Solar-Cell Measurements:
Extracting Information and Avoiding Pitfalls

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(1) Current-voltage (J-V) curves

(2) Current-voltage analysis

- Visual messages and reality checks

(3) Diode equation parameters

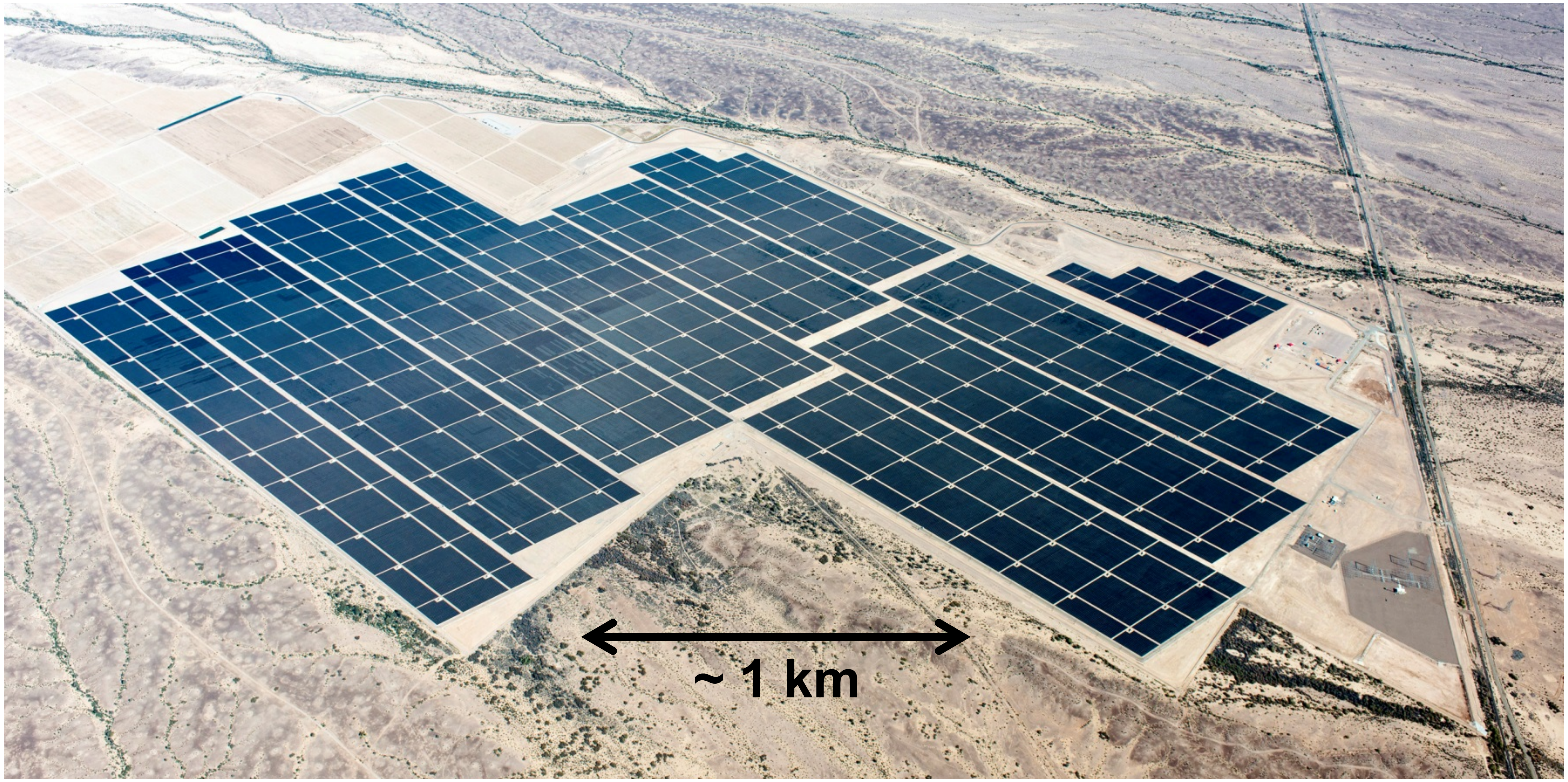
- Specific case step-by-step

(4) Quantum efficiency and capacitance

Thanks to many current and former students including our own HOPE graduates, especially Russell Geisthardt (2012)

The Big Picture

PV is attaining very large scale: 500+ GW worldwide

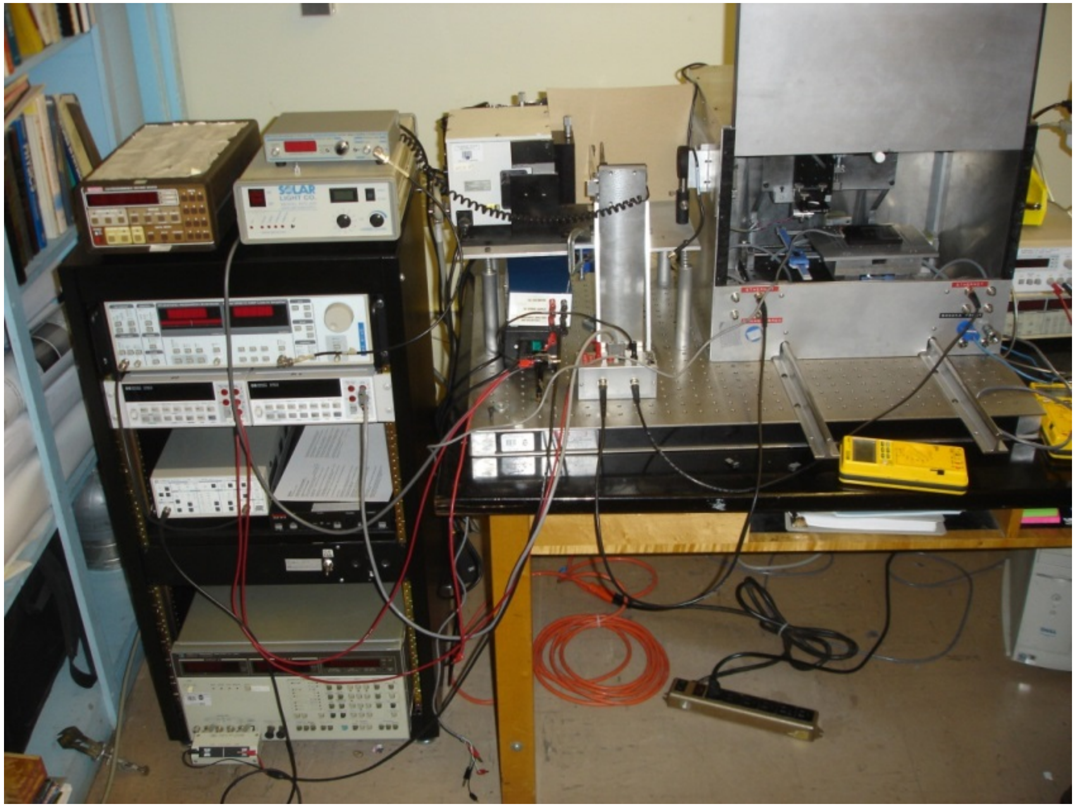


Major progress with Si, CdTe, and CIGS technologies.
Others coming along?

Important to know what is working at the cell level.

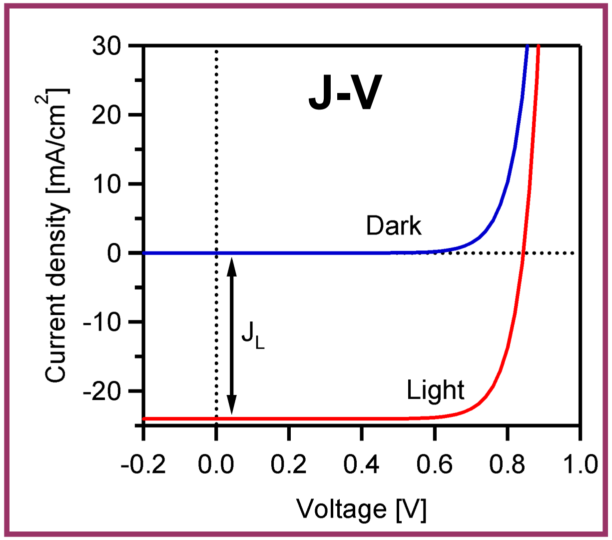
Basic Cell Measurements

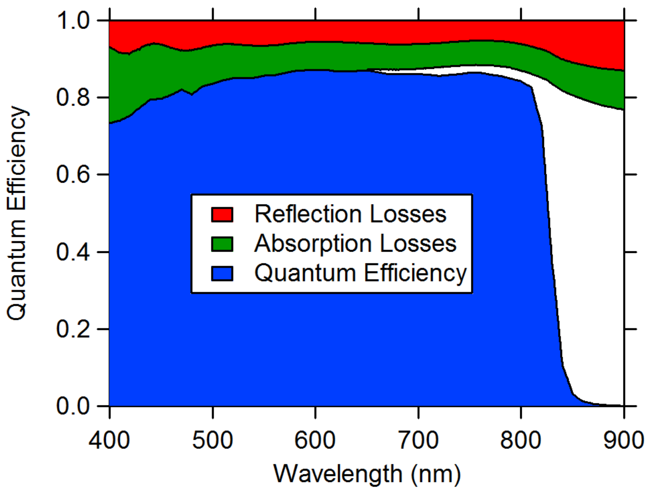
PV Cell Measurements at CSU



Current-voltage, quantum efficiency, and capacitance

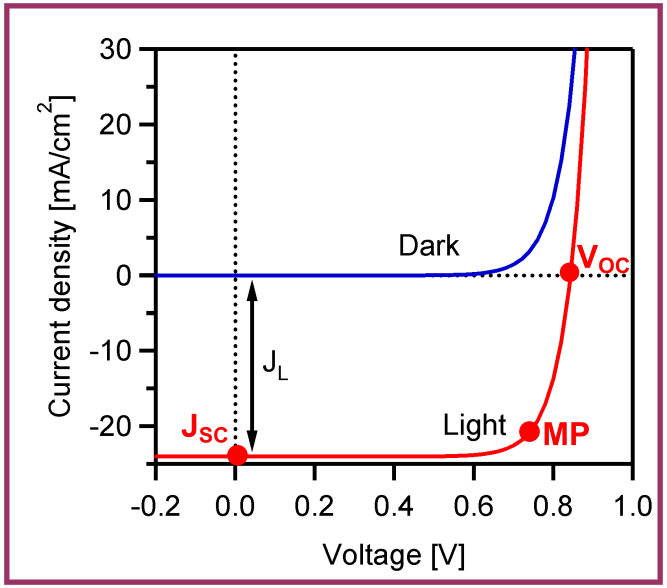
(not shown: optical, EL, LBIC, and PL)





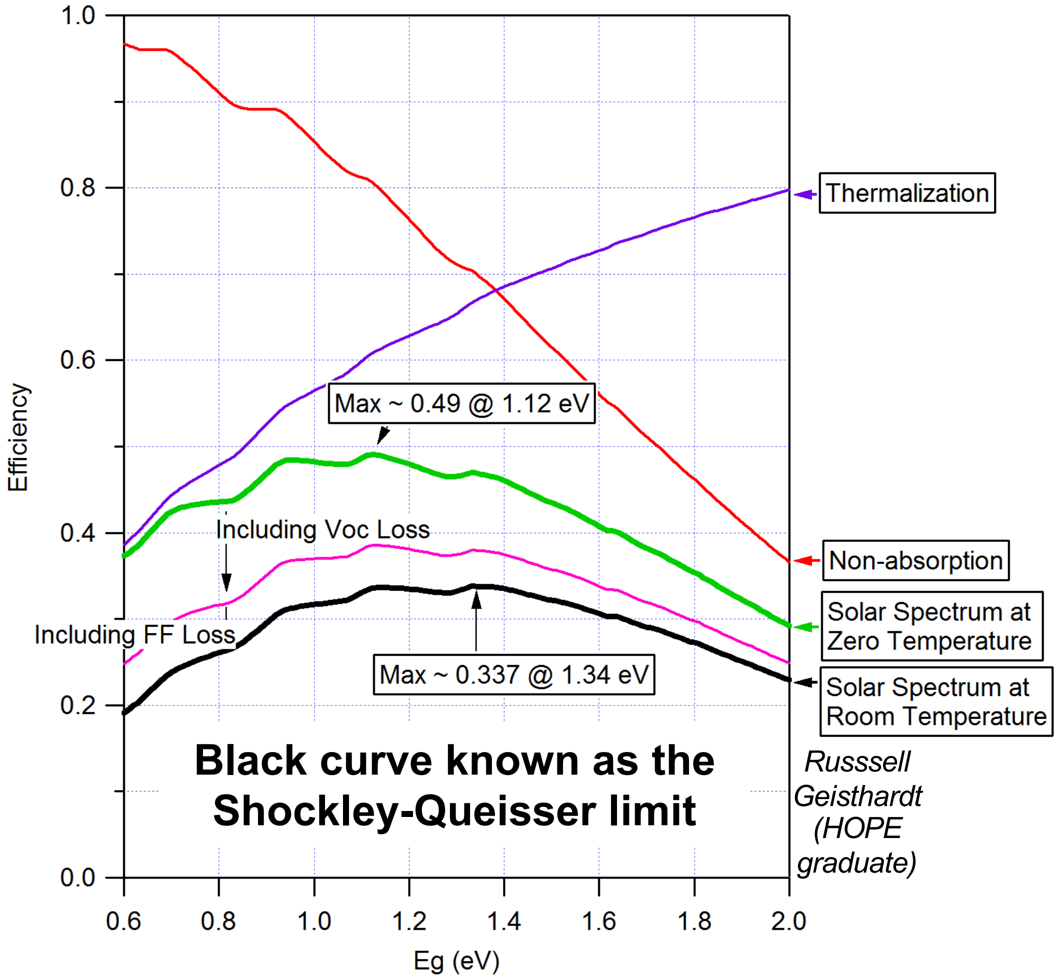
Maximum Cell Efficiency

Good to keep a target in mind
Band gap determines dark curve
Solar spectrum determines maximum current



Efficiency: $$\eta = \frac{V_{OC} \cdot J_{SC} \cdot FF}{P_{in}}$$

Fill-Factor: $$FF = \frac{V_{MP} J_{MP}}{V_{OC} J_{SC}}$$

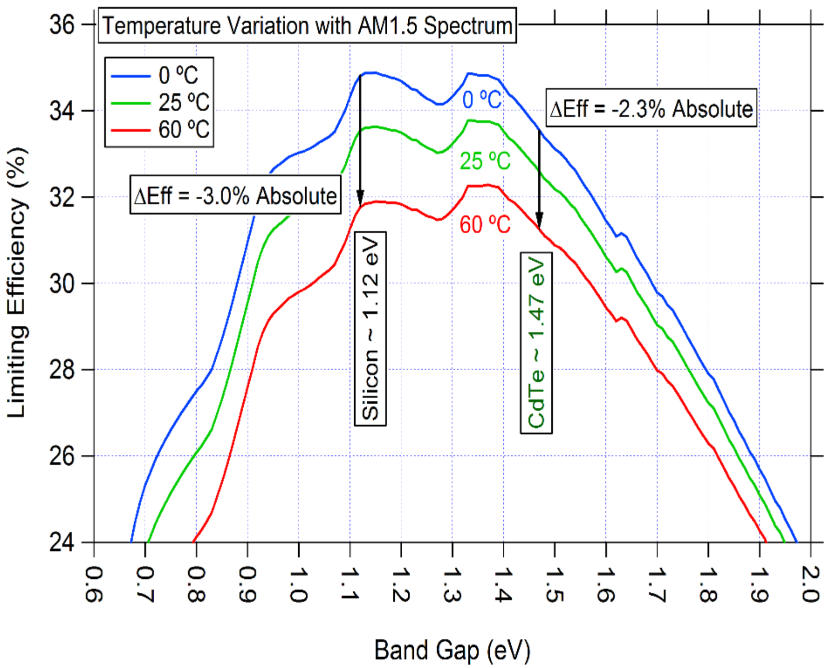


More on Ideal Cells

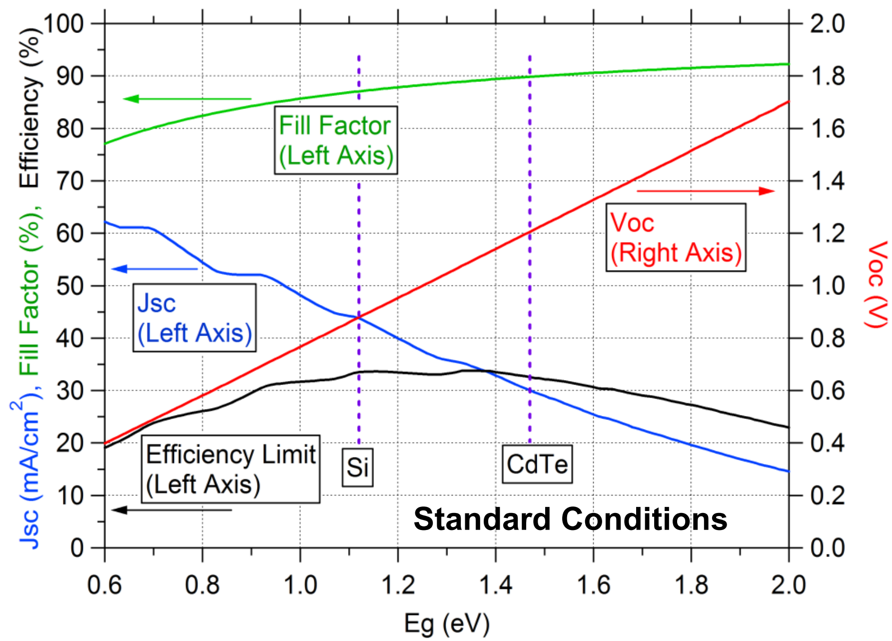
Efficiency curves (both ideal and actual) vary with temperature, solar intensity, and the spectrum.

Individual ideal parameters can also be calculated.

Temperature variation



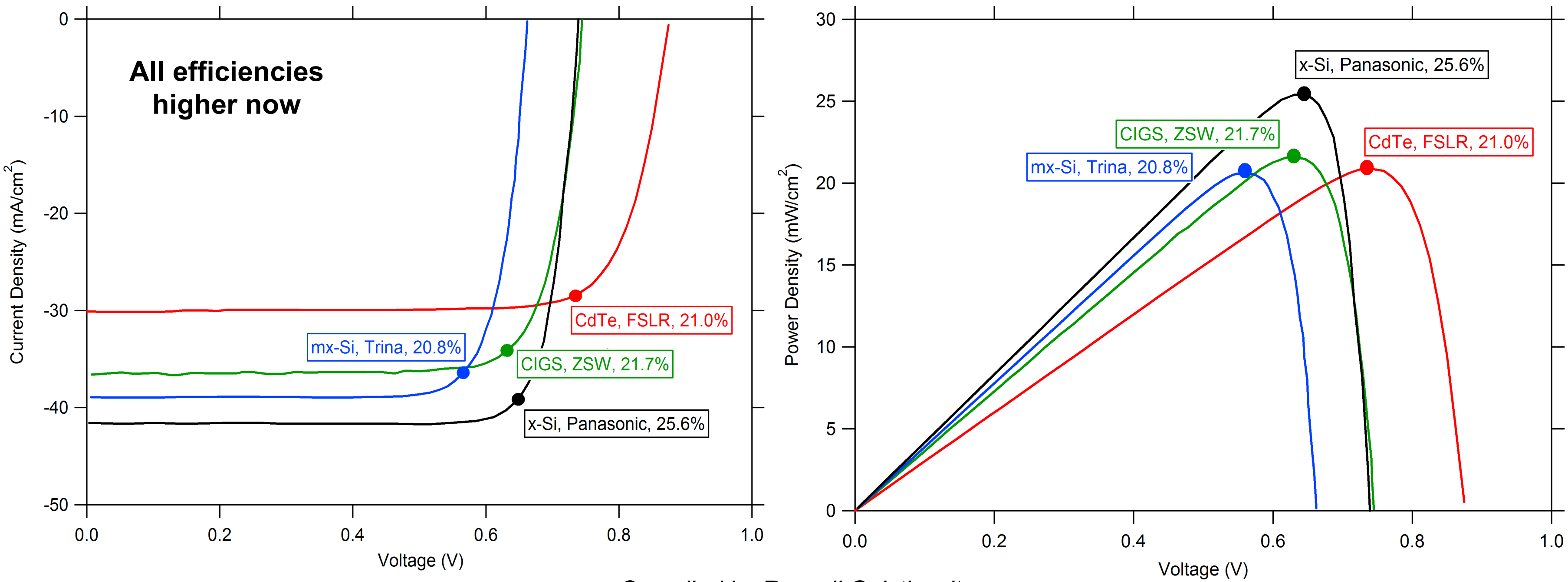
Individual Parameter Variation



Russell Geisthardt

J-V and Power Comparison

For the most commercially competitive technologies



Compiled by Russell Geisthardt

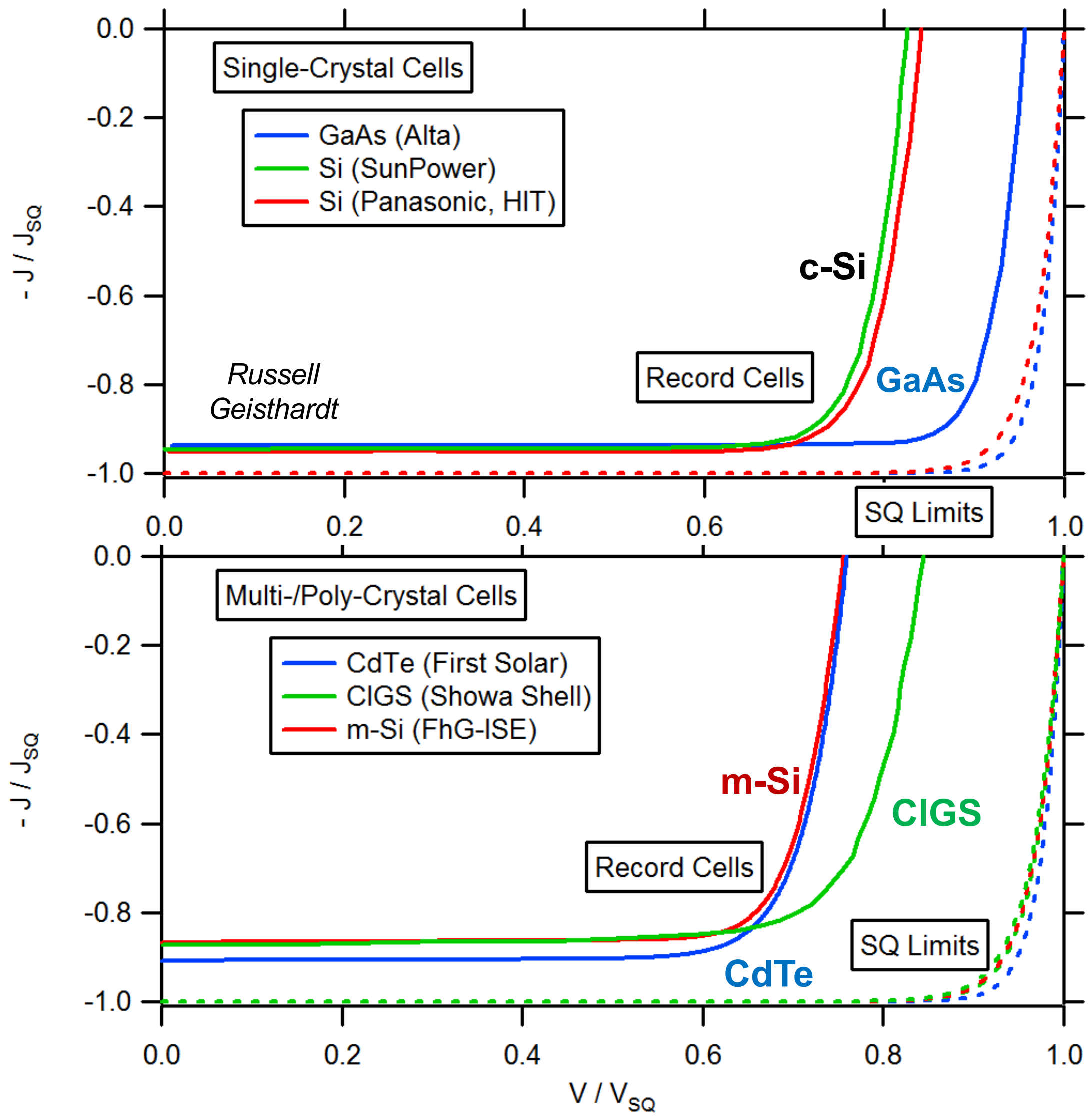
Higher band gap (CdTe): higher V, lower J.

Overlaid curves are useful for cell comparisons in general.

Record Efficiencies Compared to Ideal

Current and voltage as fraction of ideal

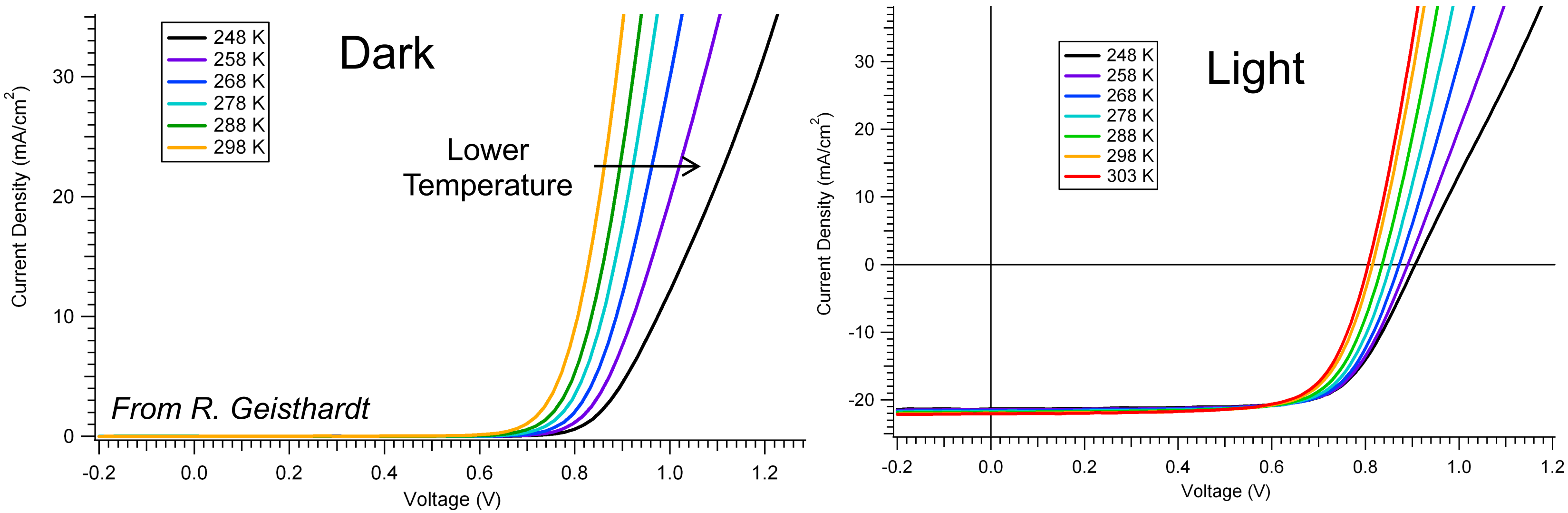
Note: not completely up to date



Polycrystalline CIGS and CdTe compare very favorably

J-V Temperature Dependence

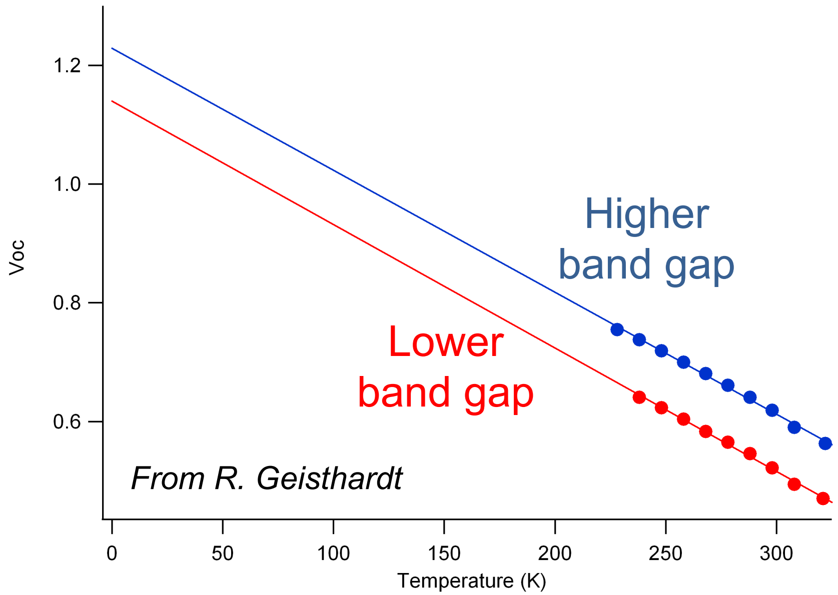
CdTe Cell



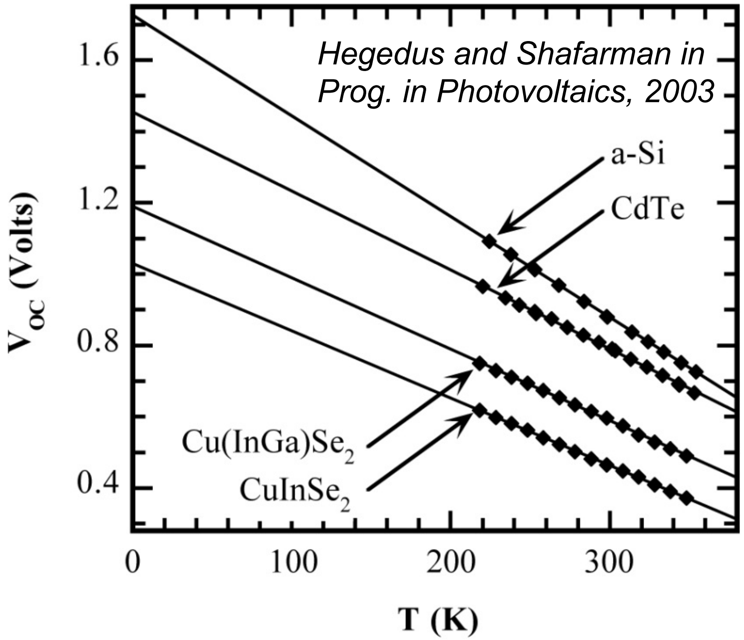
Note: Curves shift roughly parallel towards higher voltage as temperature is reduced. At still lower temperatures, pattern is distorted as the contact barrier starts to impede current flow.

Extrapolation to T = 0

V_{OC} should be approximately linear with temperature (slope ≈ -2 mV/K) and extrapolate to near the absorber band gap at T = 0. Failure to do so is an indication of various non-idealities.



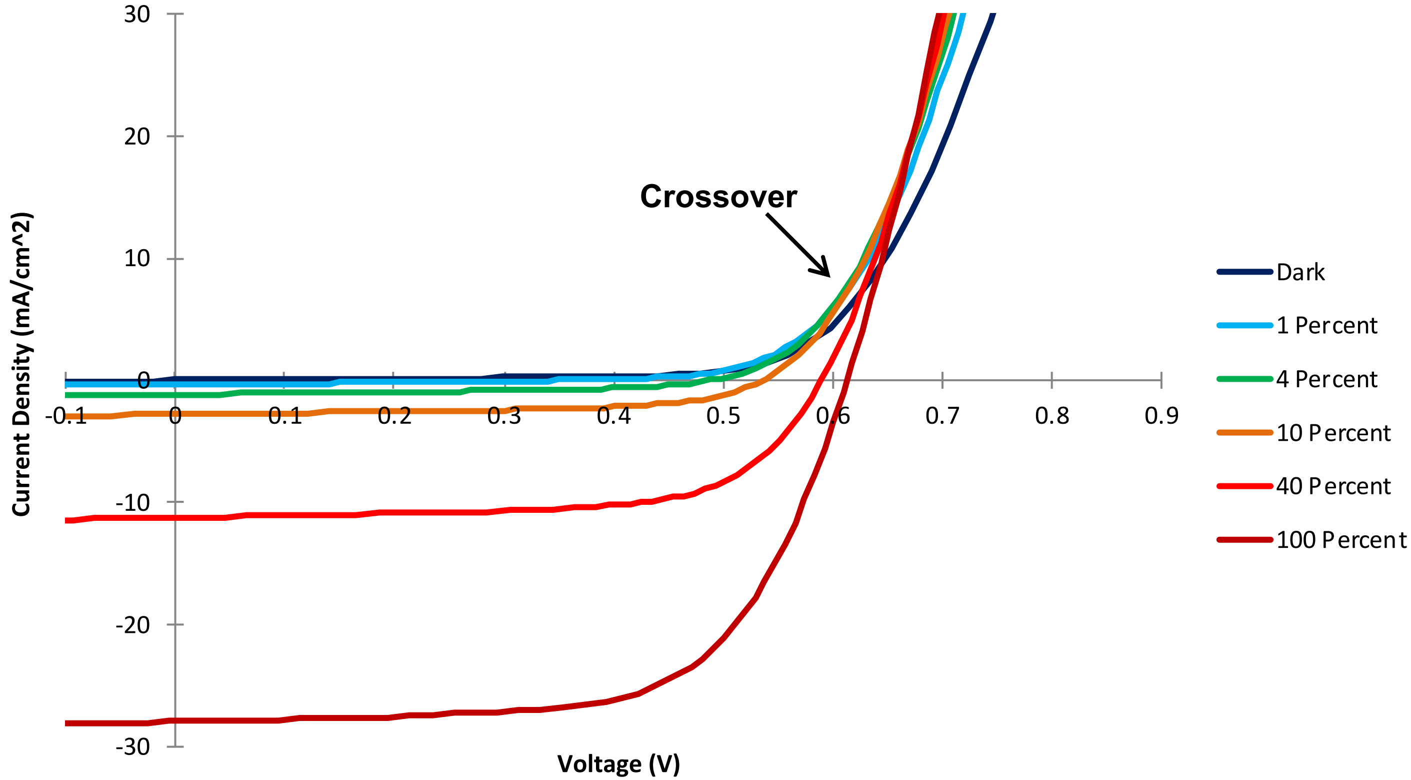
Two CIGS cells with different Ga/In ratios



Four technologies. All intercepts near the respective band gaps

J-V Intensity Dependence

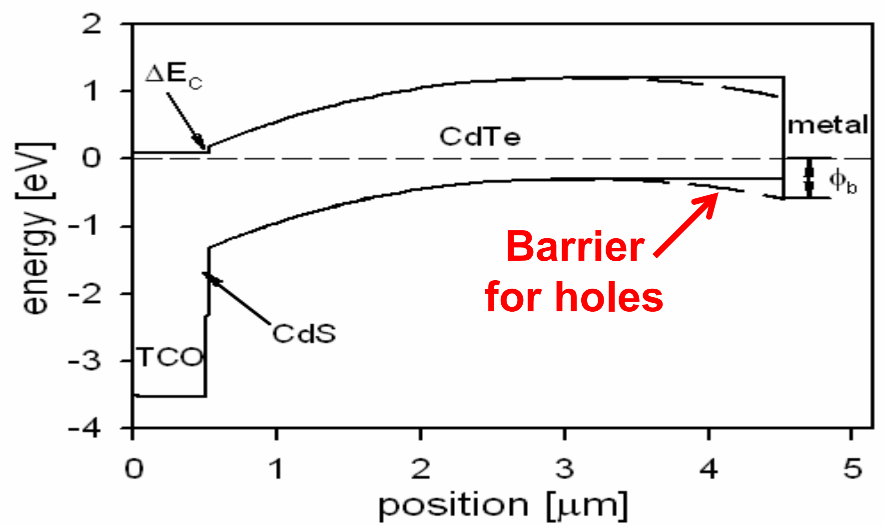
Shift in J-V is <u>nearly</u> proportional to light intensity

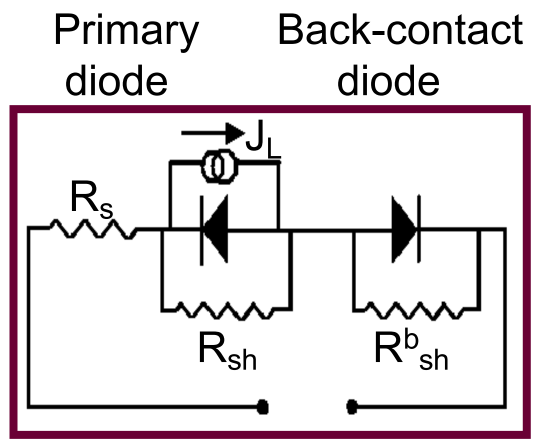


However, slope is also getting steeper with intensity
Hence, "crossover" of light and dark curves

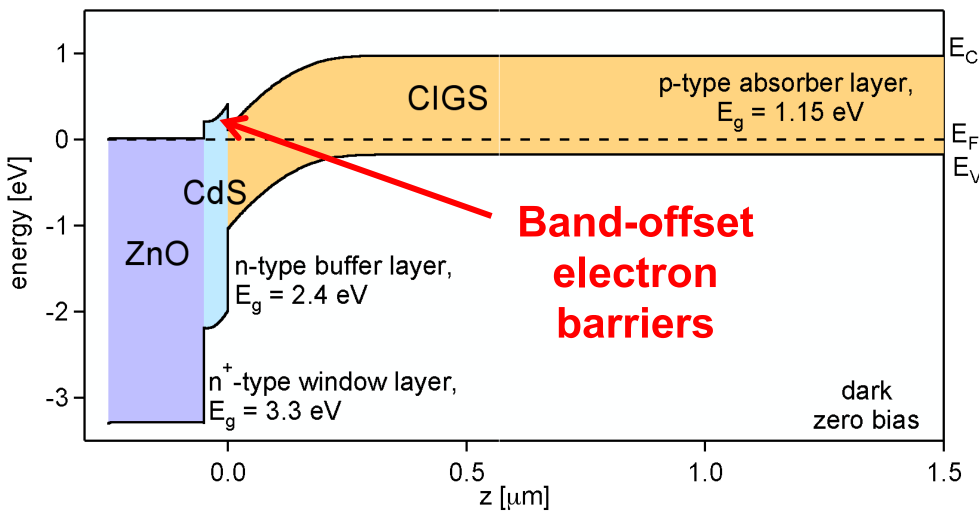
Internal Energy Barriers

Potential problem (or opportunity) at any interface





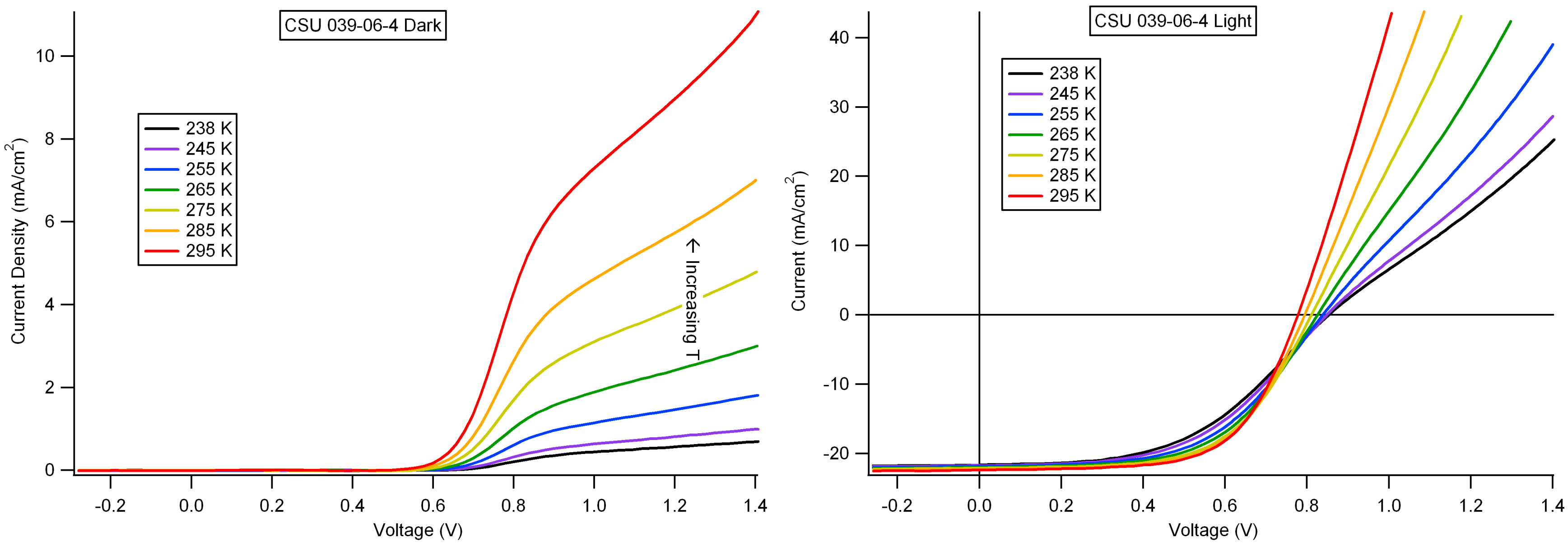
Model: Two opposite polarity diodes in series



Impact often more obvious in forward bias

Effects of Back-Contact Barrier

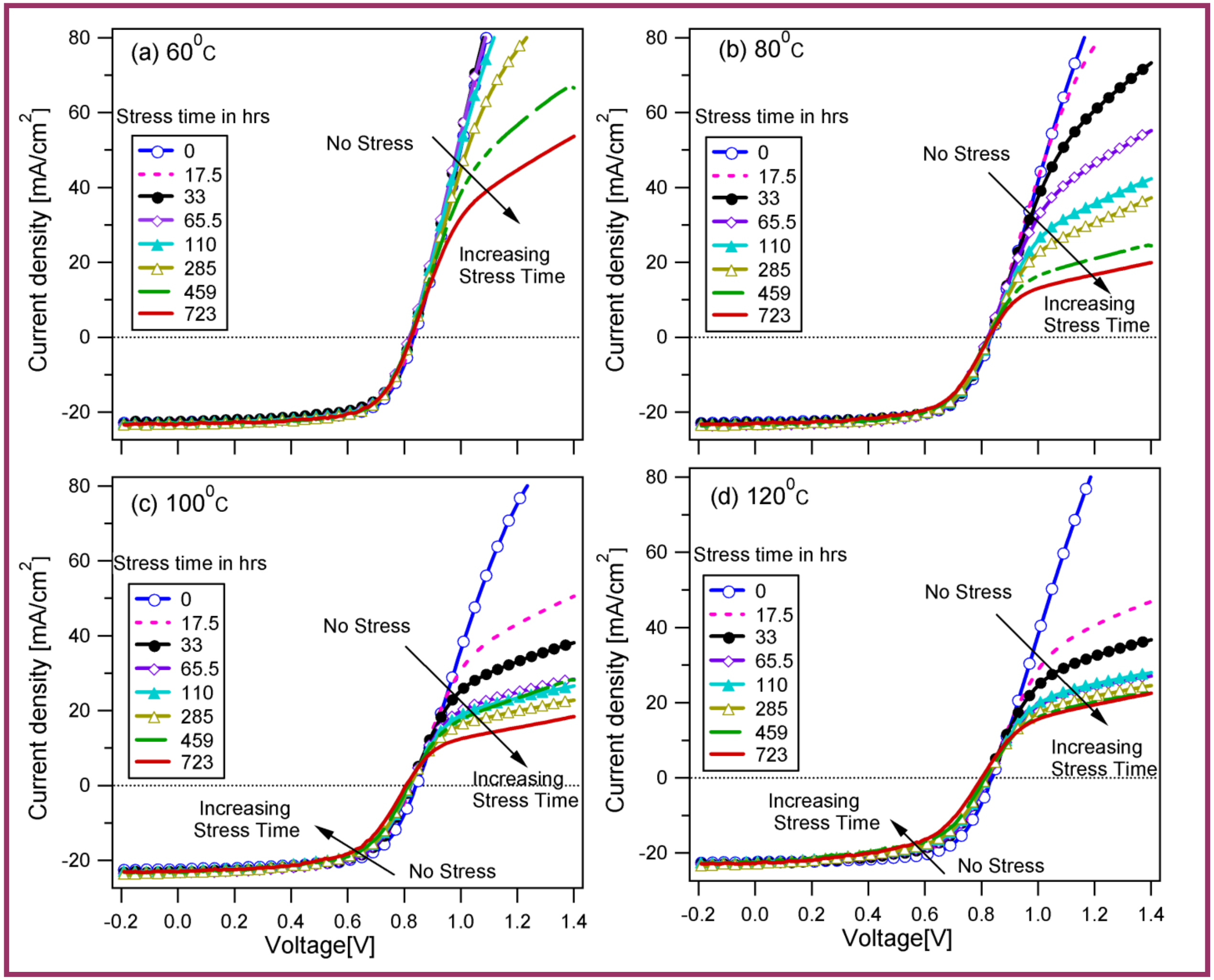
(1) Severe current limitation at low temperature
(2) Residual effect at room temperature
(3) Modest decrease in fill-factor
(4) Good reason to measure J-V as a function of temperature



From R. Geisthardt

Efficiency not Always Stable with Time

CdTe example: With elevated-temperatures, atomic diffusion changes back-contact barrier



From S. Demtsu

The Solar-Cell Diode Equation

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

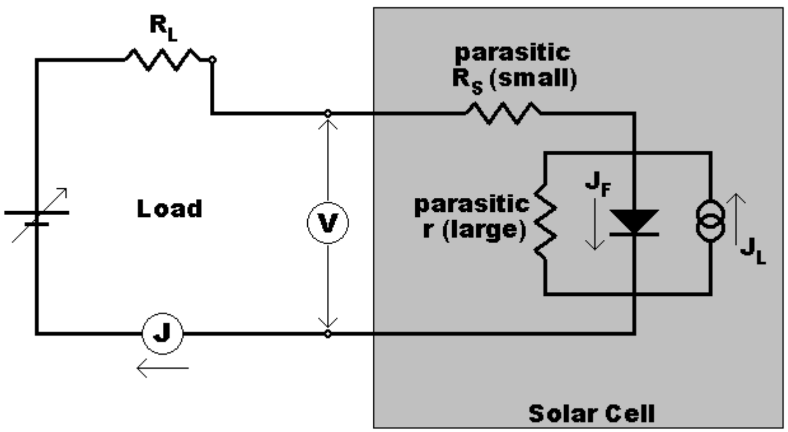
J_0 is constant ~ 10^{-4}-10^{-10} mA/cm^2 (decreases with E_g)

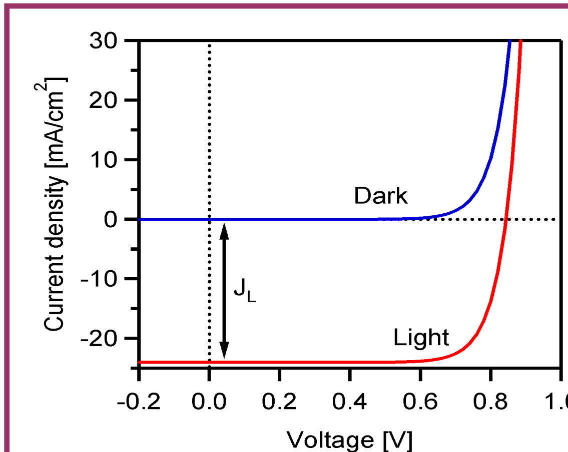
R is series resistance ~ 0.1-2 ohm-cm^2

A is the diode quality factor ~ 1-2

G is conductance (1/shunt resistance) ~ 0.1-2 mS/cm^2

J_L is the light-generated current ≈ J_{SC}





Notes: (1) Sign convention for J and/or V is sometimes reversed

(2) Curves usually reported for room temperature and full sunlight; they will of course be different with other conditions

J-V Uncertainties and Complications

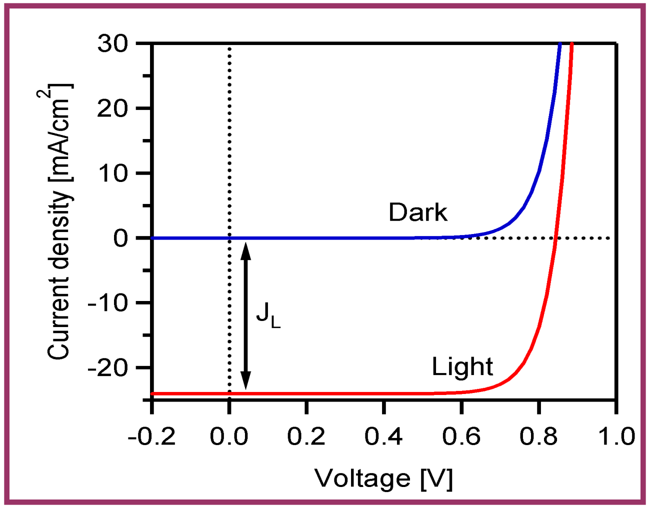
Measurement Uncertainties (best of circumstances)

Current density: ± 0.3 mA/cm^2 (~1%)

Voltage: ± 3 mV (~½%)

Fill factor: ± ½%

Efficiency: ± 1½% relative, e.g. 19.4 ± 0.3%



Other Features

(1) Temperature dependence ($\Delta V_{OC}/\Delta T$ ~ -2 mV/K)

(2) Light intensity and spectrum (some sources short on UV)

(3) Internal barriers (additional diodes in circuit)

(4) Time dependence (hysteresis in J-V curve)

Less Fundamental Problems

(1) Contact resistance between probe and cell

(2) Impedances in external electronics

(3) Light source not properly calibrated

(4) Wrong area used for $J = I/A$

(5) Current generated past cell's edges

(6) Cell not uniform over its entire area

(7) Light source not uniform

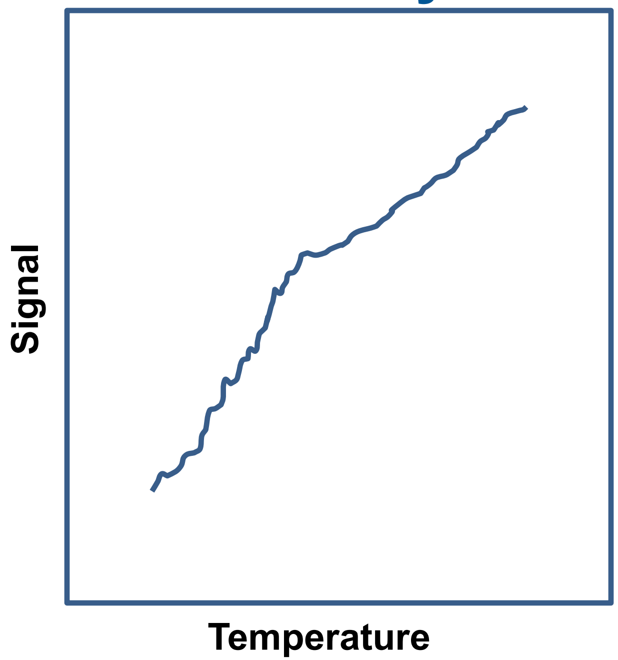
(8) Cell damaged (scratched, dropped, current overload)

(9) Human error: + and – reversed; probe not contacting cell; units (e.g. mA and A) confused, etc, etc

Always Good to Plot and Look at Data

Story from 1971:

University A



University B

Temperature	Signal
1.5	x.xxxx
1.6	x.xxxx
1.7	x.xxxx
1.8	x.xxxx
1.9	x.xxxx
2.0	x.xxxx
2.1	x.xxxx
2.2	x.xxxx
2.3	x.xxxx
2.4	x.xxxx
2.5	x.xxxx

Same experiment, same time frame

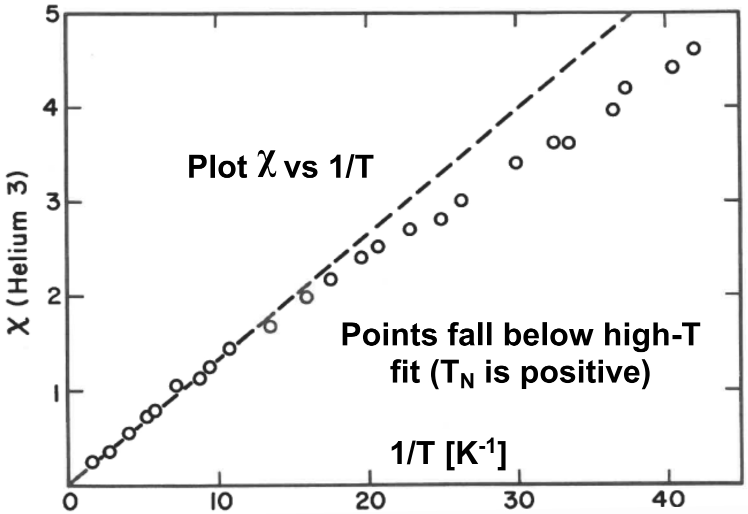
University A noticed the kink, explained it (eventually), and received the Nobel Prize for discovering superfluid ^3He

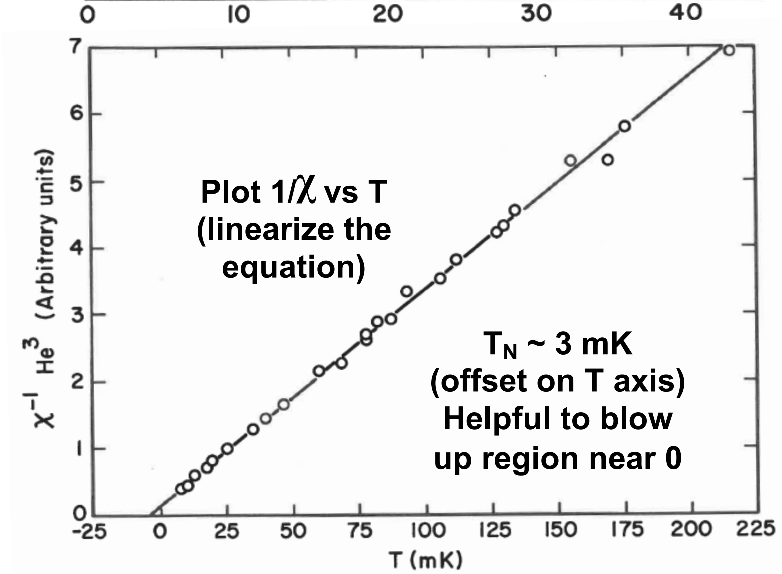
University B looked back at its data; it contained the same effect

Also Helps to Plot Data in Different Ways

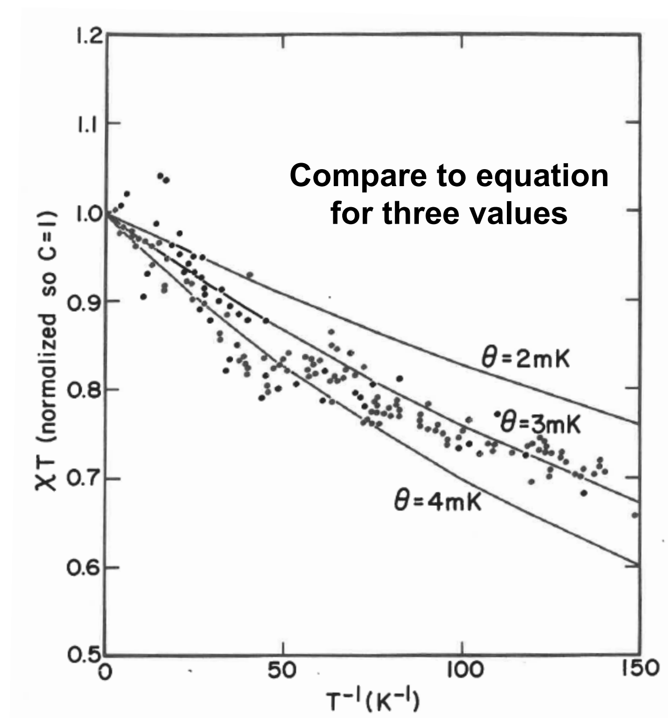
Low Temperature Magnetic Ordering of Solid ^3He

Susceptibility: $\chi = C/(T + T_N)$; find T_N





Same data plotted three ways. Which is most useful?



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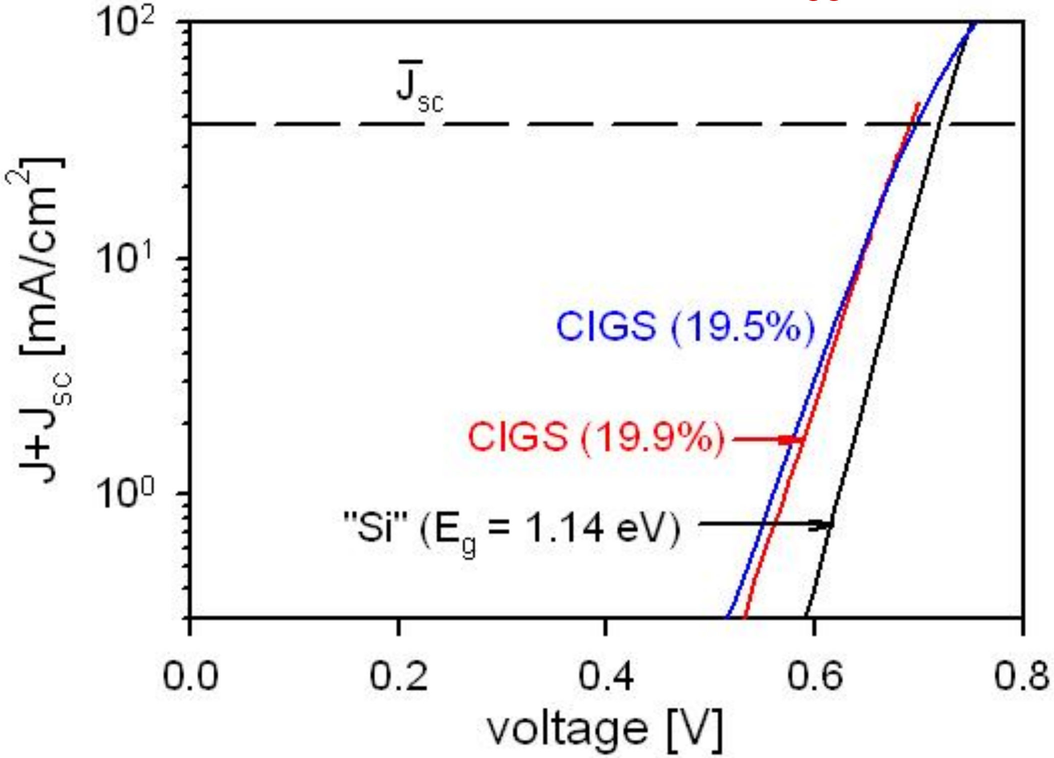
How Does That Apply to Solar Cells?

Log scale often useful, since diode J-V (nearly) exponential

Light data shifted by J_{SC}



CIGS	19.5%	19.9%	"Si"
V_{OC} [mV]	693	692	721
J_{SC} [mA/cm^2]	35.3	35.5	39.0
Fill-factor	79.4	81.0	84.5
R_S [Ω-cm^2]	0.4	0.25	0.1
G [mS/cm^2]	0.1	0.02	0.02
A-factor	1.3	1.2	1.0
J_0 [mA/cm^2]	3×10^{-8}	4×10^{-9}	3×10^{-11}

Based on Diode Equation:

$$J = J_0 \exp[(V-JR_S)/AkT] + GV - J_{SC}$$

Data overlay helps accentuate differences

Note series-resistance deviation in blue curve; extrapolations to different values of J_0

Analysis of J-V Data: Plot Four Ways

Assume $J = J_0 \exp[q(V-JR)/AkT] + GV - J_{SC}$

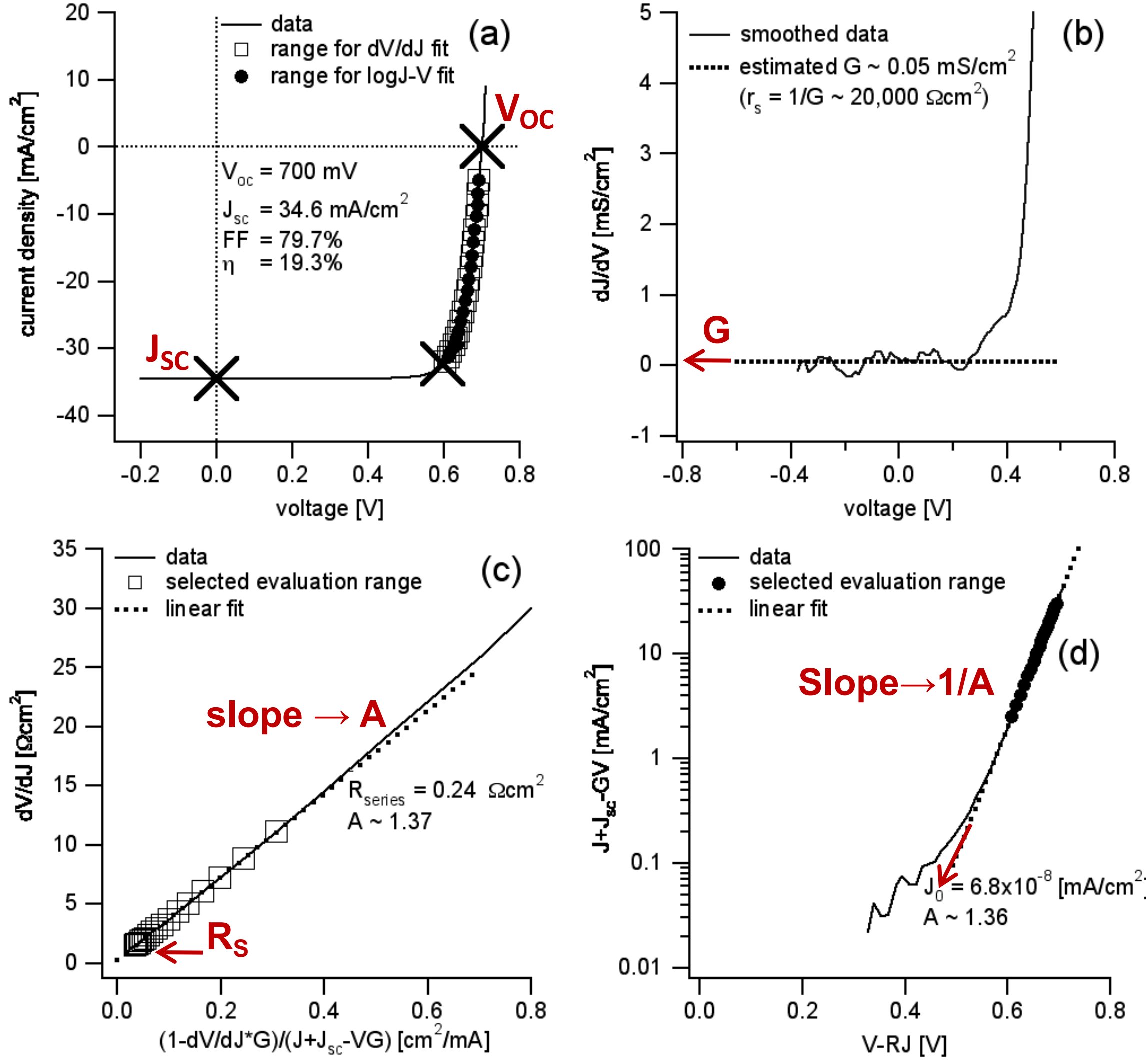
Applied here to high-efficiency CIGS cell

Following Hegedus and Shafarman, Prog. in PV **12**, 155, (2004)]:

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

Process automated for computer by Markus Gloeckler (CurVA)

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

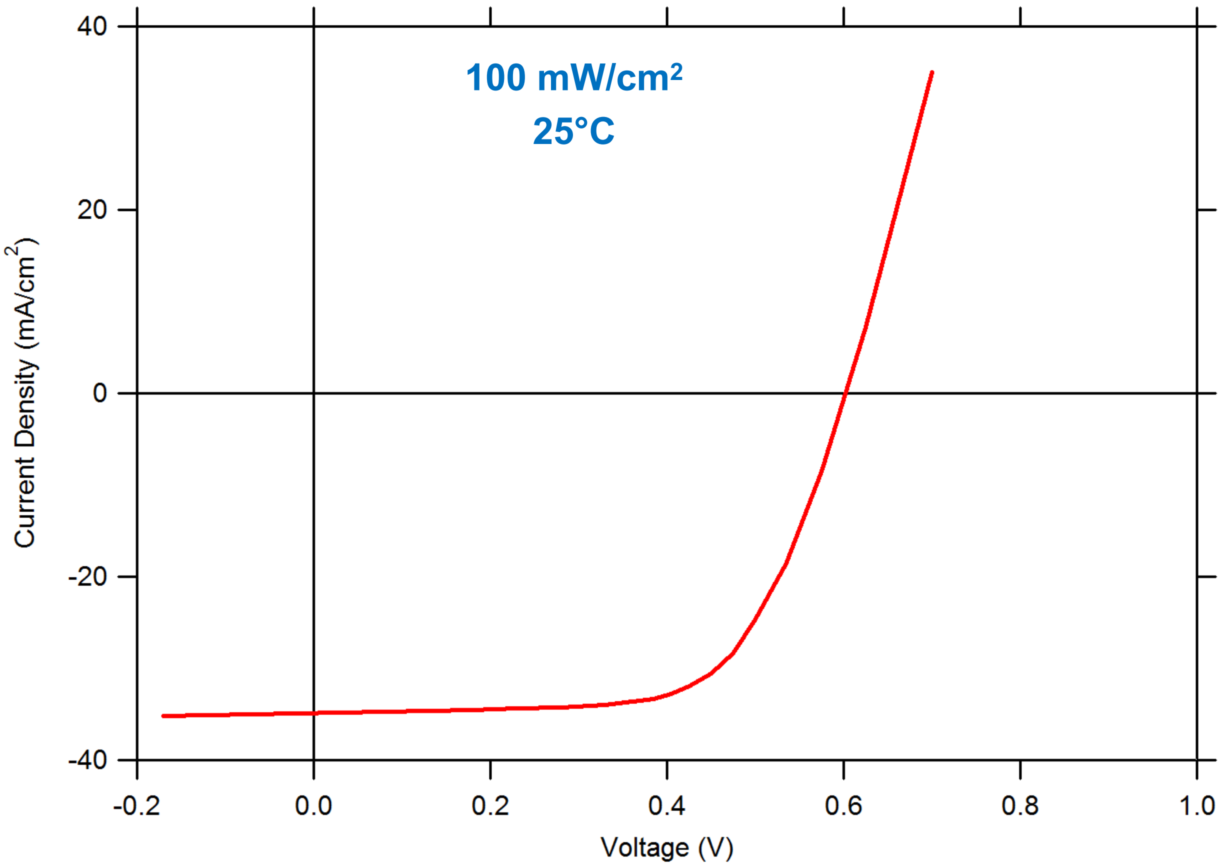


Example: J-V Data and Graph

$$J(V) = J_0 \exp[q(V-JR)/AkT] + GV - J_{SC}$$

V	J
-0.17	-35.2
-0.12	-35.05
-0.07	-35
-0.02	-34.9
0.03	-34.85
0.08	-34.7
0.13	-34.65
0.18	-34.5
0.23	-34.35
0.28	-34.25
0.33	-34
0.385	-33.35
0.405	-32.8
0.425	-31.9
0.45	-30.6
0.475	-28.3
0.5	-24.6
0.535	-18.6
0.575	-8.5
0.625	7.2
0.66	20
0.7	35

Generally more points



J_{SC} _____ V_{OC} _____ P_{MAX} _____ efficiency _____ FF _____

G _____ R _____ A _____ J_0 _____

J-V Data and Graph

V	J
-0.17	-35.2
-0.12	-35.05
-0.07	-35
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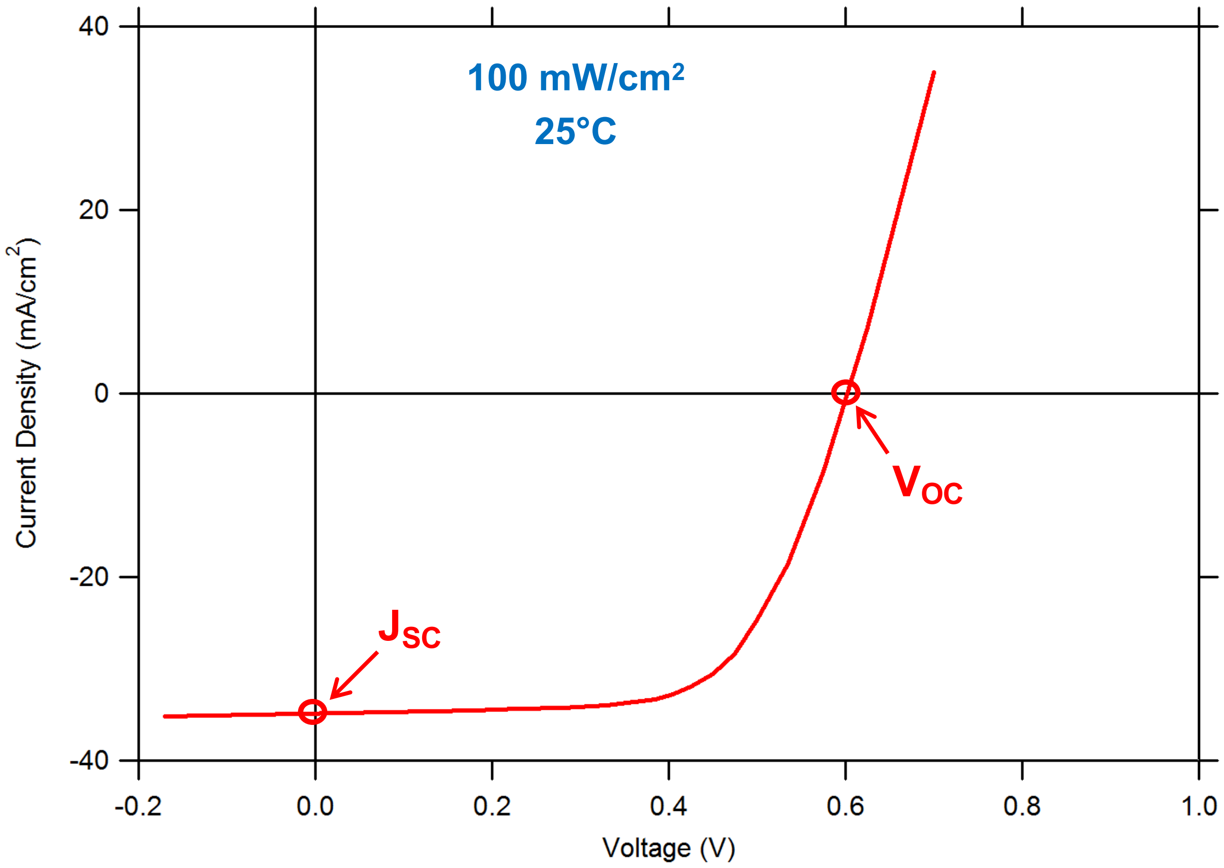
Generally more points

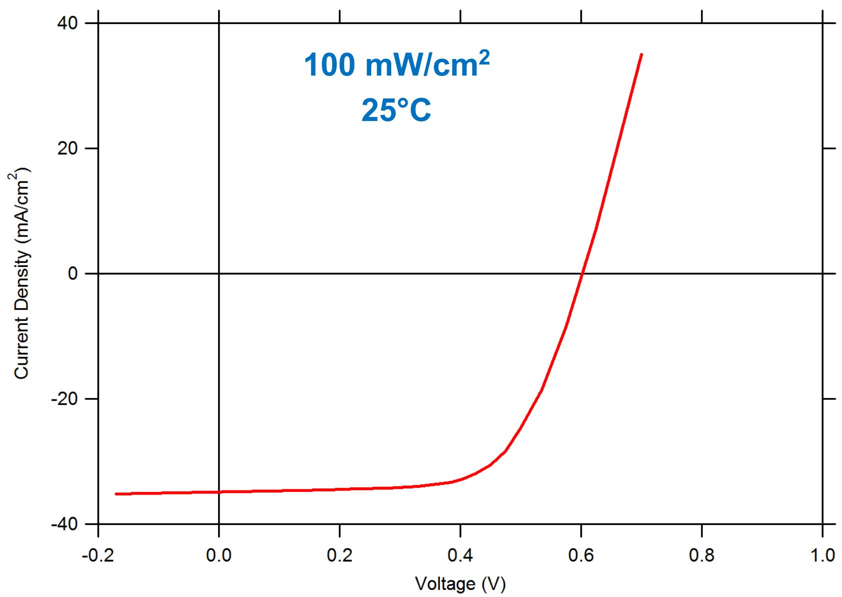


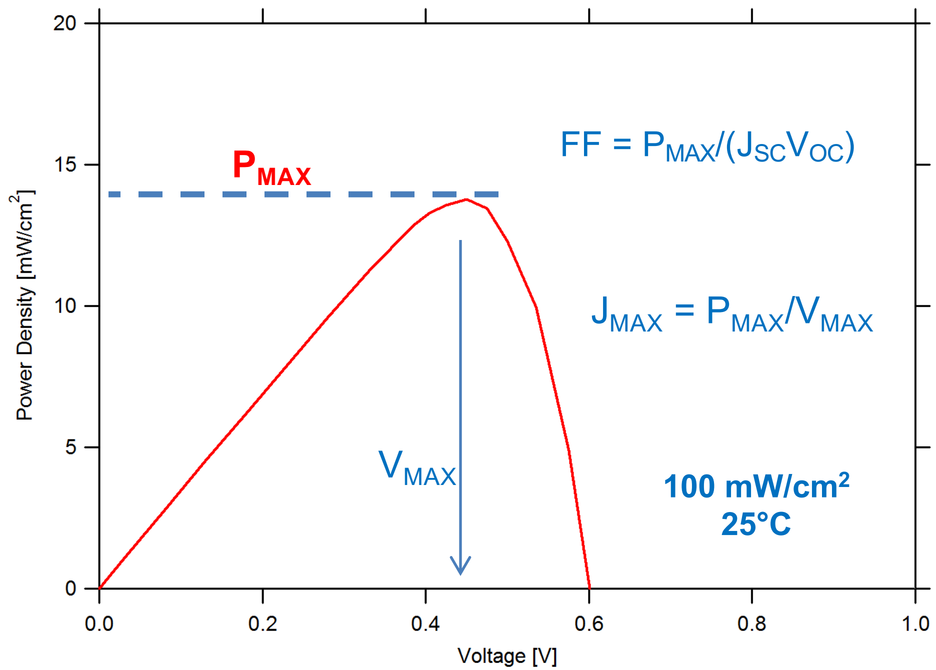
J_{SC} **35 mA/cm²** V_{OC} **0.60 V** P_{MAX} ______ efficiency ____ FF ____

G ____ R ____ A ____ J_0 ____

J-V Data: Maximum Power

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



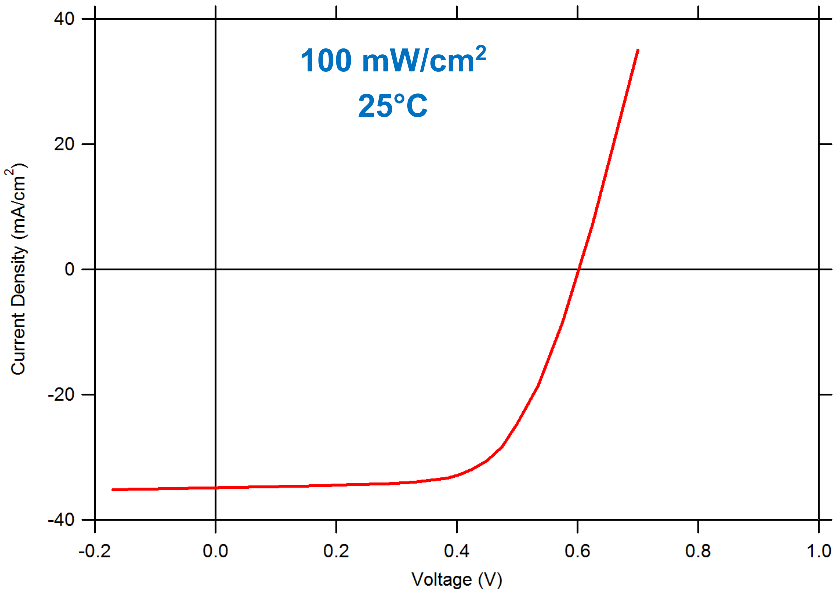


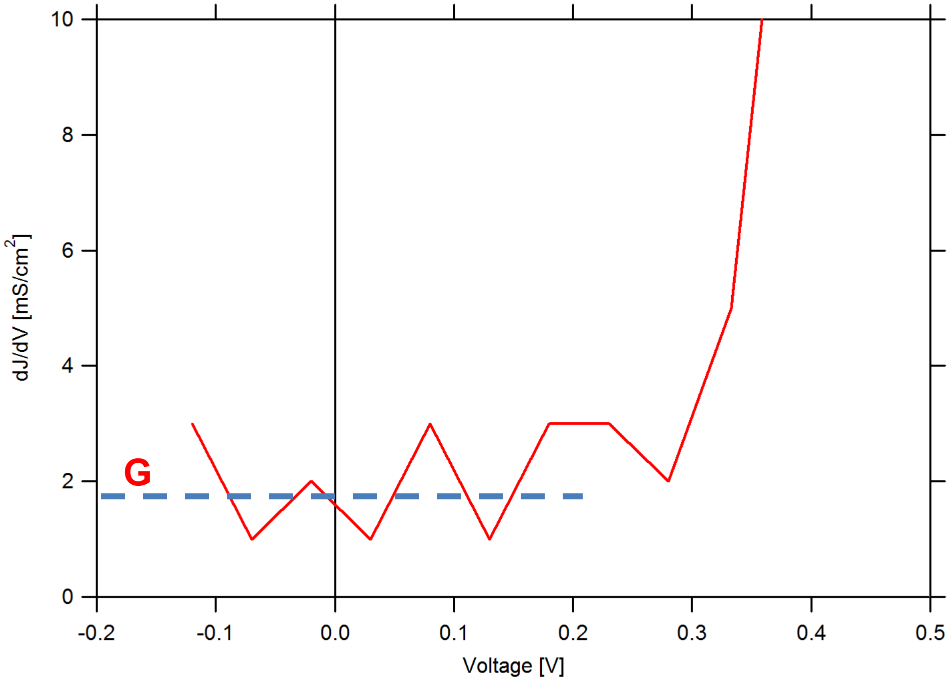
J_{SC} 35.0 mA/cm² V_{OC} 0.60 V P_{MAX} 14.0 mW/cm² efficiency 14.0% FF 67%

G ____ R ____ A ____ J_0 ____

J-V Data: dJ/dV

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





J_{SC} 35.0 mA/cm² V_{OC} 0.60 V P_{MAX} 14.0 mW/cm² efficiency 14.0% FF 67%

G 1.9 mS/cm² R ______ A _____ J_0 ______

Now for (c) and (d)

Assume $J = J_0 \exp[q(V-JR)/AkT] + GV - J_{SC}$

Applied here to high-efficiency CIGS cell

Following Hegedus and Shafarman, Prog. in PV **12**, 155, (2004)]:

(1) Plot data four ways
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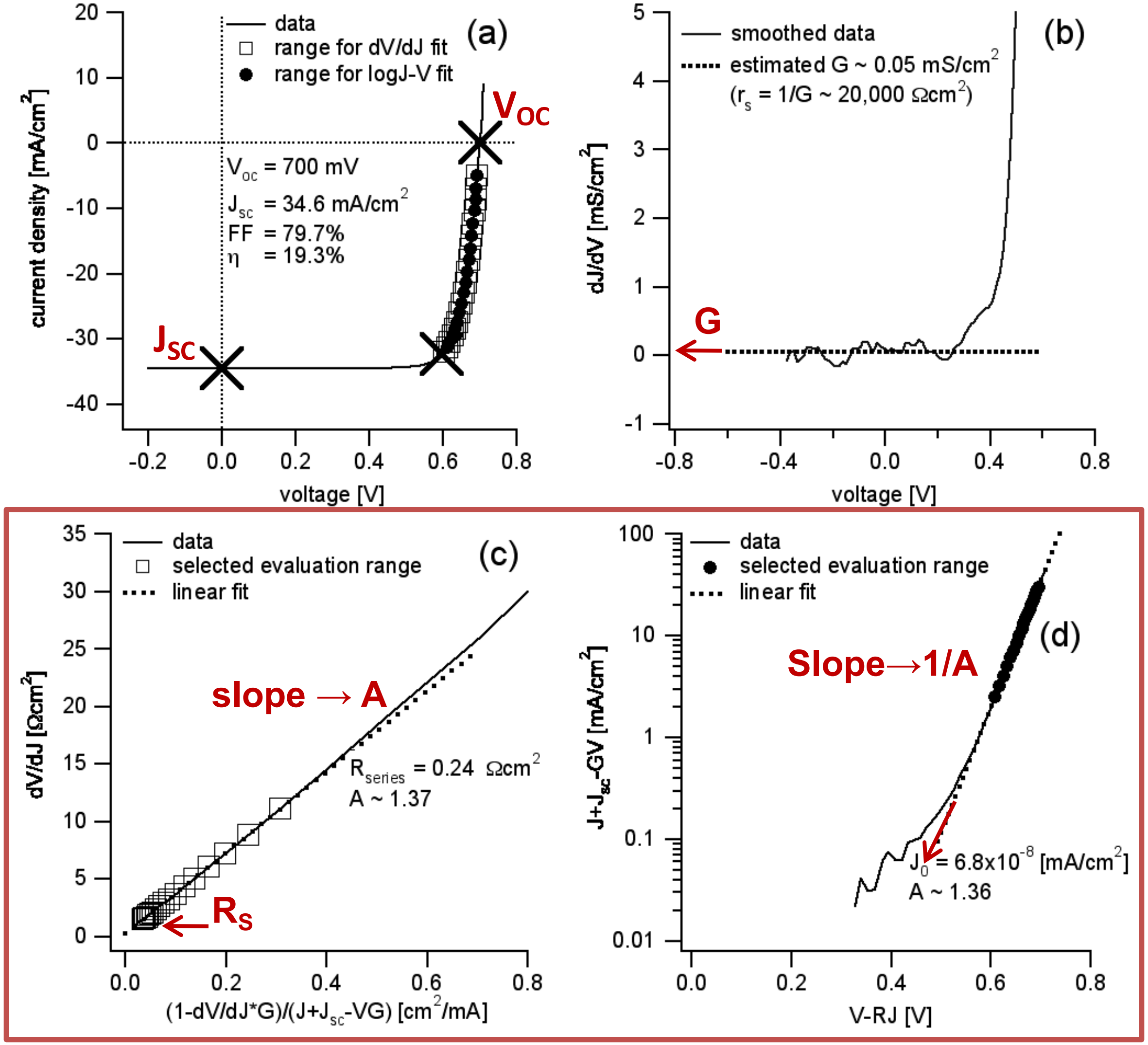
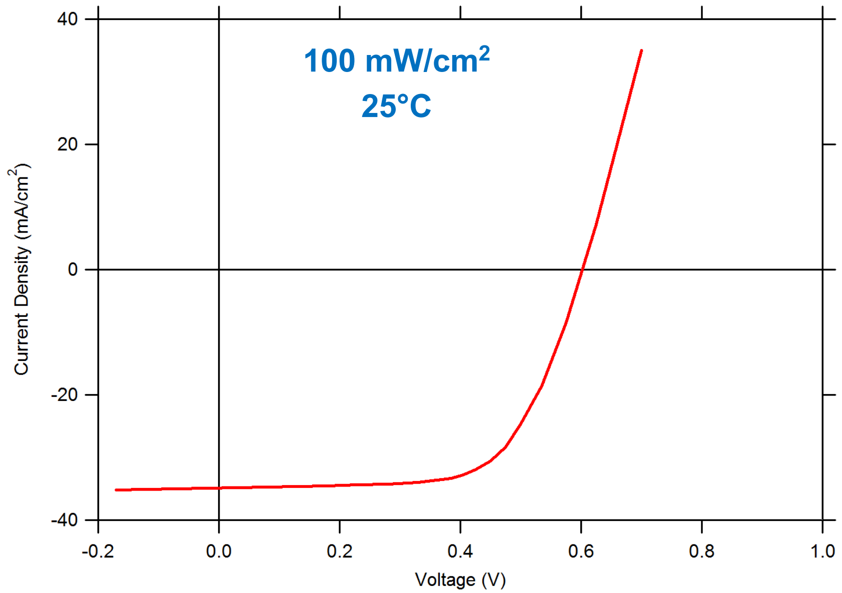
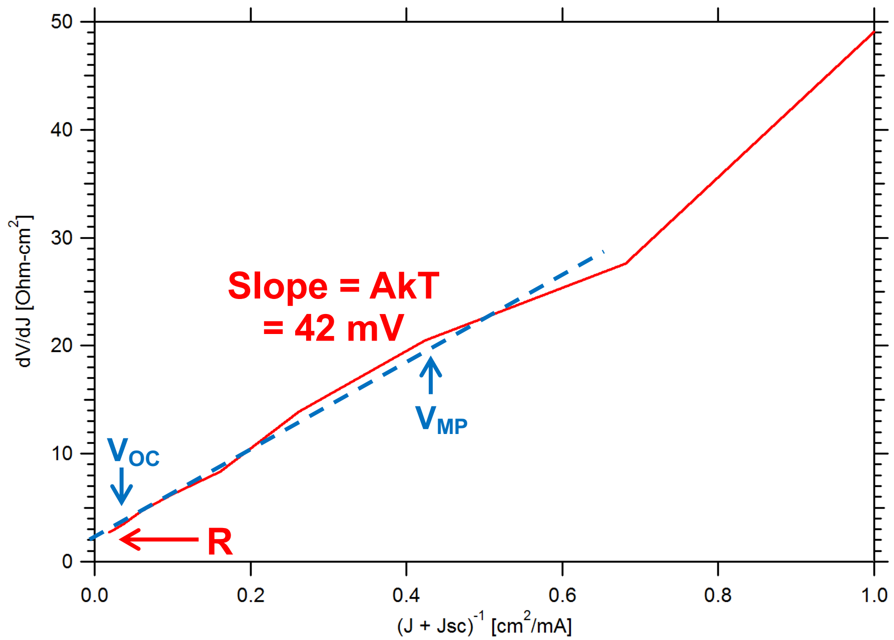


J-V Data: dV/dJ vs 1/(J + J_{SC})

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



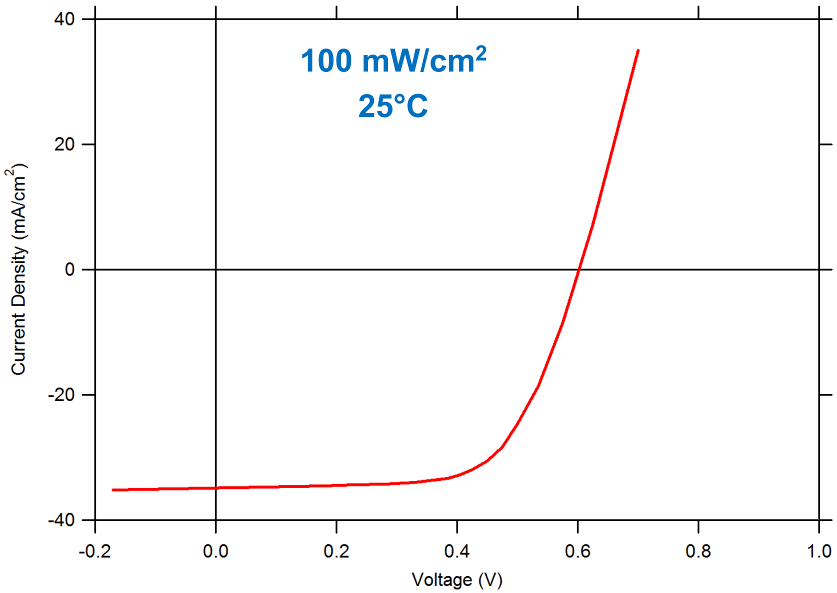


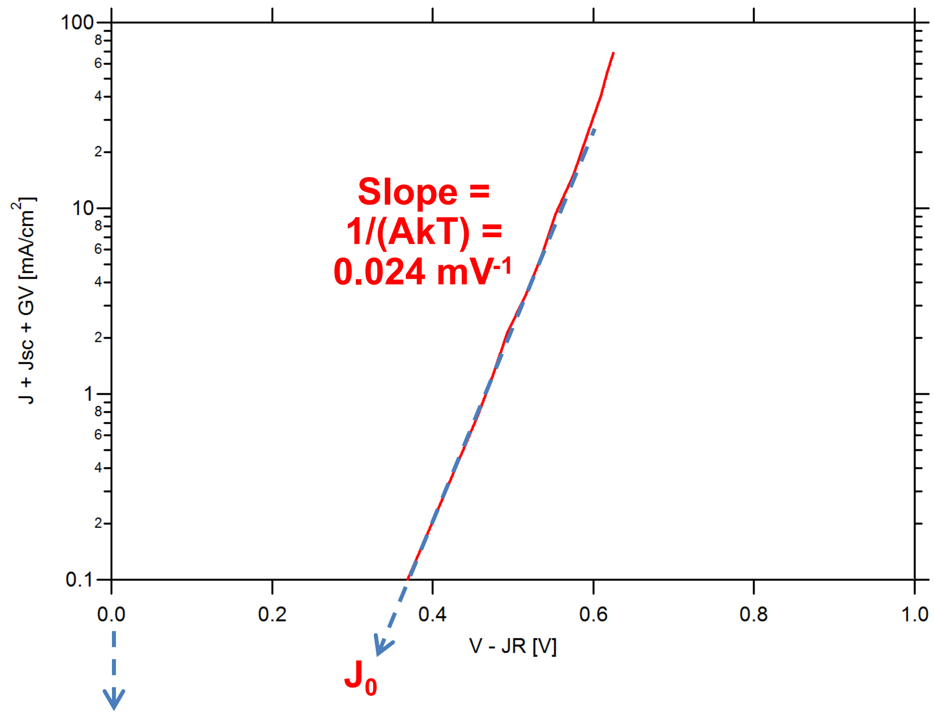
J_{SC} **35.0 mA/cm²** V_{OC} **0.60 V** P_{MAX} **14.0 mW/cm²** efficiency **14.0%** FF **67%**

G **1.9 mS/cm²** R **2.0 Ω-cm²** A **1.65** J_0 ____

J-V Data: Semi-log Plot

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



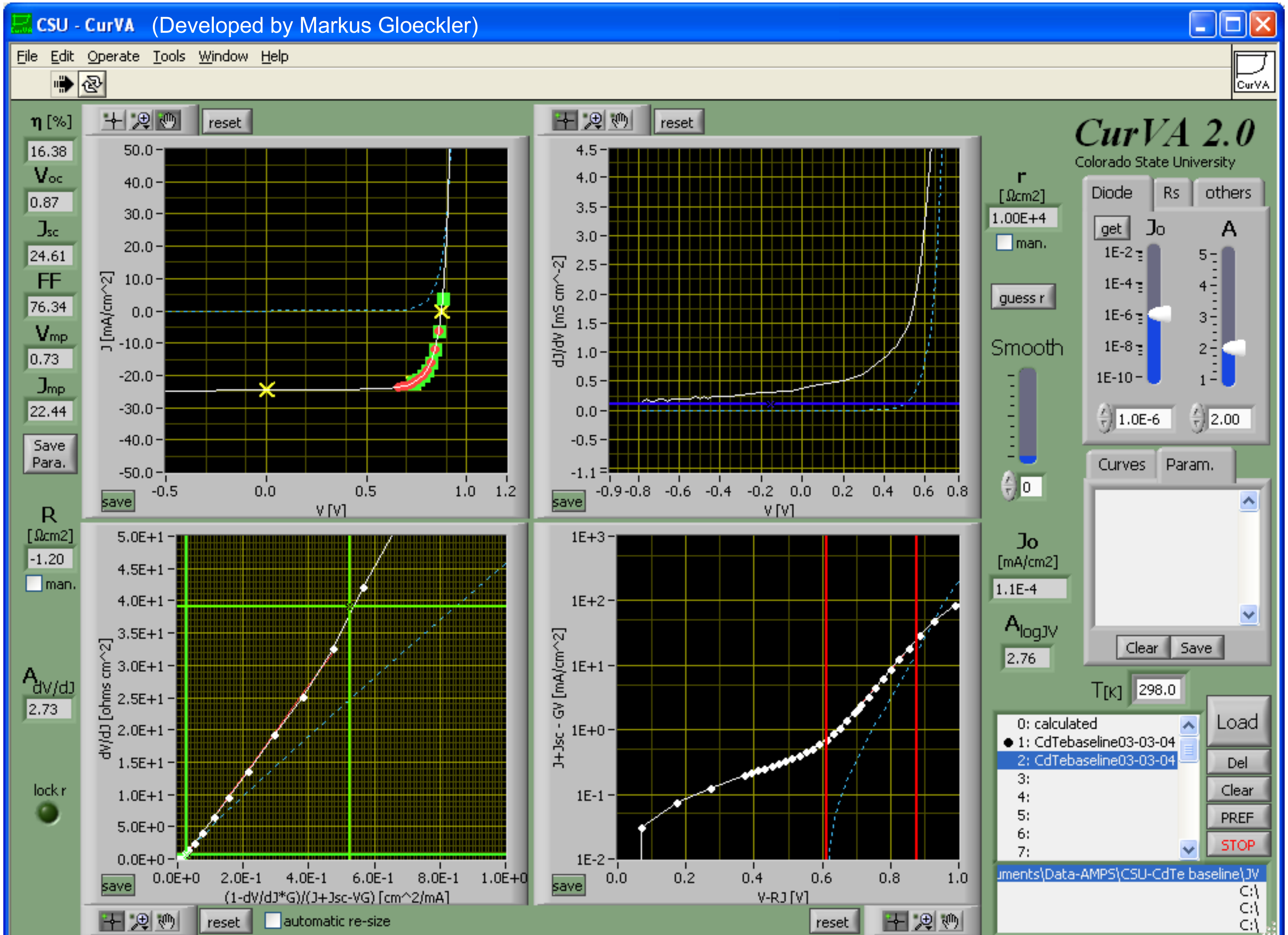


J_{SC} **35.0 mA/cm²** V_{OC} **0.60 V** P_{MAX} **14.0 mW/cm²** efficiency **14.0%** FF **67%**

G **1.9 mS/cm²** R **2.0 Ω-cm²** A **1.65** **1.65** J_0 **1.0 x 10⁻⁵ mA/cm²**

CurVA Screen View: CdTe

Sliders used to vary range of points and fit parameters



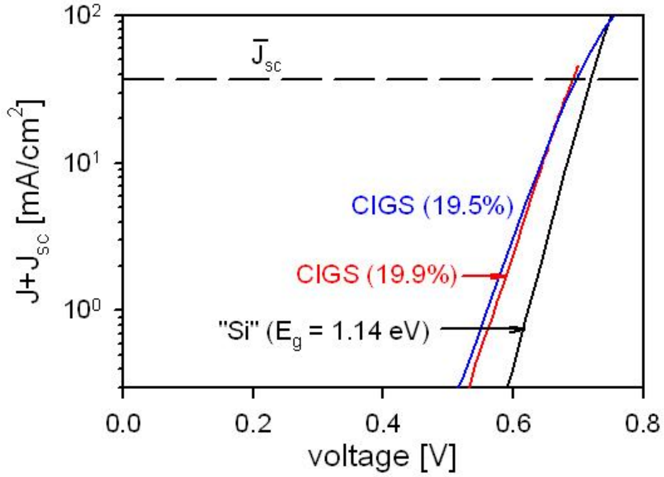
General Principles about Cell Performance

Efficiency = J_{SC} V_{OC} FF

(1) Losses in J_{SC} deduced from quantum efficiency (next slides)

(2) V_{OC} is reduced by approximately the difference between band gap and ideal voltage multiplied by A–1 [about 150 mV in the example from the last few slides]

(3) V_{MP} is further reduced by approx kTln(1-J/J_{SC})(A-1) [about 100 mV in the example, somewhat less in the diagram to the right]. $\Delta FF \sim \Delta V_{MP}/V_{MP}$



(4) J_0 is not independent [determined by V_{OC}, J_{SC}, and A

(5) Series resistance: reduces voltage at MP:

$$\Delta V_{MP} \sim RJ_{MP} \sim 2x30 \sim 60 \text{ mV}$$

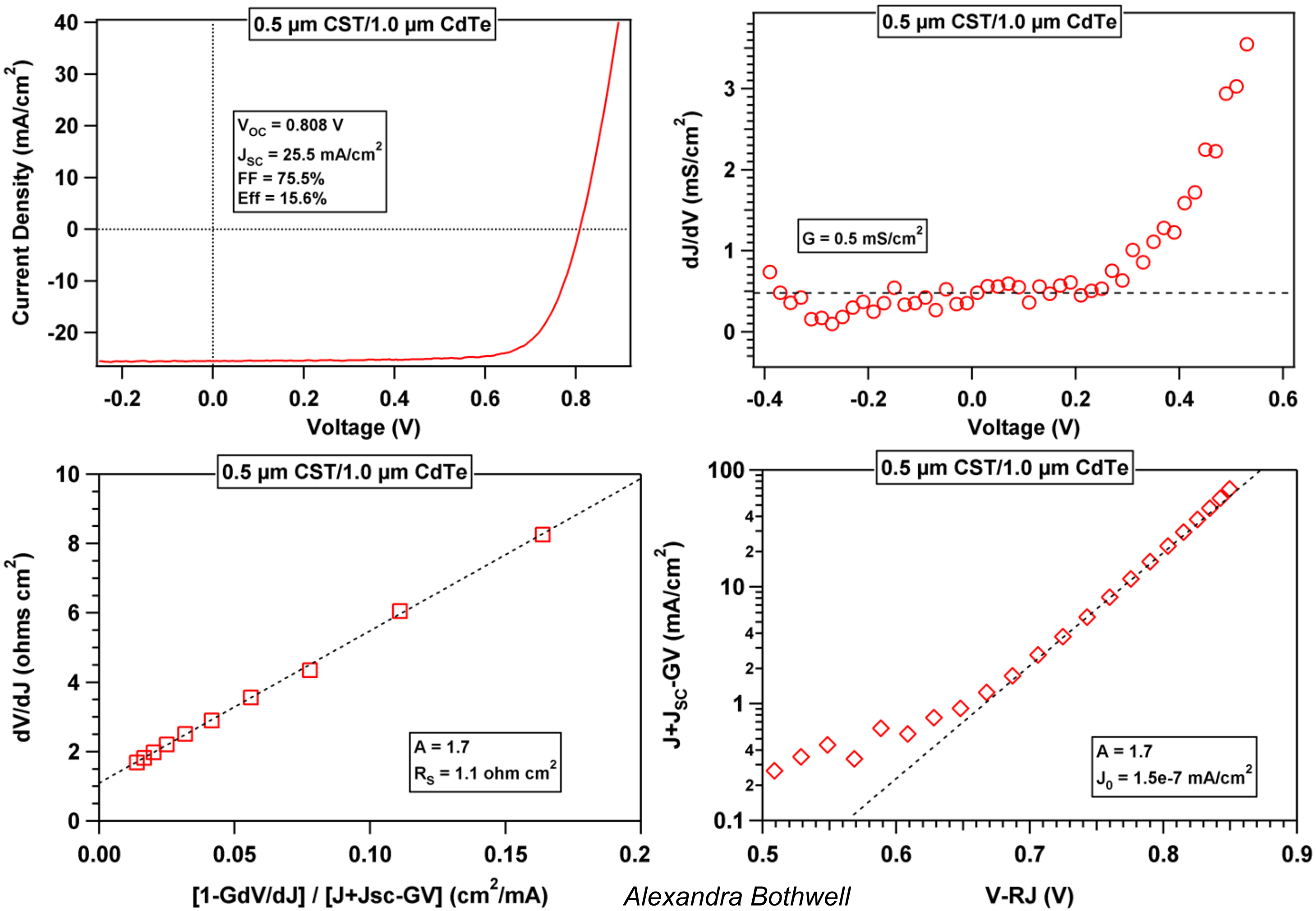
(5) Conductance: reduces current at MP:

$$\Delta J_{MP} \sim GV_{MP} \sim 0.009x450 \sim 0.9 \text{ mA/cm}^2$$

Cell Analysis: Recent CdTe Example

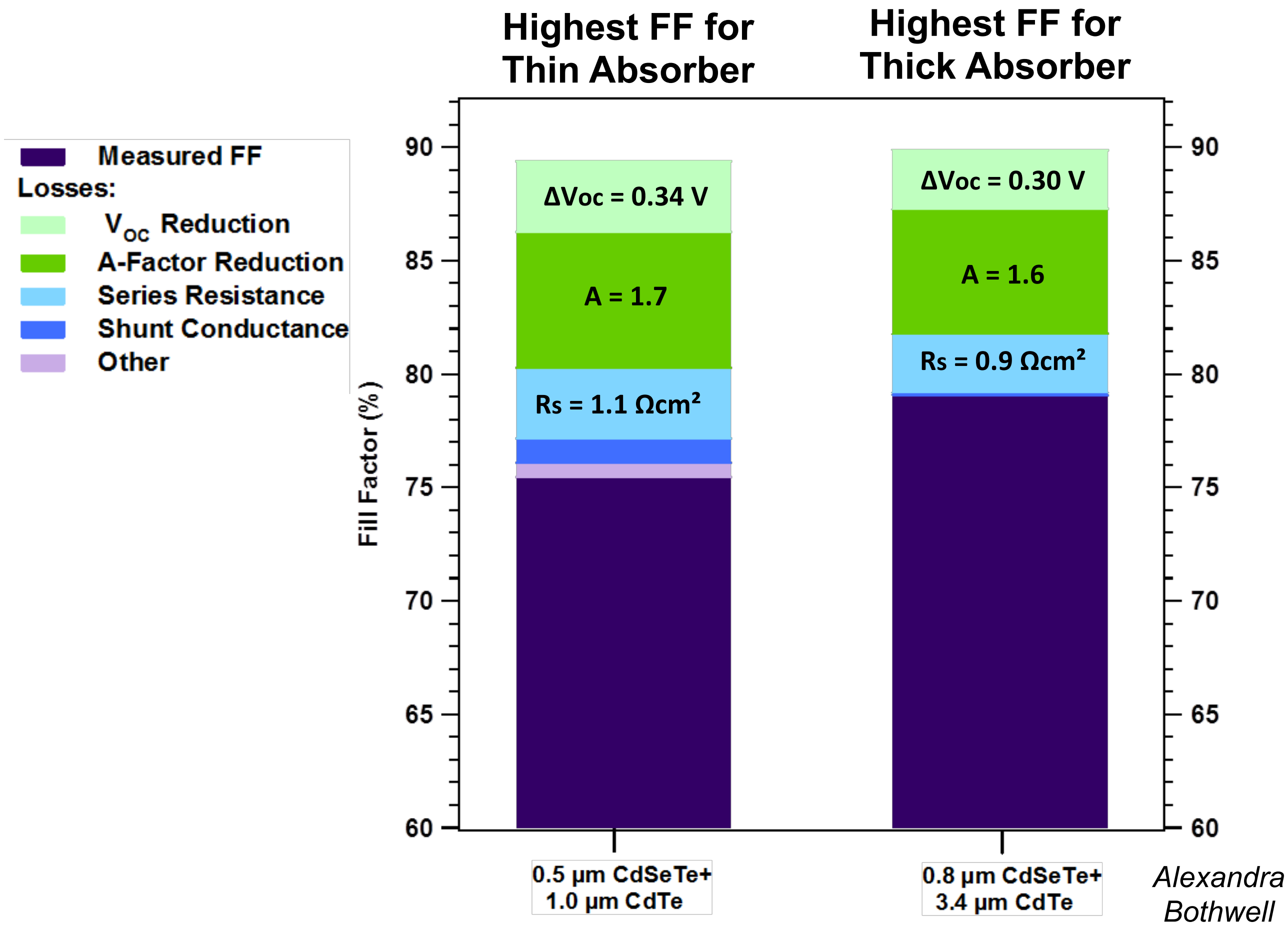
Note that G, R_S, and A all affect the fill factor

$$J = J_o e^{q(V-R_sJ)/AkT} + GV - J_{SC}$$



Alexandra Bothwell

Separation of Fill-Factor Losses



Percentage FF Losses

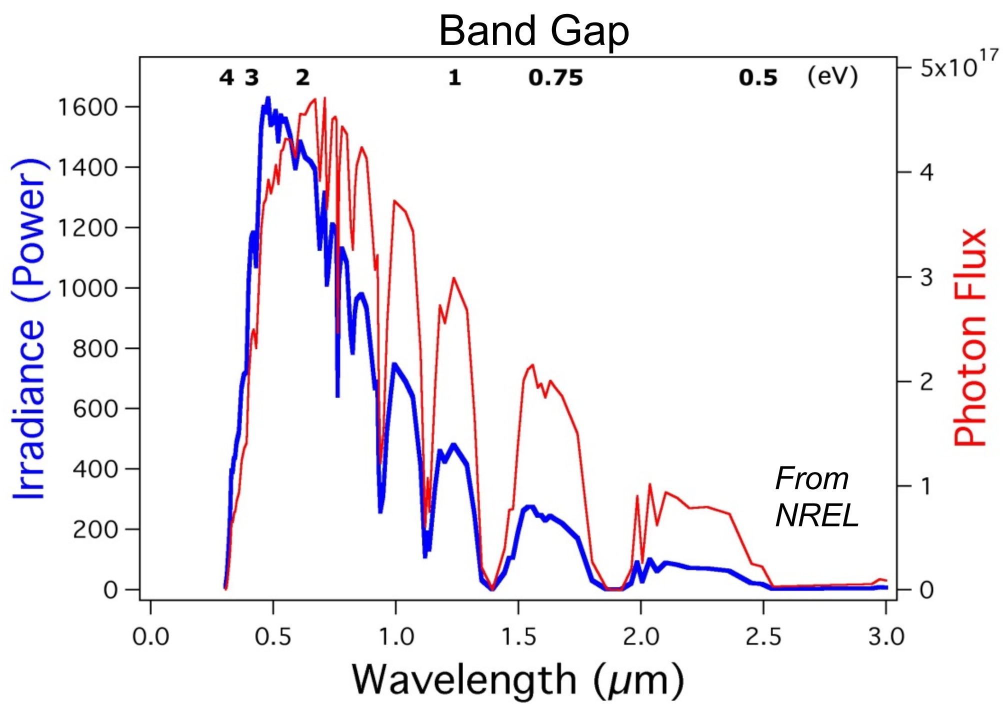
Absorber Thickness (µm)	Voc (%)	A-Factor (%)	Series (%)	Shunt (%)	Other (%)
1.5 (thin)	3.1	6.1	3.0	1.2	0.6
4.2 (thick)	2.6	5.5	2.6	0.1	--

Quantum Efficiency

QE(λ) = electrons/photons(λ)

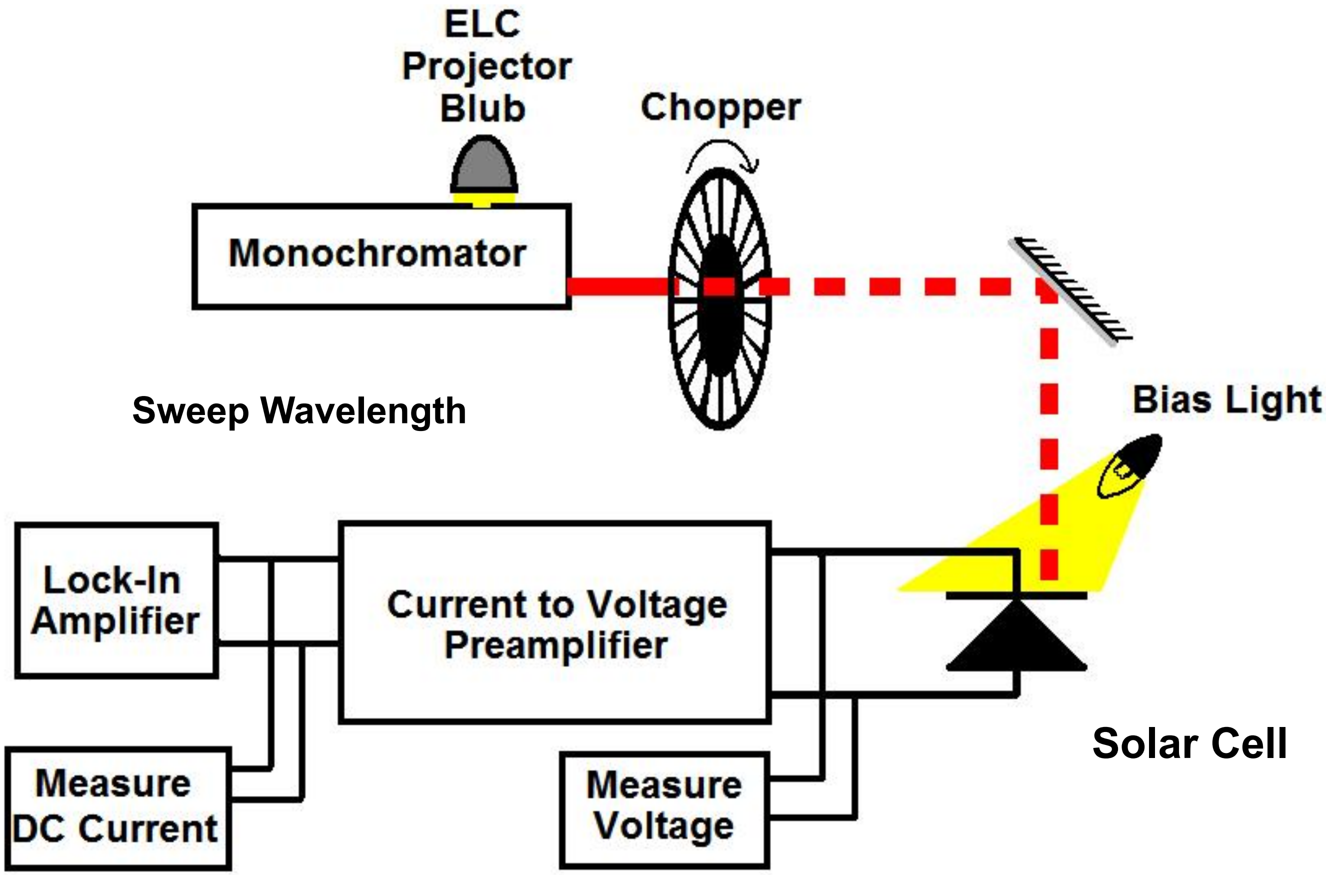
Solar spectrum plotted two ways

- Photon flux (photons/sec-cm^2/μm) is most useful for QE calculations
- Maximum current (integration of red curve) is ≈70 mA/cm^2 for zero band gap; ≈30 mA/cm^2 for 1.5 eV



Optimal band gap at maximum of photon spectrum? Close, but actually slightly smaller (about 1.4 eV).

Quantum Efficiency Measurement

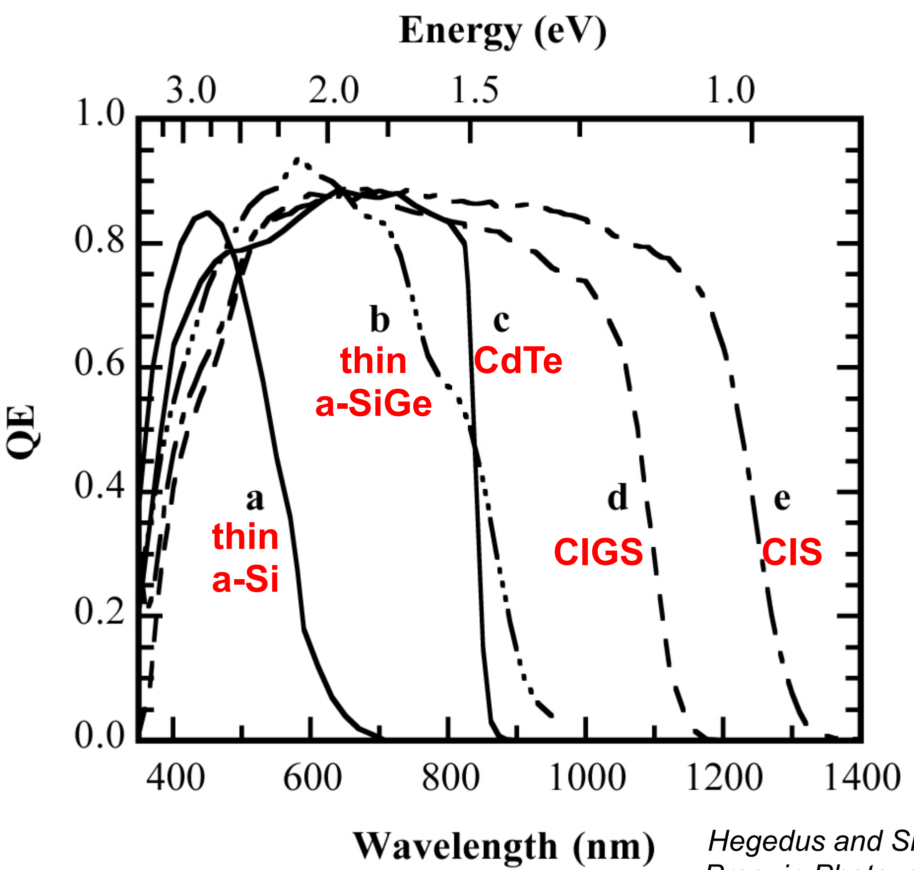


From T. Nagle

QE (sample) = QE (reference) x signal (sample) / signal (reference)

Quantum Efficiency from Different Types of Cell

Long-wavelength cutoff determined by the band gap; generally sharper for thicker absorbers



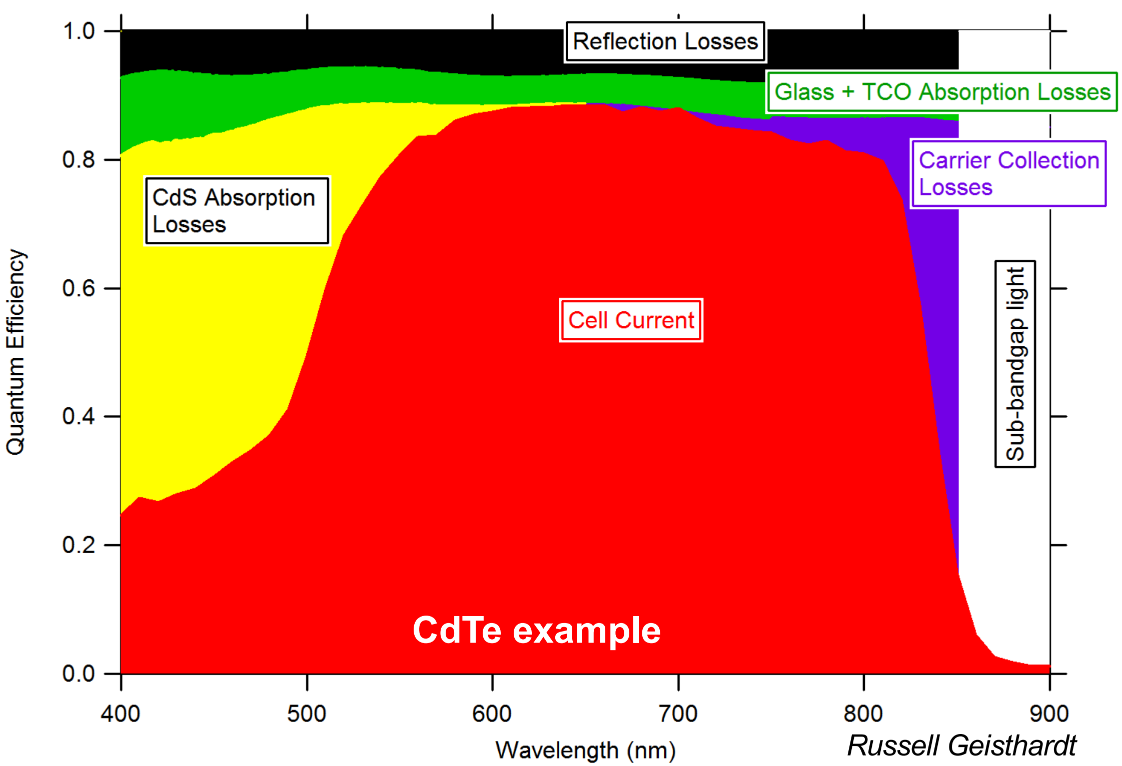
Hegedus and Shafarman in Prog. in Photovoltaics, 2003

Quantum Efficiency and Optical Analysis

(1) Measure QE and optical properties of each layer.

(2) Weight by spectrum and integrate up to band-gap cutoff for J_{SC} (should equal measured J_{SC}) and current losses.

(3) Result is a quantitative measure of each current loss and a consistency check on current measurement.

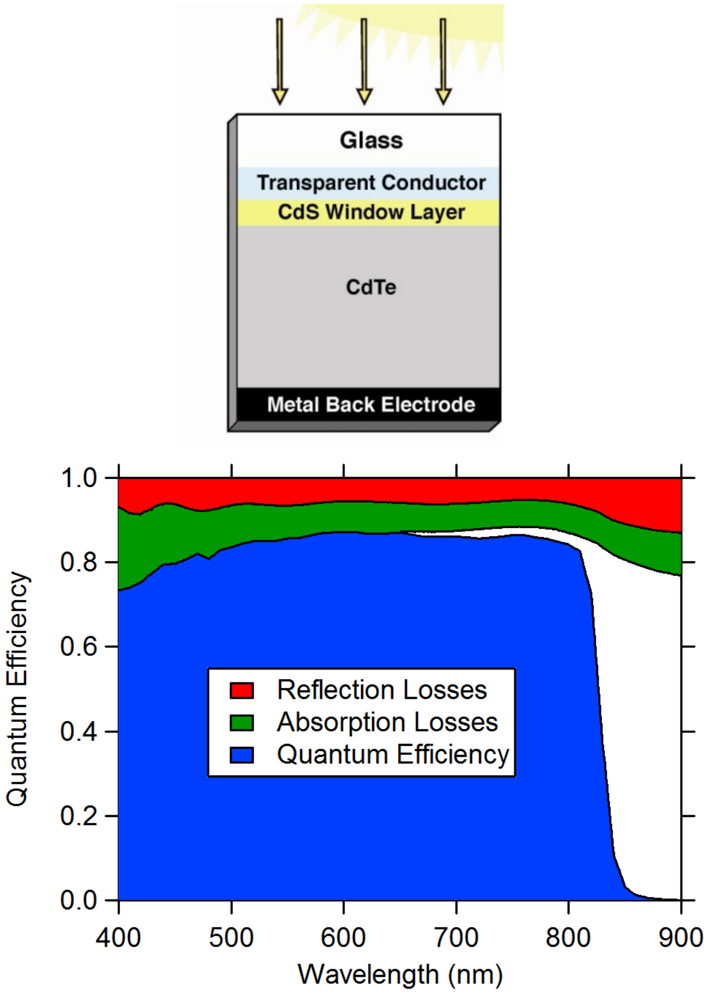


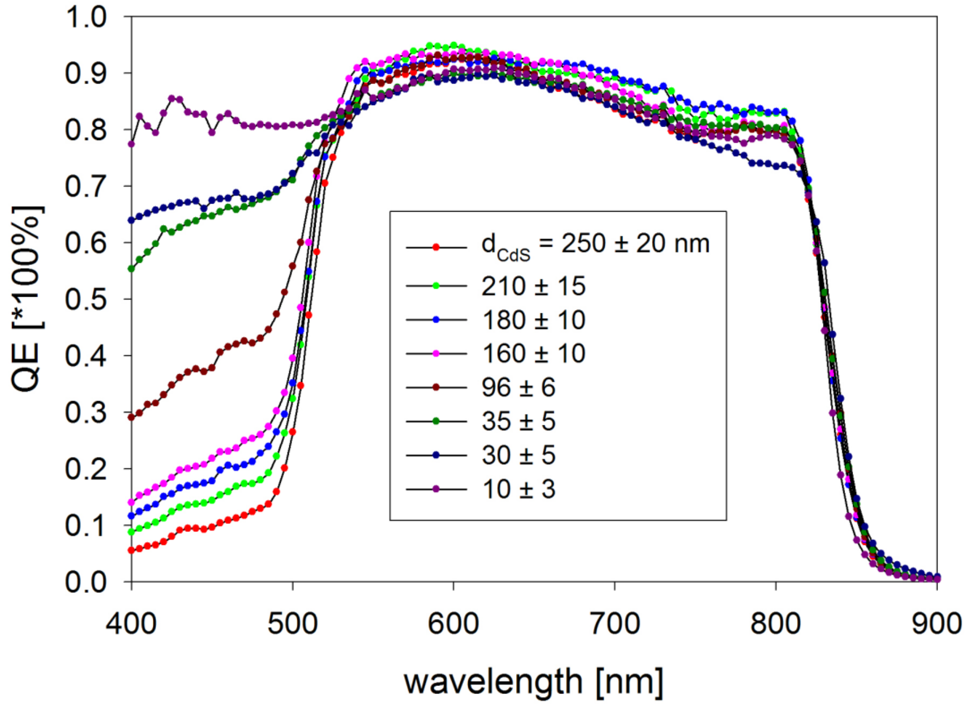
$$J_{SC} = \int QE(\lambda)\, J_{solar}(\lambda)\, d\lambda$$

$$J_{loss} = \int Loss(\lambda)\, J_{solar}(\lambda)\, d\lambda$$

CSU Cell Optical Losses; QE	Current (mA/cm²)
Reflection	2.1
Glass + TCO Absorption	1.7
CdS Absorption	3.4
Collection Loss	0.9
Cell Current	21.0
Ideal Current	29.1

Example of Quantum-Efficiency Variation





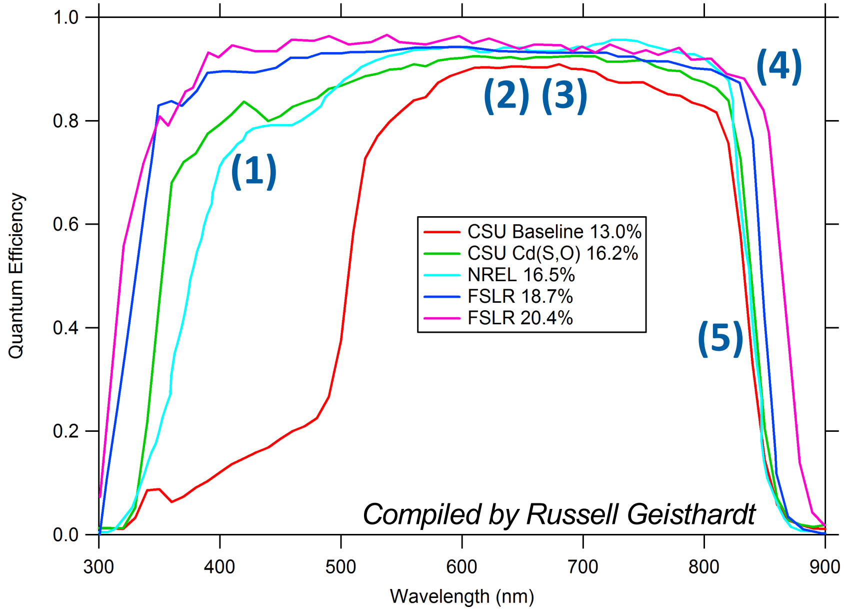
Large variation in CdS loss; little change in other losses

QE (sample) = QE (reference) x signal (sample) / signal (reference)

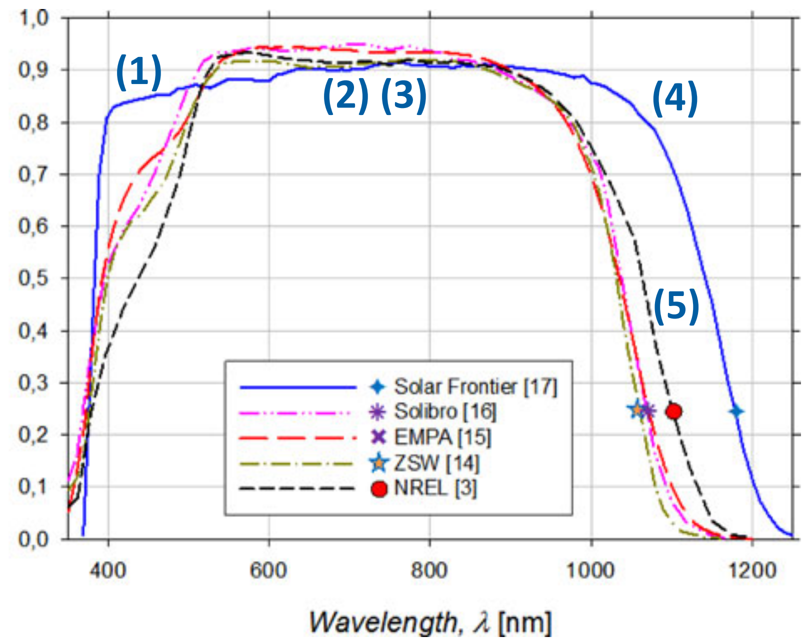
QE Tracking of Improvements in Cell Current

And identification of what has changed

CdTe



CIGS



(1) Less use of CdS

(2) More use of AR coatings

(3) Less absorbing contact layer

(4) Sharper knee

(5) Band-gap variation

Quantum Efficiency Measurement Pitfalls

(1) Use of calibrated reference cell critical (light flux and spectrum can vary over time).

(2) Light spot can may not fall completely within the cell, or be partially blocked by grid fingers. Its area can also shift somewhat with wavelength.

(3) Correct QE interpretation requires little or no slope in J-V curve at measurement bias (usually 0); not always the case.

(4) If light/dark superposition is poor, QE measured in not that under operational conditions. Can be addressed with bias light.

(5) QE beam often weak, hence possible signal-to-noise issues.

(6) Non-uniform cells will give different QE in different places.

(7) And of course, possible user errors.

Reality check: make sure integrated QE, weighted by solar spectrum equals measured J_{SC}.

Capacitance in Absence of Defect States

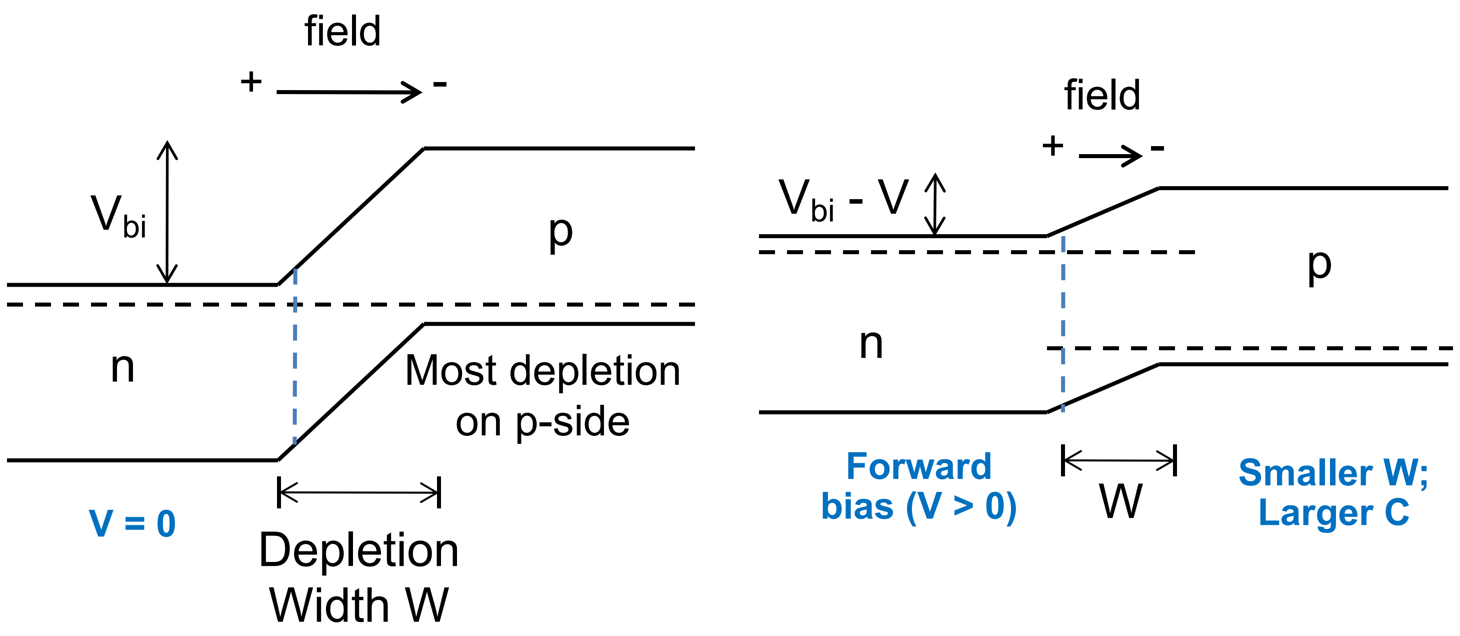
Measures depletion width (parallel-plate capacitor):

$C = \varepsilon A/W$

$W = [2\varepsilon(V_{bi}-V)/qp]^{1/2}$ assuming p << n

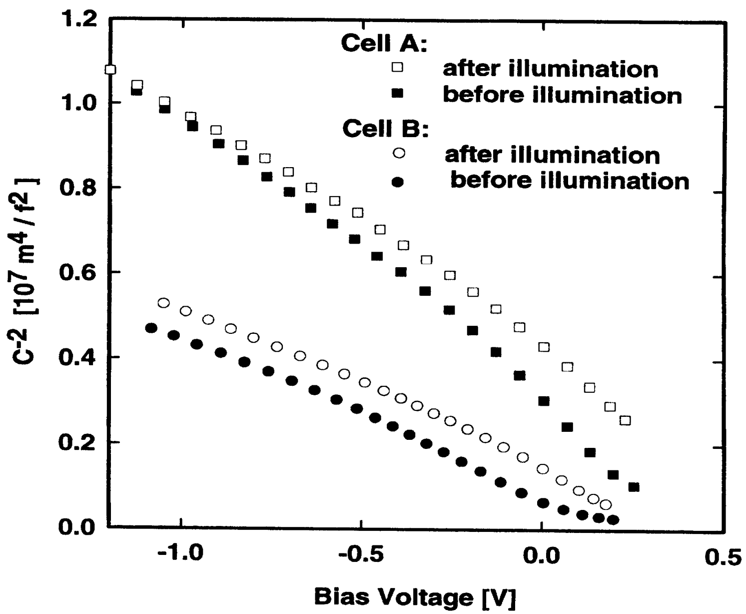
$$(C/A)^{-2} = 2(V_{bi}-V)/q\varepsilon p \quad [m^4/f^2]$$

Slope of C^{-2} vs V gives hole density p



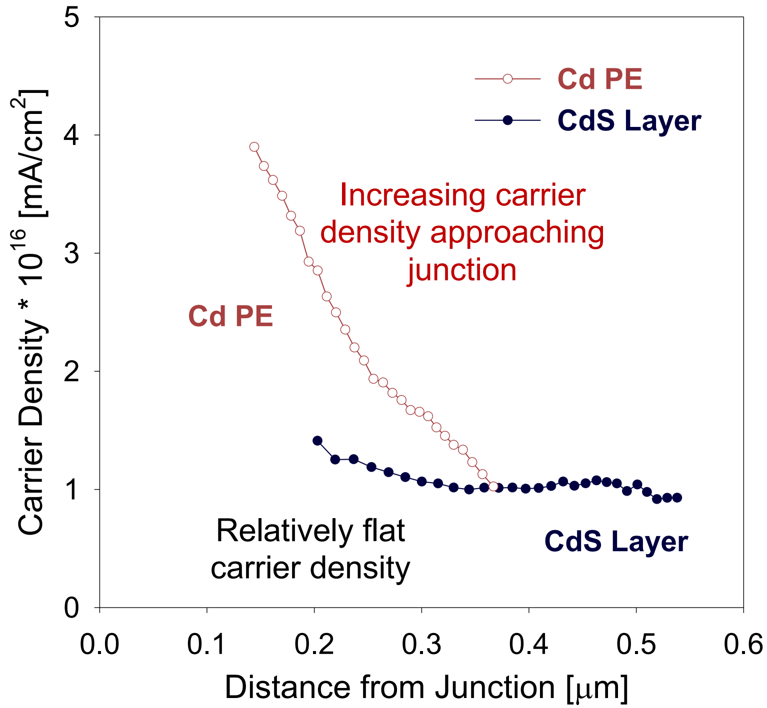
$1/C^2$ vs. Voltage

In ideal case, slope yields carrier density p, and intercept is V_{bi}



In practice, curvature means a gradient in carrier density

Capacitance defines distance from junction, slope at that voltage gives carrier density



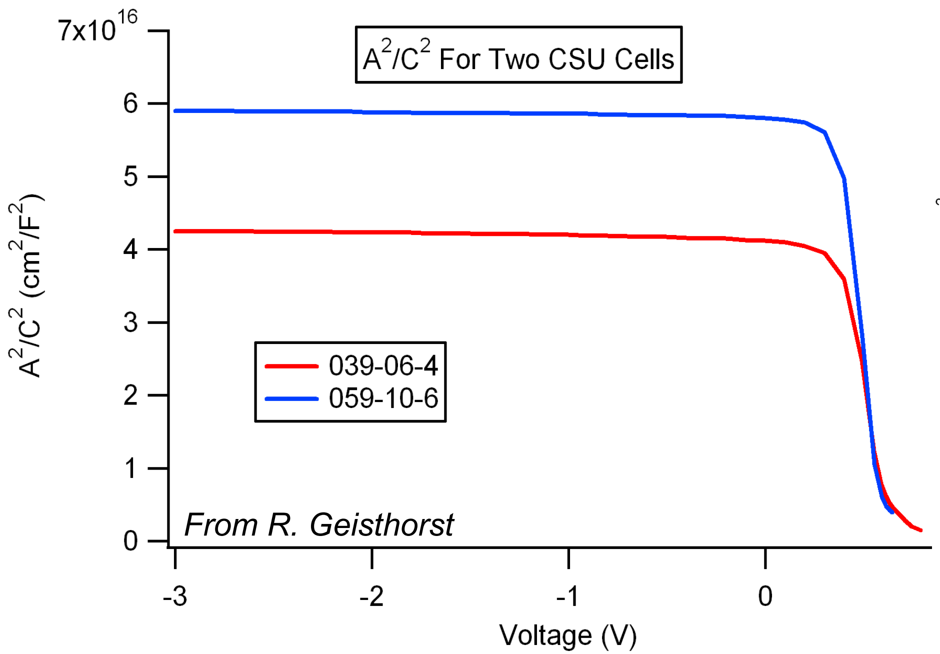
P. Johnson et al, 17th European PVSC (2003)

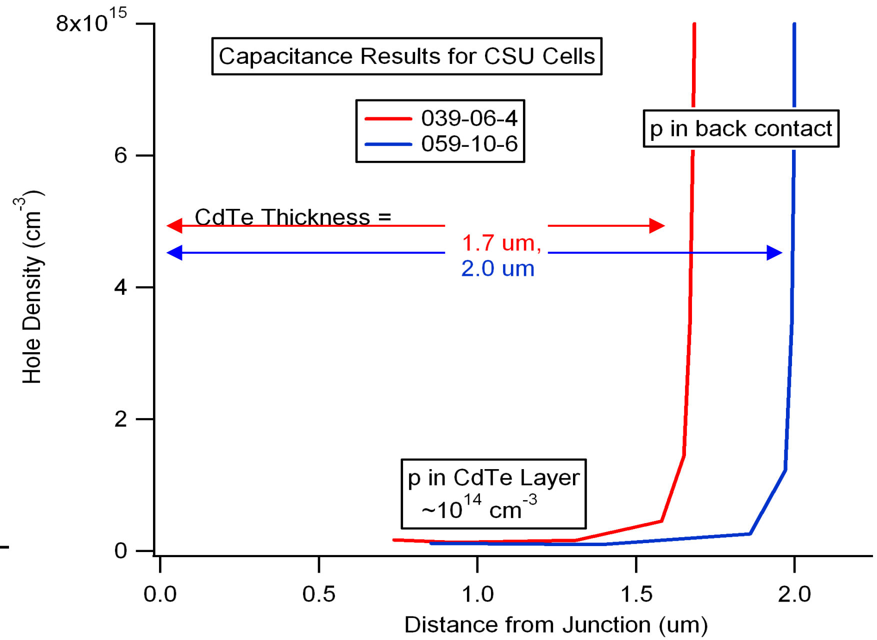
Note: Capacitance needs to be measured at a frequency where it is not affected by other circuit elements, typically ~ 100 kHz

Nearly Fully Depleted Cells

Flat part means entire absorber is depleted (capacitance determines thickness. Steep part, however can determine carrier density.

Carrier density is actually very small. The steep rise is the approach to metal-like back contact.





Much more information available from capacitance measurements also, but won't try to cover today

Summary

(1) Current-voltage (J-V) measurement key to overall picture of a solar cell; expansion to variations with temperature, intensity, and time is often valuable as well.

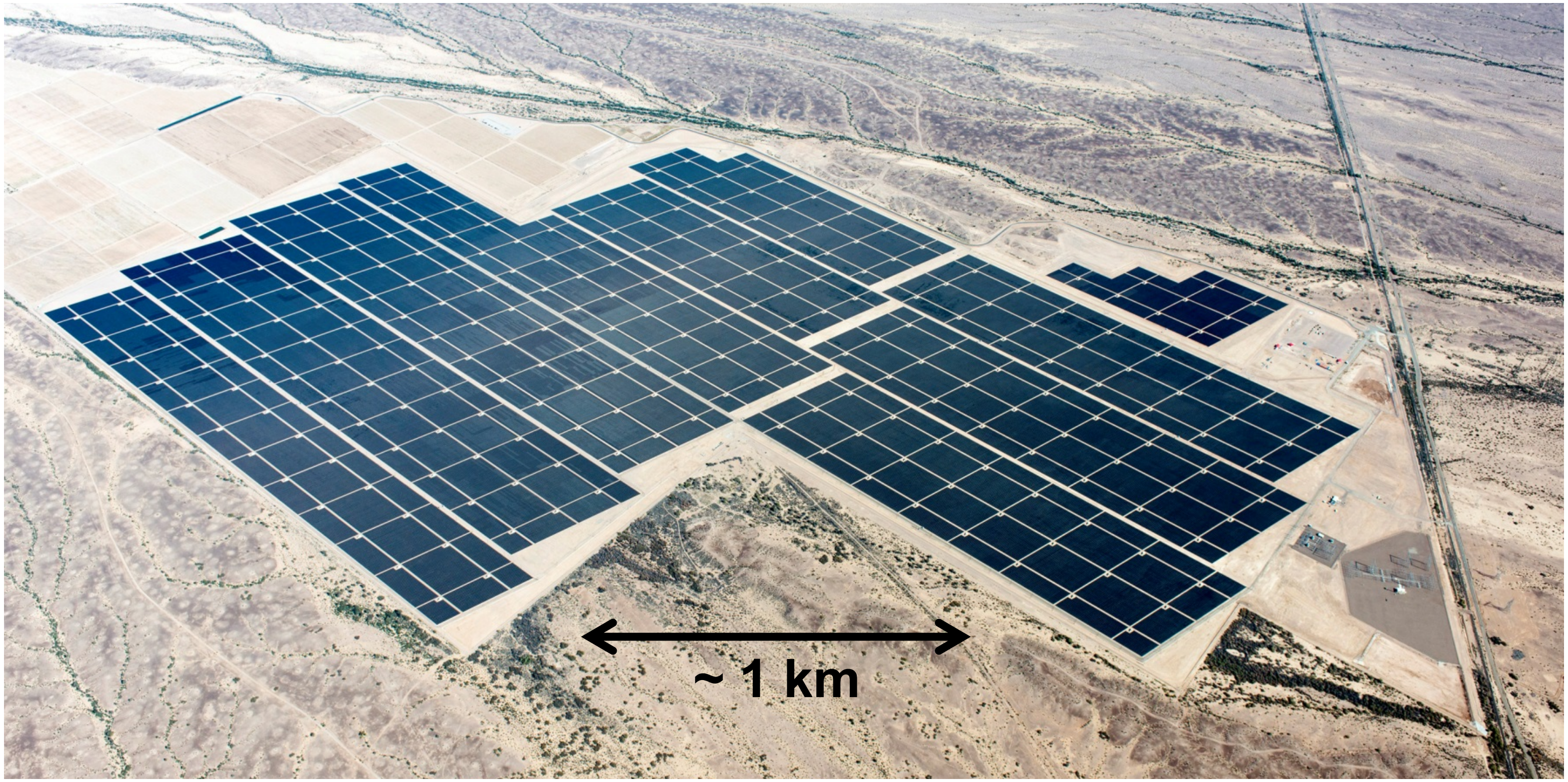
(2) Careful analysis can (usually) extract diode-equation parameters and can also identify features not included in the diode equation.

(3) Quantum efficiency and capacitance reveal additional information about a cell. Again careful measurement and analysis, and sensitivity to non-standard features, is required.

(4) Many more measurement and analysis strategies available, and others you might develop.

Final Message

Today's cells may be tomorrow's power plants



First Solar Aqua Caliente CdTe PV Installation in Arizona
290 MW, 9 sq. km.