Modeling Approaches for CIGS and CdTe Solar Cells: Focus on Uniformity

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With help from a large number of students, especially Galym Koishiyev

Financial Support from NREL, NSF, and DOE

Advantages and Problems for CIGS and CdTe

ADVANTAGES:

(1) Fabrication of large areas is relatively inexpensive (technology similar to optical coatings on glass).

(2) Materials utilization much smaller when dealing with micron thicknesses.

(3) Energy pay-back time is low (less than one year).

(4) Entire structures can be deposited on flexible, low-weight substrates.

(5) High tolerance to additional defects and impurities.

PROBLEMS:

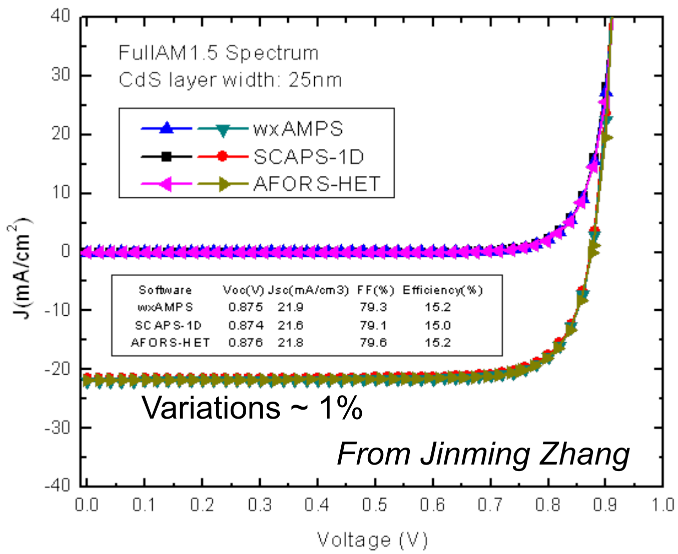
(a) Thin-film cells are generally composed of heterojunctions which may have band offsets and interfacial states.

(b) Thin-film thickness and composition may not be uniform.

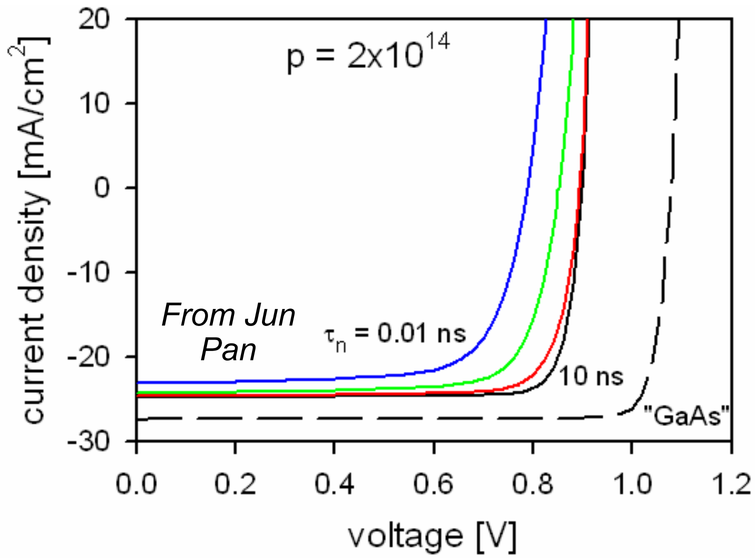
(c) Grain boundaries are potential recombination sites and diffusion paths.

(d) Thin-films tend to have compensating donor and acceptor levels and hence lower carrier densities.

Approach (1): Numerical Simulation



Three software packages

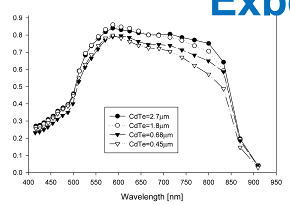


Variation with recombination lifetime

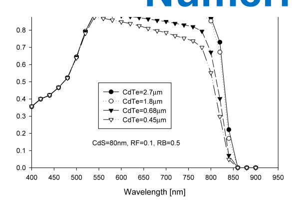
Experimental Data

Numerical Simulation

QE as a function of absorber thickness



From Univ. Toledo



From Jun Pan

Simulation reproduces general features, but not the details.

Approach (2): The Diode Equation

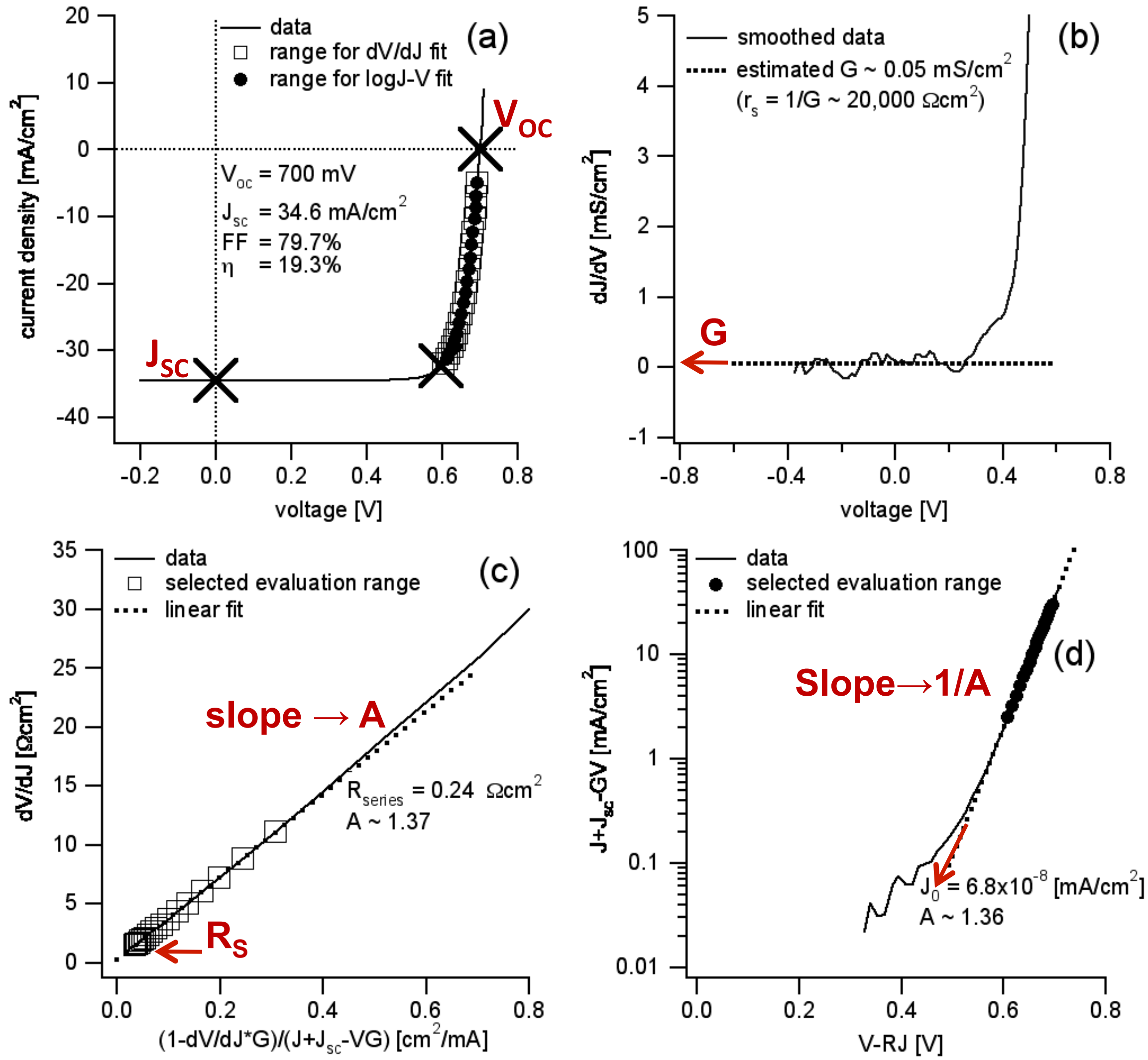
CurVA
by Markus Gloeckler
[*based on Hegedus and Shafarman, Prog. in PV* ***12***, *155, (2004)]*

Applied here to high-efficiency CIGS cell

Assumes $J = J_0 \exp[q(V-JR)/AkT] + GV - J_L$

(1) Plot data four ways
(2) Select data to fit
(3) Adjust fit with sliders
(4) Fitting parameters appear on screen

Note: (c) linearizes the diode equation above:
$dV/dJ = R + AkT/(J+J_L)$
when G = 0



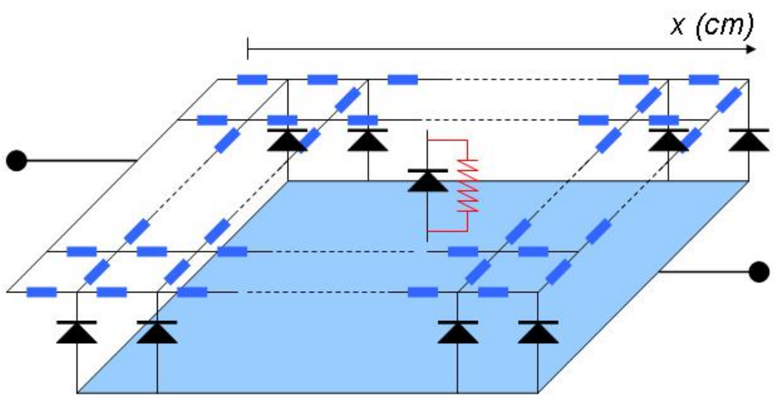
Approach (3): Circuit Modeling

(3a) Distributed Series Resistance

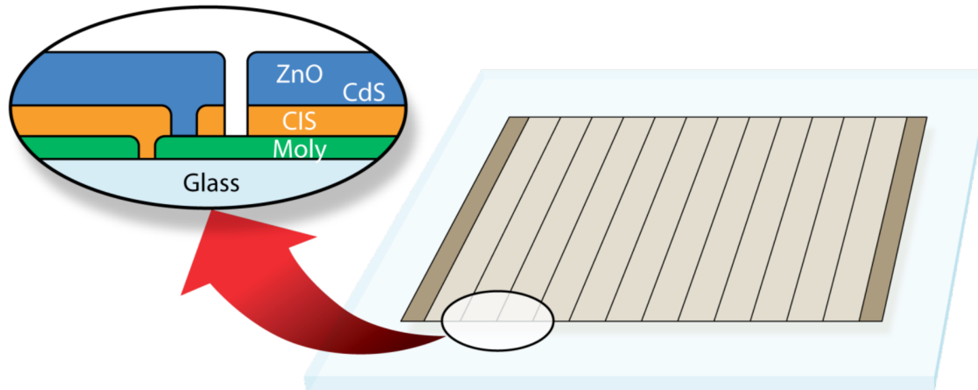
Circuit Equivalent

(light source not shown)

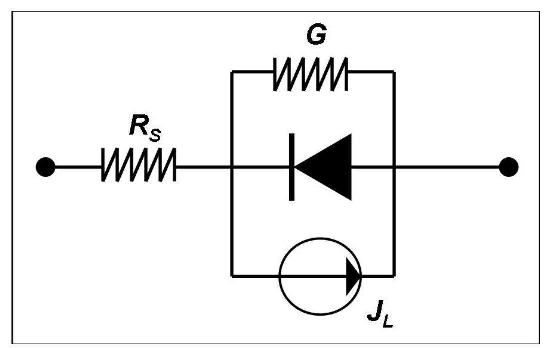
Note: voltage across cell may not be uniform.



Pspice™ works well for analysis
Single alteration to circuit element:
(will return to the shunt)

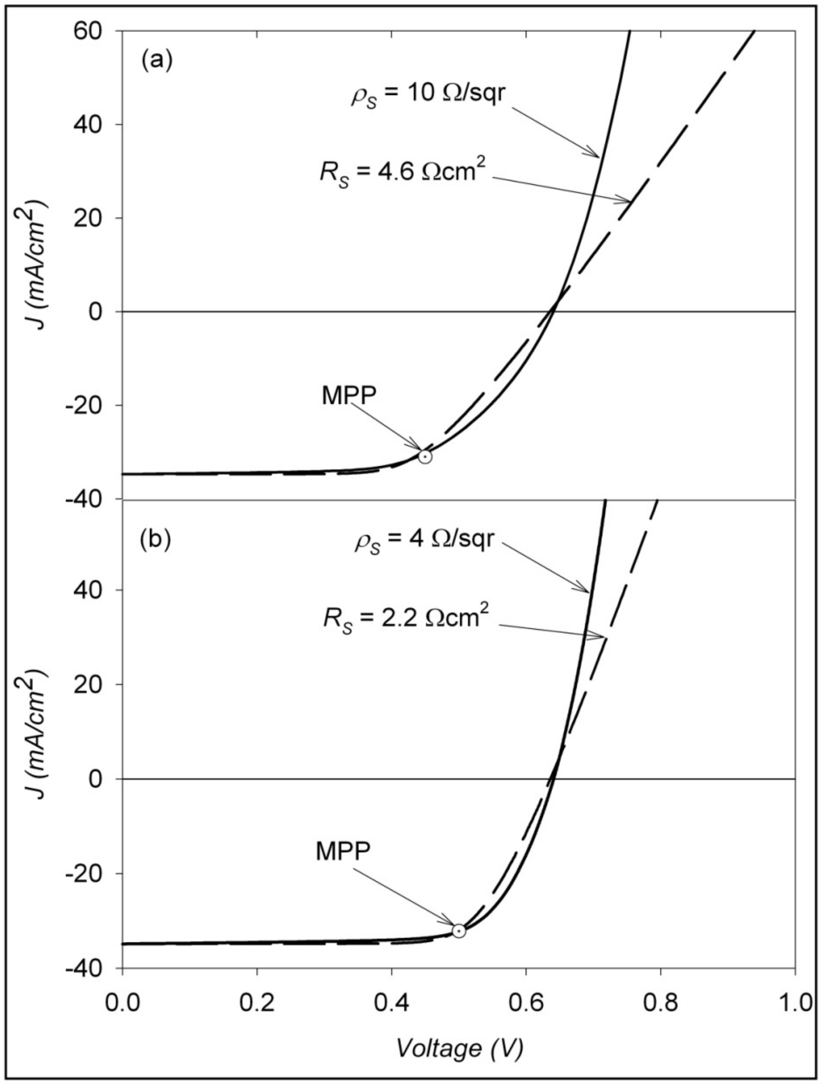


Monolithic integration without grids implies large series resistance



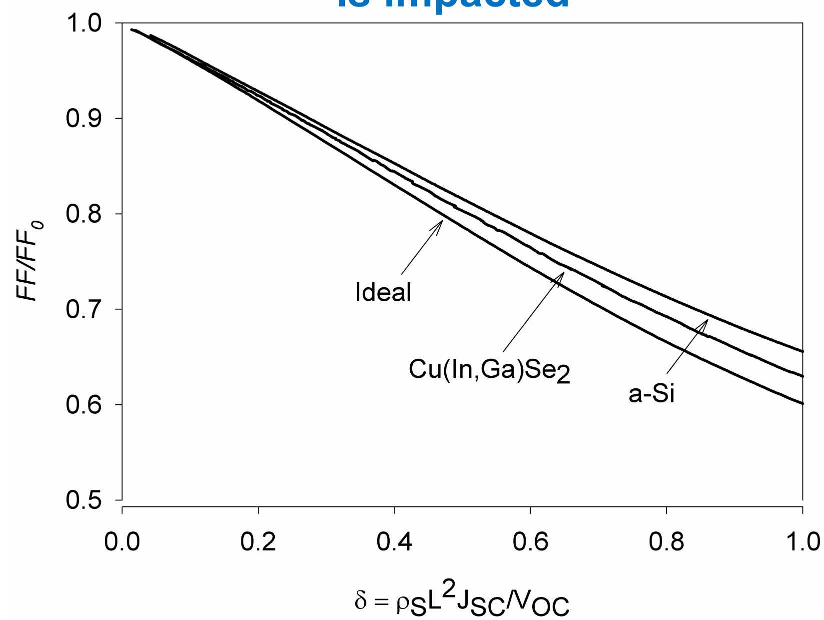
Lumped series resistance approximation likely to fail

Distributed Series Resistance



Big difference between distributed and lumped series resistance

Approximate universal relationship of how fill-factor is impacted



Koishiyev and Sites, SOLMAT 93, 350 (2009)

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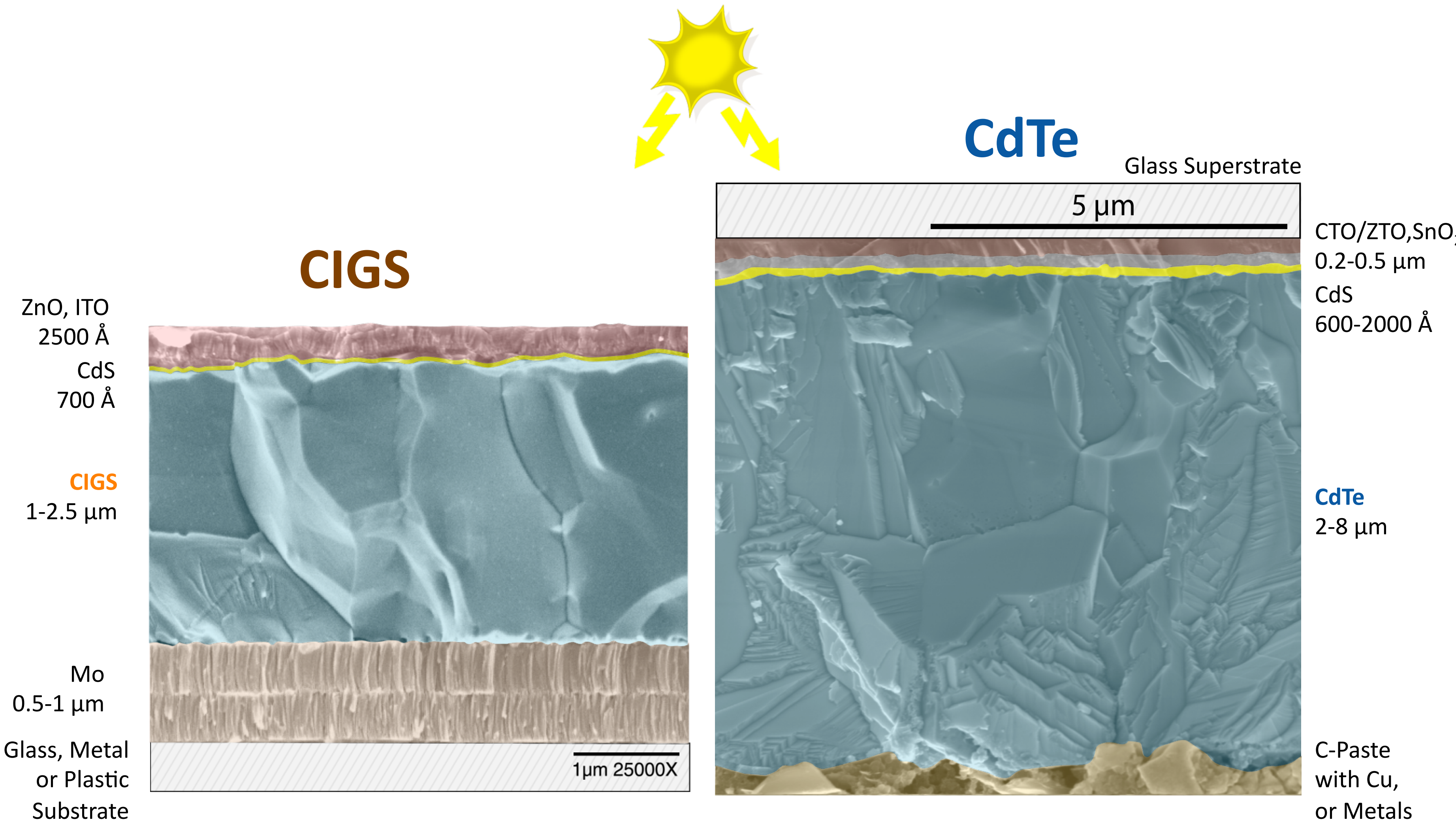
CIGS and CdTe Device Structure (Light Above)

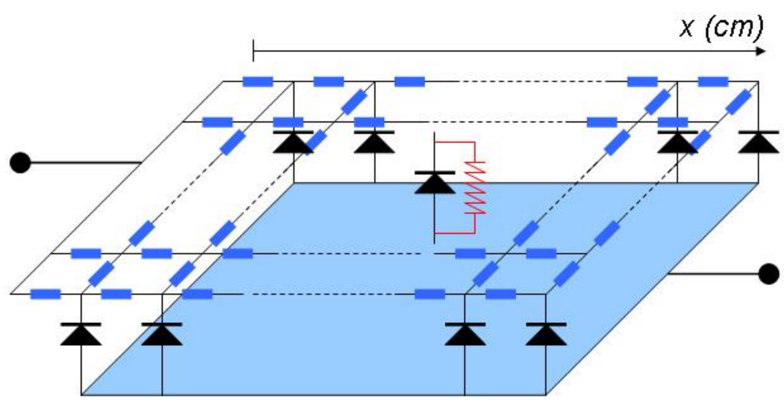


Similar crystallite sizes and shapes; color artificial

Slide from R. Noufi (NREL)

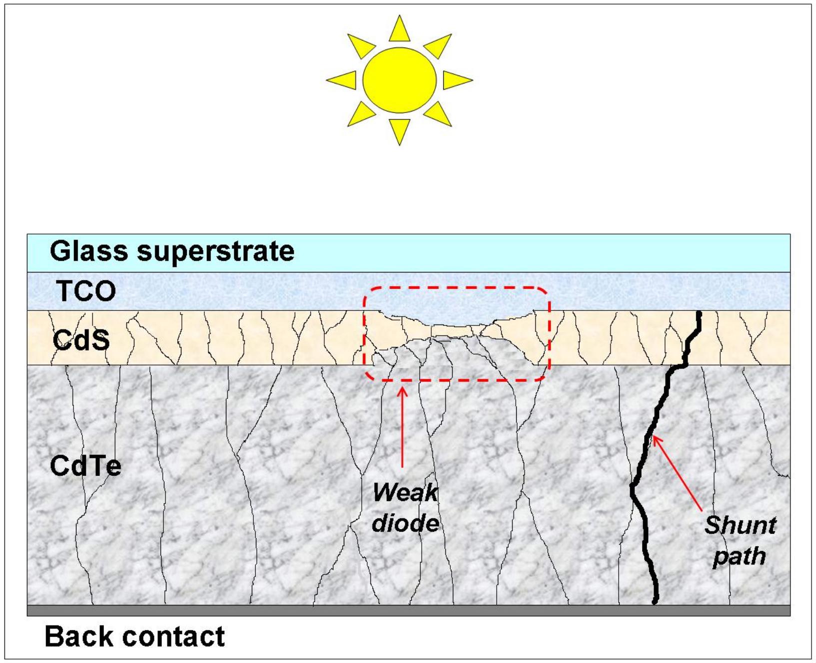
(3b) Circuit Modeling of Non-Uniforities

Circuit Equivalent



Single alteration to circuit element:
Shunt shown, could be a weak diode

Physical Picture

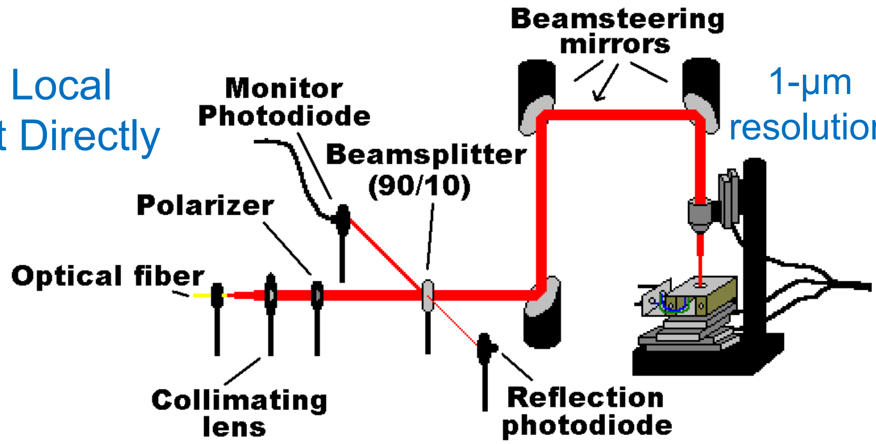


From G. Koishiyev

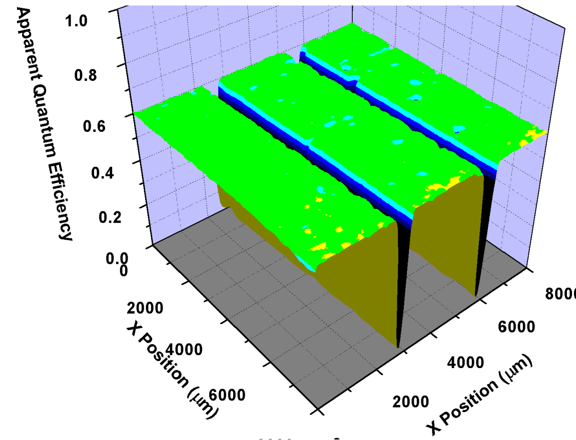
Experimental Uniformity Tools

Light-beam-induced current (LBIC)

Measures Local Photocurrent Directly



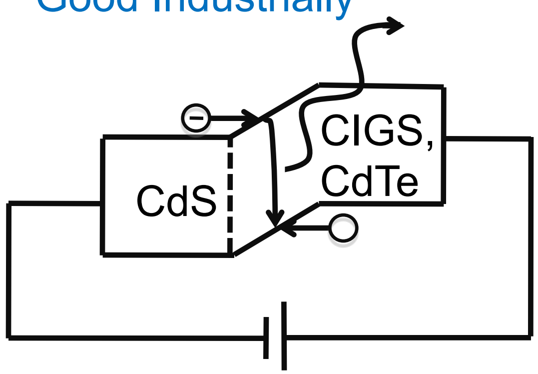
1-µm resolution

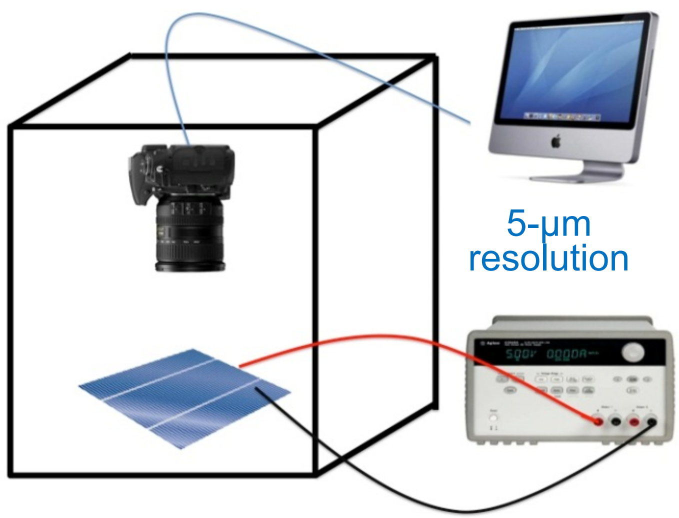


LBIC from CIGS cell

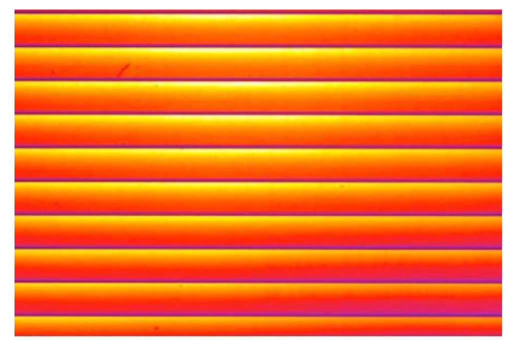
Electroluminescence (EL)

Very Fast; Good Industrially





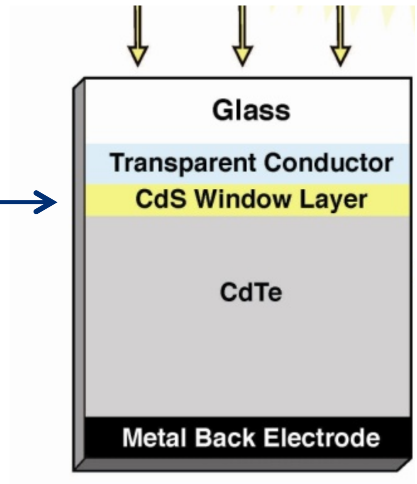
5-µm resolution

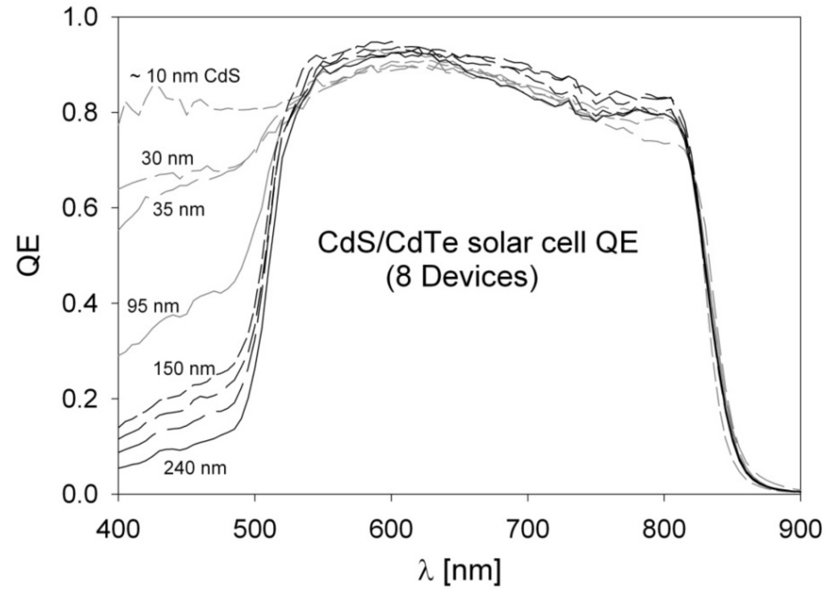


EL from CdTe module

Window Layer Uniformity

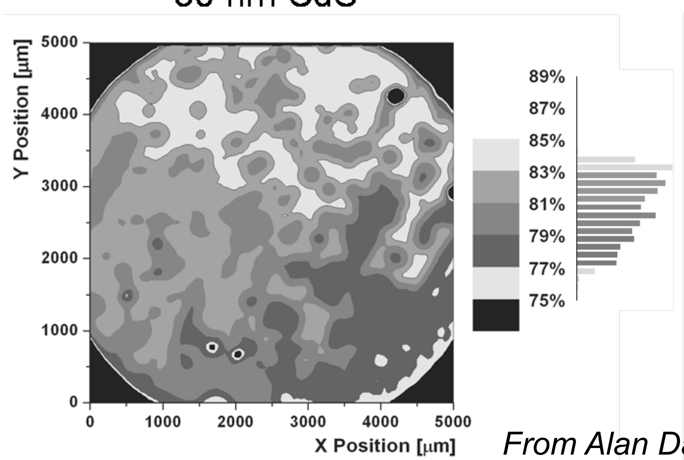
Vary Thickness



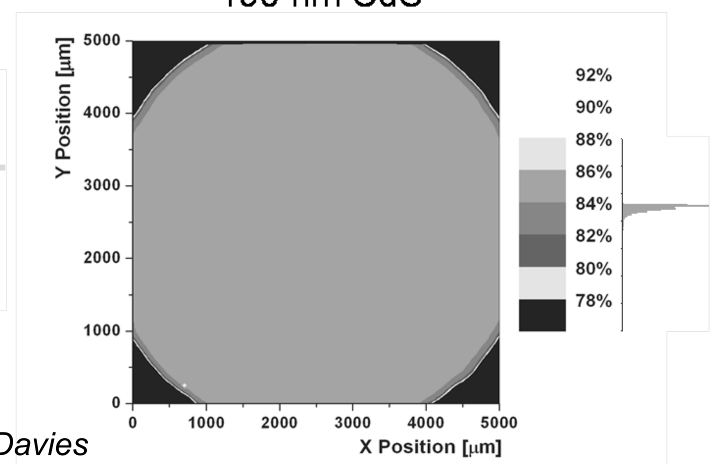


Low-Resolution LBIC

30 nm CdS

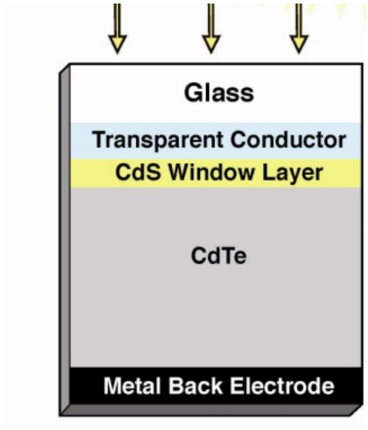


190 nm CdS

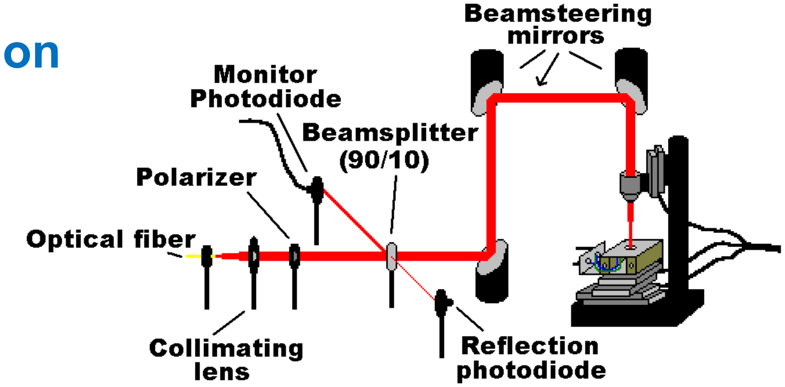


From Alan Davies

Small LBIC Defect



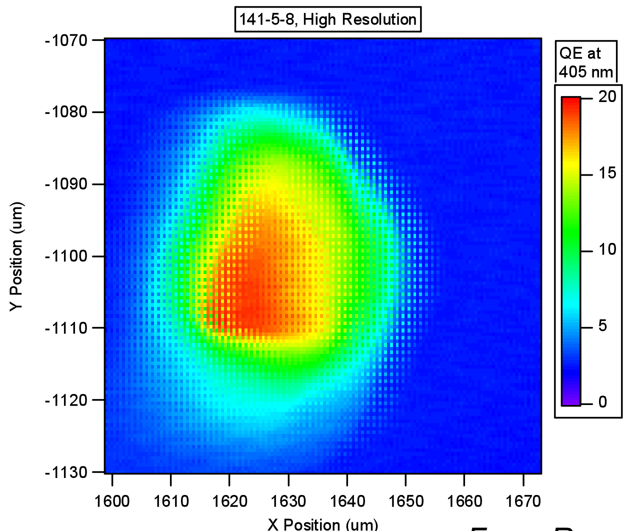
High-Resolution LBIC

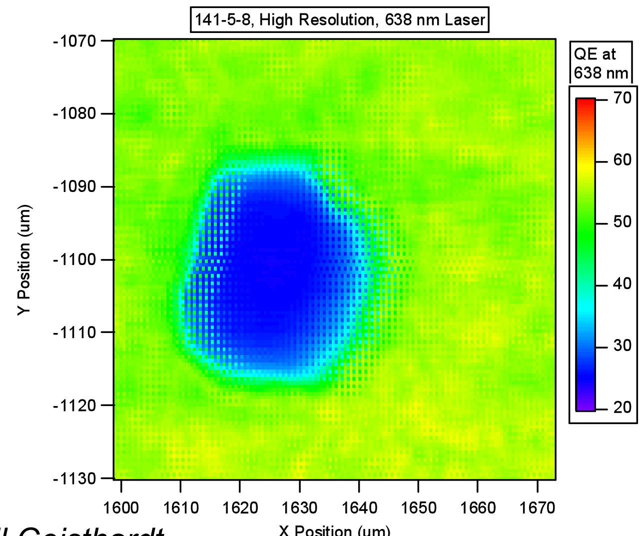


$E_{photon} > E_g(CdS)$

$E_{photon} < E_g(CdS)$

Feature size ~ 20 µm

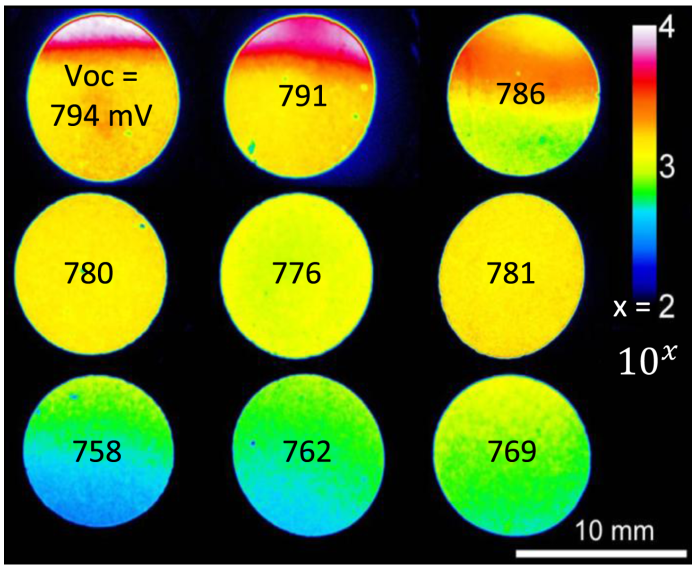


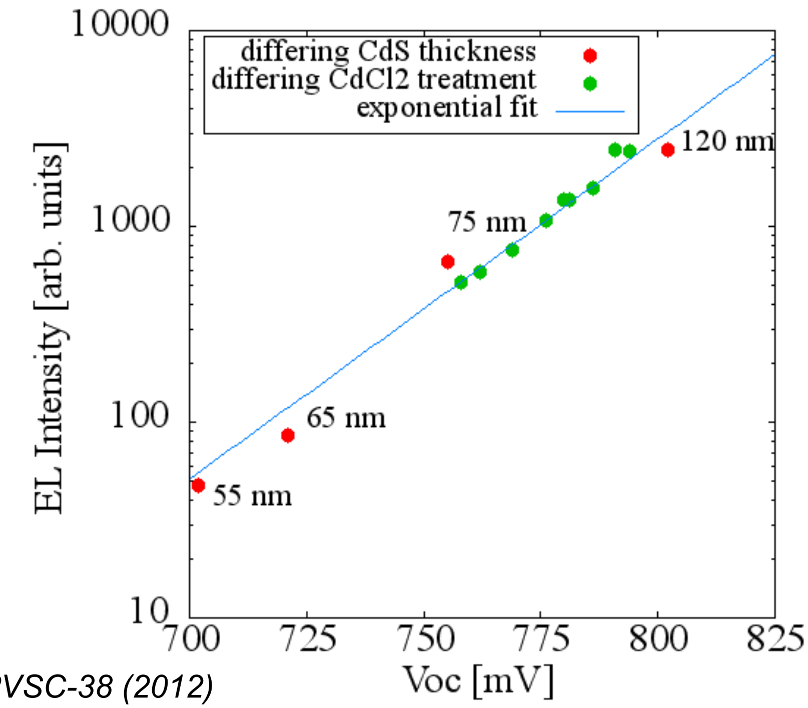


From Russell Geisthardt

EL Variations with Open-Circuit Voltage

Nine CdTe cells on same substrate with varying voltage and EL response (non-uniform $CdCl_2$ responsible)



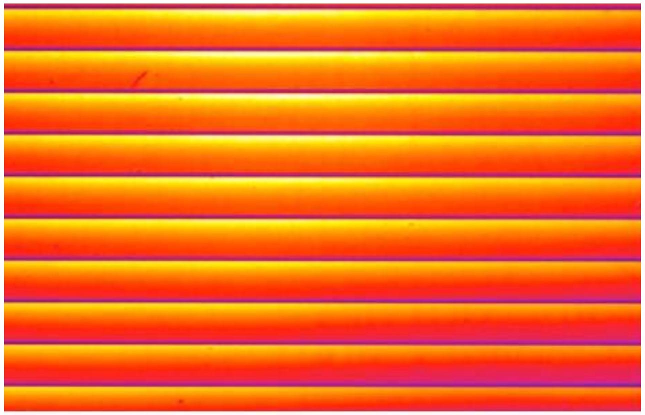


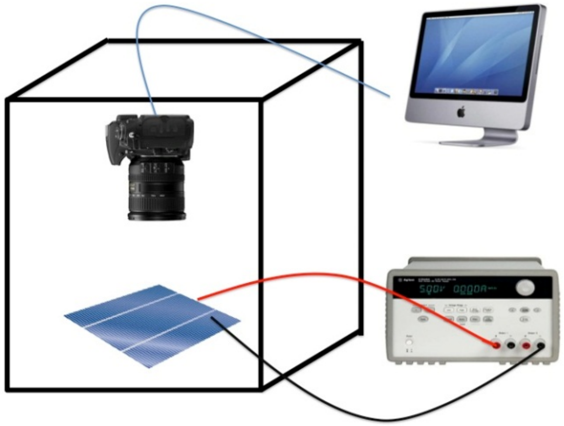
Raguse et al, PVSC-38 (2012)

Well-behaved relation between voltage and EL response

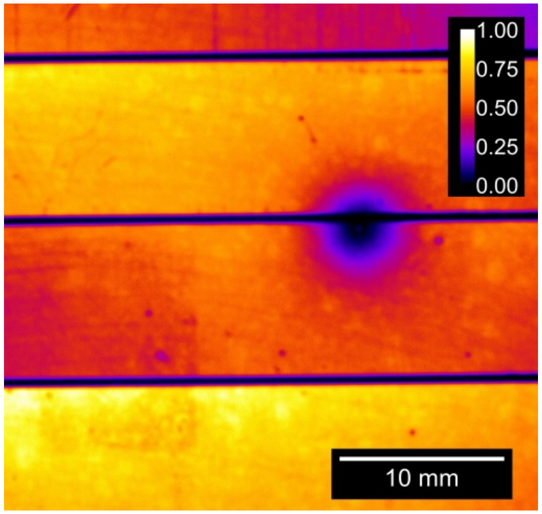
EL: Two Types of Shunt

Module from before



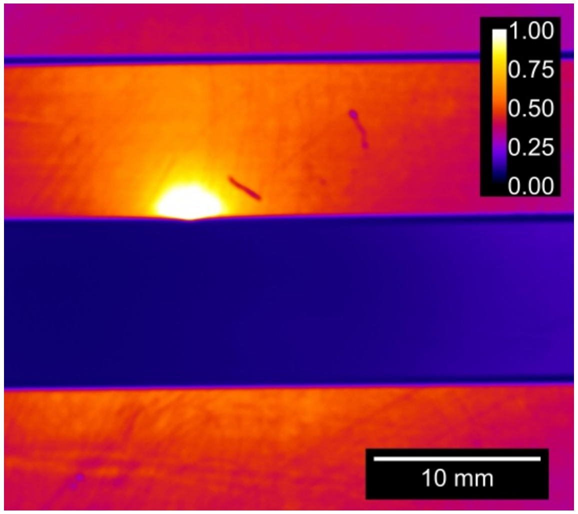


Shunt in the lower cell



Diameter of affected area ~ 3 mm

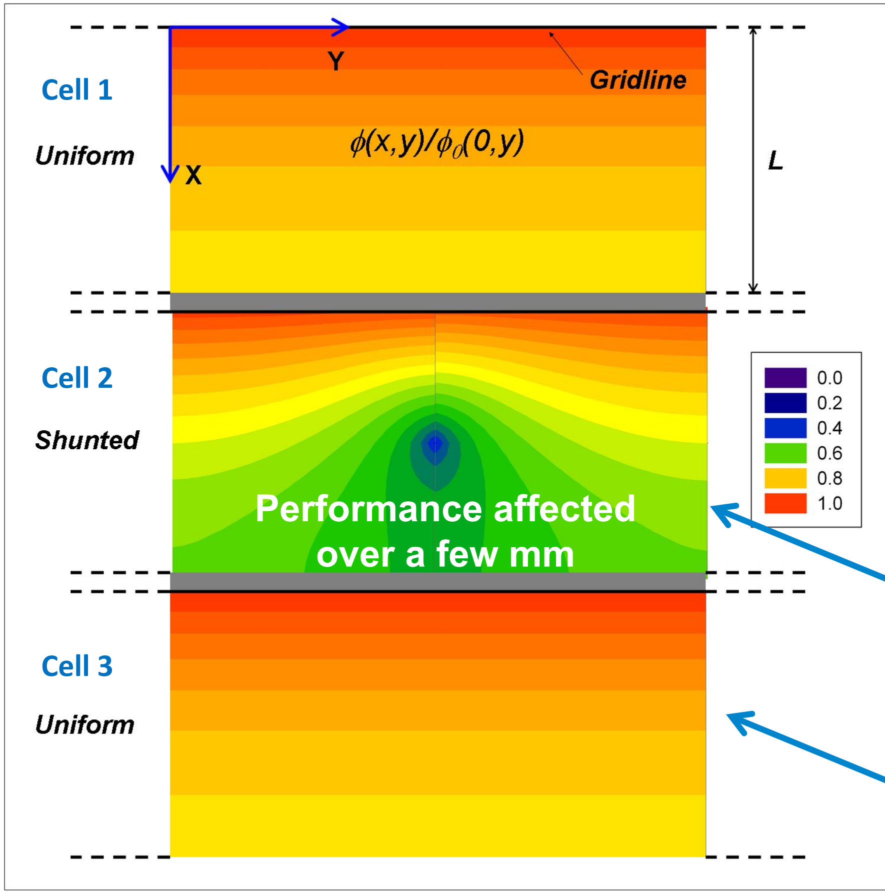
Shunt between two cells



Lower-cell current transferred to upper cell

Raguse et al, PVSC-38 (2012)

Shunt Effect Using Circuit Modeling



PSpice simulation by Galym Koishiyev

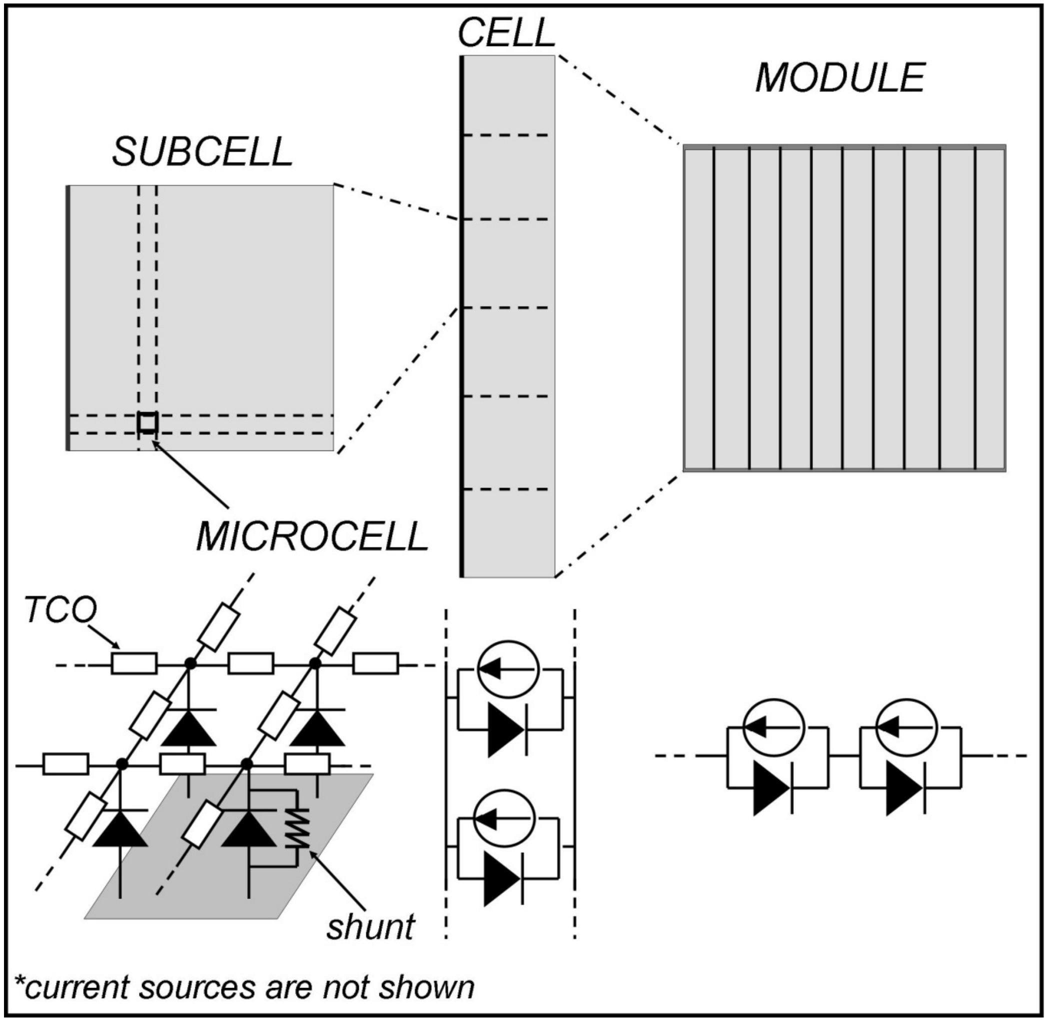
Shunts can be distinguished from dust or weak diode areas

Impacted area (about 3 mm here also) depends on TCO sheet resistance

Reduced voltage from shunt superimposed on background

No shunt: voltage drop across cell.

Extension to Multiple Shunts



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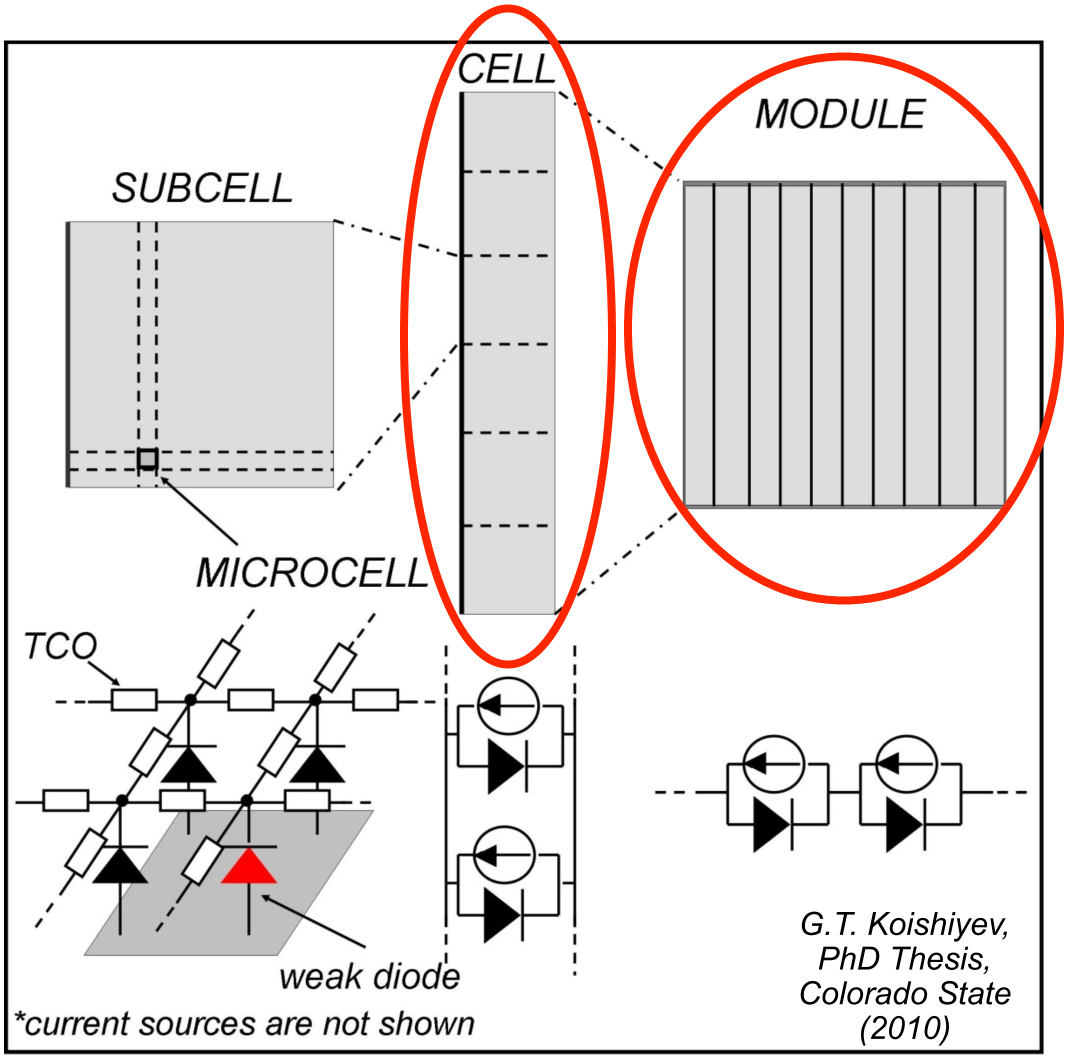
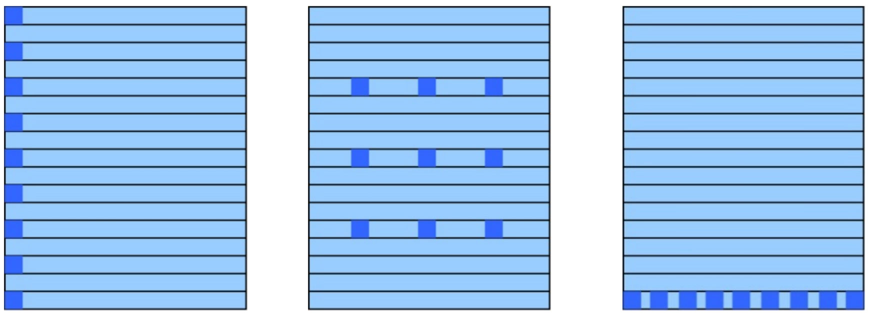


(1)Now combine subcells, some fraction of which are non-uniform, but most of which are uniform, into cells (1-D, parallel)
(2)Then combine cells into a module (1-D, series)

Distribution of Shunts in a Module



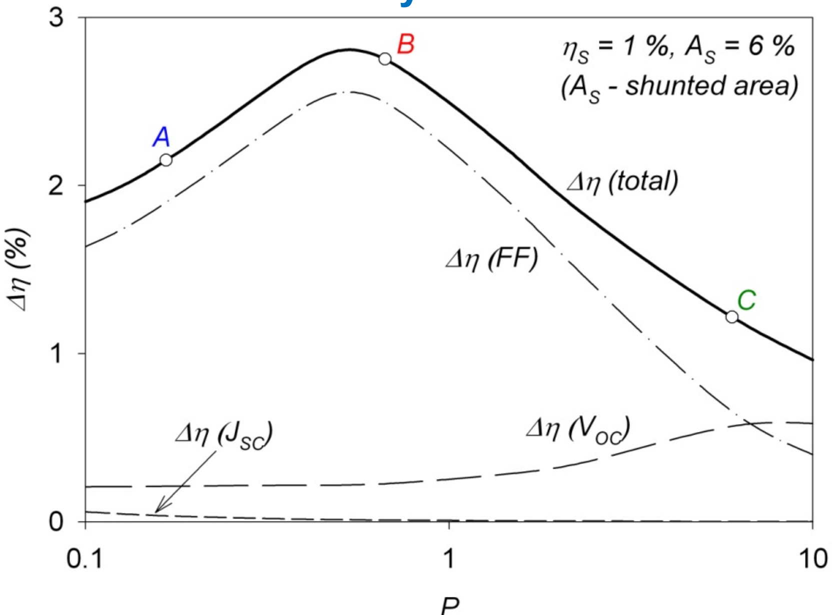
A B C

A – Shunts spread over many cells

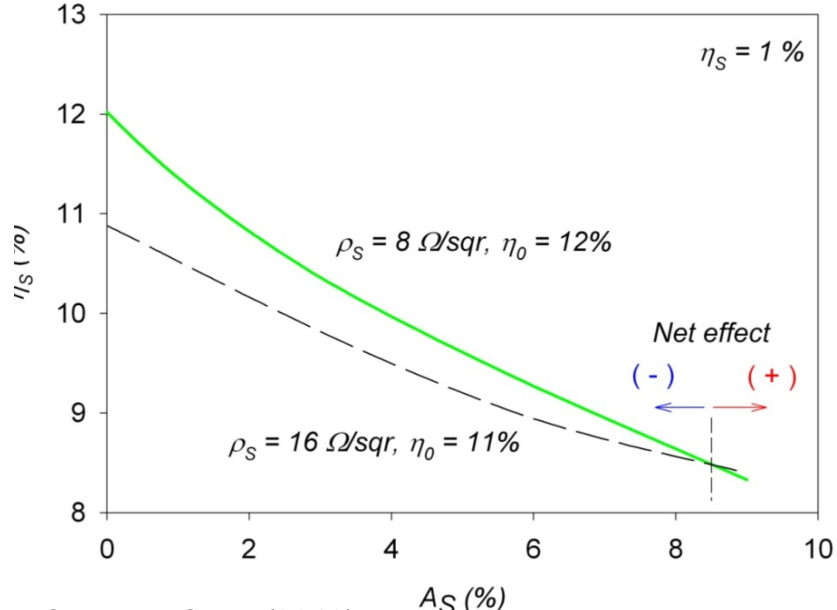
B – Intermediate

C – Shunts in one or two cells preferred for shunts (or weak diodes)

Shunts mainly affect fill-factor



Shunts mitigated by higher TCO sheet resistance



G.T. Koishiyev. PhD Thesis, Colorado State (2010)

Summary

(1) Several different types of PV modeling; each has value for specific types of problems.

(2) Uniformity modeling is particularly important for CIGS and CdTe, BUT analysis is relatively immature.

(3) Always helpful to have direct comparisons with experimental data, and if at all possible give credible physical interpretation of modeling results.

(4) Modeling failures can sometimes be as illuminating as successes.