Electrical Characterization and Measurement of Solar Cells

Horace Chen
Keithley Brand, Tektronix Technology
Date: October 2013

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Agenda

1. Solar Cell Market and Principle Overview
2. Solar Cell Efficiency
3. I-V Measurement of Efficiency
4. Understanding the Sources of Efficiency Loss
5. Measuring Key Parameters of a Solar Cell
6. Summary and Conclusions

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Solar Power Plant with MPPT of One Axis, US

Source: http://en.wikipedia.org/wiki/Photovoltaics

‘Mega Solar Panels’, 70MW, Southern JP

Source: http://www.renewableenergyfocus.com/

Japan Set to Overtake US and Europe as Leading Solar Market of 2013

Source: http://www.solarsystems-usa.net/

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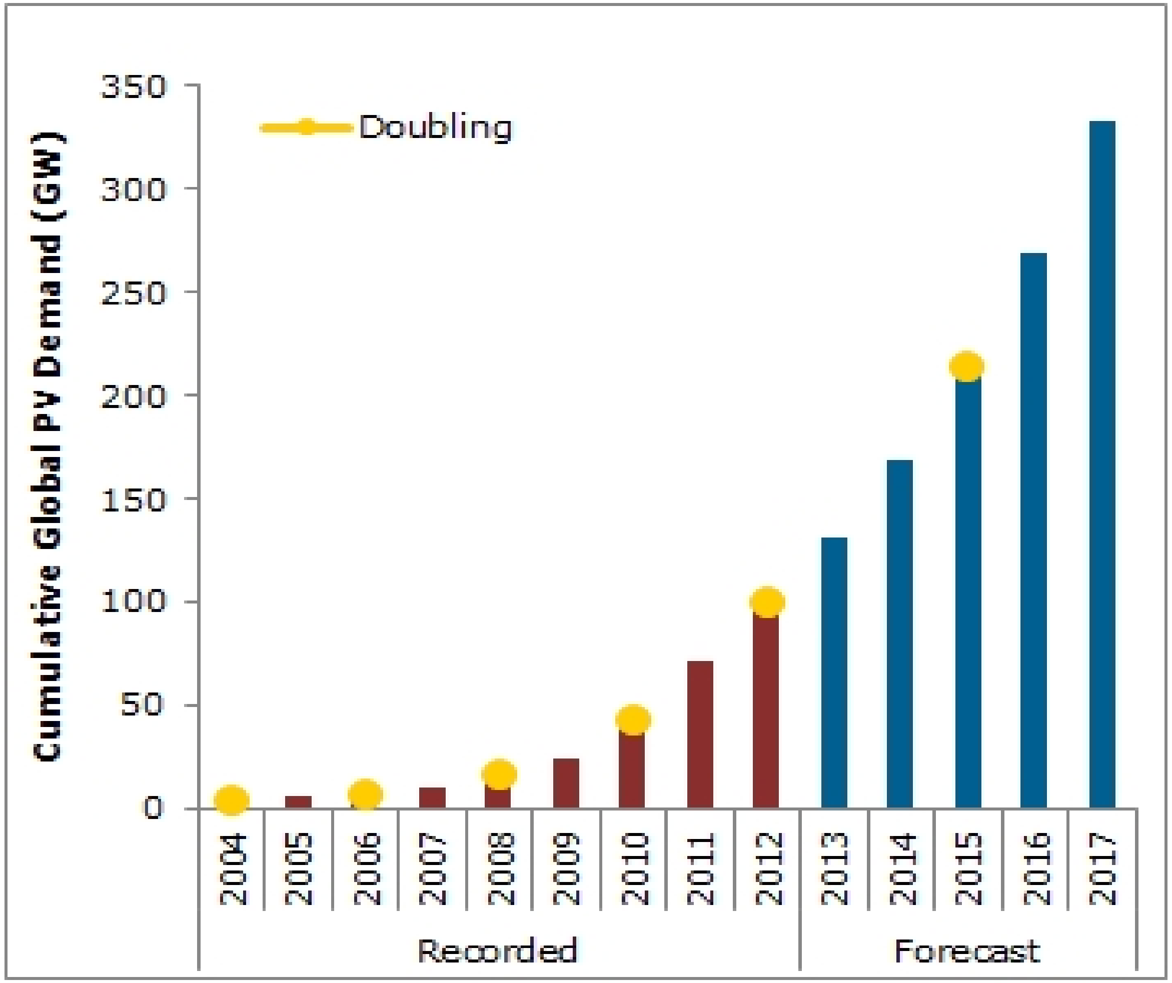
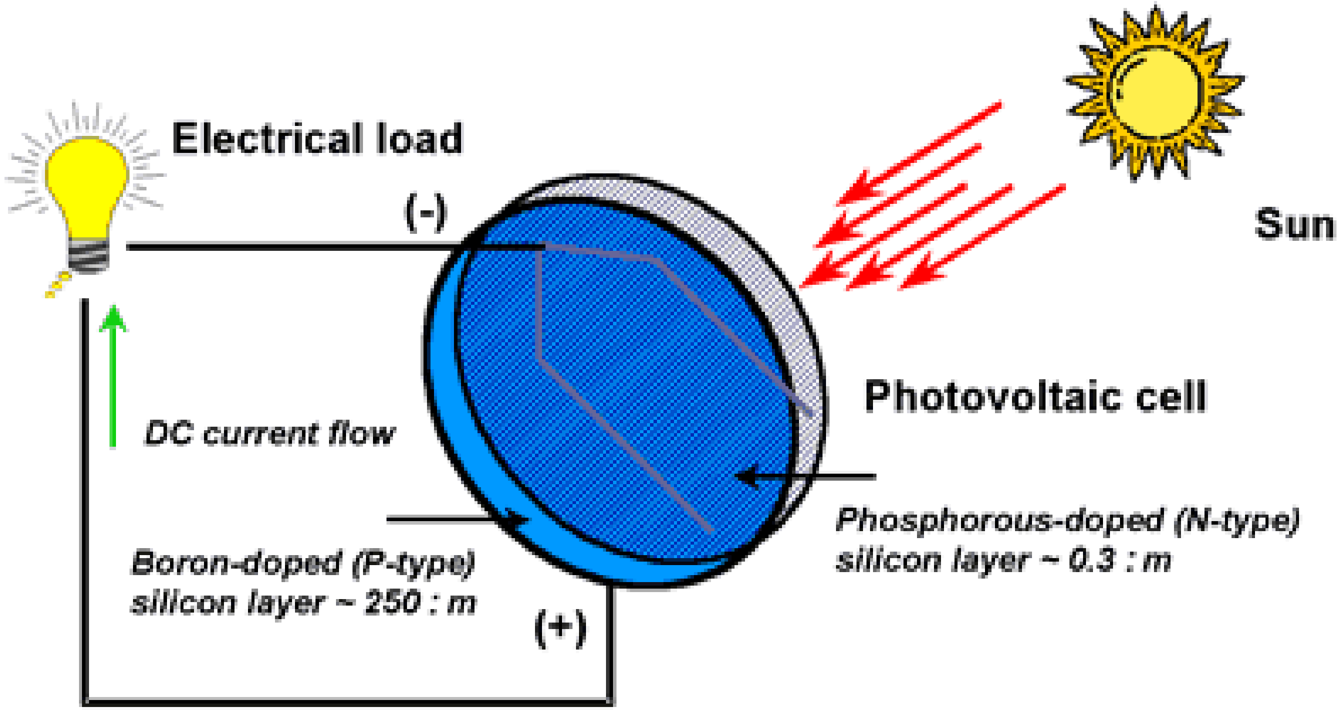
Global Solar Panel Demand to Double in 3 Years



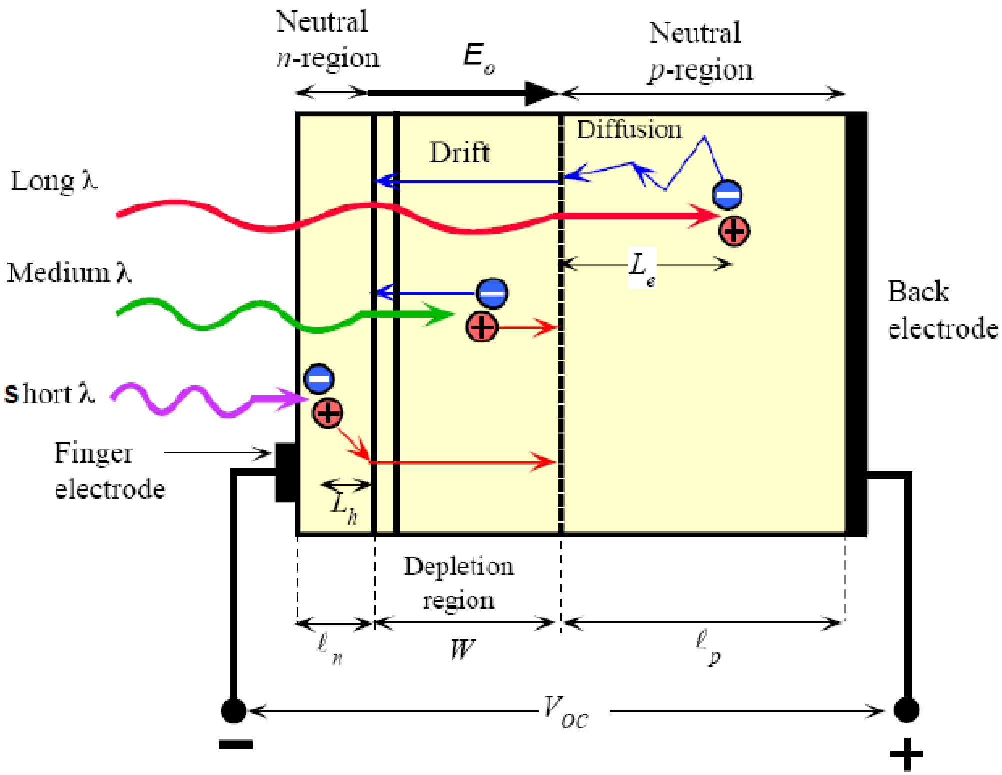
Source: http://www.solarsystems-usa.net/ ,2013

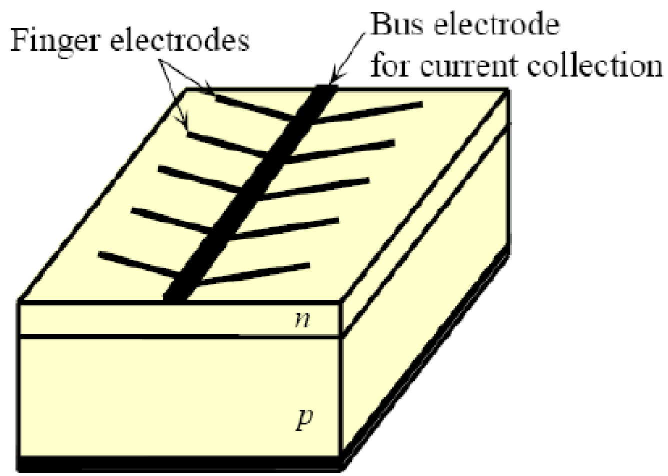
Basic Working Principle of Solar Cell



1. 單晶矽太陽電池(single crystal Si), Wafer type
2. 多晶矽太陽電池(poly crystal Si), Wafer type
3. 非晶矽太陽電池(amorphous Si), Thin film type
4. 化合物半導體太陽電池, Compound semiconductor
5. 其他太陽電池 (Other solar cells)

Schematic of a Typical Single Junction Si Solar Cell: The principle of operation of the solar cell



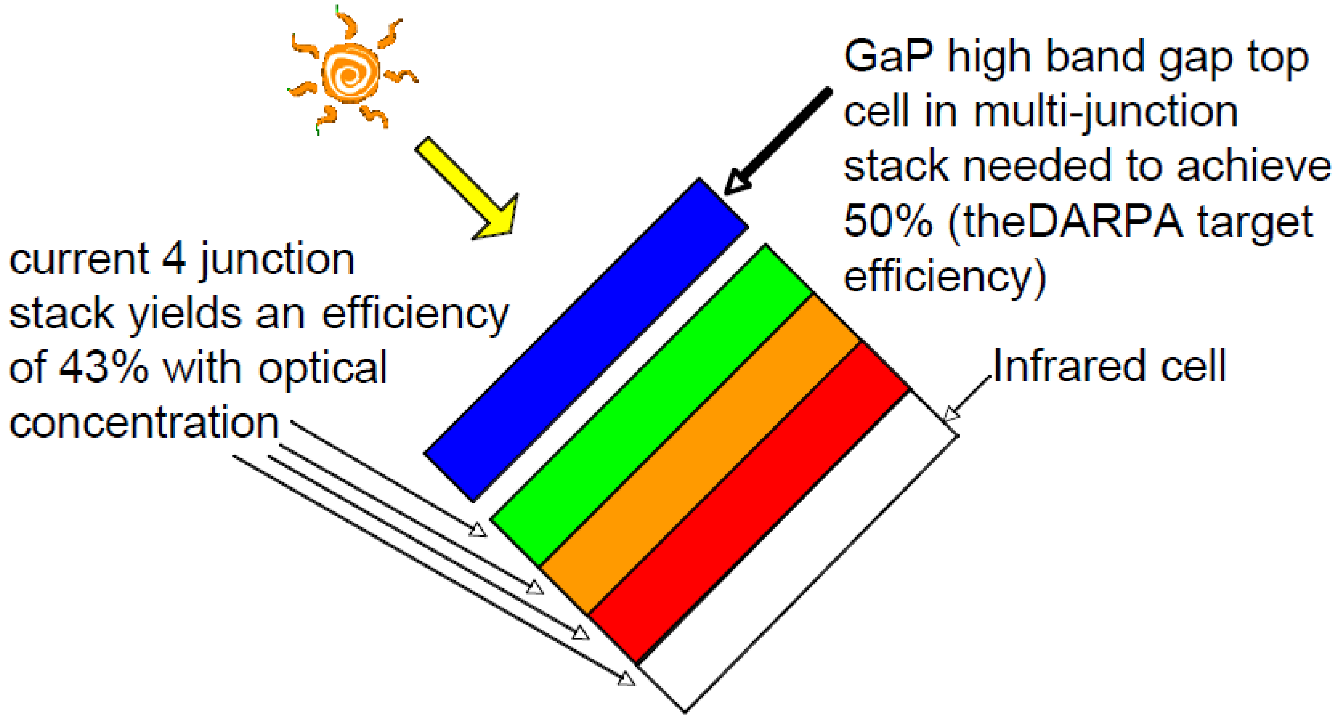


- **A Si pn junction with a very thin and more heavily doped n region**
- **Finger electrodes and thin antireflection (AR) coating on the surface**
- **Generation of Electron-Hole Pairs (EHP)**

Source: Prof. Wei-I Lee, http://ocw.nctu.edu.tw/

Four and Five Junction Solar Cells

High-Efficiency
Multi-junction Photovoltaics



Source : Purdue University Energy Center

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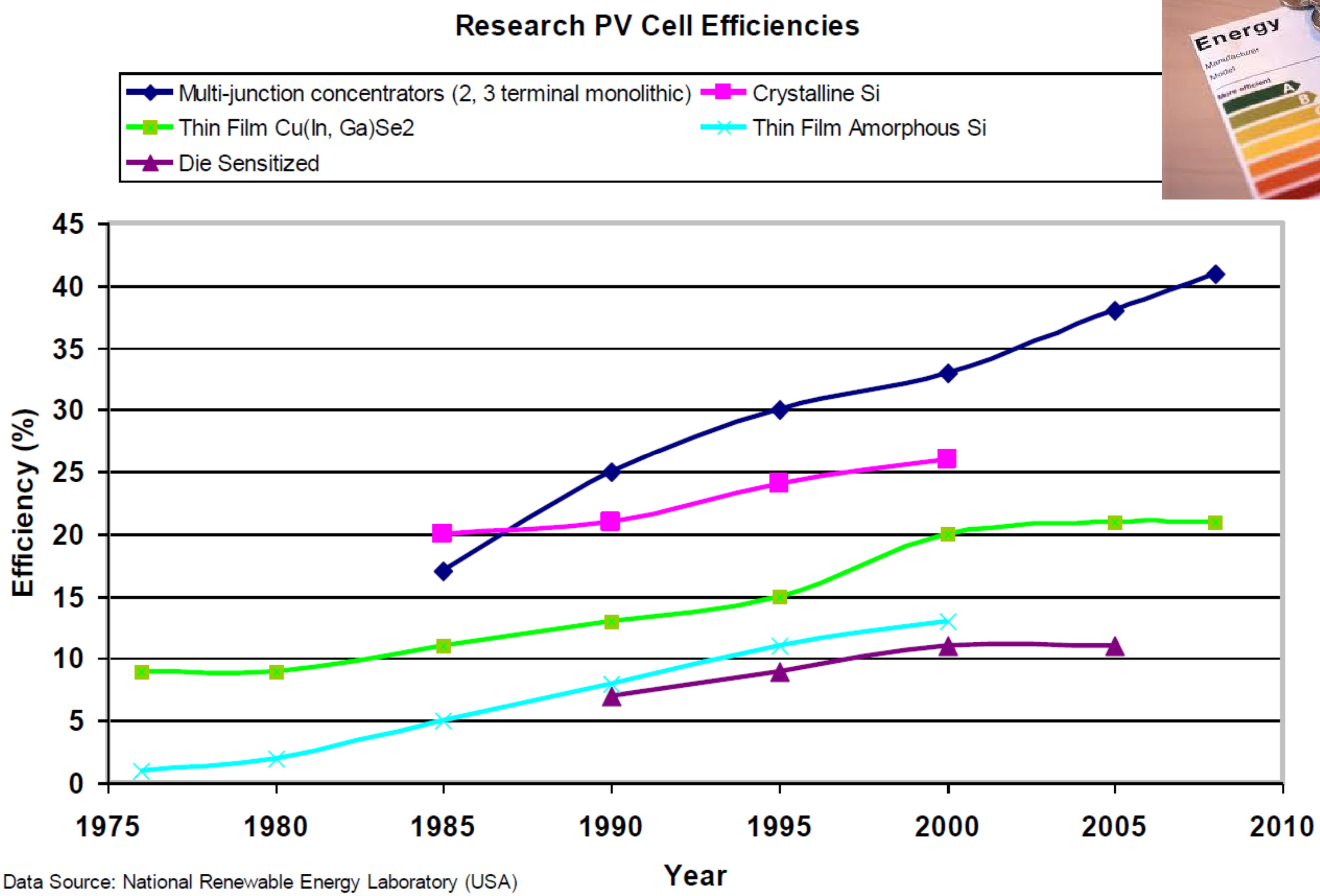
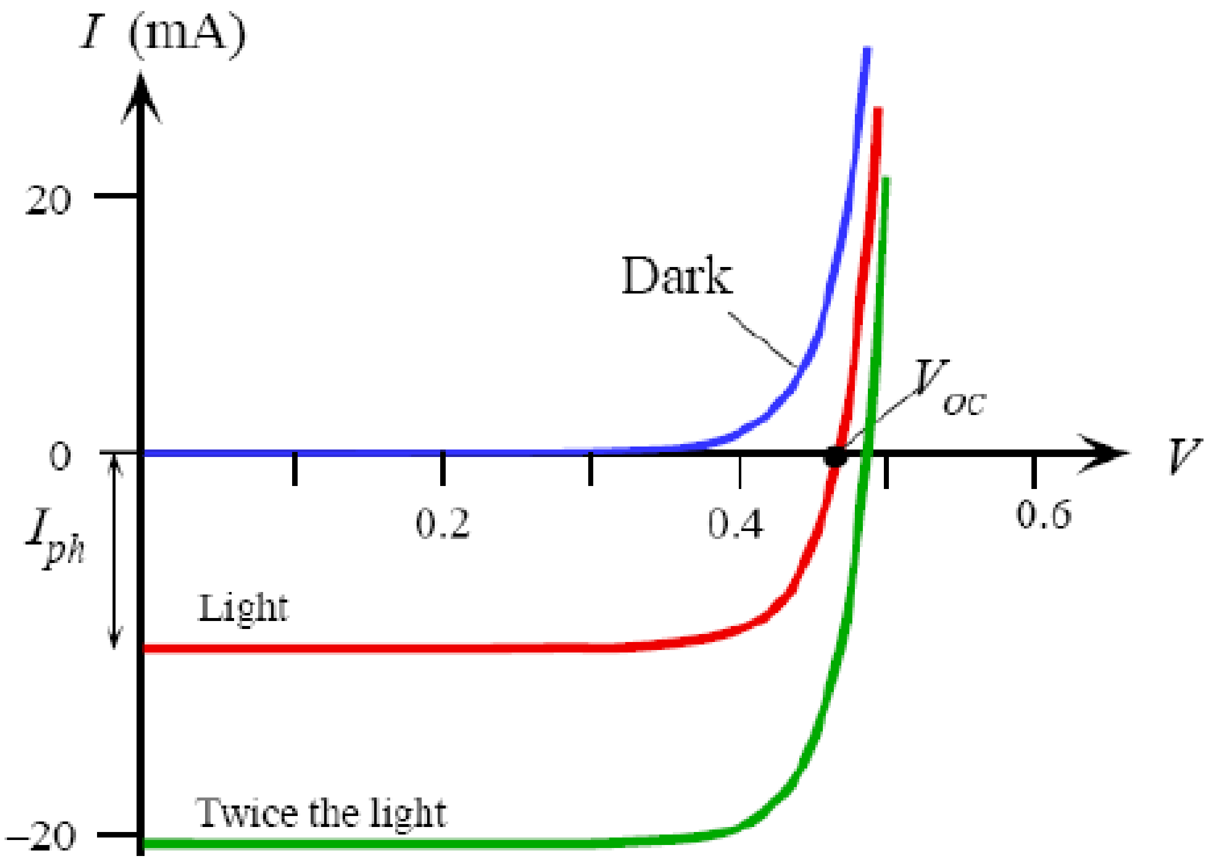
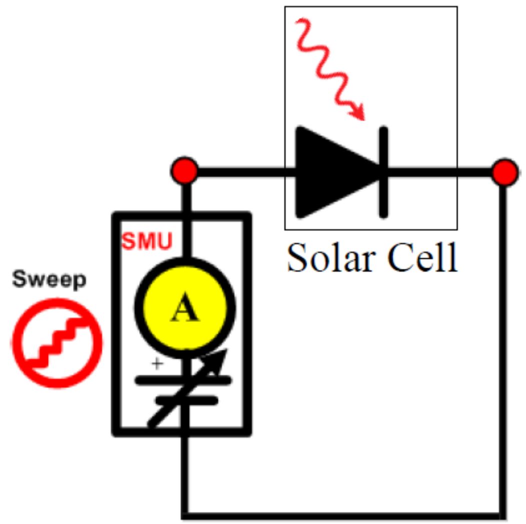
Key Technical Challenge: Increase Efficiency



Data Source: National Renewable Energy Laboratory (USA)

Current-Voltage (IV) Load Sweep of a Solar Cell





I-V under dark, or dark I-V, shifted by I_{sc} ($-I_{ph}$)

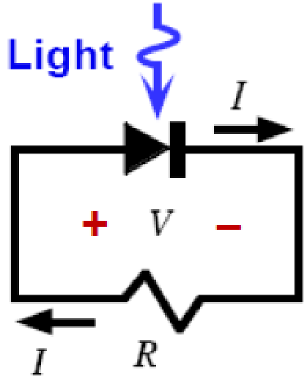
Delivered Power and Fill Factor

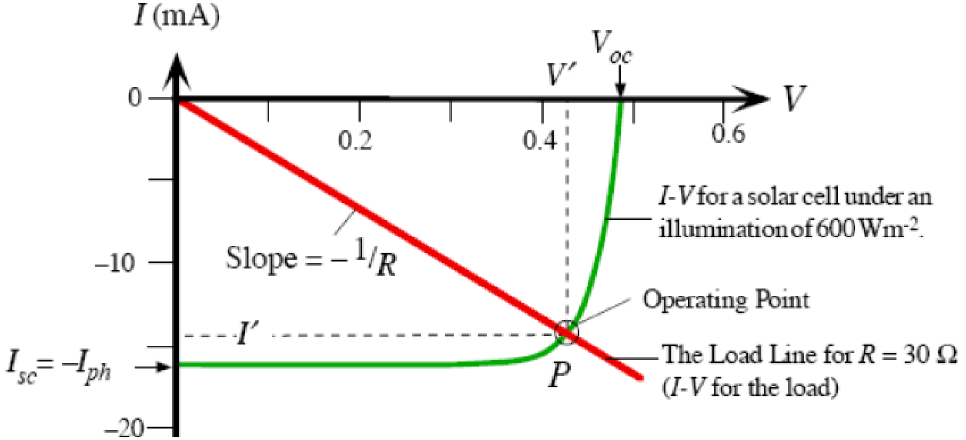
- power delivered to the load, $P_{out} = I'V'$

- fill factor $FF = (I_m V_m) / (I_{sc} V_{oc})$

  $(I_m V_m)$: maximized delivered power, i.e. the largest ($I'V'$) rectangular area obtainable (by changing R or illumination intensity)

- typical FF : 70 ~ 85%





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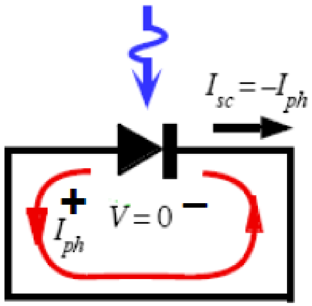
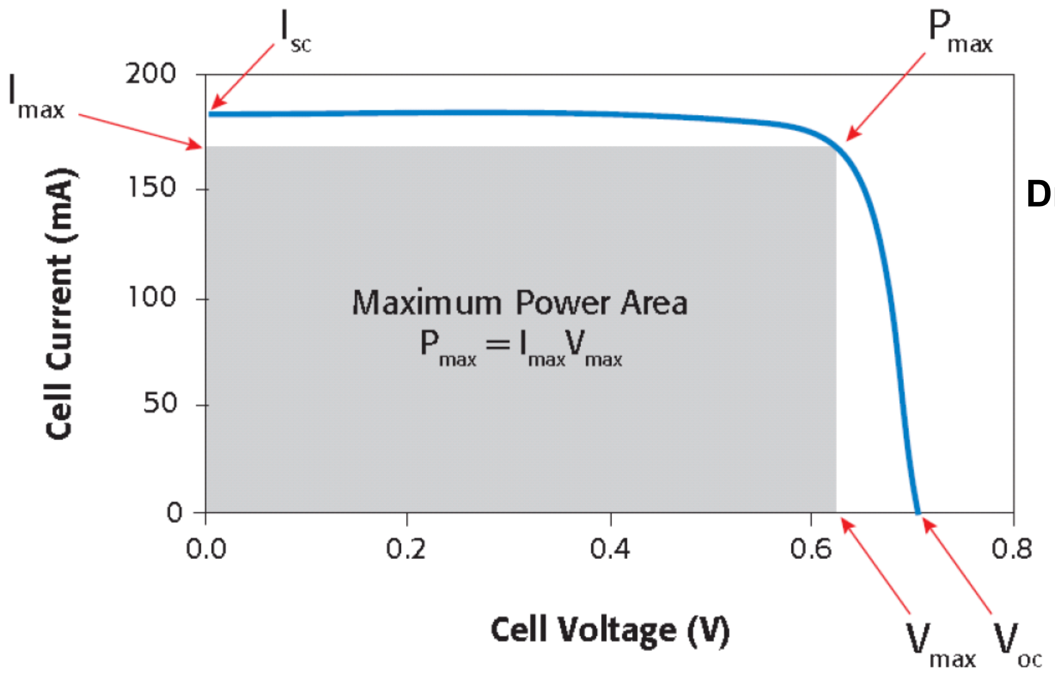
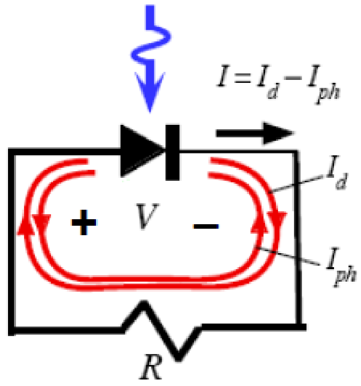
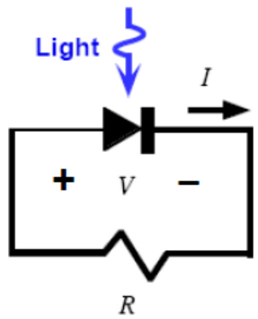


Short Circuit





Driving External Load R

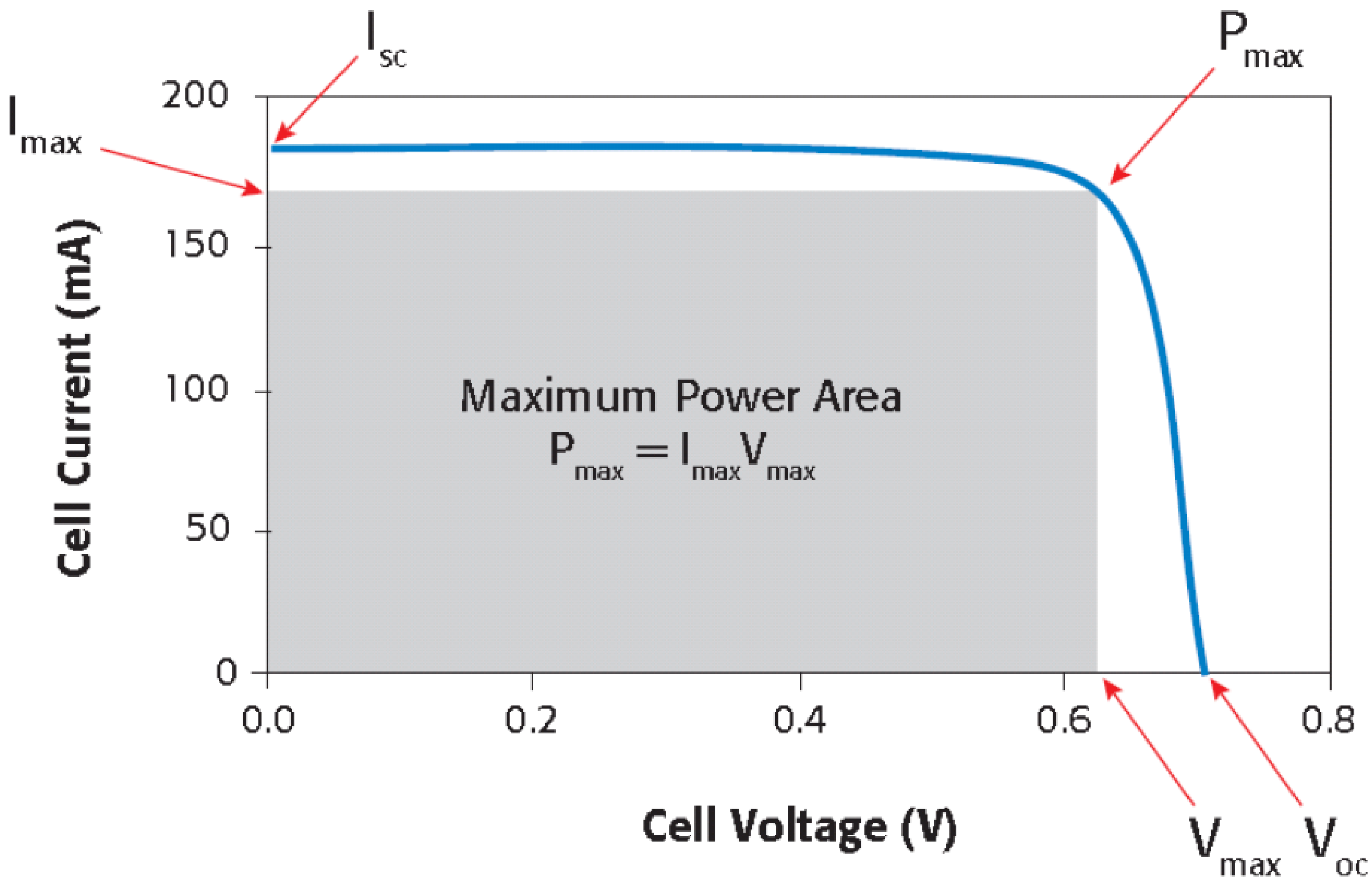


Open Circuit

total current :

$$I = -I_{ph} + I_o\left[\exp\left(\frac{eV}{nk_BT}\right) - 1\right]$$

I-V Measurements for Solar Cell Efficiency

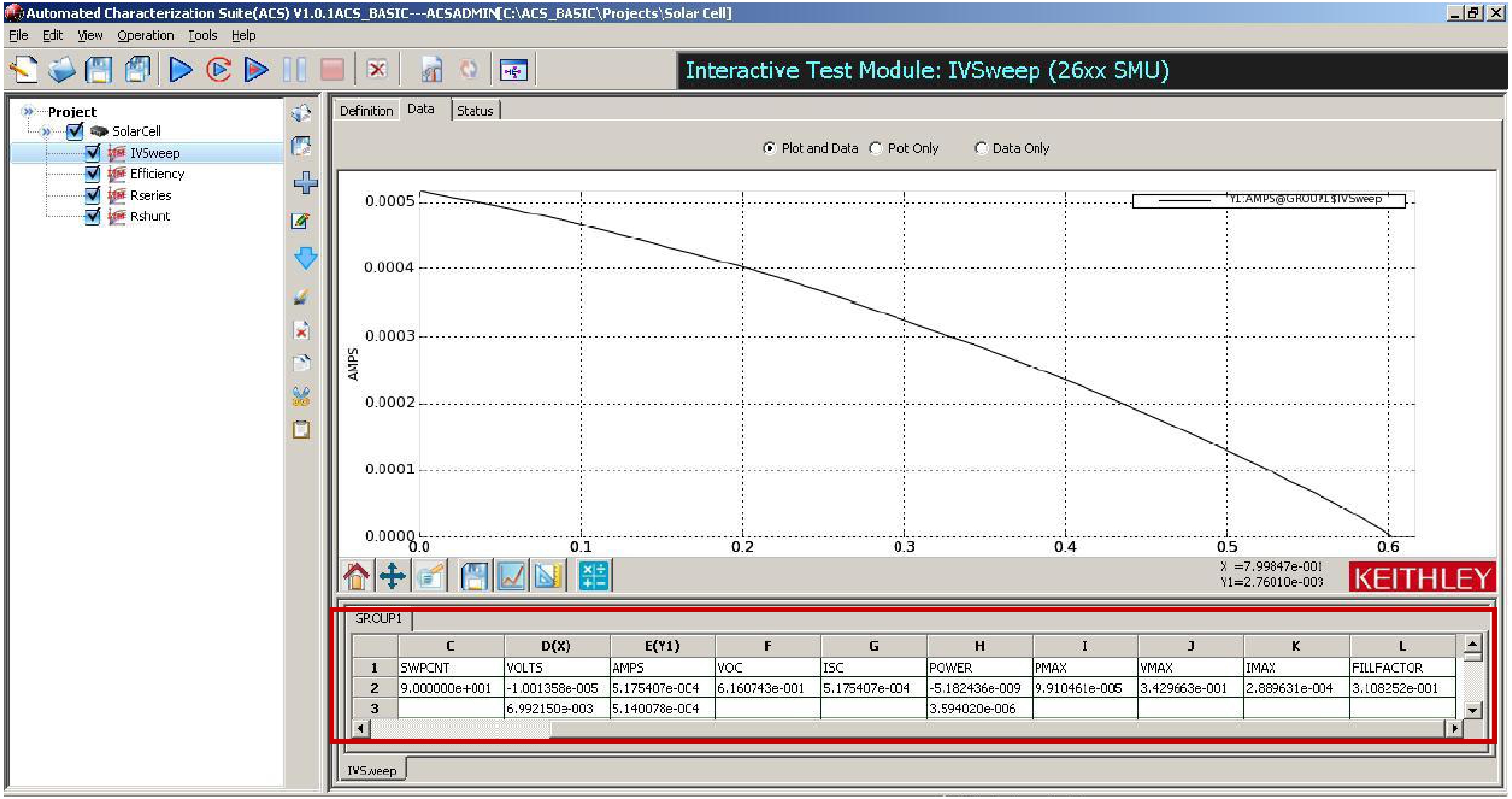


Fill Factor:

$$FF = \frac{I_{MAX} * V_{MAX}}{I_{SC} * V_{OC}}$$

% efficiency vs. an ideal cell

I-V Measurements for Solar Cell Efficiency w/ Keithley ACS (Parameter Extraction)



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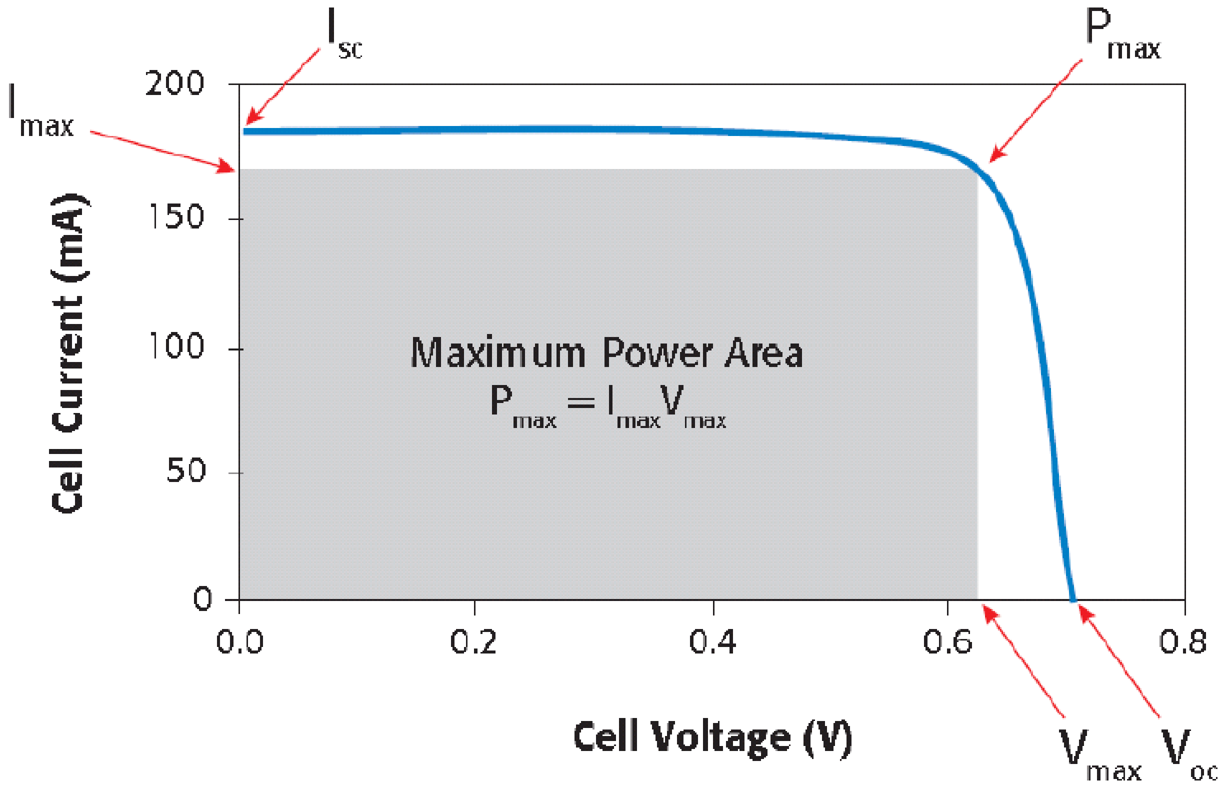
I-V Measurements for Solar Cell Efficiency



Cell Efficiency (η):

$$\eta = \frac{P_{MAX}}{P_{IN}}$$

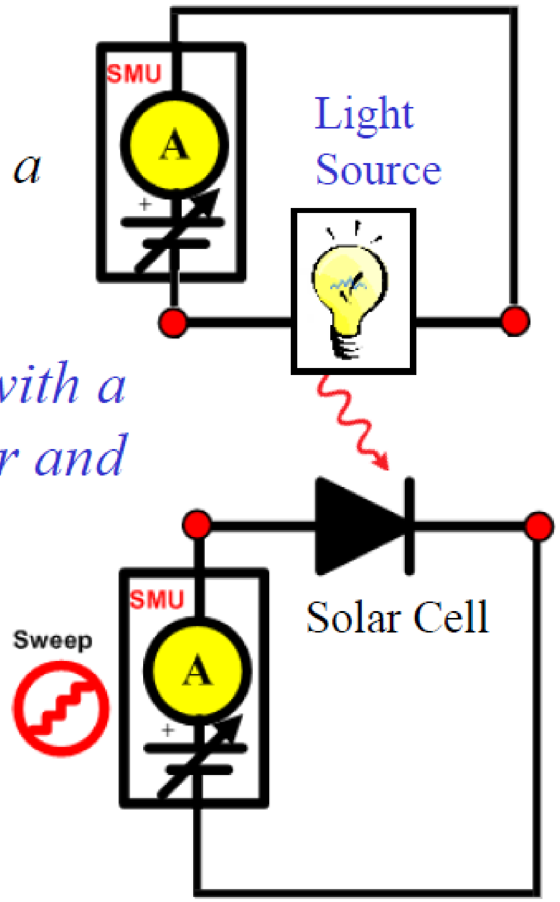
Power output as a ratio of power input to the cell. (P_{IN} is the power of the light intensity on the cell)

I-V Measurements for Solar Cell Efficiency

One SMU can be used to set and monitor power into a light source.

Use a light source with a known output power and spectrum.

One SMU conducts the I-V curve on the cell.



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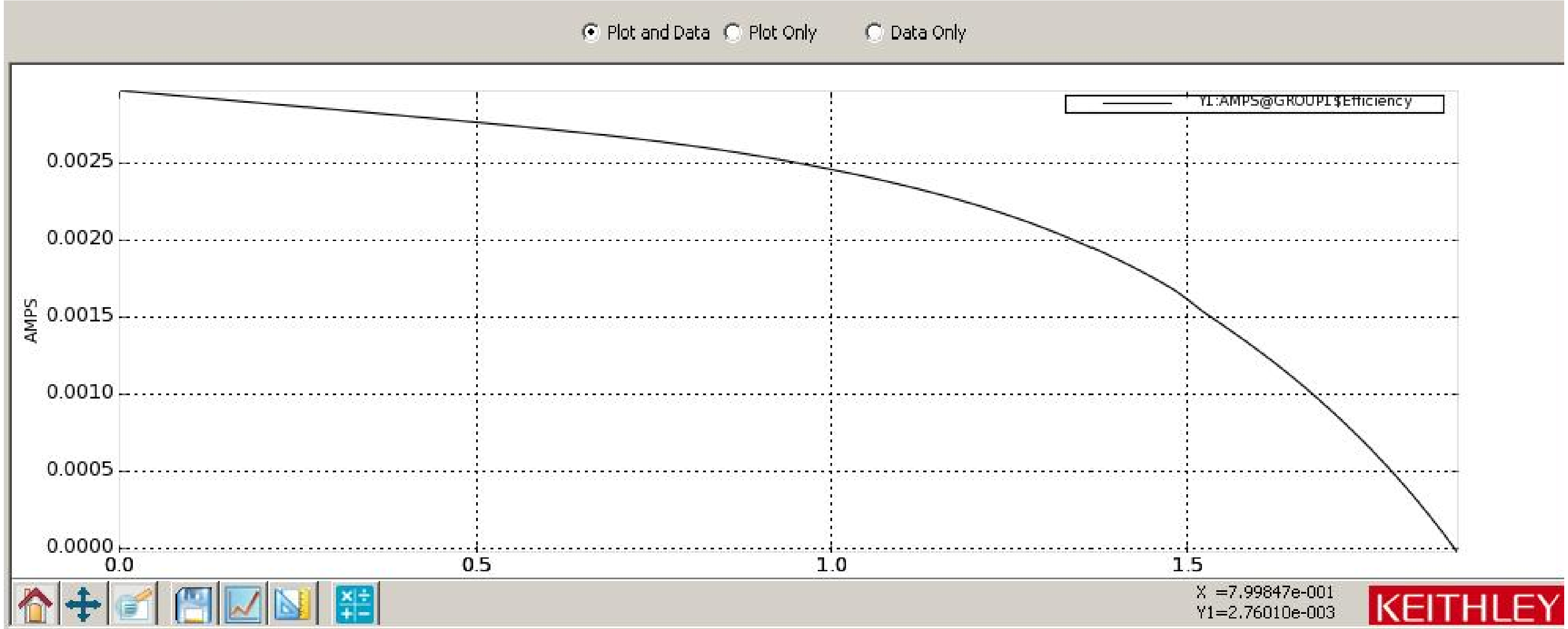
I-V Measurements for Solar Cell Efficiency w/ Keithley ACS (Parameter Extraction)



GROUP1

	I	J	K	L	M	N	O	P	Q	R
1	ISC	POWER	PMAX	VMAX	IMAX	FILLFACTOR	LIGHTPOWER	LIGHTEFF	INPOWER	CELLEFF
2	2.971569e-003	-1.891634e-007	2.704787e-003	1.280027e+000	2.113070e-003	4.841644e-001	3.805849e+000	8.784800e-003	3.343362e-002	8.090023e-002
3		5.897493e-005								

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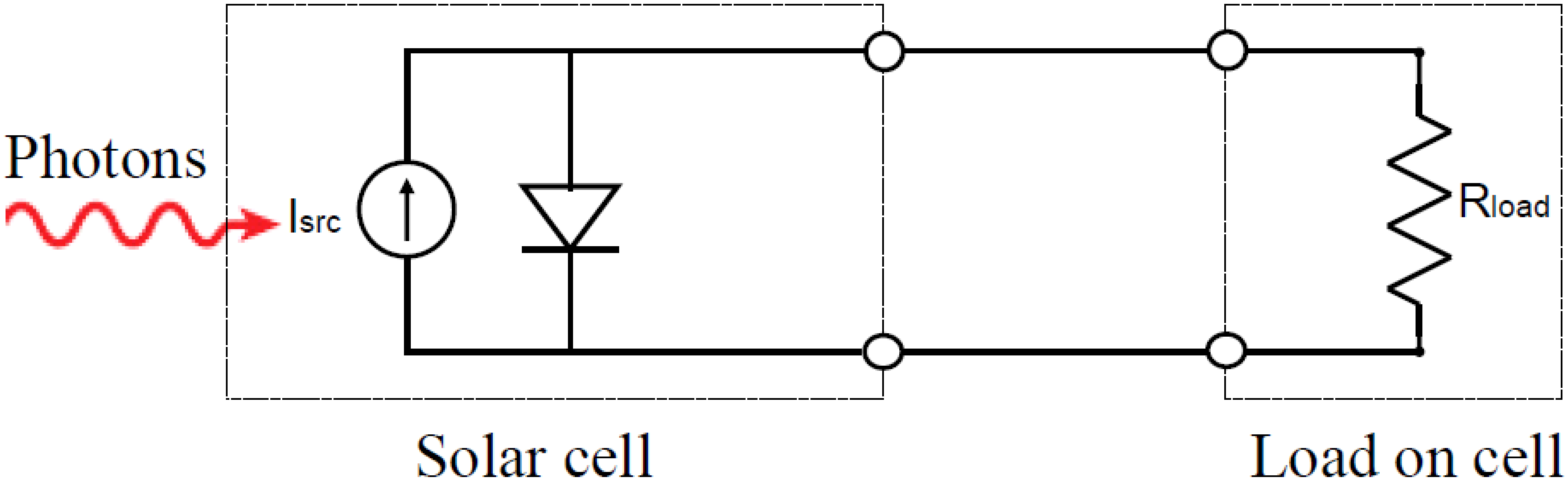
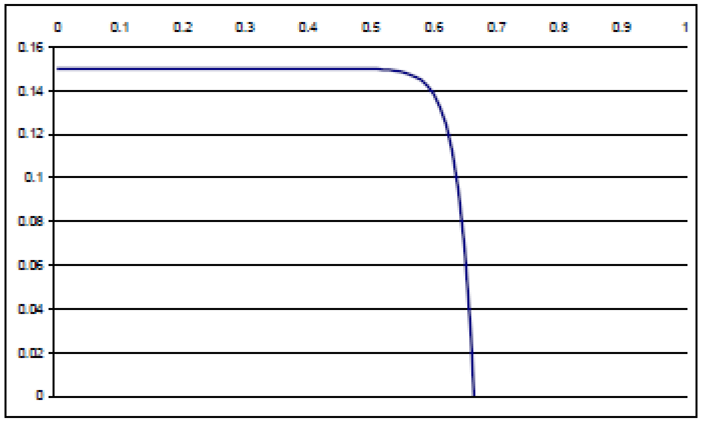
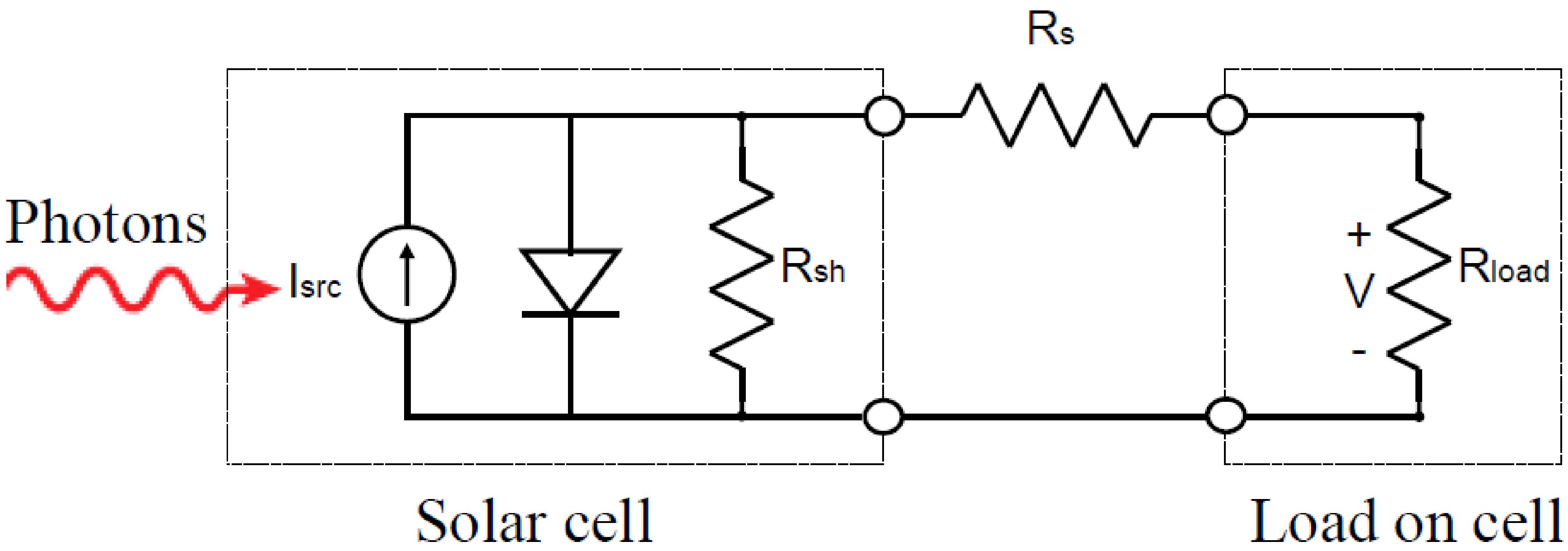
Ideal Electrical Model of a Solar Cell



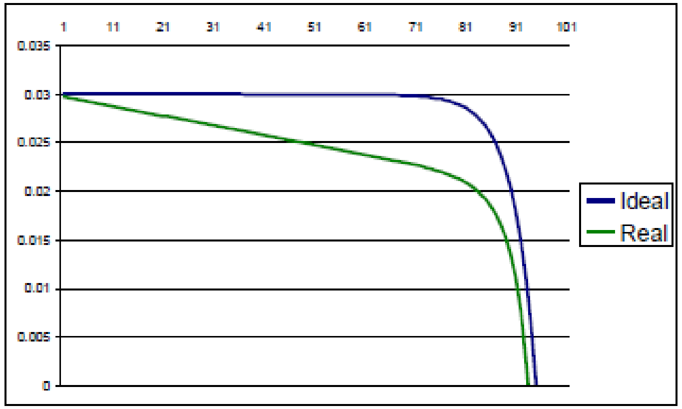
$$I = I_L - I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$



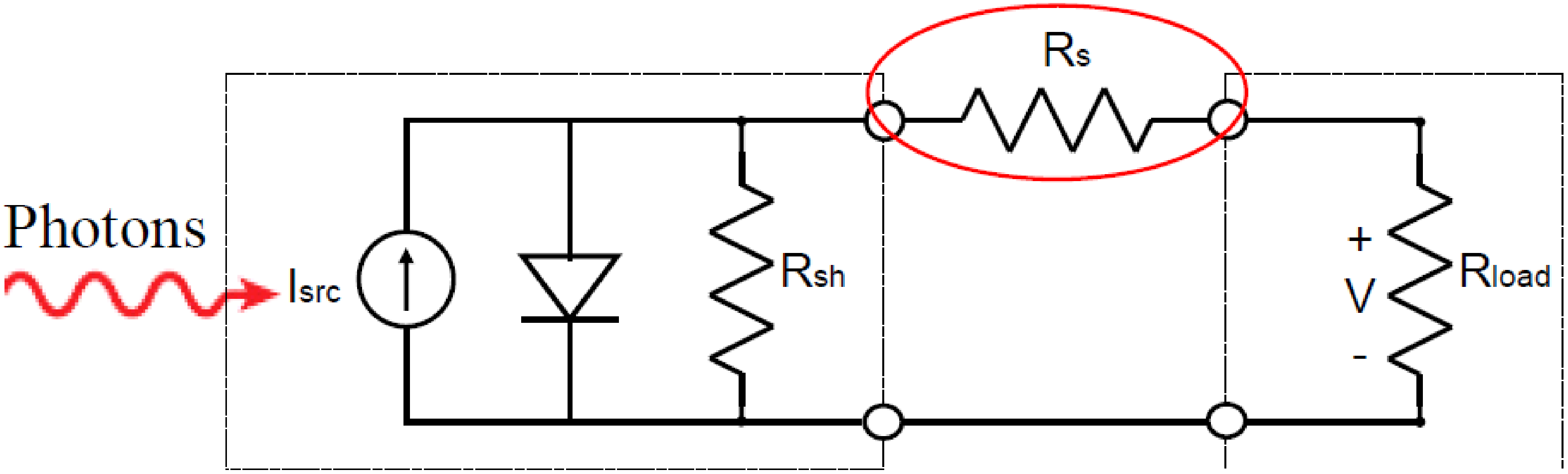
Real World Electrical Model of a Solar Cell



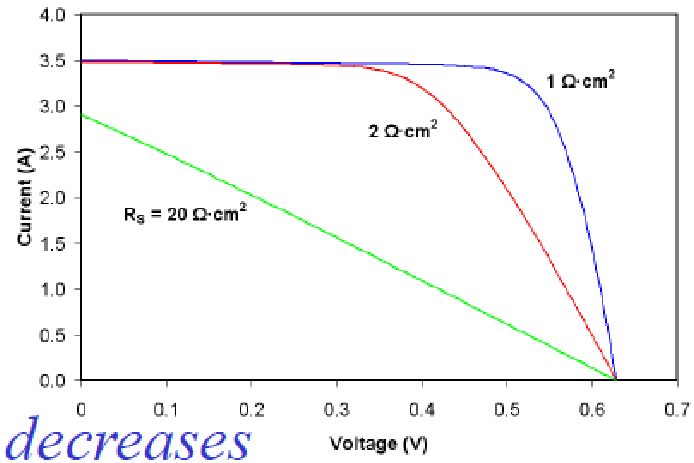
$$I = I_L - I_0\left[\exp\left[\frac{q(V+IR_S)}{nkT}\right]-1\right]-\frac{V+IR_S}{R_{SH}}$$



Real World Electrical Model of a Solar Cell, Rs



$$I = I_L - I_0 \left[\exp \left[\frac{q(V + IR_S)}{nkT} \right] - 1 \right] - \frac{V + IR_S}{R_{SH}}$$



As R_S *increases*; cell efficiency *decreases*

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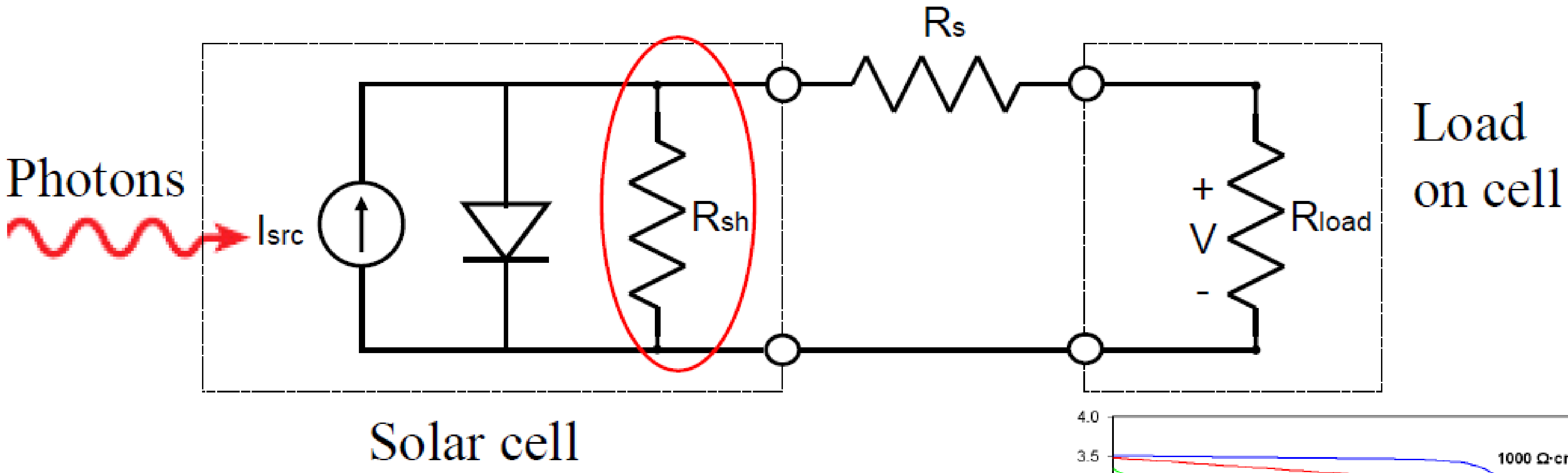
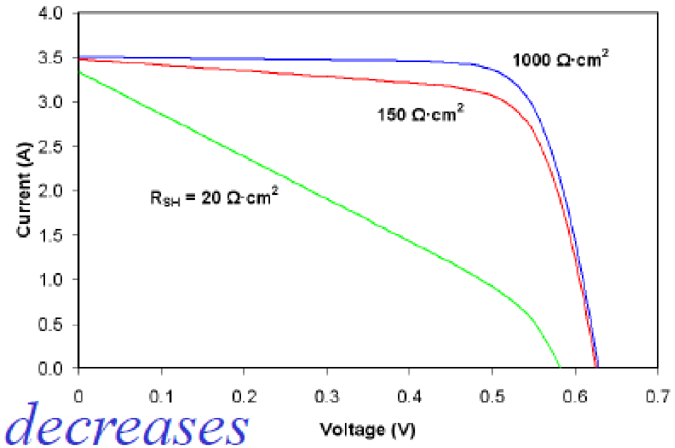
Real World Electrical Model of a Solar Cell, Rsh

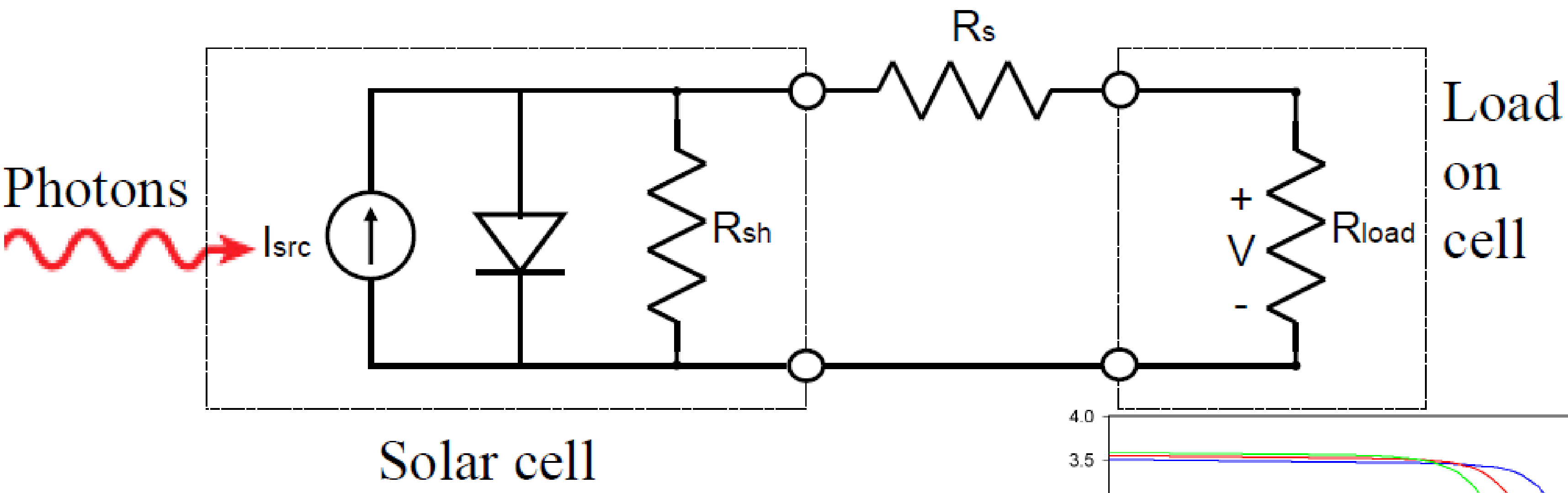


$$I = I_L - I_0 \left[\exp\left[\frac{q(V + IR_S)}{nkT} \right] - 1 \right] - \frac{V + IR_S}{R_{SH}}$$

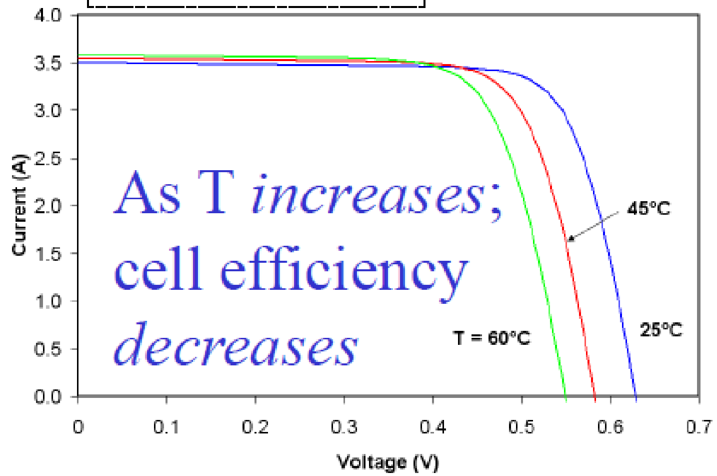


As R_{Sh} *decreases*; cell efficiency *decreases*

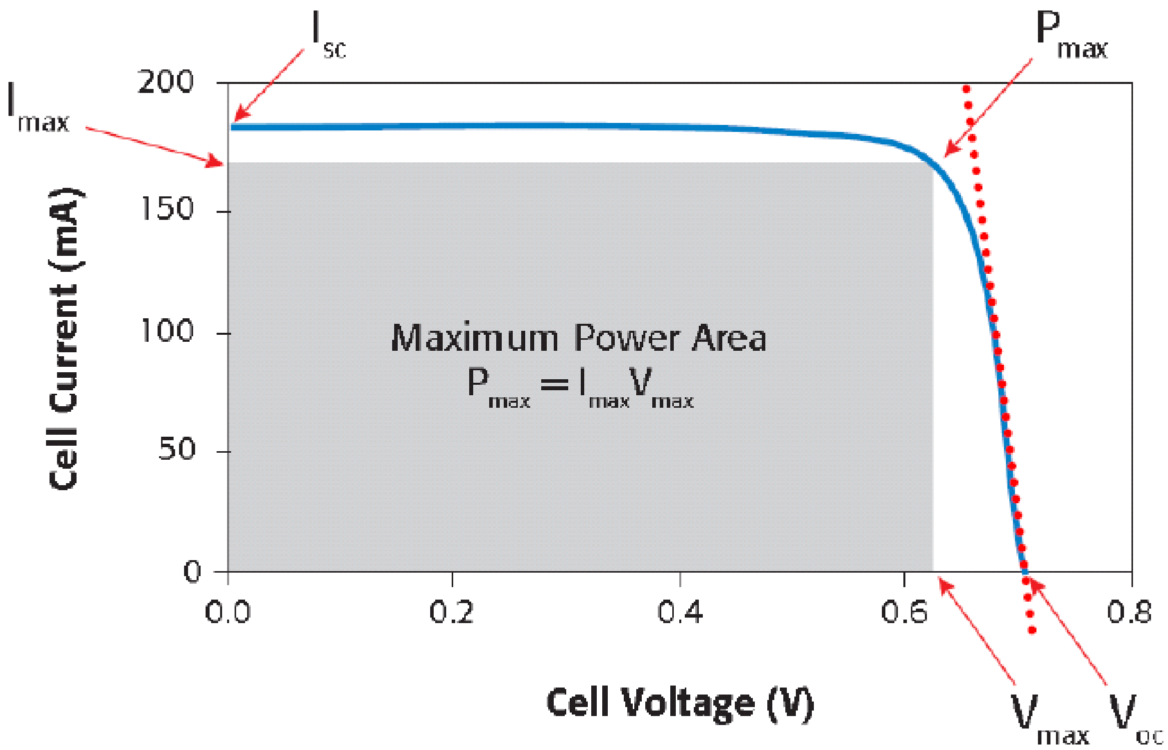
Real World Electrical Model of a Solar Cell, T



$$I = I_L - I_0\left[\exp\left[\frac{q(V+IR_S)}{nkT}\right]-1\right]-\frac{V+IR_S}{R_{SH}}$$

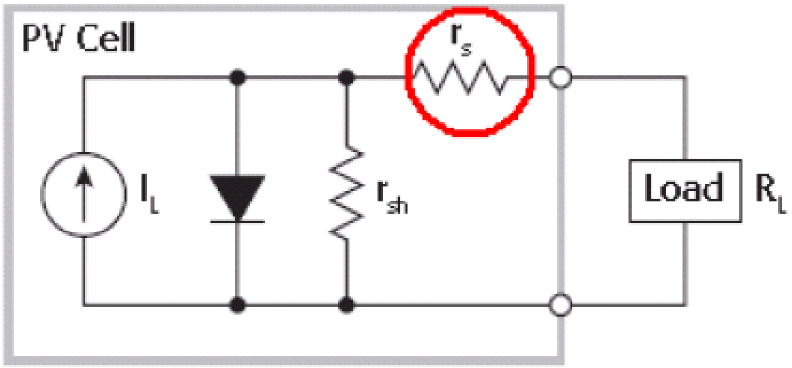


Measuring Series Resistance (Rs)
Low Rs → Low Parasitic Loss → Better Efficiency

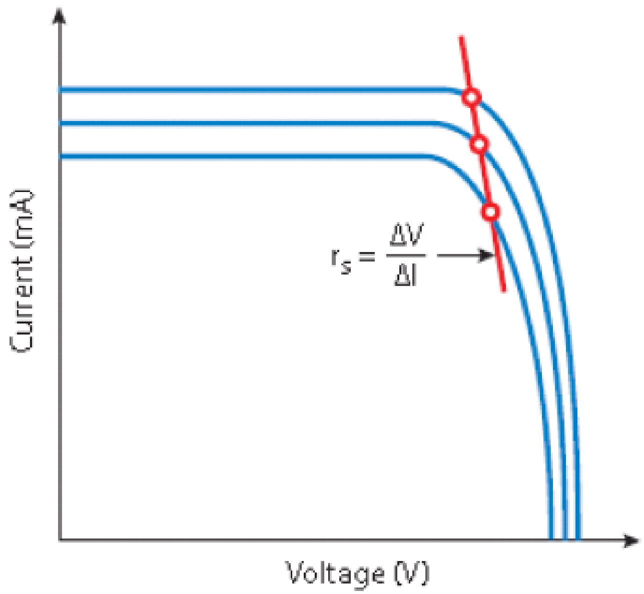


Rs can be roughly approximated from the slope of this portion of the curve, but there are errors!

Measuring Series Resistance (Rs)
Low Rs → Low Parasitic Loss → Better Efficiency



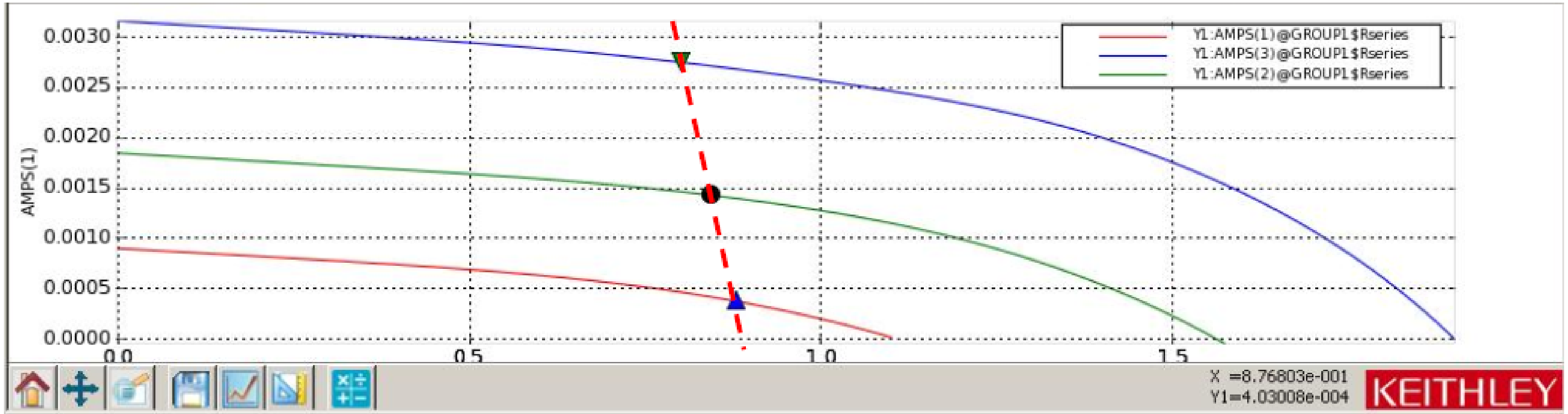
Parameter to be measured: Rs



Rs Measurement with Slope Method
(from a series of forward IV sweeps)

This differential method makes the measurement independent of n, I_0, and R_{Sh} which are more difficult to accurately measure.

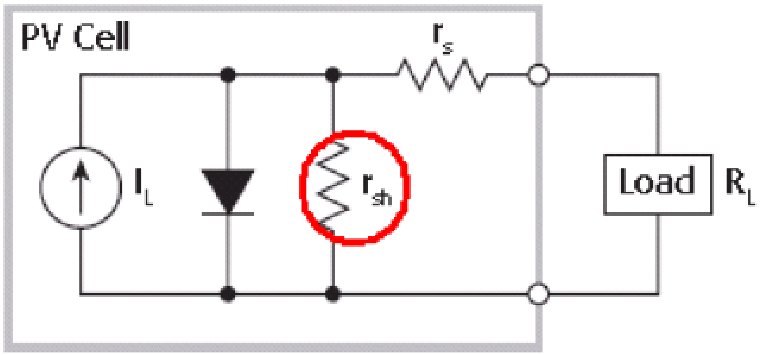
Measuring Series Resistance (Rs)
Low Rs → Low Parasitic Loss → Better Efficiency

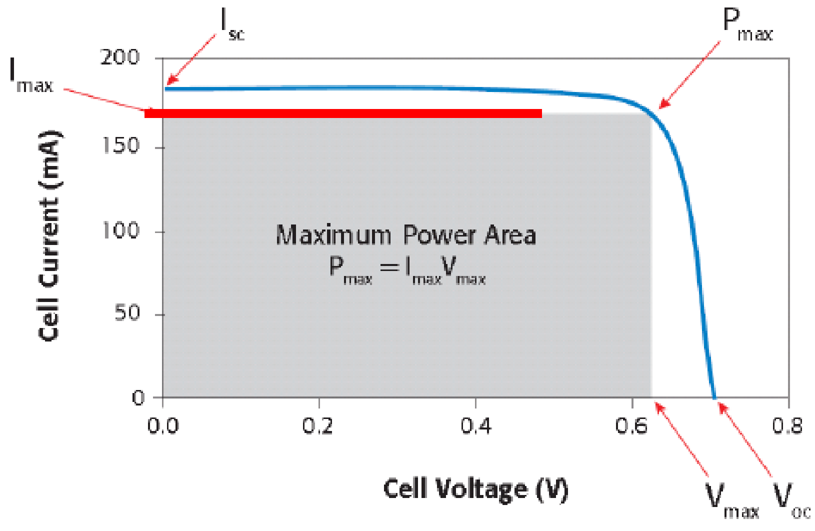


GROUP1

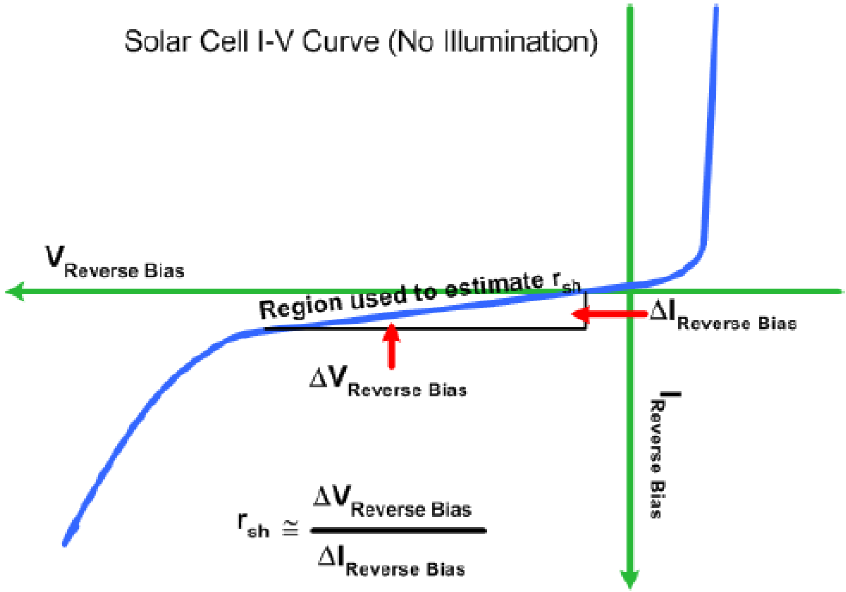
	X	Y	Z	AA	AB(X)	AC(Y1)	AD	AE	AF	AG
1	I_Pos(3)	V_neg(3)	I_neg(3)	SWPCNT(3)	VOLTS(3)	AMPS(3)	ISC(3)	IDELTA(3)	RS_CURRENT(3)	RS_VOLTAGE(3)
2	-3.161867e-003	1.399915e+001	2.715696e-001	7.800000e+001	-3.886223e-004	3.161867e-003	3.161867e-003	4.000000e-004	2.761867e-003	7.994223e-001
3	-3.151629e-003	1.399905e+001	2.715726e-001		2.438545e-002	3.151629e-003				
4	-3.141103e-003	1.399918e+001	2.715679e-001		4.948139e-002	3.141103e-003				
5	-3.130829e-003	1.399909e+001	2.715731e-001		7.429838e-002	3.130829e-003				
6	-3.120304e-003	1.399913e+001	2.715771e-001		9.939194e-002	3.120304e-003				
7	-3.109952e-003	1.399916e+001	2.715698e-001		1.244926e-001	3.109952e-003				
8	-3.099494e-003	1.399922e+001	2.715806e-001		1.492977e-001	3.099494e-003				
9	-3.089061e-003	1.399907e+001	2.715793e-001		1.744318e-001	3.089061e-003				

Measuring Shunt Resistance (Rsh)
High Rsh → Low Internal Loss → Better Efficiency



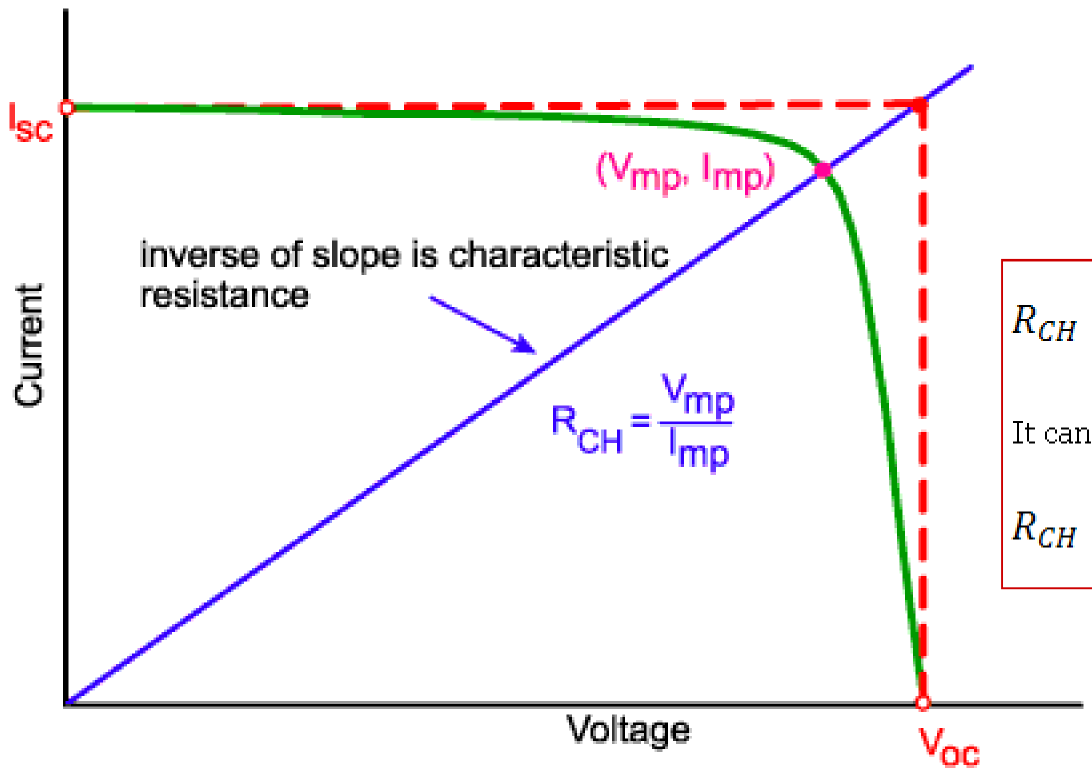


Solar Cell I-V Curve (No Illumination)



Rsh can be estimated from slope of a reverse I-V sweep

Measuring Characteristic Resistance:
Max Output Efficiency with R_{CH} Matching



$$R_{CH} = \frac{V_{MP}}{I_{MP}}$$

It can alternately be given as an approximation where:

$$R_{CH} = \frac{V_{OC}}{I_{SC}}$$

Characteristic Resistance: Resistance at Pmax tells you how to connect (set R for load) to avoid external losses

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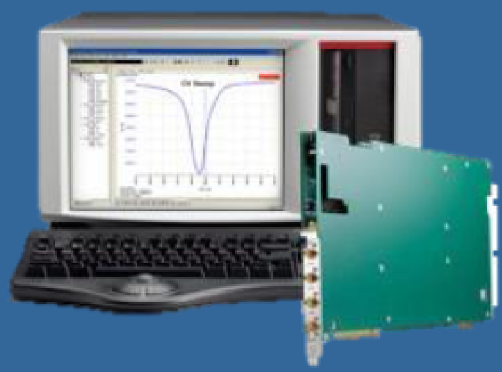
Summary of Electrical Characterization for Solar Cells & Key Parameters

I-V Test (Current-Voltage)	DC Instrument Requirements	Available Instruments
• open circuit voltage (Voc) • short circuit current (Isc) • maximum power output (Pmax) • Voltage at Pmax (Vmax) • fill factor (ff) • series resistance (Rs, Ω) • shunt resistance (Rsh, Ω) • conversion efficiency (η) • cell resistivity (ρ)	• Four Quadrant Operation • Ability to source and sink current and voltages up to 50A, 40V (dark and illuminated) • Remote Sense • Suitable Keithley Models: **2430**: 2nA-10A, 5µV – 100V **2440**: 2nA – 5A, 5µV – 40V **2612A**: 1pA – 10A ,5uV – 200V **2651A**: 1pA – 50A, 5µV – 40V **4200-SCS**: 1fA – 1A, 1µV – 200V	

Summary of Electrical Characterization for Solar Cells & Key Parameters

C-V Test (Capacitance-Voltage)	C-V Instrument Requirements	Available Instruments
• Doping Density (N) • Defect Density (defects/unit area)	• Variable AC drive • Variable DC Bias (up to 30V), must be able to sink current • Multi-frequency • Wide operating range (pF to µF) • Suitable Keithley Model: 4210-CVU: **C**: 10fF – 10µF **ACV**: 10 mVrms – 100 mVrms **Frequency**: 1kHz – 10MHz	

Summary of Electrical Characterization for Solar Cells & Key Parameters

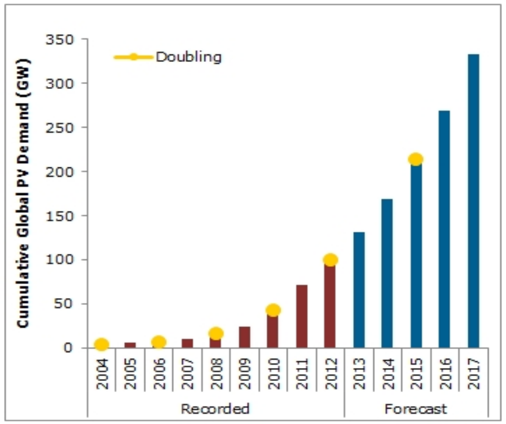
Pulsed I-V Test	Pulsed Testing Instrument Requirement	Available Instruments
• Involves measuring photons-input vs. electron-output (across wavelength) • Minority Carrier Lifetime • Pulsed open circuit voltage (Voc) • Pulsed short circuit current (Isc) • Pulsed maximum power output (Pmax) • Pulsed Voltage at Pmax (Vmax) • Pulsed conversion efficiency (η)	•Large cells require large current output (> 20 A) •Requires the ability to perform fast current and voltage measurements (carrier lifetimes can be << 100μs) •Suitable Keithley Instruments: 4225-PMU (high speed pulse-measure unit) 2651A (high current pulse and high speed acquisition	 

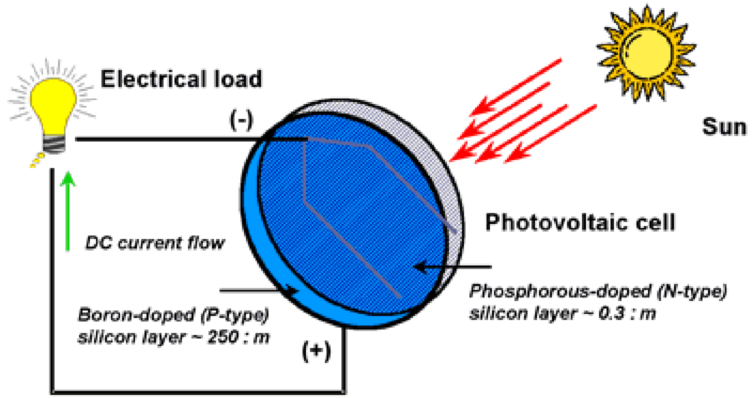
Conclusions

1. Solar cell is a good technology of **green energy** with **double digits** in 3 Years.
2. Developing processes can be improved with **precision I-V measurements of cell parameters (Isc, Voc, Imax, Vmax, Pmax, FF, η, Rs, Rsh, R_{CH}, …)**
3. Solar Cell tests can be done **quickly** and **easily** with Keithley single instrument solution.
4. **Difficult I-V/C-V measurements** of properties of the semiconductor material and doping technologies **can be made simple with Keithley measurement system.**
5. **Right DUT and right tools.** Keithley offers different series of SMUs for different requirements of voltage, current, power and accuracy levels.

Q & A

- Thanks for participating in this topic of today's seminar.
- For more information about electrical characterization of solar cells feel free to visit and view Keithley web site or contact us.
- Any questions





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Thanks for your time ~~

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