Hole Mobility Limits for Amorphous and Nanocrystalline Silicon Solar Cells

Eric Schiff

Syracuse University

Forschungszentrum Jülich: Thorsten Dylla, Friedhelm Finger

NREL: Howard Branz, Dick Crandall, Paul Stradins, Qi Wang, Kai Zhu

Penn State: Joshua Pearce, Chris Wronski

United Solar: Gautam Ganguly, Subhendu Guha, Baojie Yan, Jeff Yang

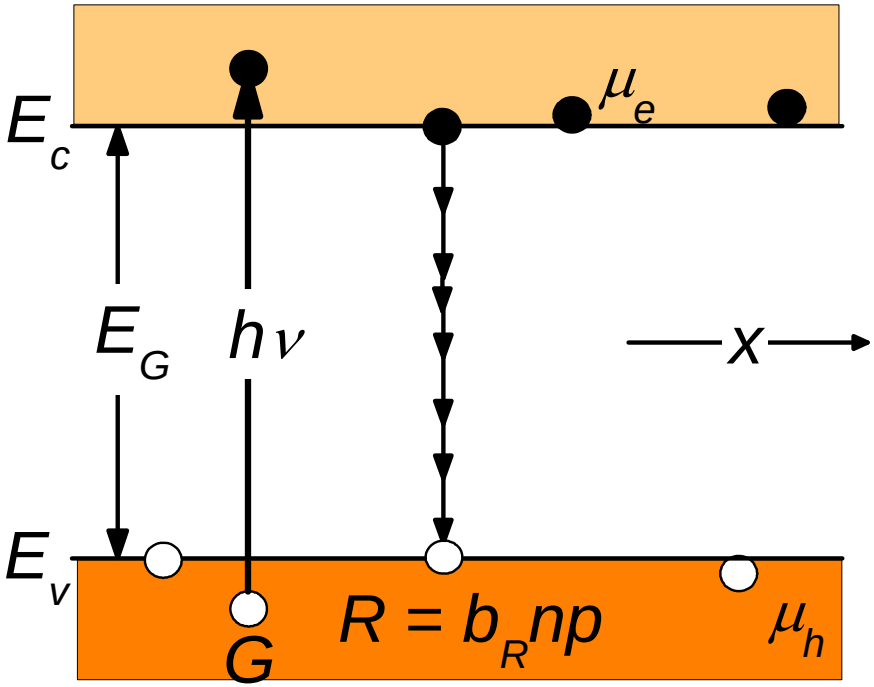
Syracuse: Steluta Dinca, Jianjun Liang

DOE Solar Energy Techologies Program Review, Nov. 7-10, 2005, Denver.

Themes of this Presentation

- Describe "minority carrier mobility limitation" concept for *pin* solar cells
  - For low-mobility absorbers, the magnitude of recombination parameters can have very little effect.
- Describe experimental testing of hole mobility limited description for United Solar Ovonic Corp.'s a-Si:H solar cells Answer "what if" questions about initial state of a-Si:H and nc-Si:H solar cells:
  - improve mobility? reduce recombination?
  - Why are nc-Si:H solar cells about 2 microns thick?
- Apply description to the light-soaking problem
  - Modest defect recombination plays well with H-collision.
  - Suggests that light-soaking in United Solar Ovonic cells is *self-limiting*

Low-mobility *pin* Solar Cells: "Toy" Model and Analytical Solution



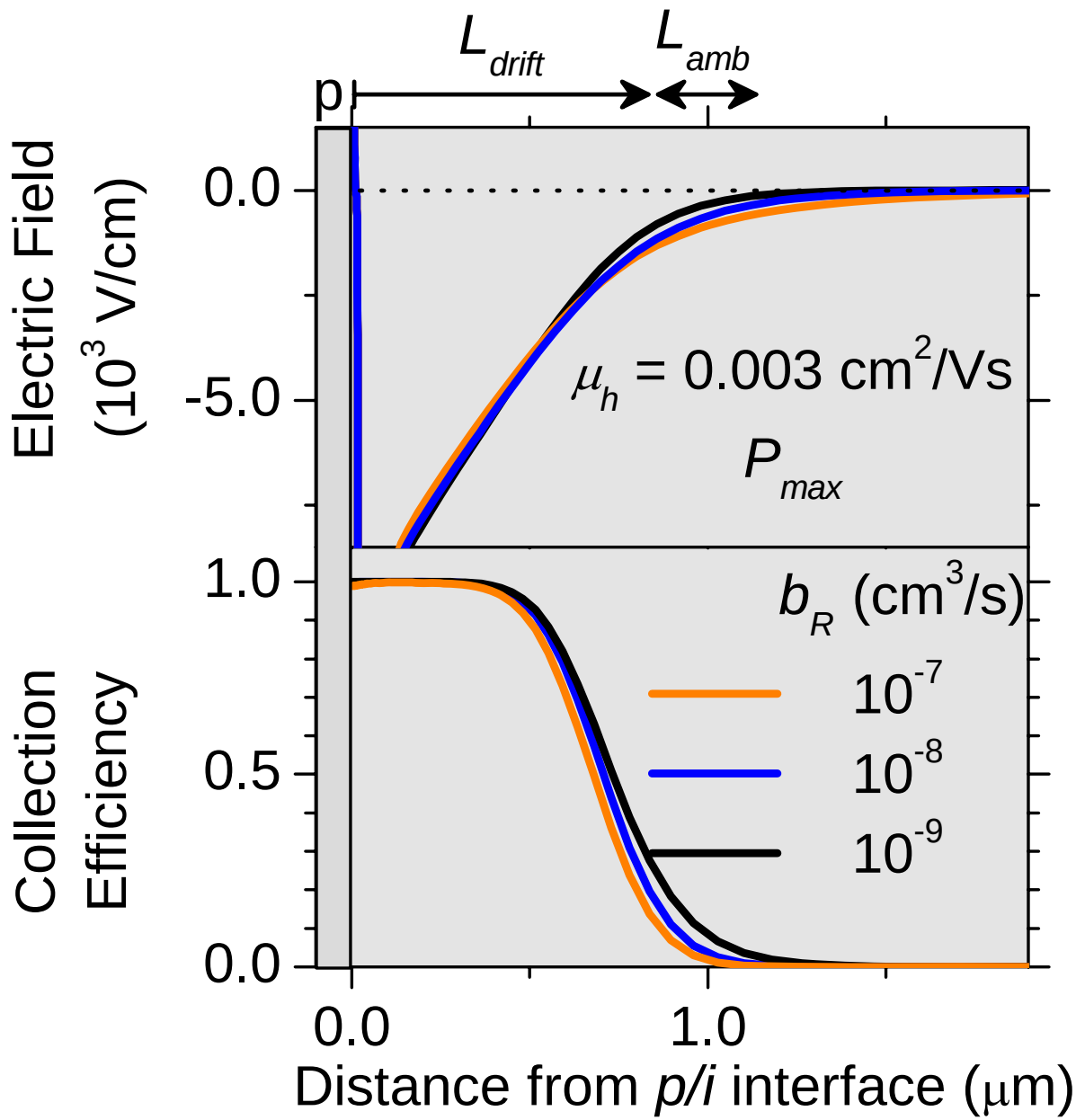
$$P_{\max} = \left(\mu_h \varepsilon (eG)^3\right)^{1/4} \left((2/3)V_{OC}\right)^{3/2}$$

$$\mu_e >> \mu_h$$

$$eV_{OC}^0 = E_G + kT \ln\left(\frac{G}{b_R N_C N_V}\right)$$

E. A. Schiff, *Solar Cells and Solar Energy Materials* **78**, 567-595 (2003).[.pdf]

Recombination Effects on a Low-mobility *pin* Solar Cell



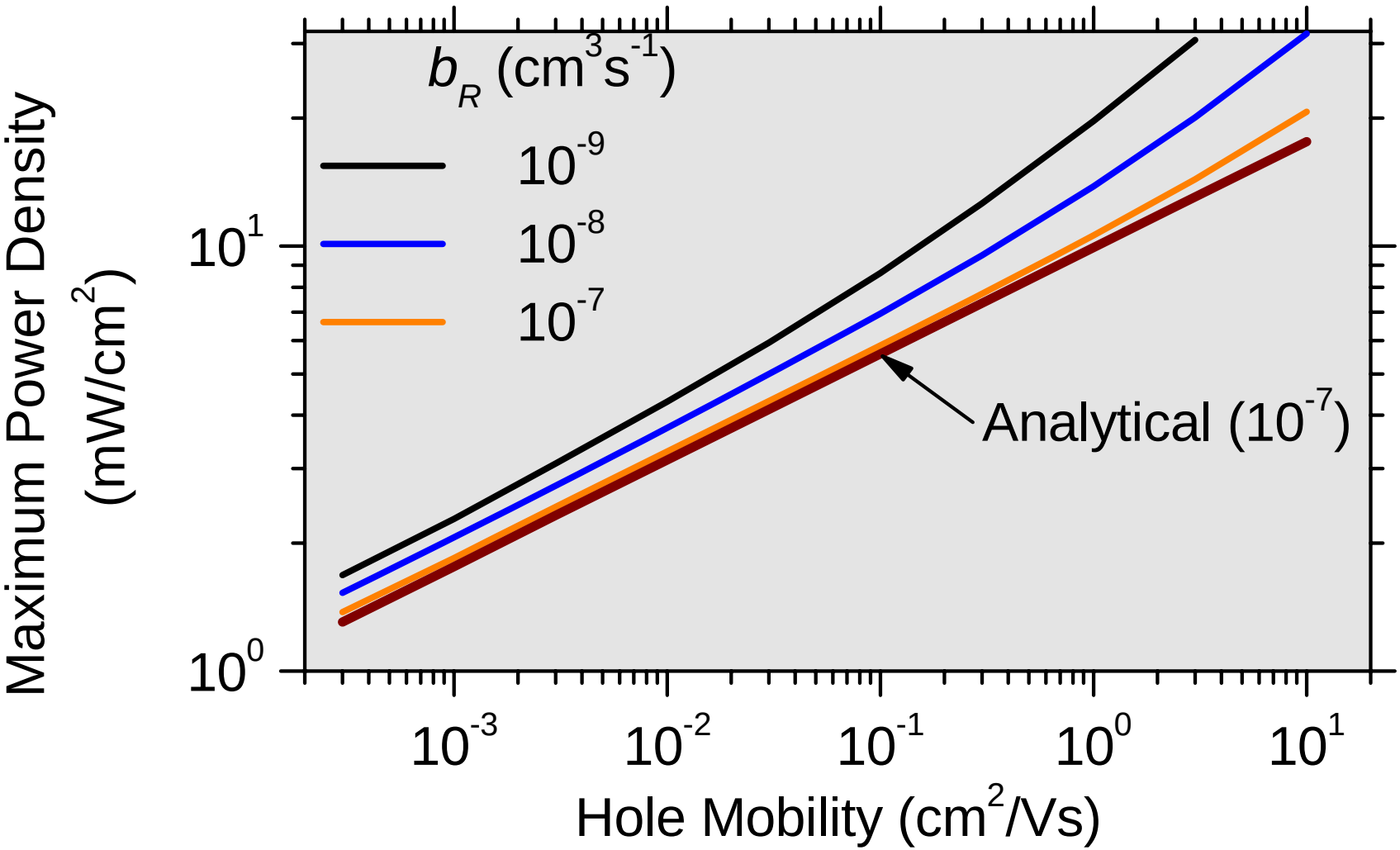
Computer Calculations

L_{drift}: width of space charge layer

L_{amb}: ambipolar diffusion length (shown for $b_R = 10^{-9}$ cm^3/s)

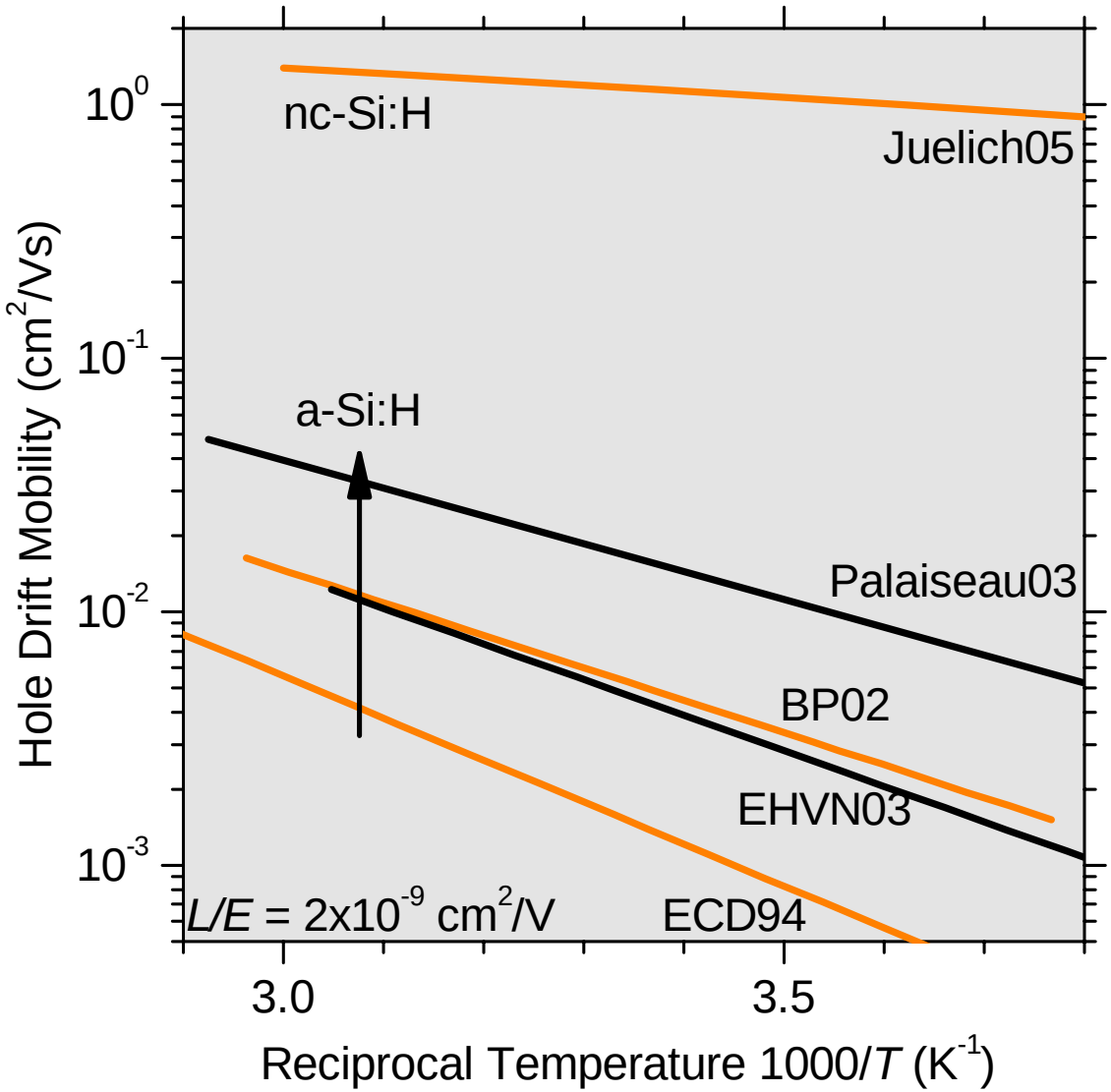
E. A. Schiff, *J. Non-Cryst. Solids, in press* (ICANS 2005).

Mobility Is Power: Computer and Analytical Calculations



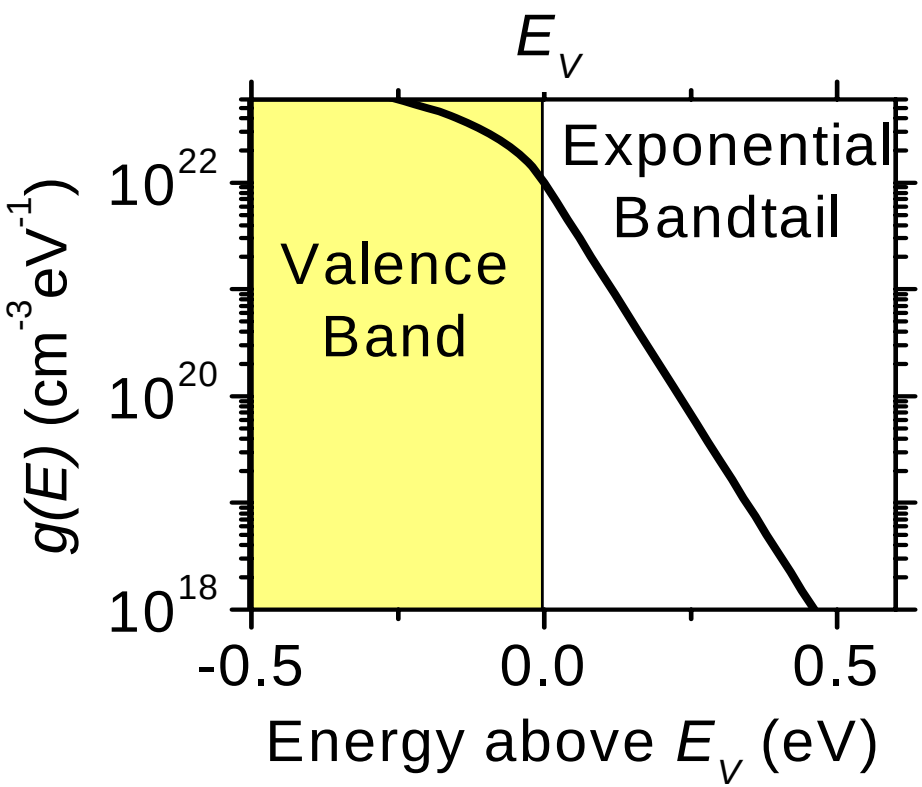
E. A. Schiff, *J. Non-Cryst. Solids*, *in press* (ICANS 2005).

Hole Drift-Mobilities in Disordered Silicons



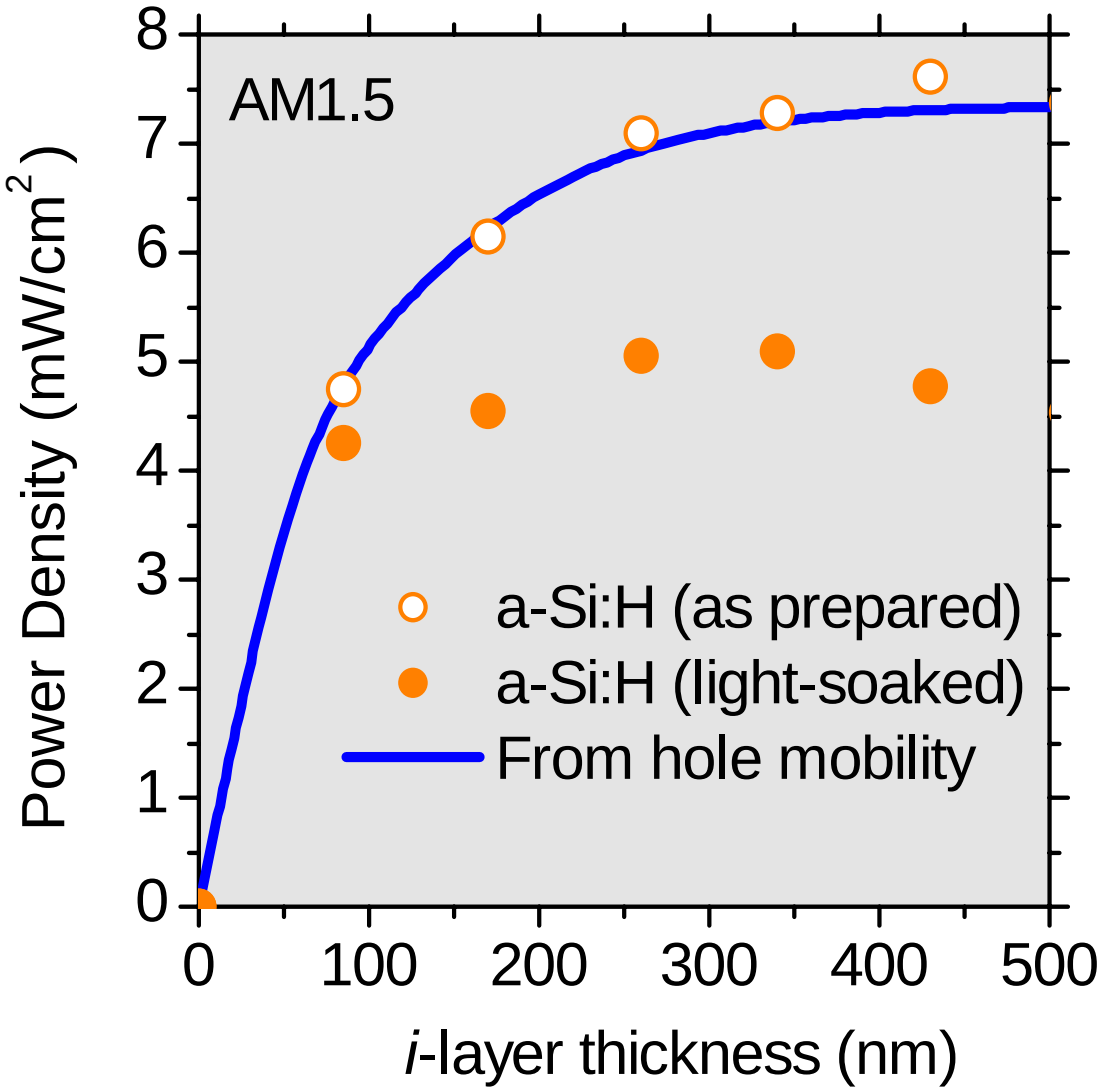
E. A. Schiff, *J. Non-Cryst. Solids*, *in press* (ICANS 2005).
nc-Si:H - T. Dylla, F. Finger, and E. A. Schiff, *Appl. Phys. Lett.* **87**, 032103 (2005) [.pdf].
E. A. Schiff, *J. Phys.: Condens. Matter* **16**, S5265-5275 (2004) [.pdf].

Bandtail Multiple-Trapping Model for Hole Drift Mobility



Bandtail Parameters	
ΔE_V	Valence Bandtail Width
μ_h	Hole Band Mobility
$N_V b_T$	Attempt Frequency

Power Density in (simple) United Solar Ovonic Cells

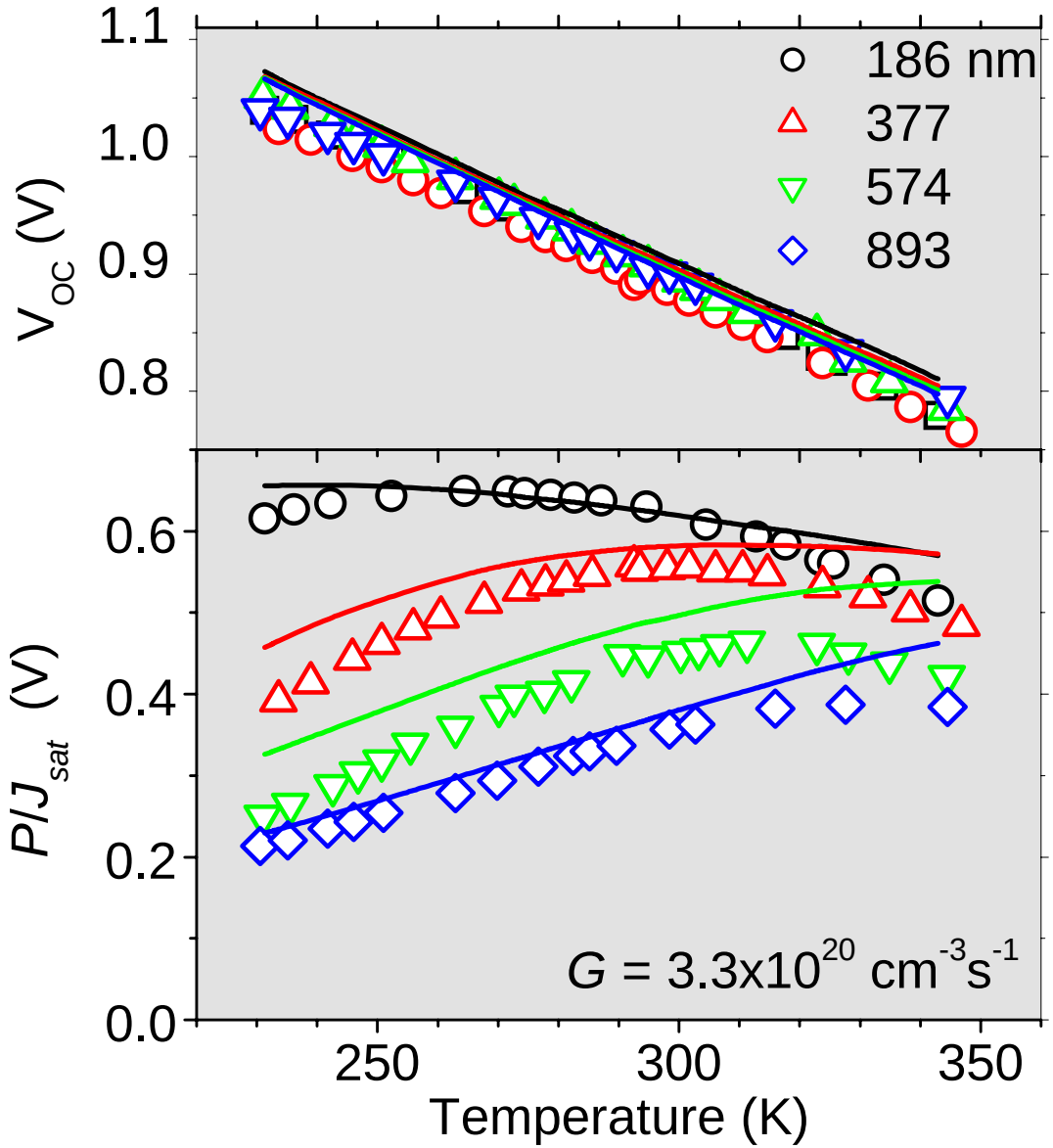


Model Parameters	
μ_p	0.3 cm^2/Vs
ΔE_v	0.040 eV
N_v, N_C	4×10^{20} cm^{-3}
b_T	1.3×10^{-9} cm^{3}s^{-1}
E_g	1.74 eV
b_R	1.0×10^{-9} cm^{3}s^{-1}
No defects. Ideal *p,n*. Other parameters are less important	

http://physics.syr.edu/~schiff/AMPS/

K. Zhu, *et al.*, in *Amorphous and Nanocrystalline Silicon Based Films – 2003*, edited by J.R. Abelson, *et al.* (Materials Research Society Symp. Proc. Vol. 762, Pittsburgh, 2003), pp. 297--302.[.pdf]

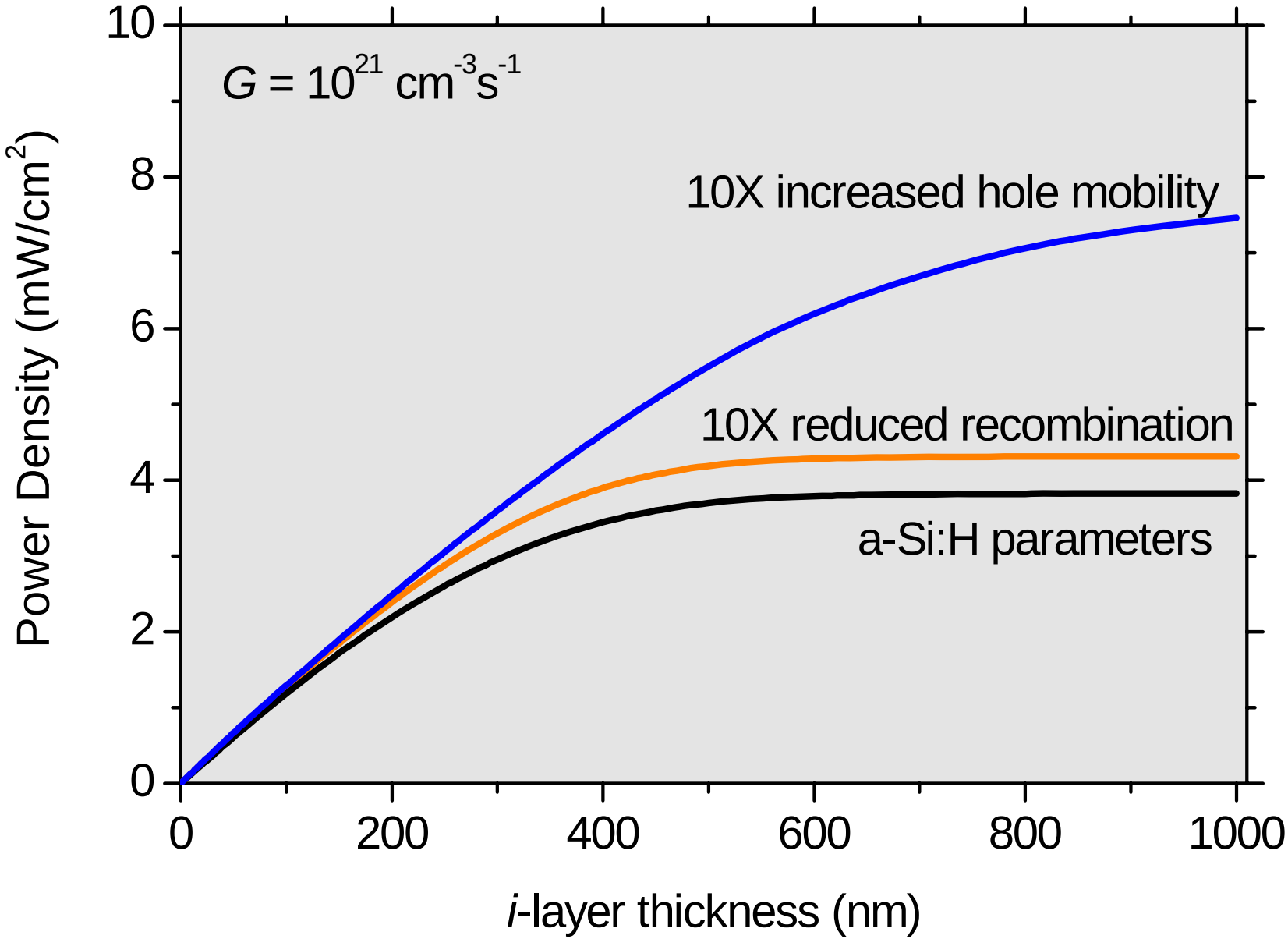
Power Density vs. Temperature, Uniform Generation: A Better Test for Mobility Limitation



Model Parameters	
μ_p	0.3 cm^2/Vs
ΔE_v	0.040 eV
N_v, N_C	4×10^{20} cm^{-3}
b_T	1.3×10^{-9} cm^{3}s^{-1}
E_g	1.74 eV
b_R	1.0×10^{-9} cm^{3}s^{-1}

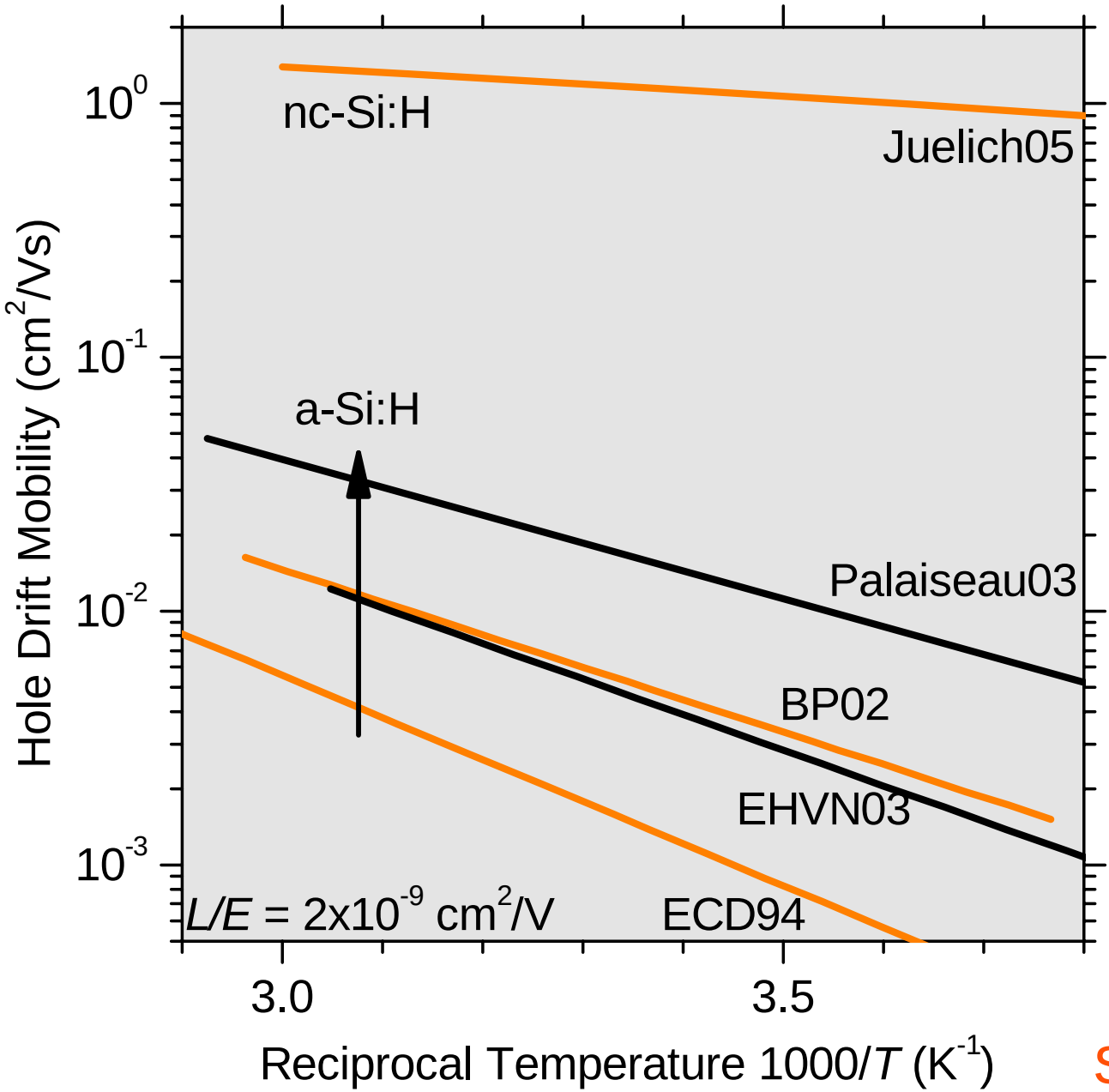
L. Jiang, E. A. Schiff, S. Guha, B. Yan, and J. Yang, manuscript under review.

What if – hole mobility increases?



E. A. Schiff, unpublished

Hole Drift-Mobilities in Disordered Silicons



Nanocrystalline and Crystalline Si Cells

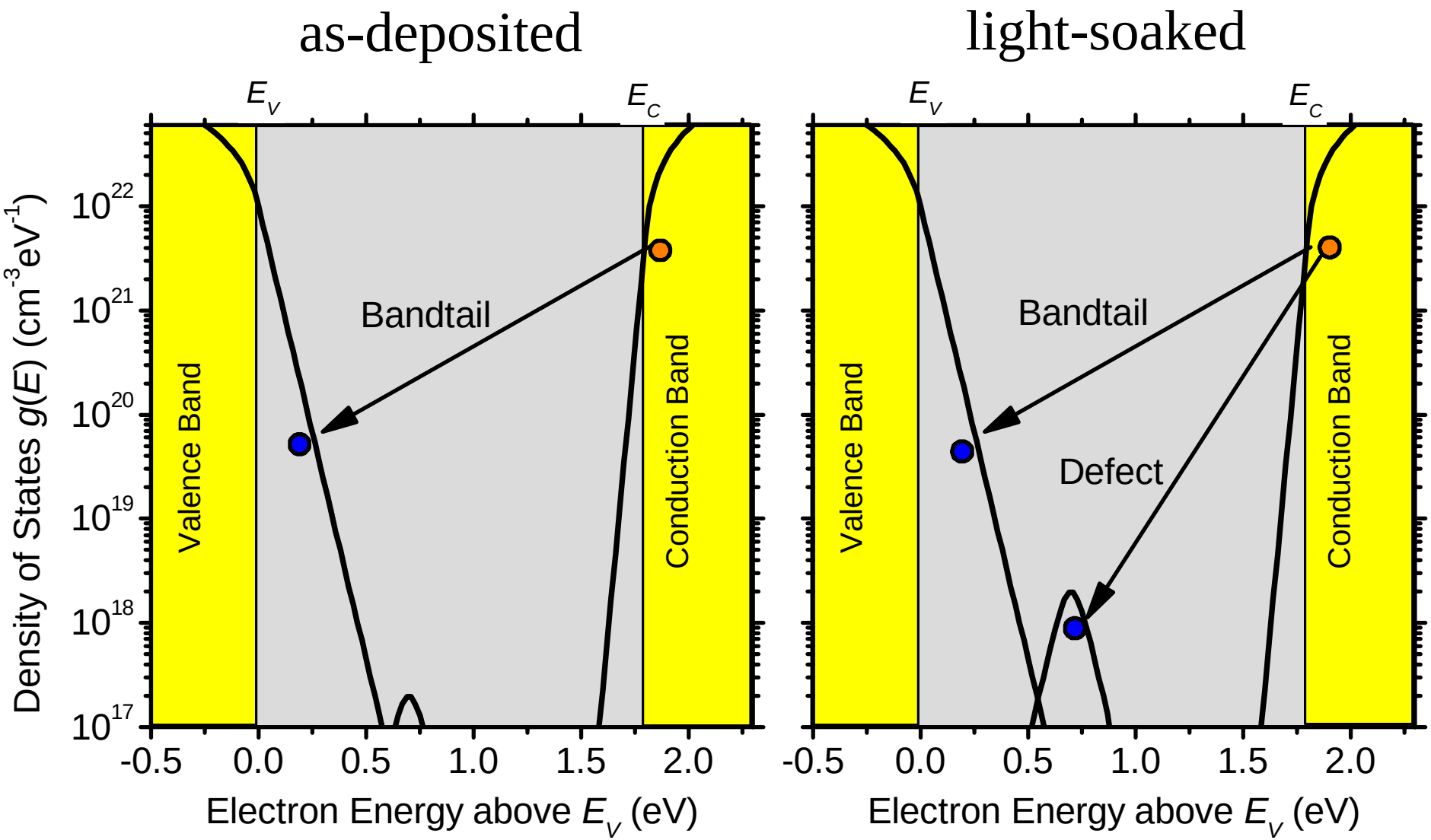
- nc-Si:H absorbers are typically a "few" microns thick, but crystalline silicon absorbers can be 100's of microns thick. Why the large difference?
- Low-mobility expression for optimum absorber thickness:[1]

$$L_{drift} = \left((2/3)V_{OC}\right)^{1/2}\left(\mu_h \varepsilon / eG\right)^{1/4}$$

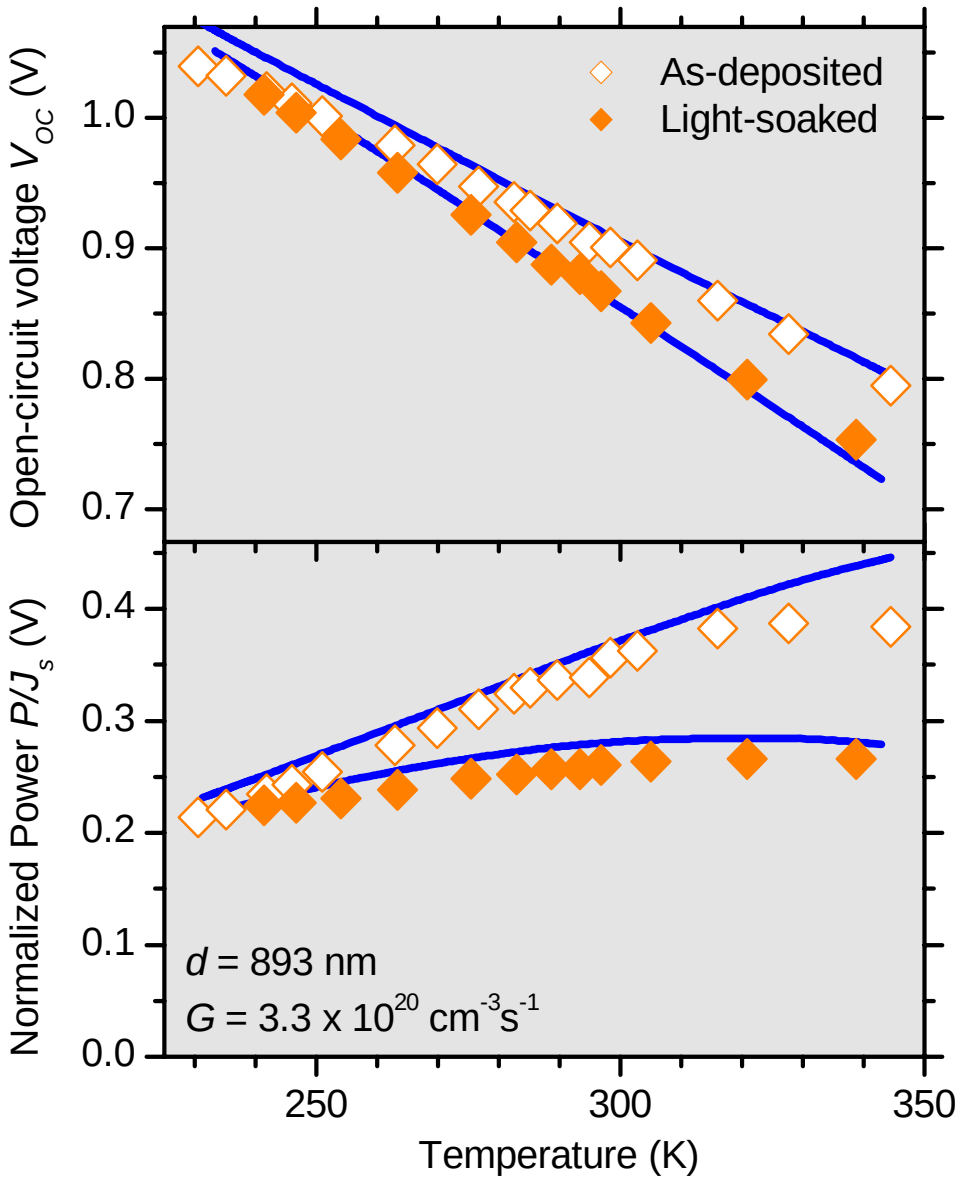
- Evaluating for a mobility of $\mu_h \approx 1$ cm^2/Vs in nc-Si:H, L_{drift} for the nc-Si:H absorber is about 2 μm.[2]
  - Agrees pretty well with device makers' experience
  - nc-Si:H absorbers are close to mobility-limitation.

[1]E. A. Schiff, *Solar Cells and Solar Energy Materials* **78**, 567-595 (2003).[.pdf]
[2]Used V_{OC} = 0.6 V, G = 5x10^{20} cm^{-3}s^{-1}.

Recombination & Light-Soaking



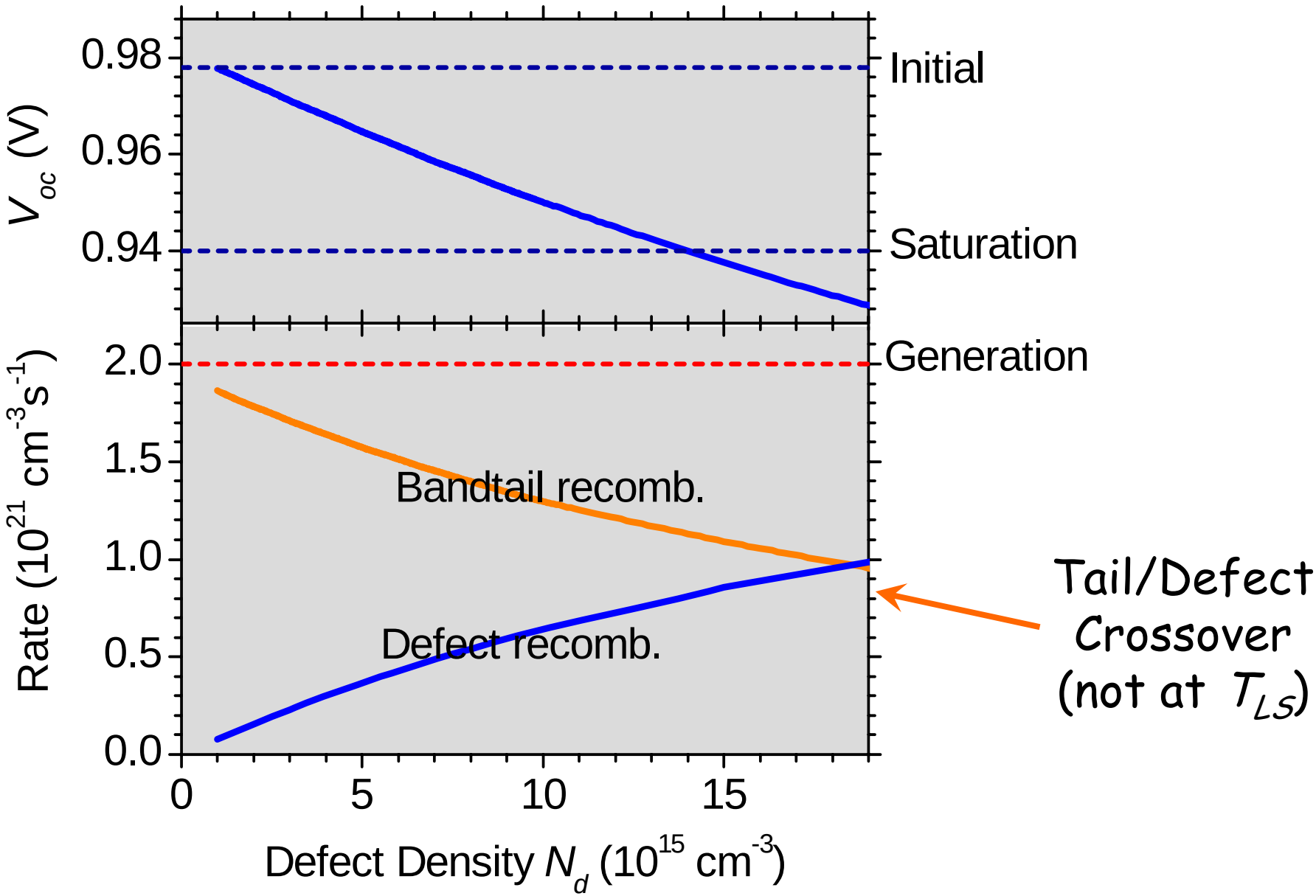
United Solar Ovonic Cells: Temperature Effects



- United Solar Ovonic cells
  - 685 nm laser illumination
- Lines are computer calculations
  - As-deposited: only bandtails significant
  - Light-soaked: bandtail+defect
  - Defect density about $2x10^{16}$ cm^{-3}
  - Defect parameter values from Street's deep-trapping measurements

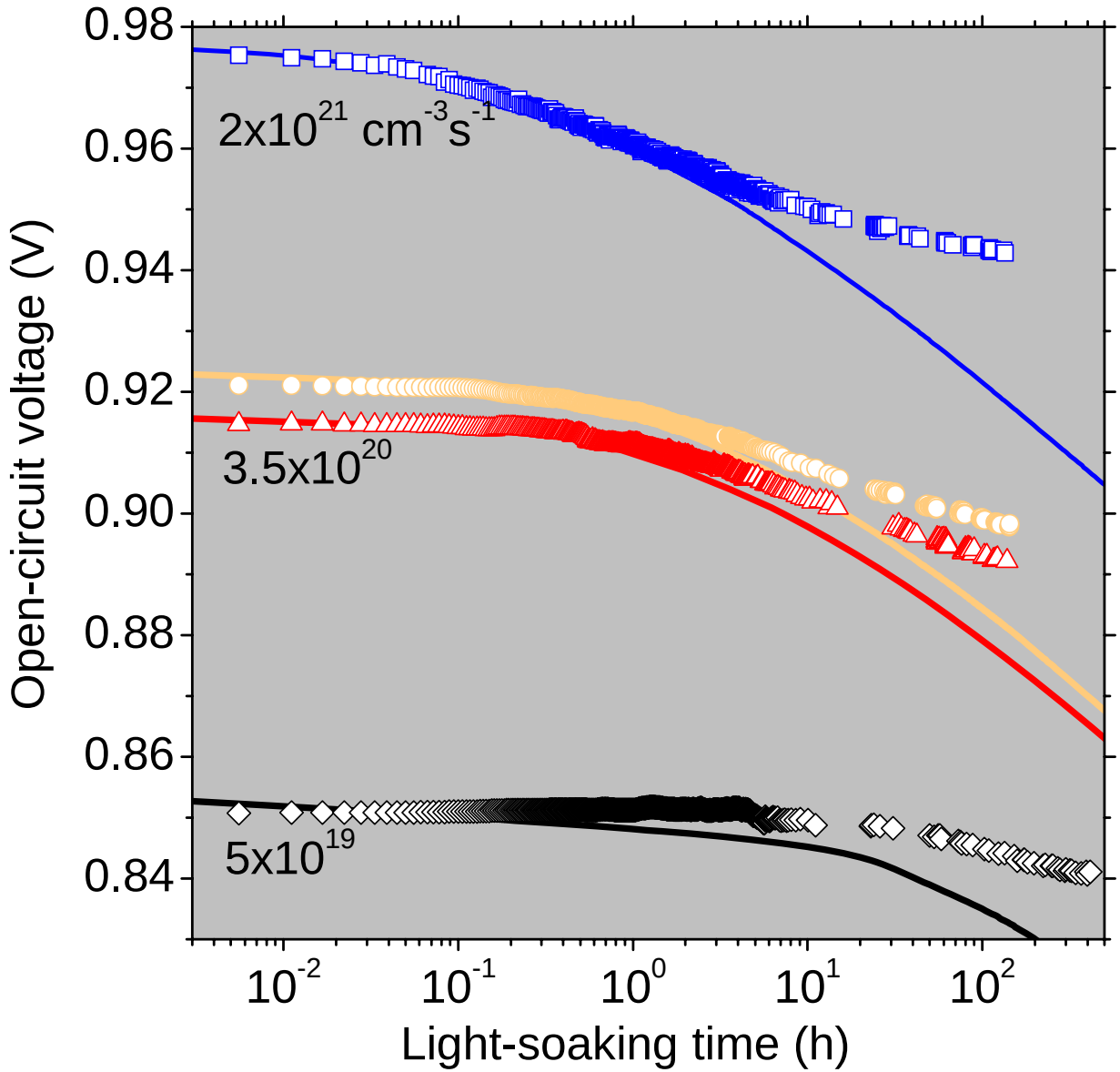
J. Liang, et al., in *Amorphous and Nanocrystalline Silicon Science and Technology – 2005*, edited by R. Collins, et al. (Materials Research Society Symp.Proc. Vol. 862, Pittsburgh, 2005), A21.8 [.pdf]. .

Light-Soaking & Bandtail+Defect Model



L. Jiang and E. A. Schiff, unpublished.

Measured Light-soaking Kinetics of V_{OC}



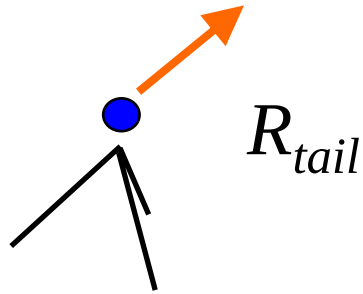
- United Solar Ovonic cells
- 893 nm thick
- Uniform laser absorption
- 4 cells

J. Liang, et al., in *Amorphous and Nanocrystalline Silicon Science and Technology – 2005*, edited by R. Collins, et al. (Materials Research Society Symp.Proc. Vol. 862, Pittsburgh, 2005), A13.6 [.pdf].

Models for Kinetics for $N_D(t)$

H-collision (modified)[1,2]

$$\frac{dN_d}{dt} \propto H_m^2 = C_{SW}\left(\frac{R_{tail}}{N_d}\right)^2$$



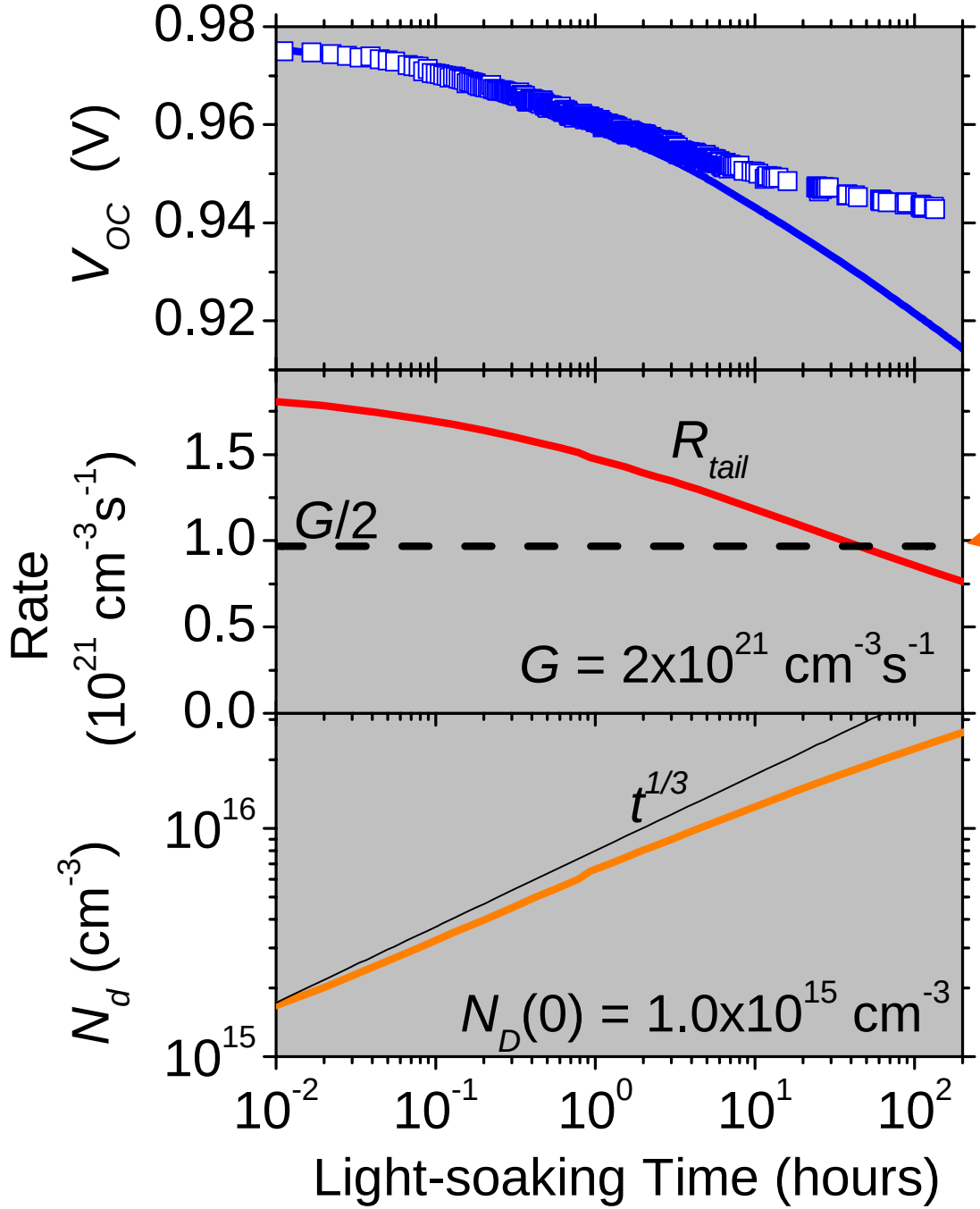
SJT[3]

$$\frac{dN_d}{dt} = A_{SW} R_{tail}$$

Doesn't account for kinetics of these cells

[1]H. M. Branz, *Phys. Rev. B* **59**, 5948 (1999).
[2]J. Liang, et al., in *Amorphous and Nanocrystalline Silicon Science and Technology – 2005*, edited by R. Collins, (Materials Research Soc. Symp. Proc. Vol. 862, Pittsburgh, 2005), A13.6 [.pdf].
[3]M. Stutzmann, W. B. Jackson, C.-C. Tsai, *Phys. Rev. B* (1985)

H-Collision Calculations: V_{OC} Decline & Recombination Crossover

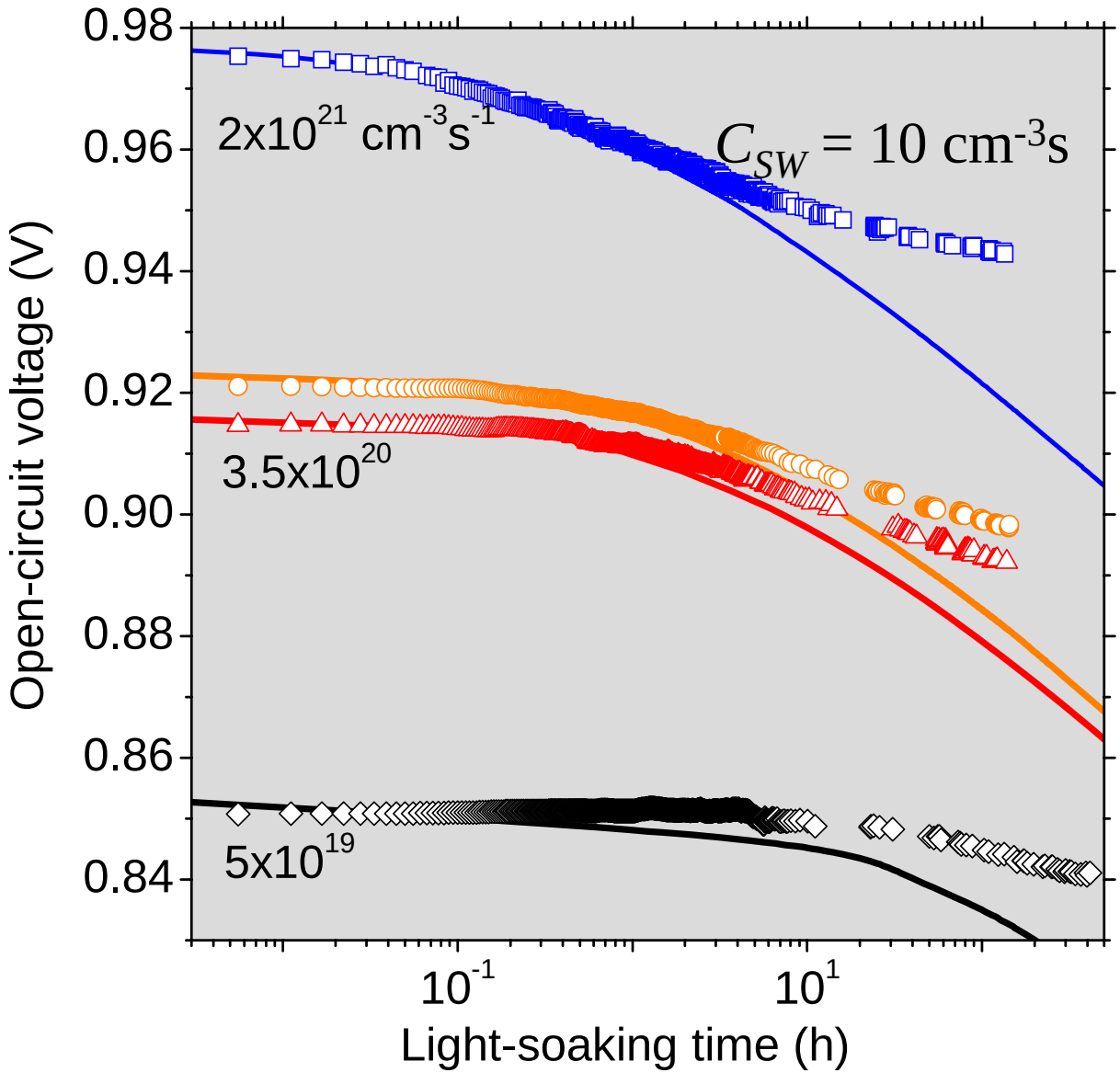


Tail/defect Crossover

$C_{SW} = 10$ cm^{-3}s

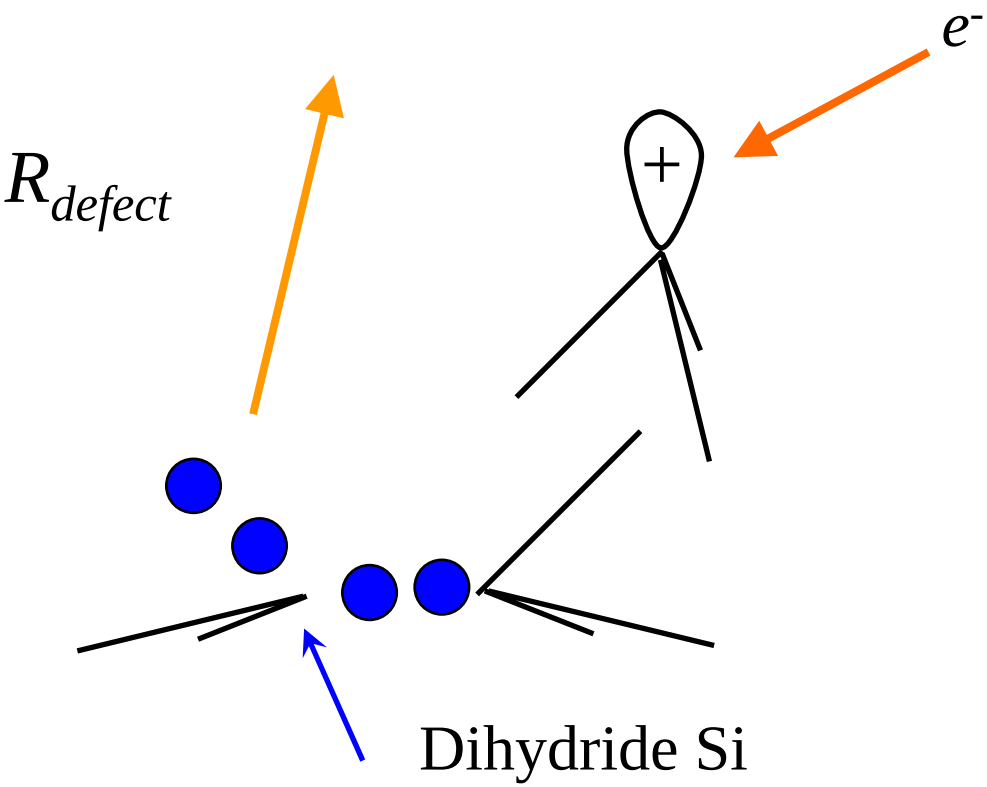
L. Jiang and E. A. Schiff, unpublished.

H-collision Predictions for $V_{OC}(t)$



J. Liang, et al., in *Amorphous and Nanocrystalline Silicon Science and Technology – 2005*, edited by R. Collins, (Materials Research Society Symp. Proc. Vol. 862, Pittsburgh, 2005), A13.6 [.pdf].

Speculation: Light-Soaking is Self Limiting



- Puzzle: Why does light-soaking degrade V_{OC} and P_{max} so *little*?
- Speculation: recombination through defects releases H, and anneals defects.

$$\frac{dN_D}{dt} \approx C_{SW}\left(\frac{R_{tail}}{N_D}\right)^2 - D_{LIA}R_D\left(N_D/2\right)$$

Open Questions & Future Pathways

- Higher power a-Si:H, nc-Si:H cells require better holes
  - Necessary, but not sufficient.
  - Will higher mobility, "polymorphous" materials yield higher efficiency cells?
  - Are a-SiGe cells also mobility-limited?
- Light-soaking of United Solar Ovonic's material appears to be "self-limiting."
  - Surprising in the context of some thin-film studies on older materials.
  - How did that happen? Will higher mobility cells still have good light-soaking properties?