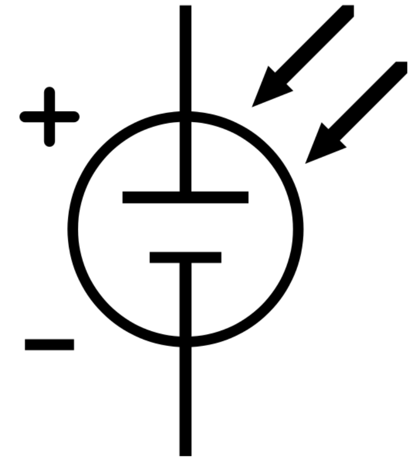
Solar cell performance characterization: current-voltage, and quantum efficiency

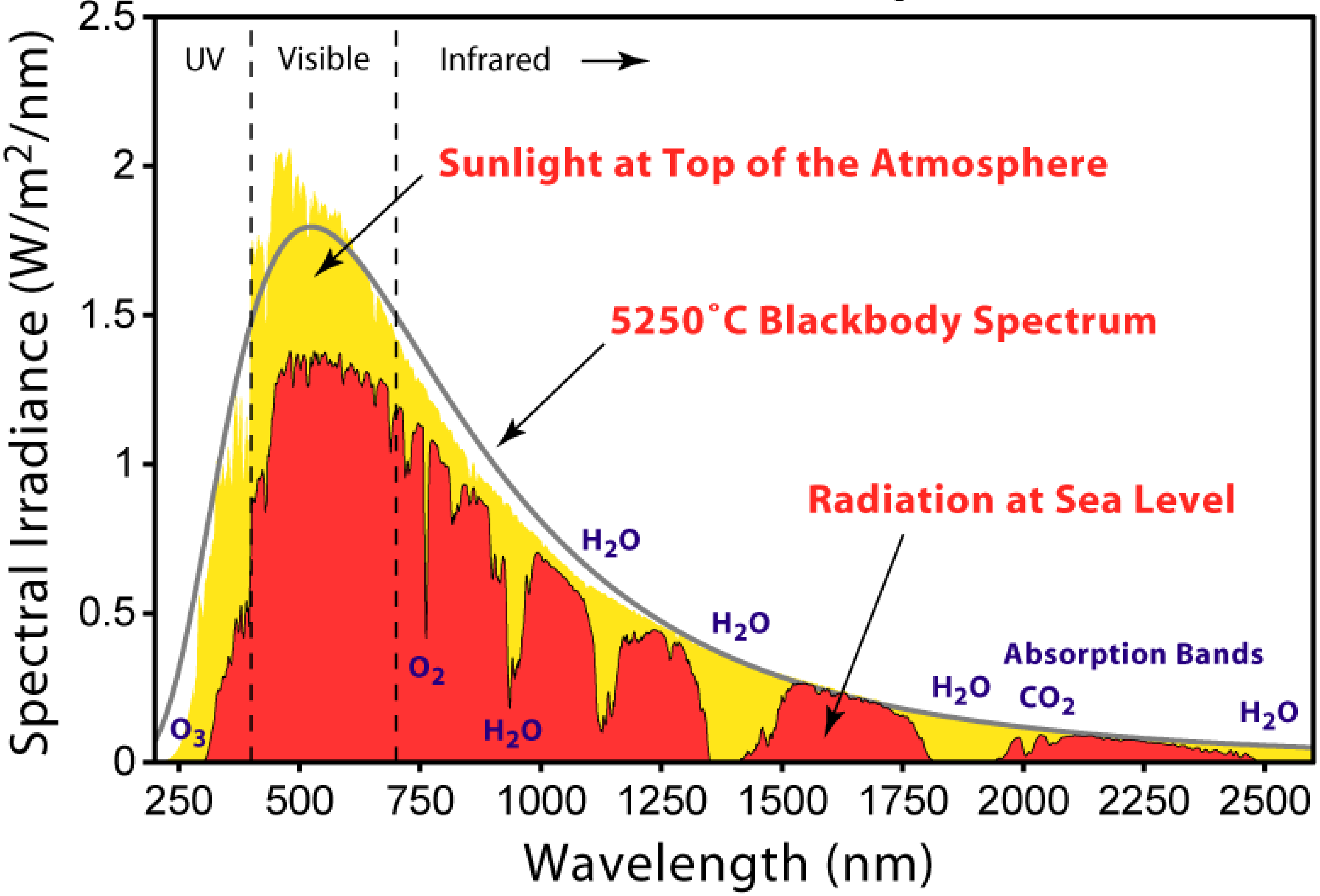
November 6, 2012

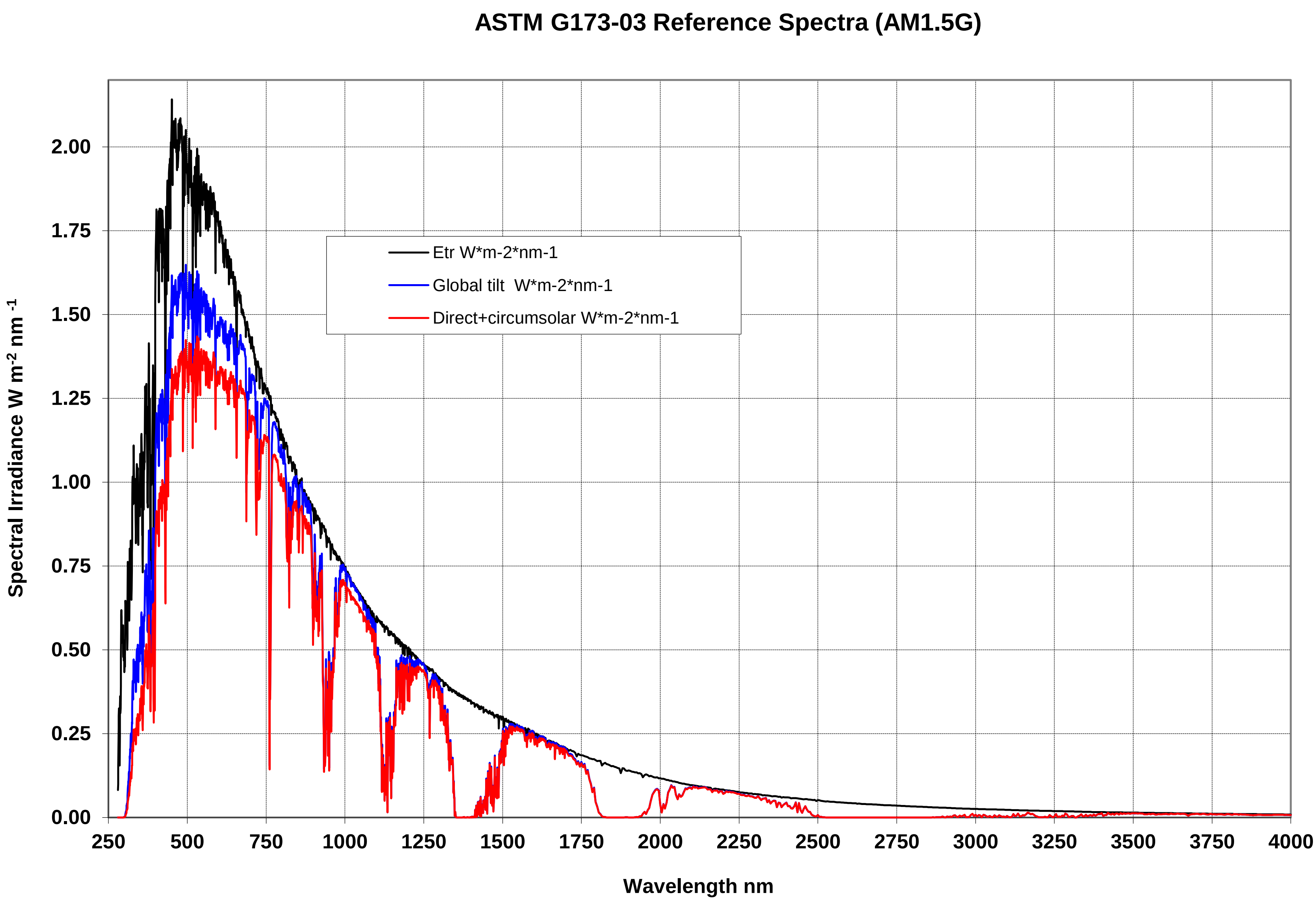


Molecular and Condensed Matter Lab (PHYS 4580)
PV Materials and Device Physics Lab (PHYS 6280)

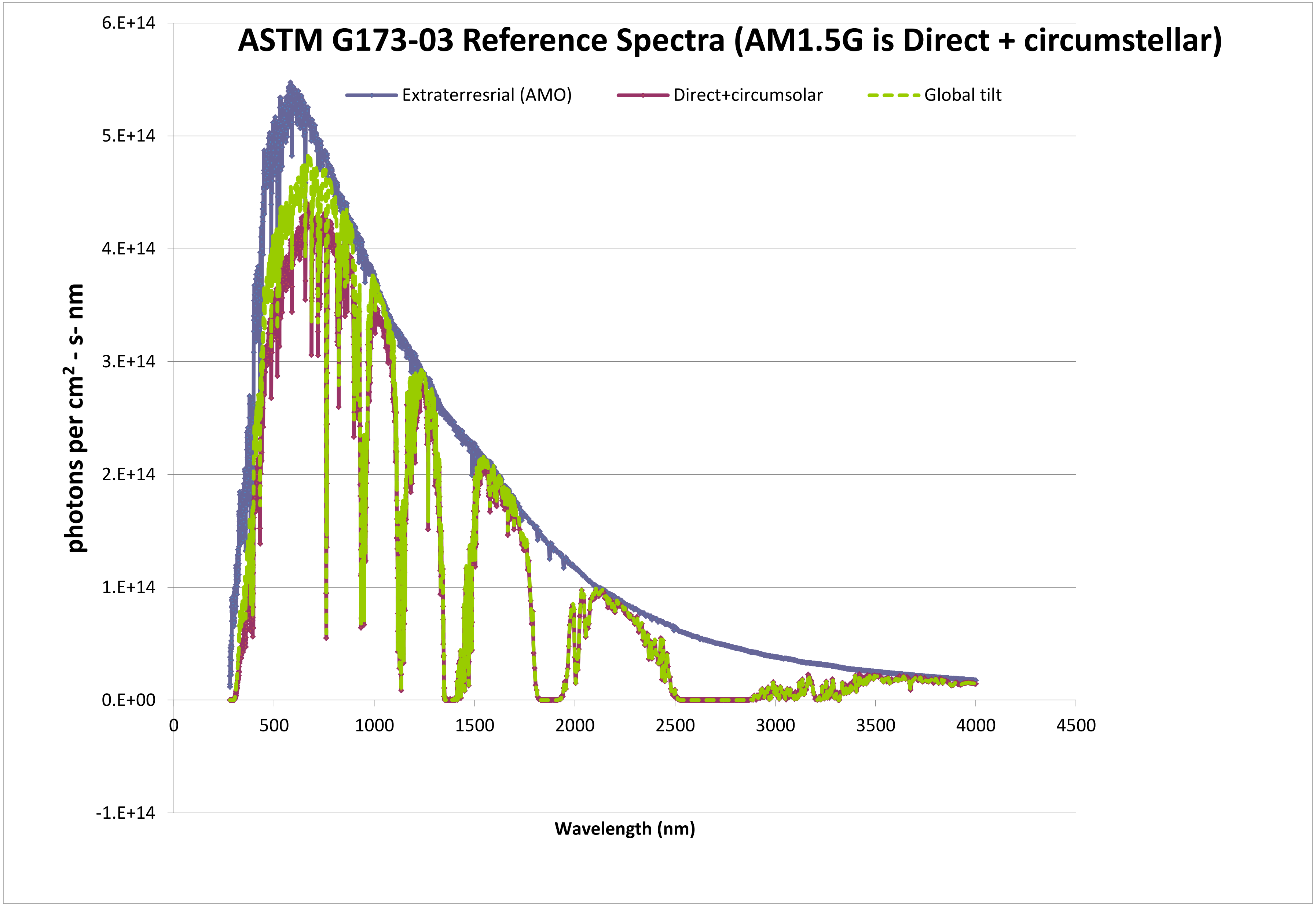
The University of Toledo
Instructors: R. Ellingson, M. Heben

Solar Radiation Spectrum

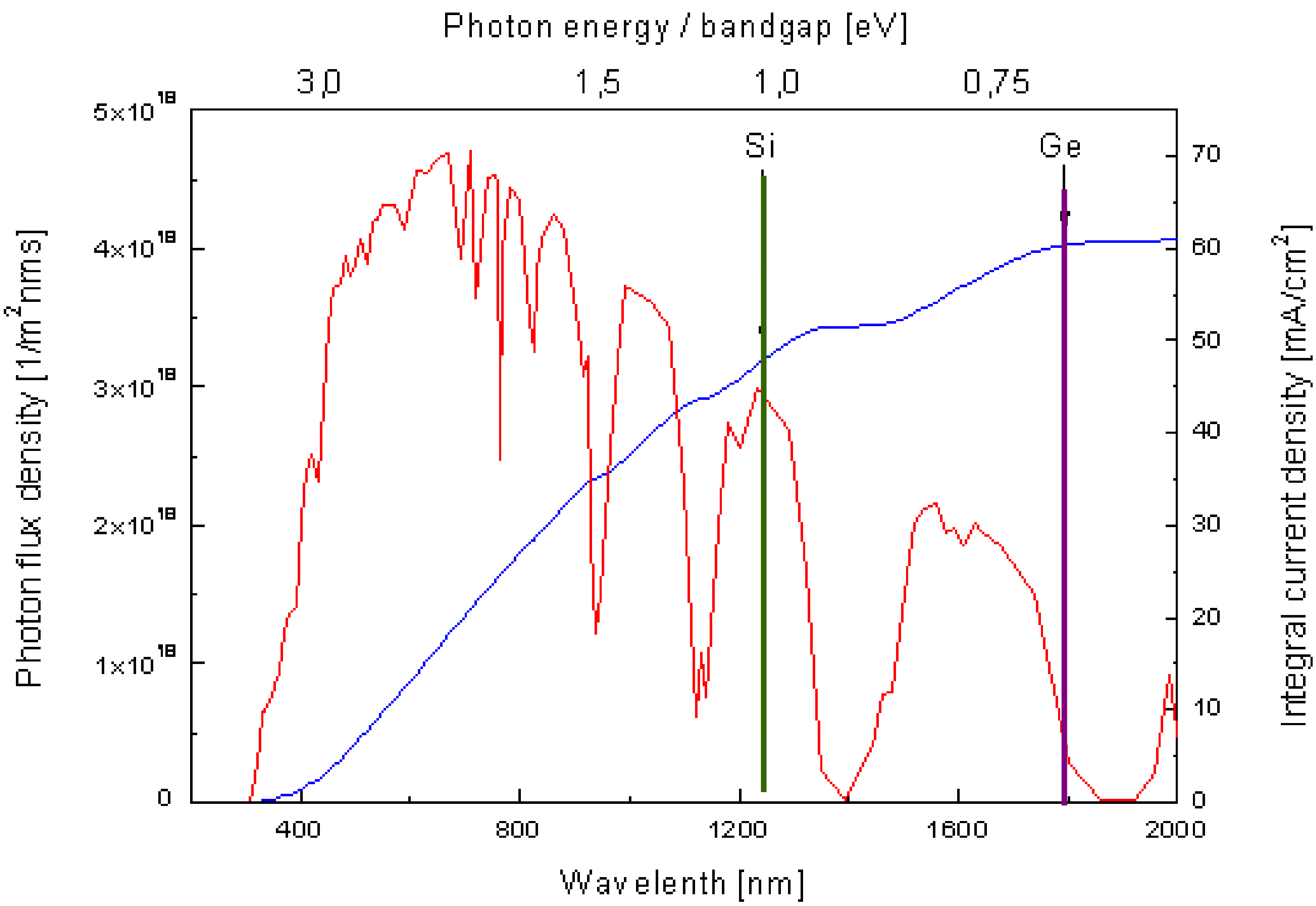




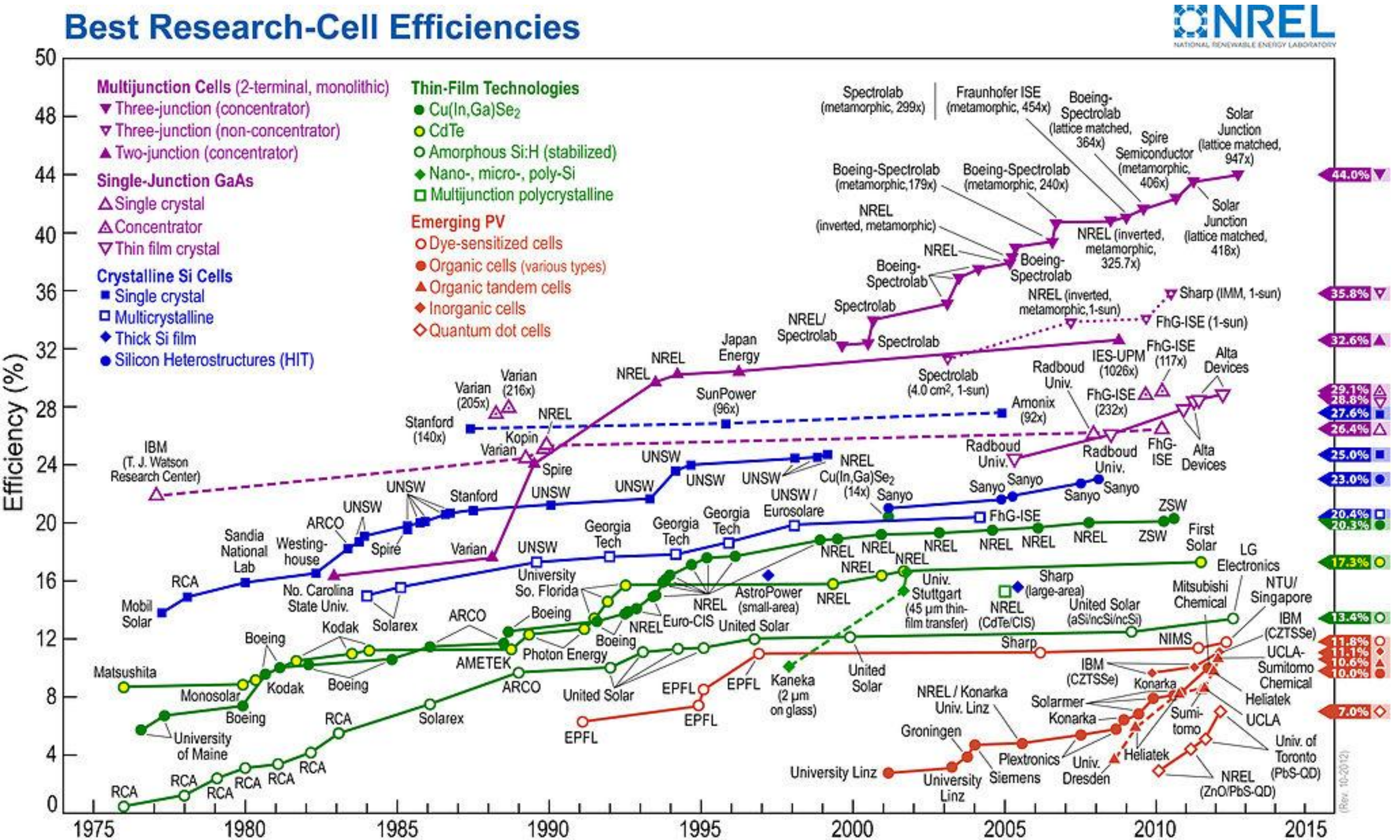
ASTM G173-03 Reference Spectra (AM1.5G)
Etr W*m-2*nm-1
Global tilt W*m-2*nm-1
Direct+circumsolar W*m-2*nm-1
Spectral Irradiance W m-2 nm -1
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3500
3750
4000
Wavelength nm


ASTM G173-03 Reference Spectra (AM1.5G is Direct + circumstellar)
Extraterresrial (AMO)
Direct+circumsolar
Global tilt
photons per cm2 - s- nm
6.E+14
5.E+14
4.E+14
3.E+14
2.E+14
1.E+14
0.E+00
-1.E+14
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Wavelength (nm)

Integrating the Solar Spectrum



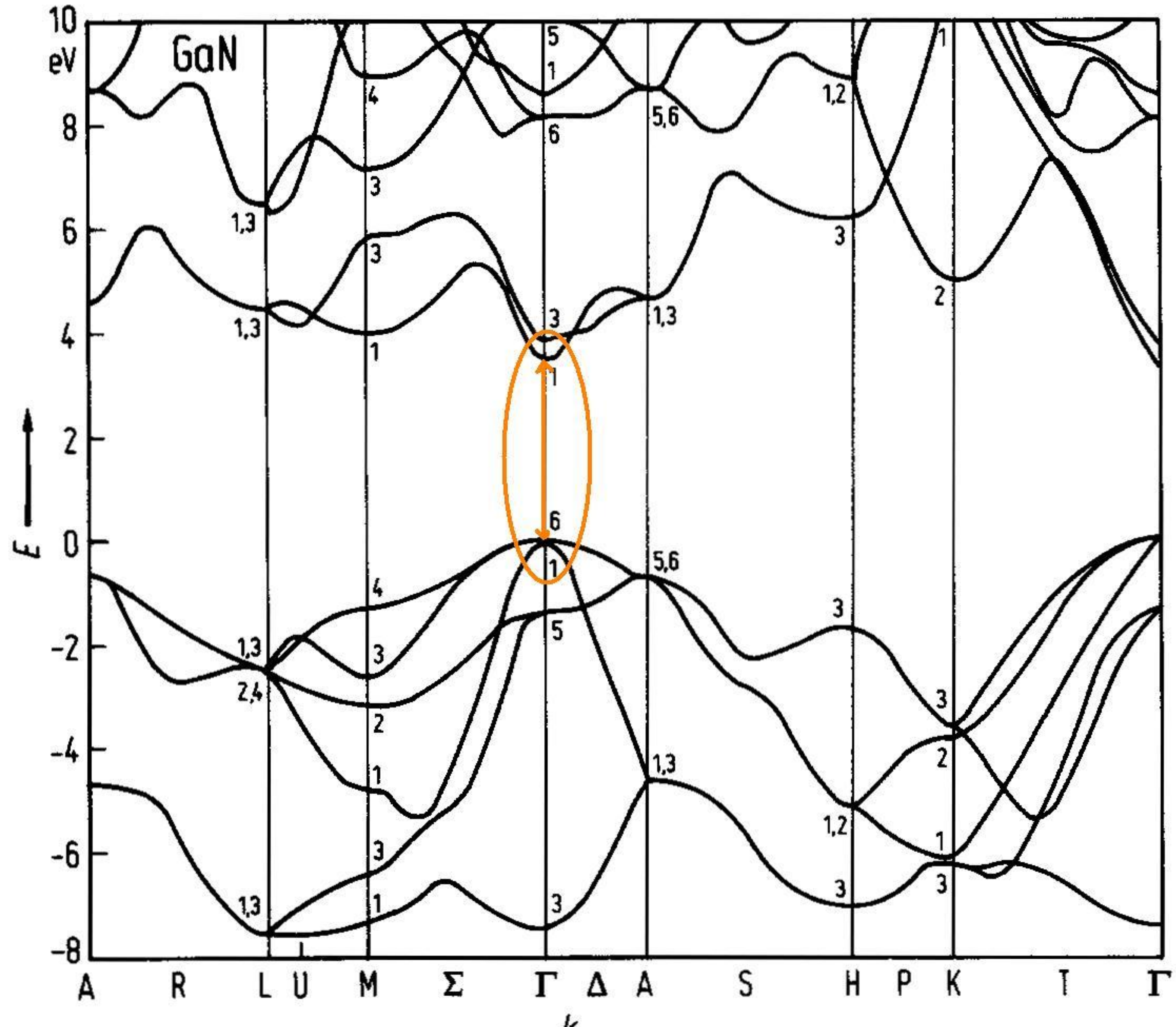
Solar cell efficiency trends (Nov. 6, 2012)



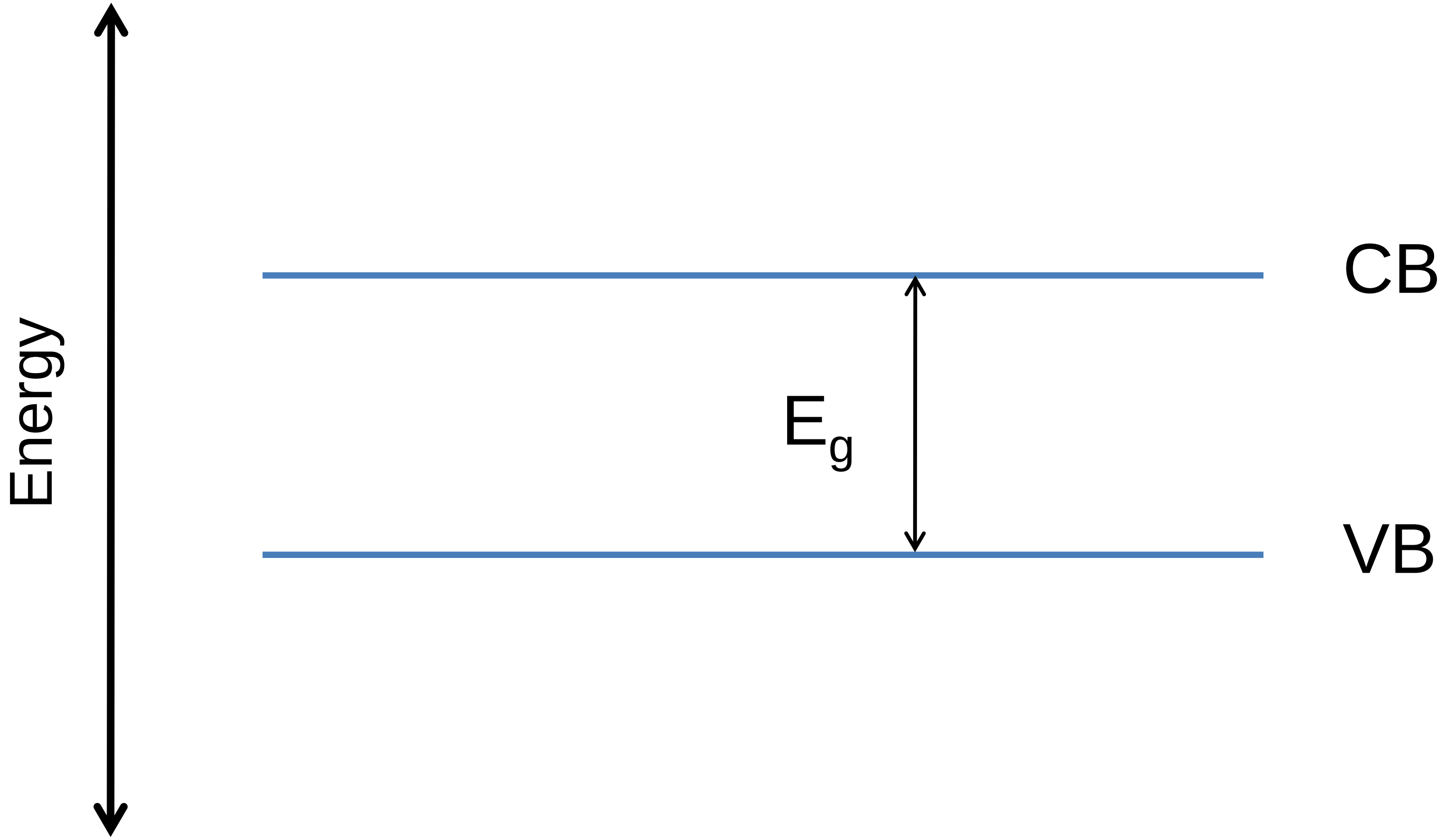
Semiconductor concepts

- Bandgap, conduction band, valence band, band edges
- Electrons and holes
- Mobility
- T = 0 behavior, thermal excitation of population (Fermi distribution)
- Doping
- p-n junction
- Rectification (diode behavior)
- Current vs. Voltage (I-V) measurements
- Quantum efficiency measurements (internal vs. external)

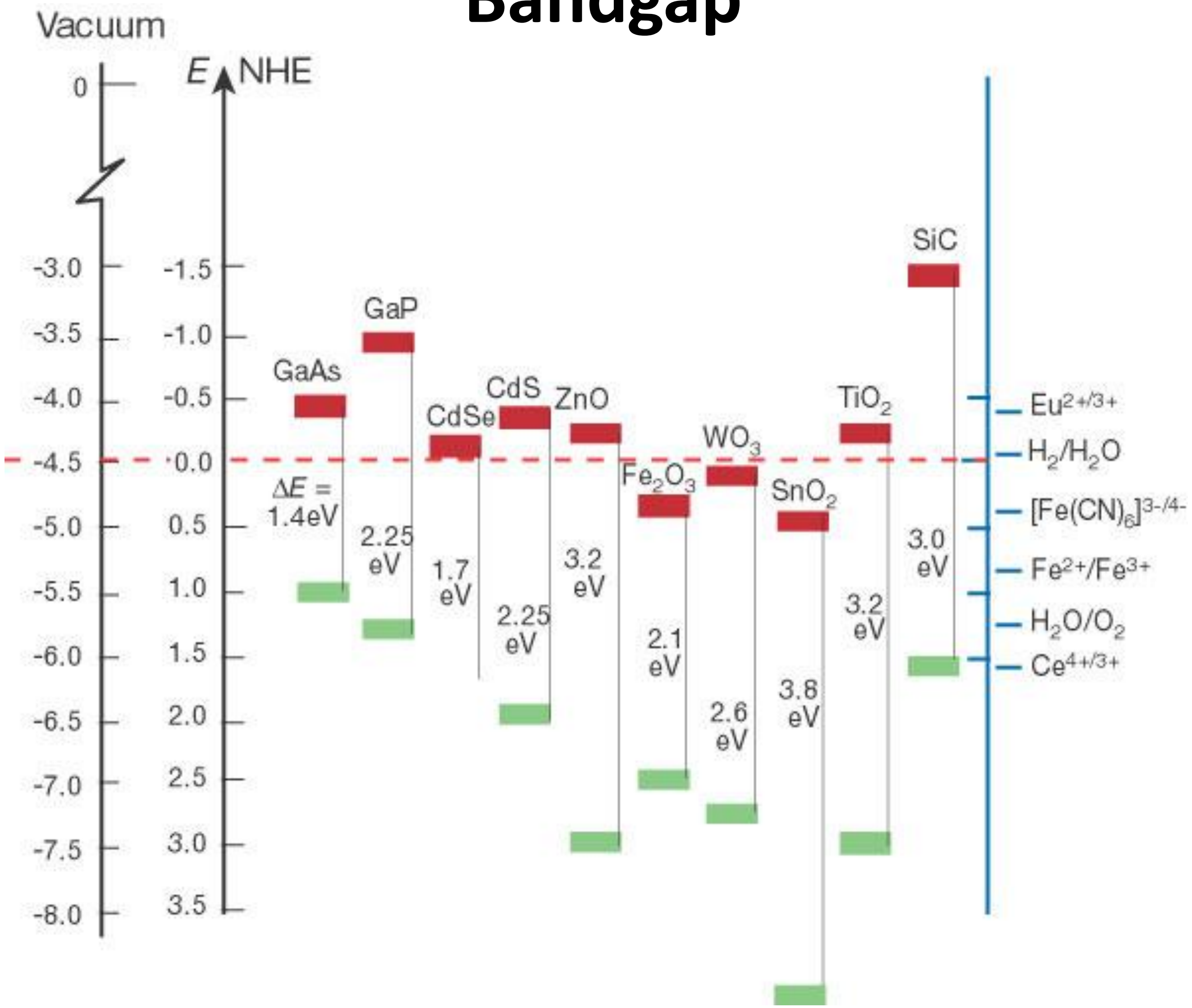
Bandgap (complicated)



Bandgap (simplified)

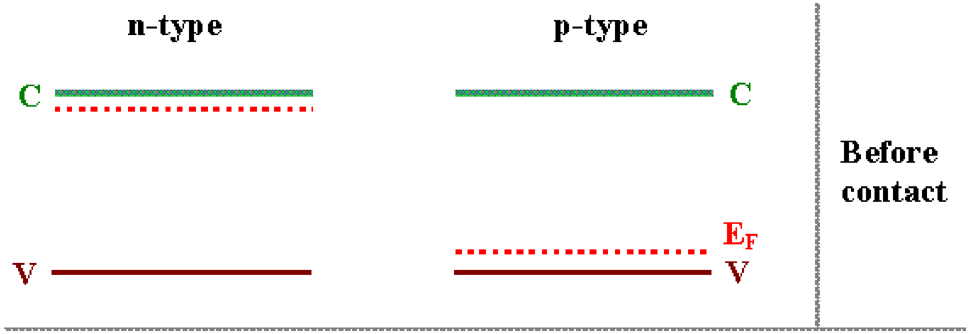


Bandgap



[“Photoelectrochemical cells”]
Michael Grätzel
Nature **414**, 338-344(15 Nov. 2001)
doi:10.1038/35104607

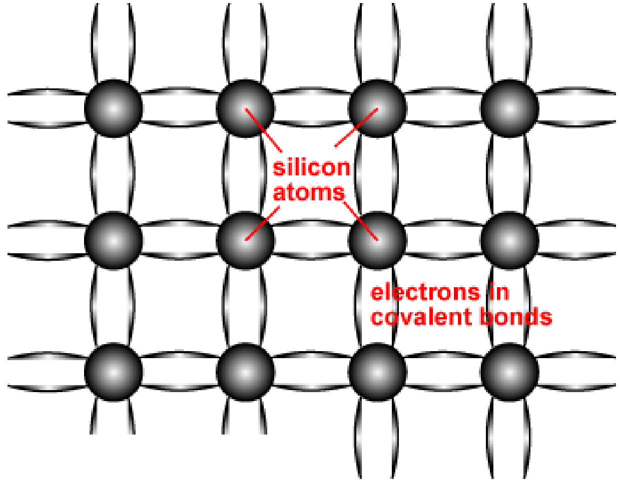
Sunlight to electricity (photovoltaic conversion)



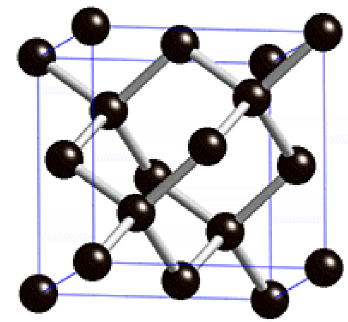
http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/backbone/r2_2_4.html

Doping a semiconductor (e.g., Si)

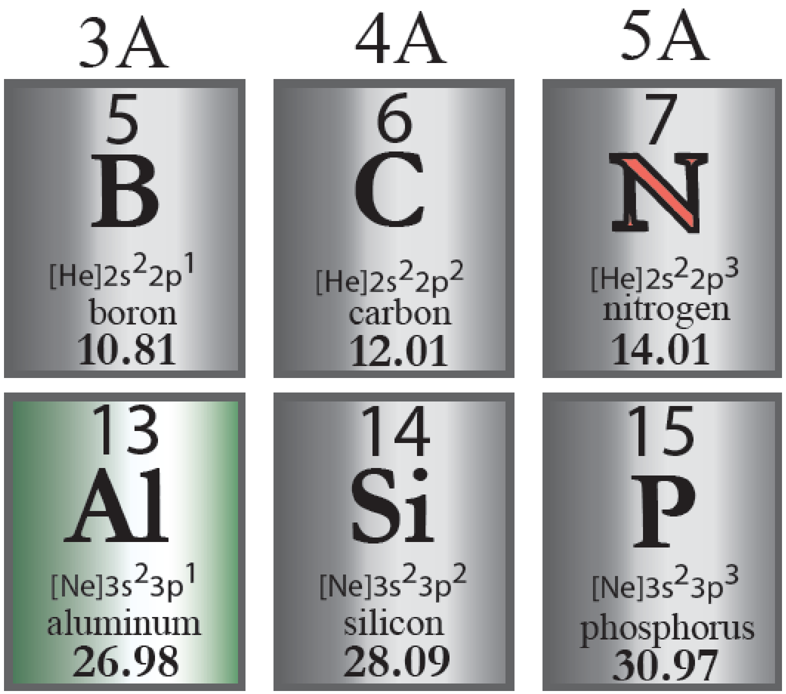
PV EDUCATION.ORG

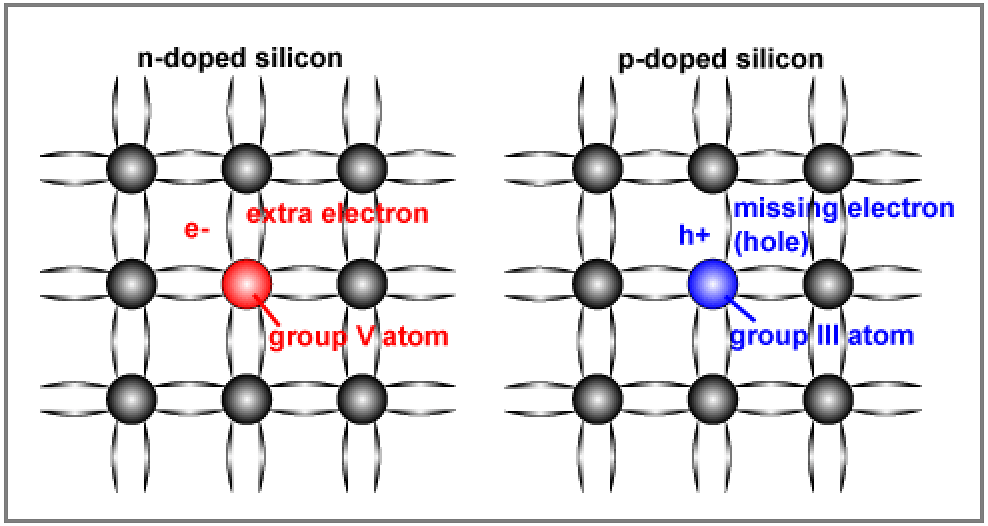


en.wikipedia.org/wiki/File:Diamond_Cubic-F_lattice_animation.gif



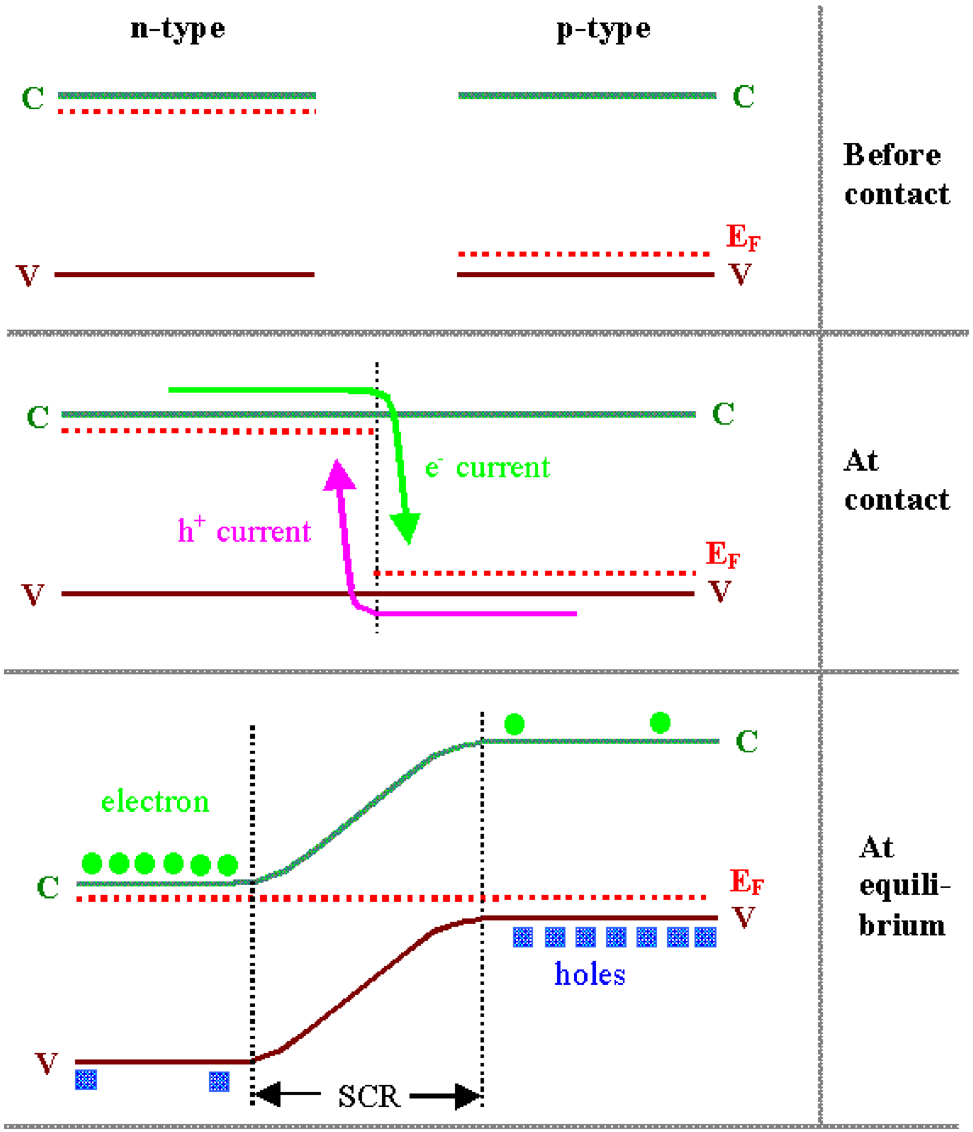
Diamond cubic crystal structure





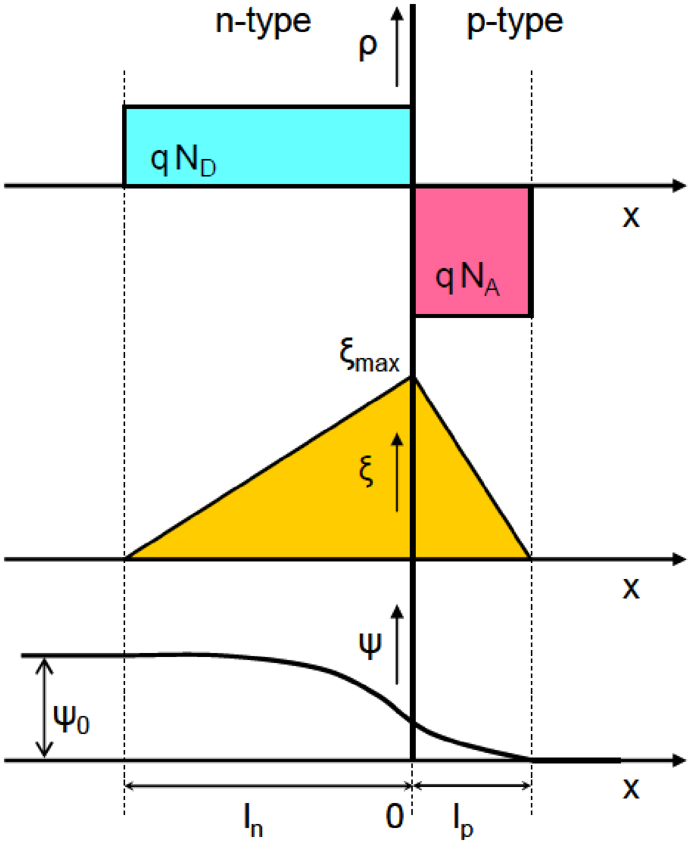
www.sciencegeek.net/tables/LosAlamosperiodictableColor.pdf

Sunlight to electricity (photovoltaic conversion)



http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/backbone/r2_2_4.html

Depletion width for p-n junction



Transport of free carriers occurs via drift (electric field) and diffusion (concentration gradient)

$$J_n = q\mu_n n(x)E + qD_n \frac{dn(x)}{dx}$$

$$J_p = q\mu_p p(x)E + qD_p \frac{dp(x)}{dx}$$

Top: space-charge density (ionized dopants)
Middle: electric field
Bottom: electrostatic potential

http://www.aerostudents.com/files/solarCells/CH4SolarCellOperationalPrinciples.pdf

Mobility

Adapted from Wikipedia, the free encyclopedia

Mobility is a quantity relating the drift velocity of a charge carrier to the applied electric field across a material, according to the formula:

$$v_d = \mu E$$

where

v_d is the drift velocity in m/s;
E is the applied electric field in V/m;
μ is the mobility in $m^2/(V \cdot s)$.

A mixed mobility unit of 1 $cm^2/(V \cdot s)$ = 0.0001 $m^2/(V \cdot s)$ is also often used.
It is the application for electrons of the more general phenomenon of electrical mobility of charged particles in a fluid under an applied electric field.

In semiconductors, mobility can apply to electrons as well as to holes.

Shockley diode equation

The *Shockley ideal diode equation* or the *diode law* (named after transistor co-inventor William Bradford Shockley) gives the Current-Voltage (*I*–*V*) characteristic of an ideal diode in either forward or reverse bias (or no bias). The equation is:

$$I = I_S(e^{V_D/(nV_T)} - 1)$$

I is the diode current,
I_S is the reverse bias saturation current,
V_D is the voltage across the diode,
V_T is the thermal voltage, and
n is the ideality factor, which varies typically from about 1 to 2 depending on the fabrication process and semiconductor material.

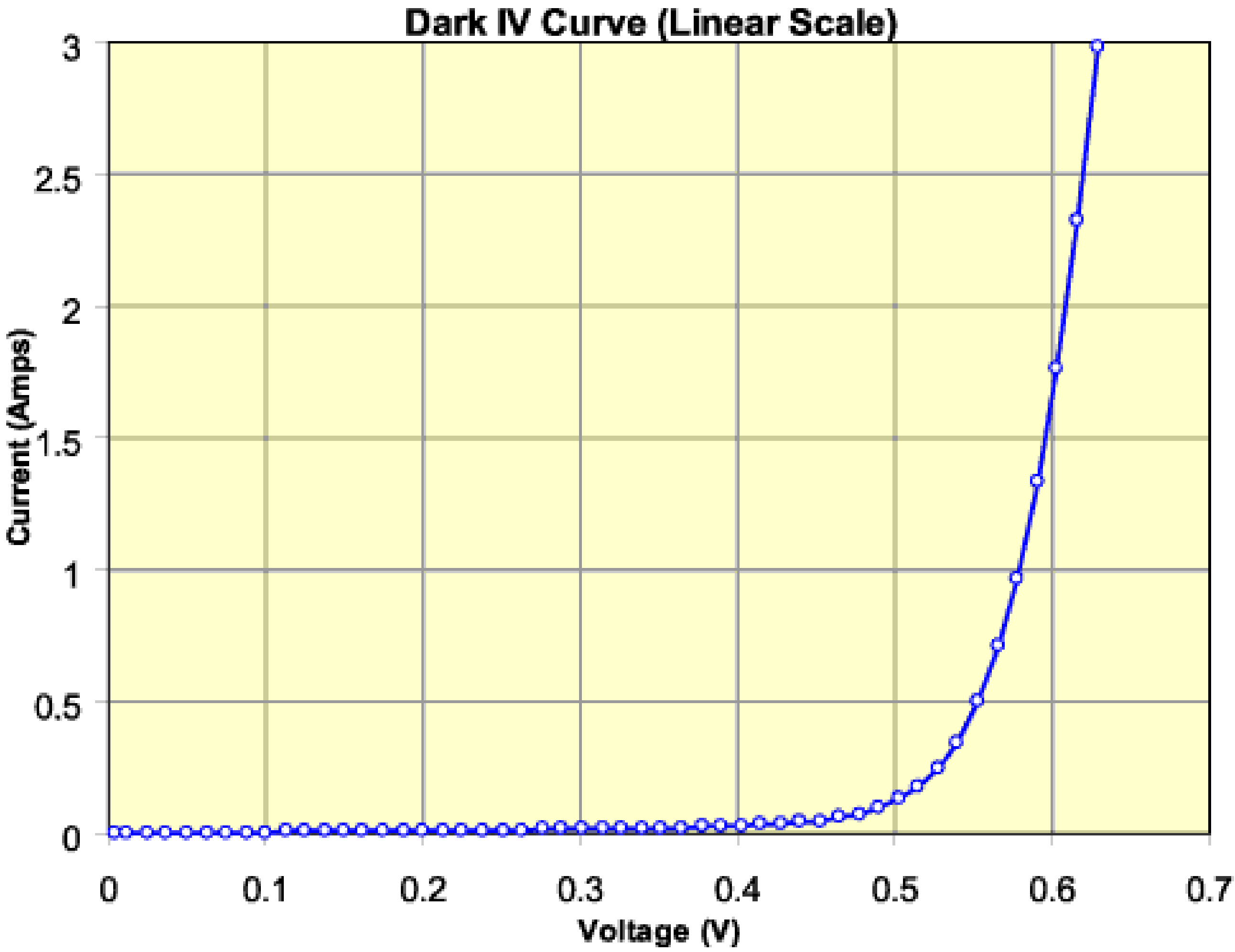
from Wikipedia.org

Thermal voltage?

$$V_T = \frac{k_B T}{q}$$

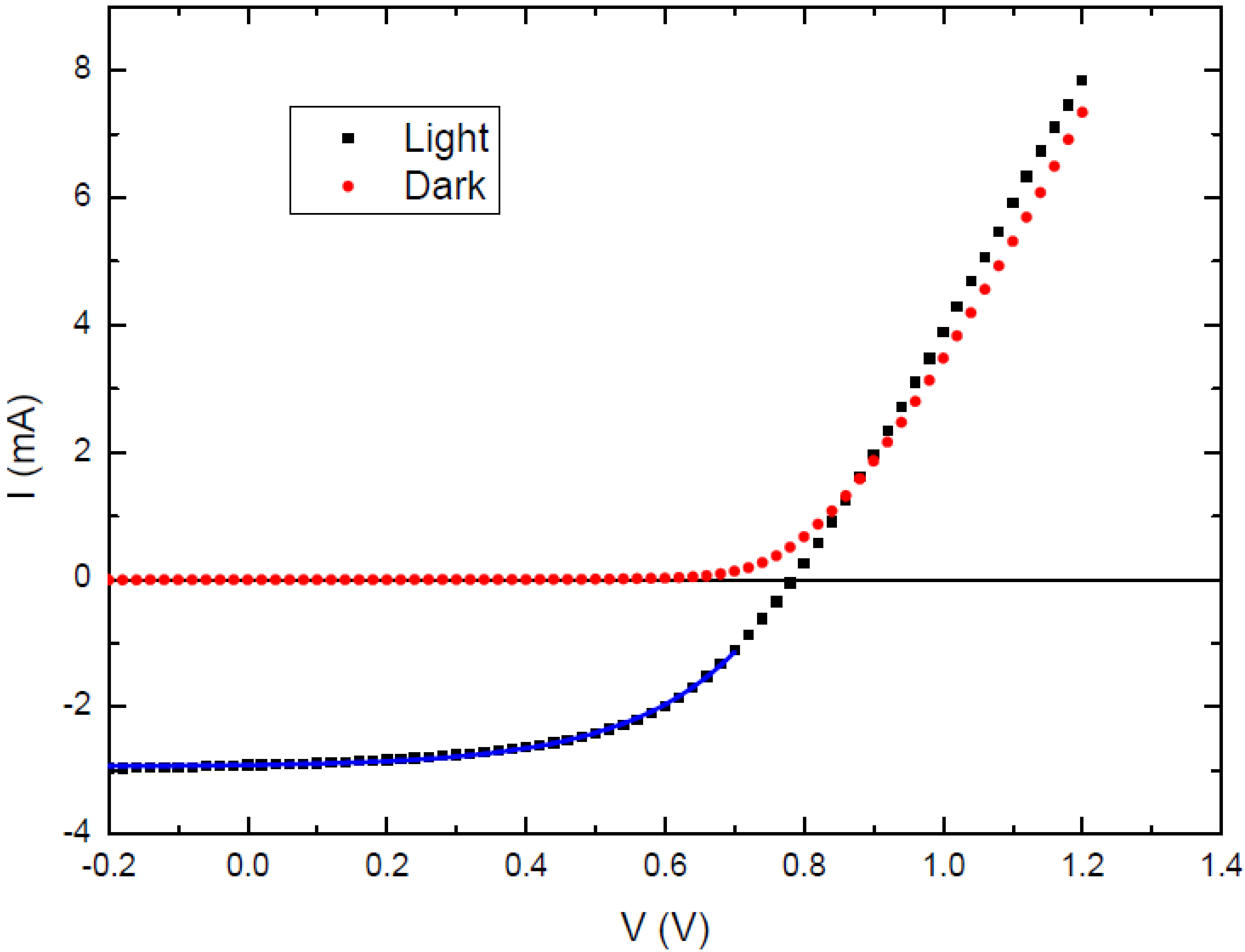
approximately 25.85 mV at 300 K

Dark I-V measurement (solar cell)



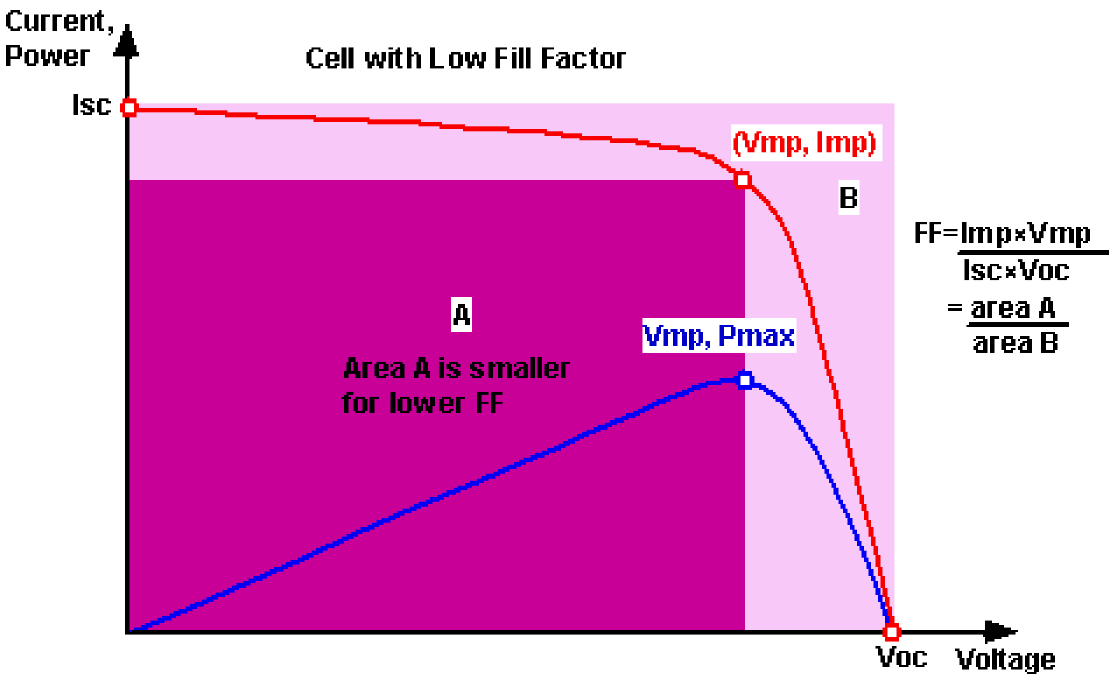
from pvcdrom.pveducation.org

Light and dark I-V measurement
(CdTe solar cell)



Solar cell fill factor (FF)

At either "short circuit" (I_{SC}) or "open circuit" (V_{OC}), the power from the solar cell is zero. The "fill factor" (FF) is the parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. Graphically, the FF is a measure of the "squareness" of the IV curve and is also the area of the largest rectangle which will fit in the IV curve, as illustrated below:



Graph of cell output current (red line) and power (blue line) as function of voltage. Also shown are the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) points, as well as the maximum power point (V_{mp}, I_{mp}). Click on the graph to see how the curve changes for a cell with low FF.

Solar cell efficiency

The efficiency of a solar cell (known also as the power conversion efficiency, or PCE, and often abbreviated η) represents the ratio where the output electrical power at the maximum power point on the IV curve is divided by the incident light power – typically using a standard AM1.5G simulated solar spectrum.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{\max} = V_{OC} I_{SC} FF$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{inc}}$$

where V_{oc} is the open-circuit voltage;
where I_{sc} is the short-circuit current; and
where FF is the fill factor
where η is the efficiency.

In a 10 x 10 cm^2 cell the input power is 100 mW/cm^2 x 100 cm^2 = 10 W.

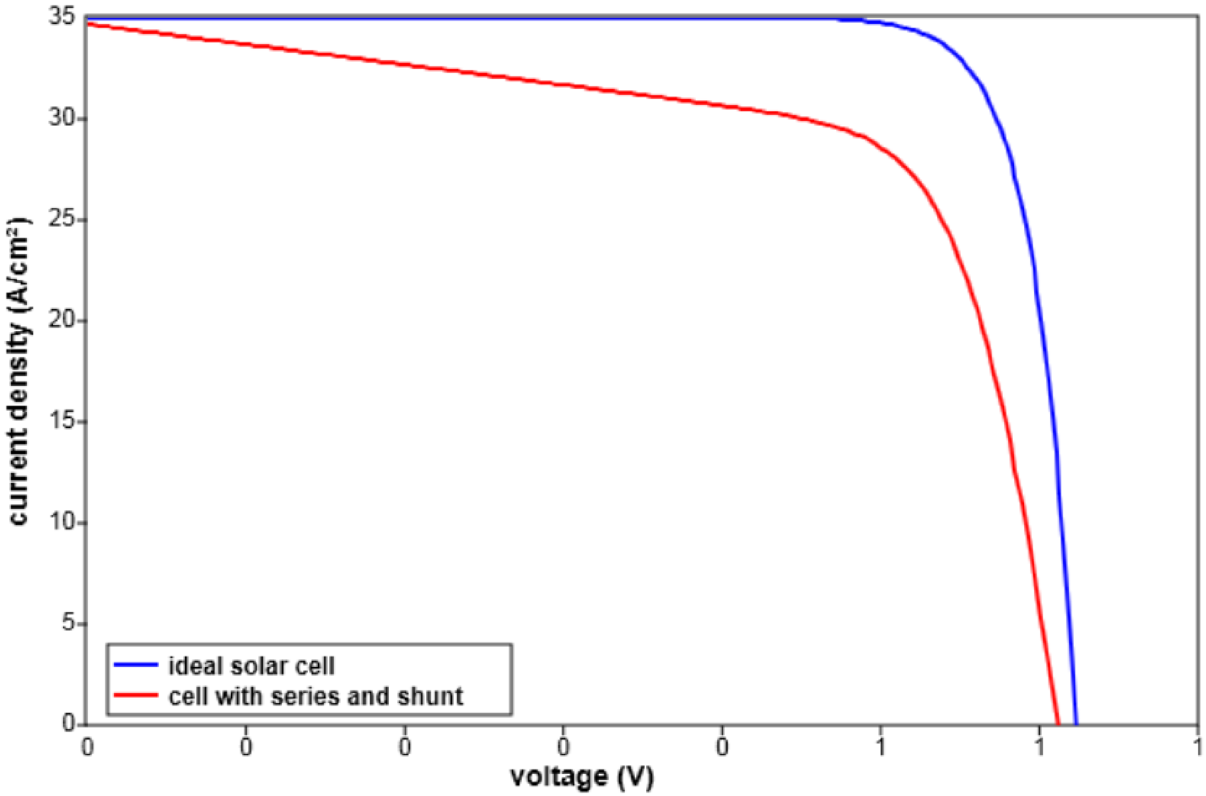
Solar cell series and shunt resistance

From http://www.pveducation.org/pvcdrom/solar-cell-operation/series-resistance

Series resistance (R_S) in a solar cell has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current.

Significant power losses caused by the presence of a **shunt resistance** (R_{sh}) are typically due to manufacturing defects, rather than poor solar cell design. Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current.

We are measuring I vs. V, so that for I in Amps and V in Volts, the apparent resistance (Ω) at any point on the curve is given by: (-1)/slope. The shunt resistance is defined at V = 0 V, and the series resistance is defined at V = V_{OC}. For optimal power generation, solar cells should have a large R_{sh} and a small R_S.



External and internal quantum efficiency

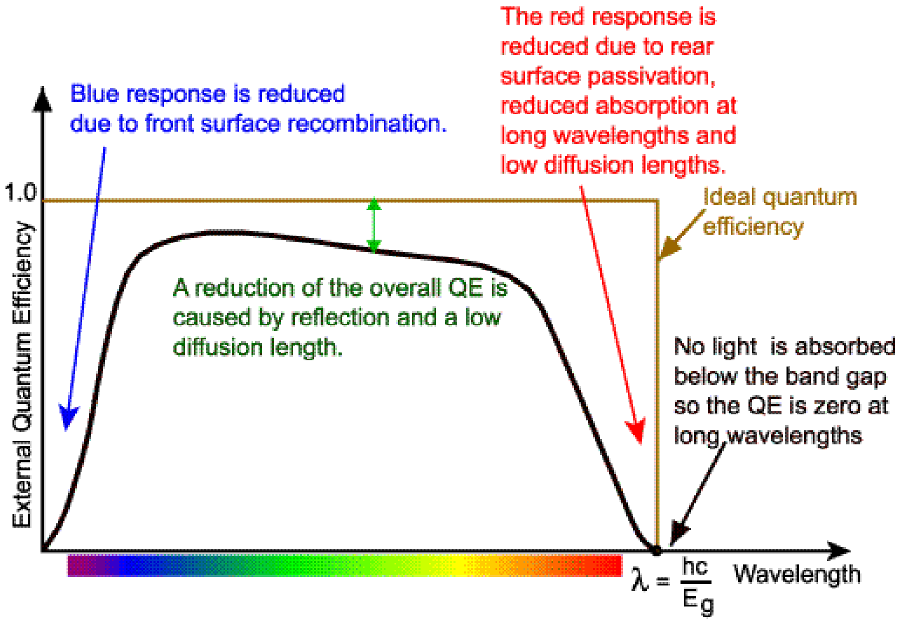
Internal and external quantum efficiency are functions of wavelength, i.e., EQE(λ) and QE(λ):

External quantum efficiency (EQE):

$$EQE(\lambda) = \frac{\text{Electrons collected as photocurrent, per second}}{\text{Photons } incident\text{, per second}}$$

Internal quantum efficiency (QE):

$$QE(\lambda) = \frac{\text{Electrons collected as photocurrent, per second}}{\text{Photons } absorbed\text{, per second}}$$



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Solar cell measurement: Current, or Current Density?

I_{SC} vs. J_{SC}

The current produced by a solar cell depends on several parameters, such as the incident light power and spectral distribution, the quantum efficiency of the solar cell as a function of wavelength, and the area of the solar cell.

To remove the effect of the area of a solar cell, one can divide the current (such as the short-circuit current, I_{SC}) by the area of the solar cell typically measured in cm^2. In doing so, one "calibrates" the response so that two different solar cells (different materials, different areas) measured under the same spectrum can be directly compared regarding current generation and conversion efficiency.

The result is that while the short circuit current (expressed as I_{SC}) has units of milliAmps (mA), the short circuit current density (expressed as J_{SC}) has units of mA/cm^2.

Lab #7 Goals [Time Period: Nov. 6 - 21, 2012] (due Nov. 27)

- Incorporate Current/Voltage measurements into your LabView program. Comment on trade-offs in data acquisition approaches.
- Measure I/V curves in the “dark” and under illumination for your CdS/CdTe solar cell under your selected spectrum.
- Calculate the power conversion efficiency of the solar cell, as well as the FF, P_{max}, J_{sc}, V_{oc}, and determine Series and Shunt resistances.
- Determine the external quantum efficiency (EQE, or spectral response) as a function of wavelength (note that you need not measure the reflectance spectrum to obtain EQE).
- Calculate the predicted power that would be generated under AM 1.5 and AM0 illumination.
- Qualitatively discuss the shape of the EQE curve (spectral response) and suggest ways to improve the performance of the solar cell.

Keithley 2400 Series Source Meter

Nov. 8, 2011, Notes from P. Roland

RS232 Communication

- Communication via rs232 requires careful control over the parameters dictating the structure of the serial communication.
  - Baud Rate
  - Data Bits
  - Parity Bit

  } Set via NI-MAX explorer for each individual port

  - Terminating Character
    - Each message must end with a specified terminating character which must match that set by the Keithley Meter.

RS232 Communication

- Source meter communication settings controlled via the front panel.

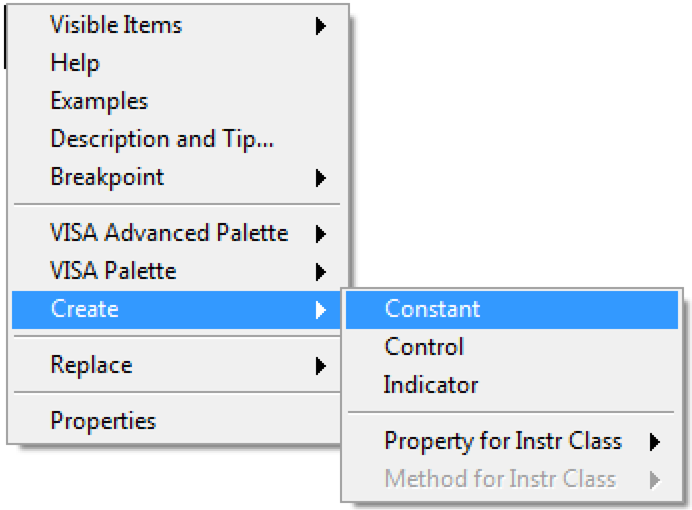
- Menu
  - Communication
    - RS232
      - Baud Rate
      - Data Bits
      - Parity Bit
      - Terminating Character
      - Flow Control (Set to none……)

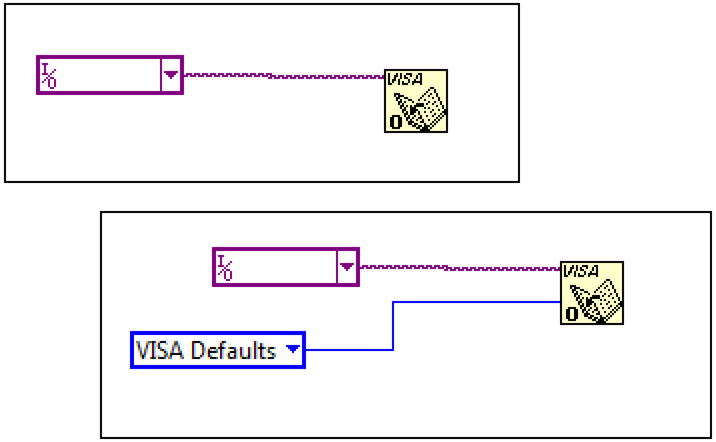
Notes on following slides

- Note that although the following approach may be of help to you, some of you may be using a slightly different approach to establish communication with the 2401.

LabView

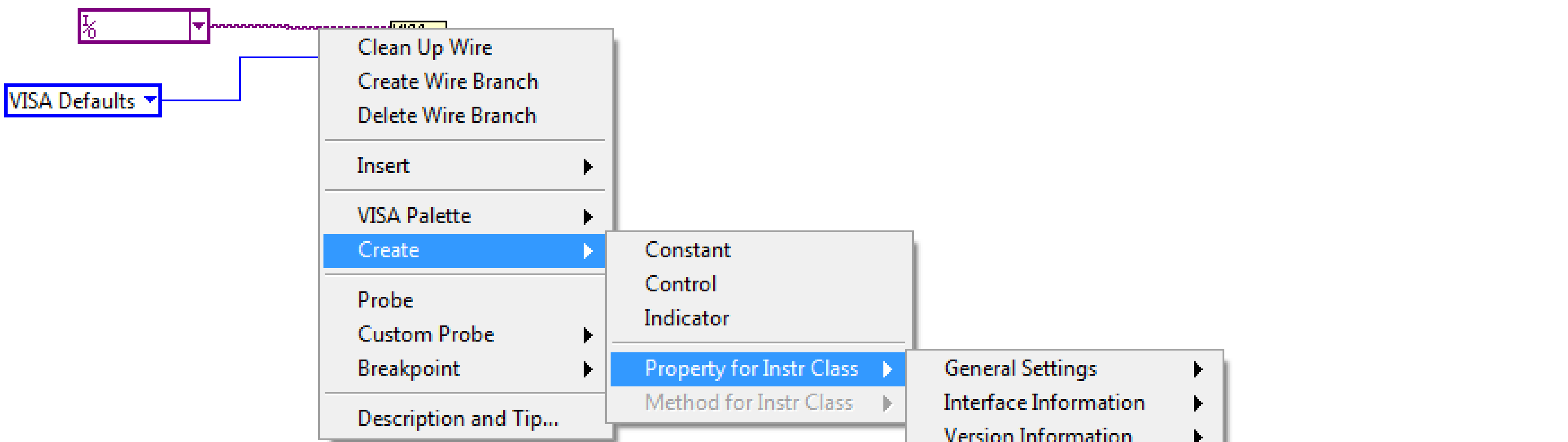
- Right click on the "VISA resource name" input and select create>constant. This will automatically generate an enumerated list of all connected communication ports.
- Repeat for "Access Mode", select VISA Defaults

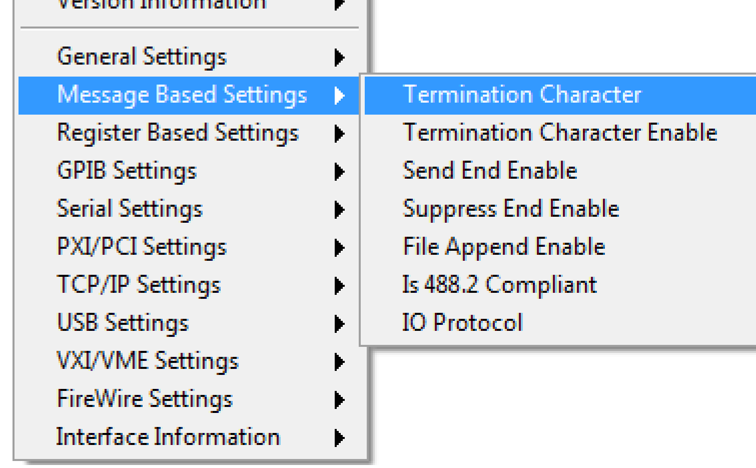




http://zone.ni.com/devzone/cda/tut/p/id/4256

LabView



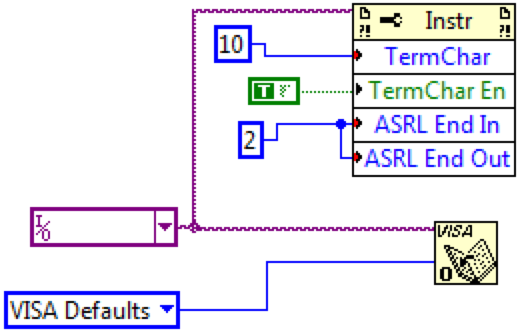


- Configuring the terminating character can be tricky.
- Right click the wire for the VISA reference and Select the terminating character as shown.
- Also add Termination Character Enable and End Modes for Reads and End Modes for Writes found under Serial Settings

http://zone.ni.com/devzone/cda/tut/p/id/4256

LabView

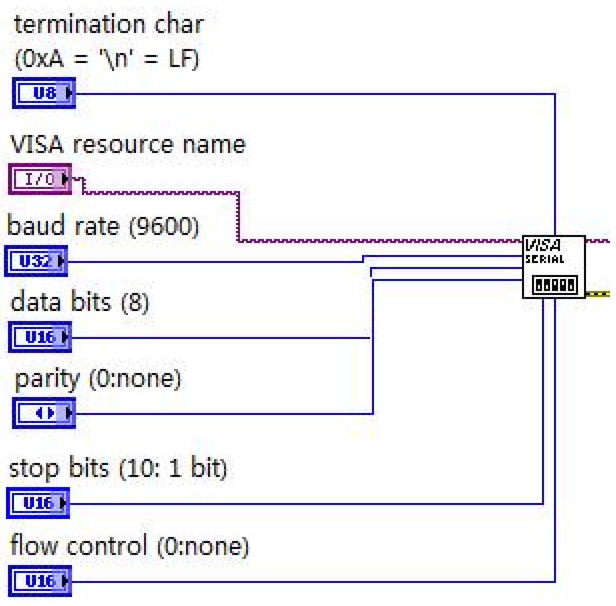
- The Terminating Character shown here, is the ASCII code for Line Feed. Configure the Keithley meter to also use line feed for termination.
- TermChar EN automatically adds the termination character for messages.
- ASRL End In and ASRL End Out (wired to a 2) specify that the terminating character, in this case Line Feed, will signify the end of all incoming and outgoing messages. This is critical for both Labview and the Meter to know when to stop listening.



http://zone.ni.com/devzone/cda/tut/p/id/4256

LabView

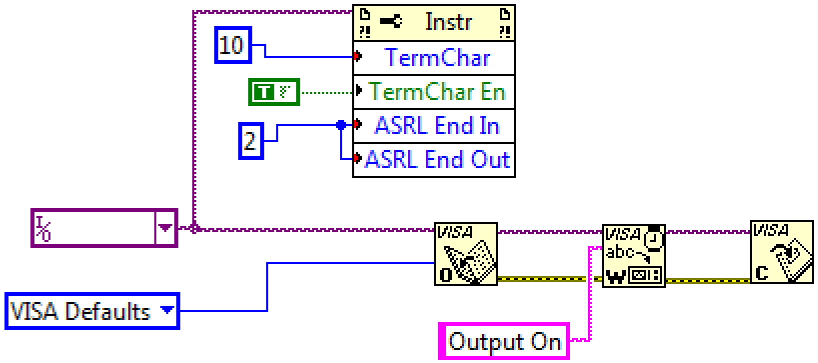
- Alternate approach (set VISA directly)



http://zone.ni.com/devzone/cda/tut/p/id/4256

LabView

- Finally, we can construct operational code. This extremely simplified example will just turn on the output of the device (same as pressing the button on the front panel of the meter).
- You can see if this worked because a light will turn on (and it will beep!!) signifying that output is active.
- It is important to always close the VISA communication path after you are done. This frees up resources for computing or talking with other devices.



http://zone.ni.com/devzone/cda/tut/p/id/4256

Comments

- Due to the USB-RS232 converter used in the lab course, the Baud Rate is limited to about 9600.
- Having labview control each data point in a sweep is one of the slowest methods. You must wait for labview to send the commands at each individual data point.
- To make communication faster, utilize the trigger system to store data points in an internal buffer (up to 2500 data points).
- For I-V curves, you can program up to 100 data points in a sweep profile. There are various sweep profiles (linear being the most widely used). For more than 100 data points, you much program separate portions of the sweep into memory.
- Integration time (NPLC) determines the resolution of each data point.
  - 1 = 5.5 digits
  - 0.1 = 4.5 digits
  - 0.01 = 3.5 digits
- Set the Sense Range to improve accuracy of data.

Comments

- So you've decided to use a pre-programmed sweep? How do you know when the meter is done?
- You can use status registers to monitor the progress of the programmed sweep.
- *SRE 1 and STATus:MEASure:ENABle 512 configure the registers to monitor the buffer status.
- **SEE Page 15-3 of the manual**
- Filling the buffer (along with bit 512 set above) will set the output of the Measurement Event Register. This, combined with the first bit of the Status Request Enable register (SRE) will set the RQS/MSS bit. This is what we are interested in.
- *STB? Will return the status byte register. Checking the RQS bit will tell you if the buffer is full yet (remember, there are 8 bits per byte).

Reading a buffer takes time (especially at a slower baud rate). Make sure to wait enough time for the data to be read. Leaving part of the buffer behind can be troublesome.

IMPORTANT

- After opening communication, send the following
  - ABORT
  - :SYSTem:PRESet
- These commands will reset <u>many</u> of the registers and communication settings to default.
- Before closing communication,
  - Reset any registers used by setting their values to Zero (*CLS is a great command to include)
  - Clear any buffers used for data storage
  - TURN OFF THE METER OUTPUT….. **<u>NO ONE NEEDS TO GET SHOCKED!!!</u>**
- If you can't get communication working, first confirm the baud rate, data bits, stop bits, parity bits, and terminating character.
- You can send the command *IDN? through the NI-MAX explorer to check which device is connected to each COMM port. Most devices respond with a string identifying themselves.