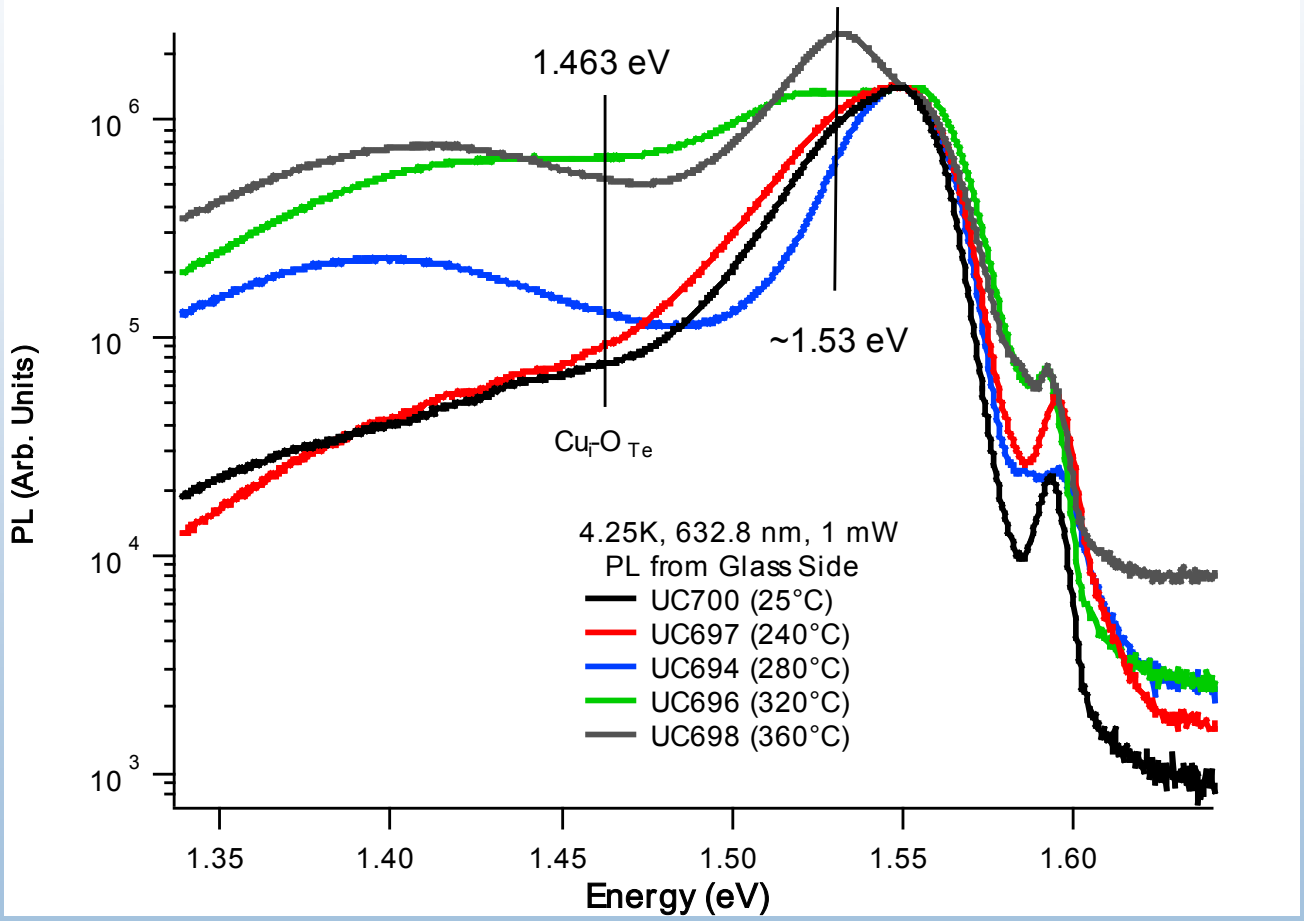
Time Resolved Photoluinescence (TRPL)



T.A. Gessert, W.K. Metzger, P. Dippo, S.E. Asher, R.G. Dhere, M.R. Young, Thin Solid Films, 517, 2370-2373 (2009)

Low-Temperature Photoluinescence (LTPL)

Increasing Contact Temperature produces peak that that has been associated with a defect complex Cu_i-O_{Te} , and an unidentified peak at ~1.53 eV

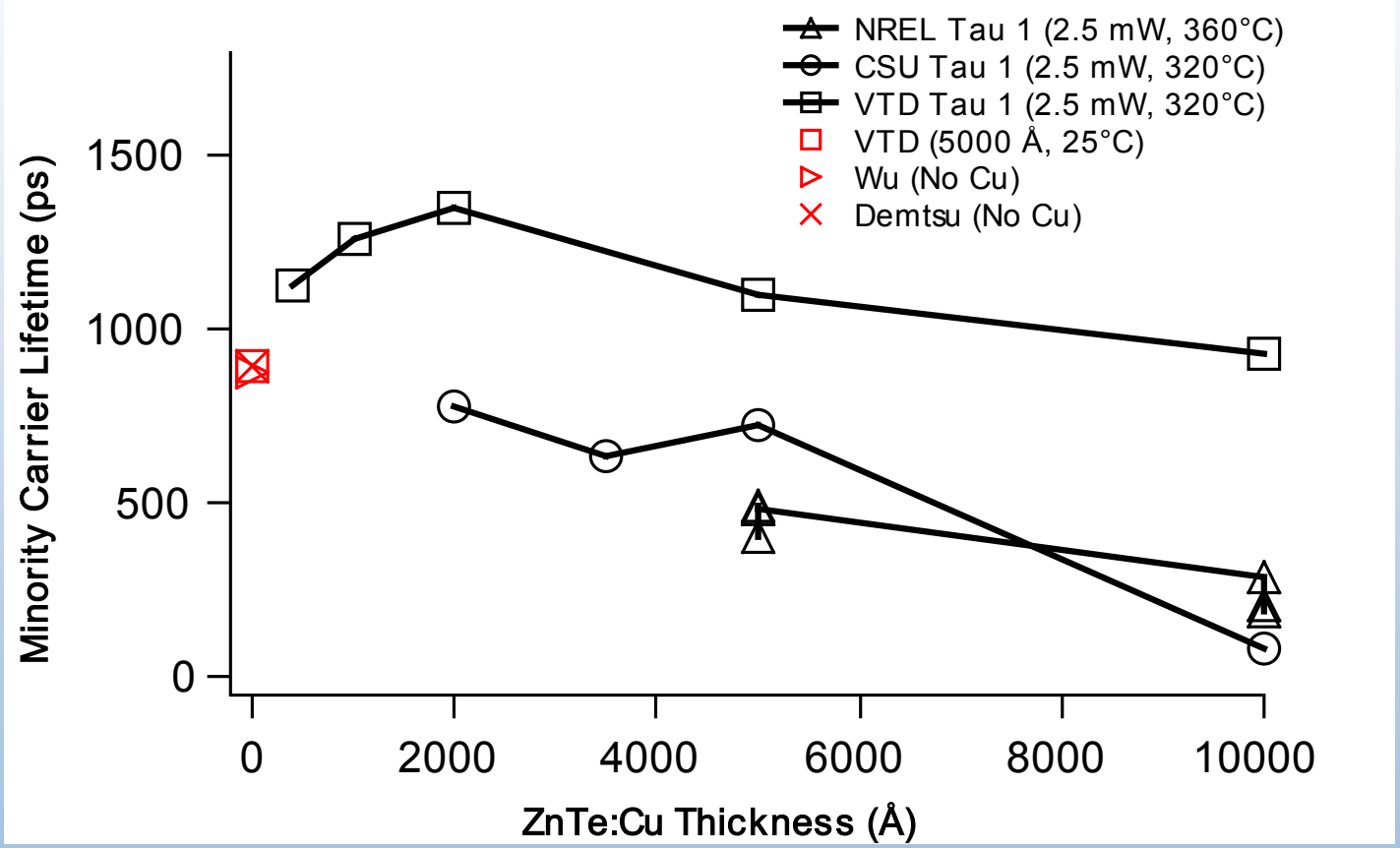


Reference for Cu_i-O_{Te}

Corwine, Sites, Gessert, Metzger, and Duda, Appl. Phys Lett. 86 (1) 221909 (2005)

T.A. Gessert, W.K. Metzger, P. Dippo, S.E. Asher, R.G. Dhere, M.R. Young, Thin Solid Films, 517, 2370-2373 (2009)

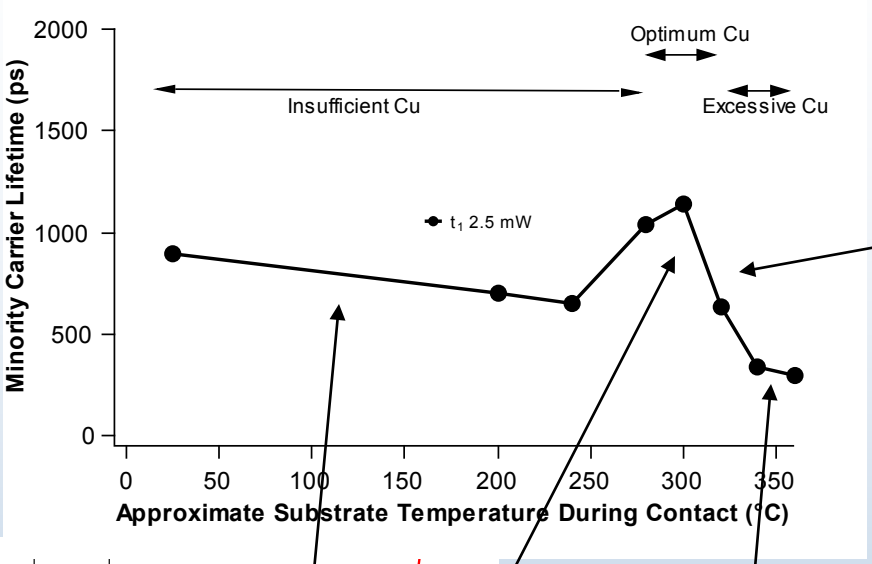
Time Resolved Photoluinescence (TRPL)

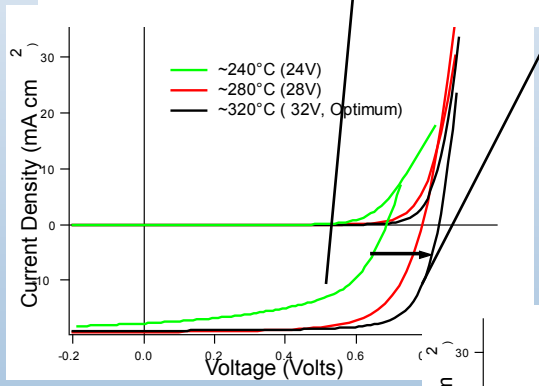


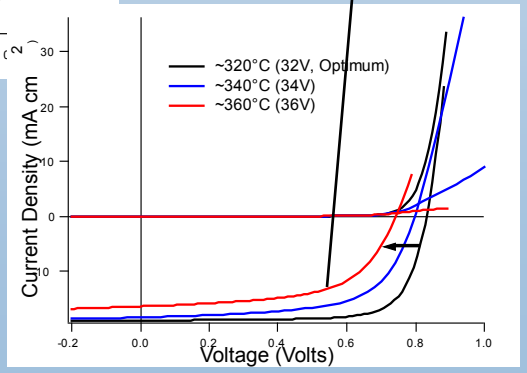
T.A. Gessert, W.K. Metzger, P. Dippo, S.E. Asher, R.G. Dhere, M.R. Young, Thin Solid Films, 517, 2370-2373 (2009)

What Does it all Mean??

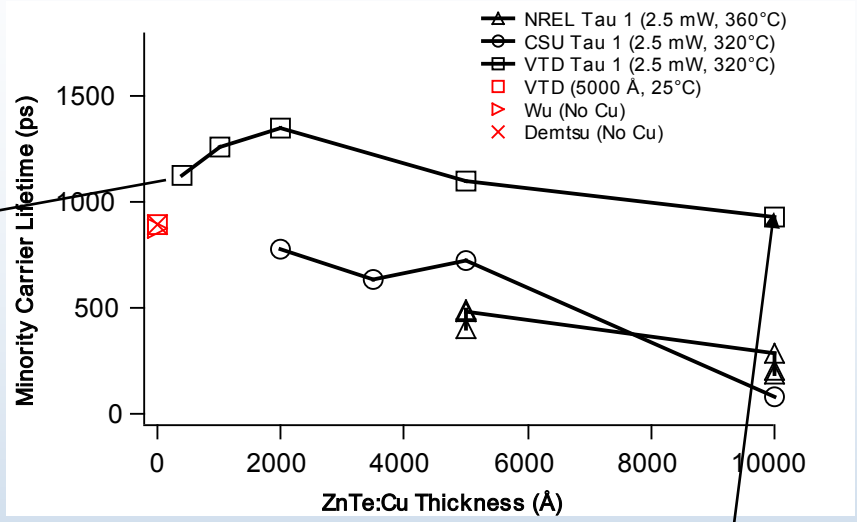
Constant Cu, Vary Temp

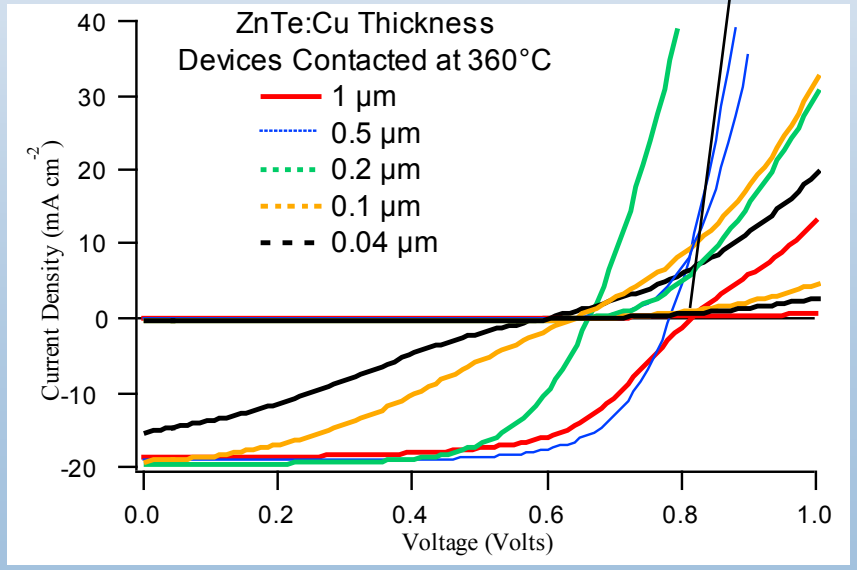






Constant Temp, Vary Cu





CdTe PV Devices Conclusions

- Net acceptor level increases during contacting, control produces optimum $W_{depletion}$
- Minority carrier lifetime can decrease and/or increase during contacting
  - Primarily depends on temperature during Cu diffusion
  - Also depends on amount of Cu diffused
  - Reason(s) remain uncertain
- For the ZnTe:Cu/Ti contact, the longest lifetimes occur at contact temperature of ~280-320°C
  - This may explain various contact-process functionalities!
- Strategy for optimization of Cu-containing contacts:
  - Understand effect of temperature on lifetime
  - Adjust Cu to optimize depletion width and V_{oc} (and limit Cu diffusion into CdS)
  - **Future work – maintain lifetime in quazi-neutral region during contacting!**

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Thank You!

