Molecular and Condensed Matter Physics Laboratory (PHYS 4580)

Photovoltaic Materials and Device Physics Laboratory (PHYS 6/7280)

Instructors: Prof. Randy Ellingson, Prof. Mike Heben
Teaching Assistant: Neale Haugen

Course catalog descriptions:

PHYS 4580 -- MOLECULAR AND CONDENSED MATTER LABORATORY

[3 hours] Experiments in molecular and condensed matter physics. Measurements and analysis based on techniques such as film thickness and surface morphology, X-ray diffraction, optical absorption, four-point probe and Hall measurements. One four-hour lab and one-hour lecture per week. ***May be offered as writing intensive (WAC section is -071).*** Prerequisite: PHYS 3320.

PHYS 6280/7280 -- PHOTOVOLTAIC MATERIALS AND DEVICE PHYSICS LABORATORY

[3 hours] Fabrication and characterization of solar cell materials and devices, addressing materials science and physics of substrate preparation, absorber and window deposition processes, metal contact formation, and measurement of physical properties. One four-hour lab and one-hour lecture per week. Prerequisite: PHYS 6140/7140.

Molecular and Condensed Matter Physics Laboratory (PHYS 4580)
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Things to discuss:

- Scheduling (lecture and lab)
- Experiments
- Lab Open Days/Times
- Lab Reports

Laboratory Scheduling for 4580, 6280

Each lab session is 4 hours. Additional lab time will be provided to enable students to repeat and/or correct measurements as necessary. Lab will generally be open Wednesday, Thursday, and Friday. Please contact us if the lab is locked during times you need access.

Your responsibilities, and grading

GRADING and EXAMS

Only material covered in class or in lab experiments will be used for quizzes. Final grades will be based on:

1. Quizzes: Three quizzes during the semester -- short (10 min.), multiple choice, and closed book, closed notes.

2. Laboratory Notebooks: Bring your laboratory notebook with you to each class, and use it to carefully record notes on procedures, parameters during procedures and measurements, etc. Your notebook will be reviewed every two weeks, with scoring of 2, 1, or 0 points.

3. Lab Reports: We encourage collaboration and significant interaction to support everyone learning as much as possible; however, Lab Reports should represent your own work and level of understanding

Include the following sections in each lab report:

> **Title Section: including** (a) Title of your Report, (b) Your name and the names of lab partners (if any), (c) Date, and (d) Abstract (Purpose of Experiment(s) and major conclusions - approximately 100 - 200 words). The Title section should not be on a separate page – we like to conserve paper where possible.
>
> **Introduction**: information on the need for, and value of, the experiments, and discussion of the general approach.
>
> **Experimental:** details of samples and equipment, including a sketch of the layout and a few words on the function of each major component.
>
> **Results and Discussion:** analysis, appropriate graphs, a thoughtful explanation of the significance of the results, sources of uncertainty, and strengths and weaknesses of the measurement approach.
>
> **Conclusion**
>
> **References**

4. Final Project: Your final project will be based on a single 2-hour laboratory session in which you'll be asked to perform or describe specific measurements on a specific photovoltaic material or sample using the equipment, capabilities, and skills you develop during the semester.

Grading

Grades will be determined according to: Quizzes = 15%, Notebook = 10%, Lab Reports = 55%, and Final Project = 20%.

Overview Information

- Website:

  http://astro1.panet.utoledo.edu/~relling2/teach/4580.6280.2014/fall2014_phys_4580.6280.html
- Laboratory location: R1 1070
- LabVIEW – used for *instrument control* (e.g., wavelength control in CM110 monochromator) and for *data acquisition*.
- Igor Pro (graphing and analysis software)
- Safety information.
- Experiment overviews – materials deposition, optical and electrical characterization (metals, transparent conductors, semiconductors), solar cell fabrication, test, and characterization.

Overview of Experiments

- Introduction to software and hardware
- Light spectrum measurements
- Optical characterization of thin films (transmission, reflection, and absorbance)
- Electrical characterization (metals, transparent conductors, semiconductors)
- Solar cell test and characterization
- Lock-in detection, Data Acquisition (DAQ) -- Analog-to-Digital Conversion, data analysis and reconciliation
- Units – importance of proper handling of units, and use of S.I. units wherever possible (provide conversion information)
- Error analysis and error propagation

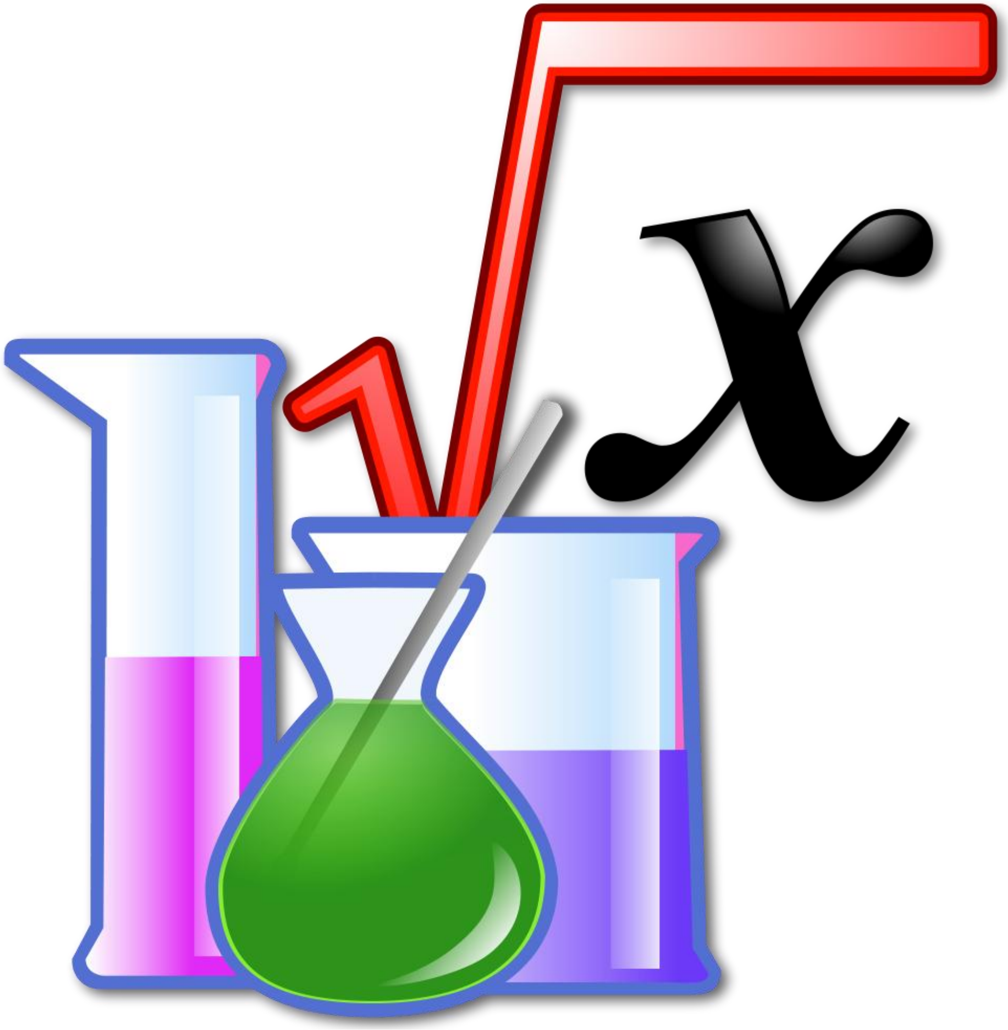
A. Experimental Practices
B. Graphing and Analysis with Igor Pro
C. Intellectual Honesty

IGOR Pro

- *Runs on Mac OS X and Windows*
- *Fast Display of Large Data Sets*
- *Interactive Data Exploration*
- *Journal–Quality Graphics*
- *Powerful Curve Fitting*
- *Extensive Data Analysis & Statistics*
- *Image Processing*
- *Data Acquisition Support*
- *Built-In Programming Environment Supports Analysis and Automation*
- *Customizable User Interface*
- *Used by Scientists and Engineers Worldwide Since 1989*

Molecular and Condensed Matter Lab
(Physics 4580)
PV Materials and Device Physics Lab
(PHYS 6/7280)
The University of Toledo
Instructors: R. Ellingson, M. Heben

Experimental Methods and Practices



http://en.wikipedia.org/wiki/Scientific_method

Key Elements of the Scientific Method

Scientific method: ask and answer scientific questions through experiment and observation.

The steps of the scientific method are to:

1. Define the question
2. Gather information and resources (observe)
3. Form hypothesis
4. Perform experiment and collect data
5. Analyze data
6. Interpret data and draw conclusions that serve as a starting point for new hypothesis
7. Publish results
8. Retest (frequently done by other scientists)

The iterative cycle inherent in this step-by-step methodology goes from point 3 to 6 back to 3 again.

It is important for your experiment to be a fair test. A "fair test" occurs when you change only one factor (variable) and keep all other conditions the same.

http://en.wikipedia.org/wiki/Scientific_method

Thoughts on the Scientific Method

Ibn al-Haytham (Alhazen, 965–1039), pointed out the emphasis on seeking truth:

Truth is sought for its own sake. And those who are engaged upon the quest for anything for its own sake are not interested in other things. Finding the truth is difficult, and the road to it is rough.

According to William Whewell (1794–1866), "invention, sagacity, genius" are required at every step in scientific method. It is not enough to base scientific method on experience alone; multiple steps are needed in scientific method, ranging from our experience to our imagination, back and forth.

http://en.wikipedia.org/wiki/Scientific_method

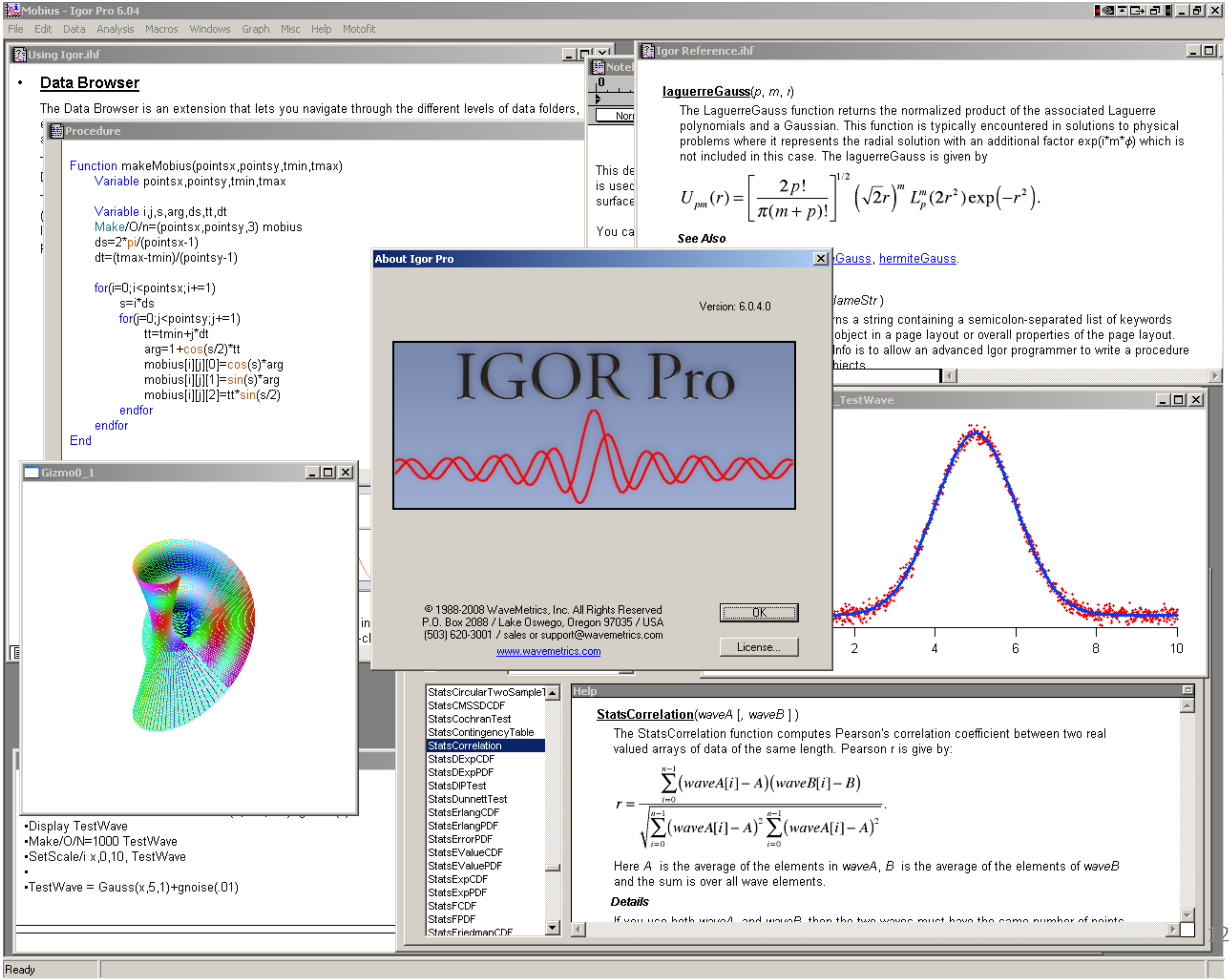
Scientific Method: Beliefs and Biases

Eadweard Muybridge's (1830 – 1904) studies of a horse galloping

The Epsom Derby (1821) by Géricault, Jean Louis Théodore. Oil on canvas.

http://en.wikipedia.org/wiki/Scientific_method

Igor Pro 6.1



- **Data Browser**

The Data Browser is an extension that lets you navigate through the different levels of data folders,

```
Function makeMobius(pointsx,pointsy,tmin,tmax)
	Variable pointsx,pointsy,tmin,tmax

	Variable i,j,s,arg,ds,tt,dt
	Make/O/n=(pointsx,pointsy,3) mobius
	ds=2*pi/(pointsx-1)
	dt=(tmax-tmin)/(pointsy-1)

	for(i=0;i<pointsx;i+=1)
		s=i*ds
		for(j=0;j<pointsy;j+=1)
			tt=tmin+j*dt
			arg=1+cos(s/2)*tt
			mobius[i][j][0]=cos(s)*arg
			mobius[i][j][1]=sin(s)*arg
			mobius[i][j][2]=tt*sin(s/2)
		endfor
	endfor
End
```

This de
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laguerreGauss(*p*, *m*, *r*)

The LaguerreGauss function returns the normalized product of the associated Laguerre polynomials and a Gaussian. This function is typically encountered in solutions to physical problems where it represents the radial solution with an additional factor exp(i*m*ϕ) which is not included in this case. The laguerreGauss is given by

$$U_{pm}(r)=\left[\frac{2p!}{\pi(m+p)!}\right]^{1/2}\left(\sqrt{2}r\right)^{m}L_{p}^{m}(2r^{2})\exp\left(-r^{2}\right).$$

See Also

eGauss, hermiteGauss.

lameStr)

rns a string containing a semicolon-separated list of keywords
object in a page layout or overall properties of the page layout.
Info is to allow an advanced Igor programmer to write a procedure

Version: 6.0.4.0

IGOR Pro

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P.O. Box 2088 / Lake Oswego, Oregon 97035 / USA
(503) 620-3001 / sales or support@wavemetrics.com
www.wavemetrics.com

```
•Display TestWave
•Make/O/N=1000 TestWave
•SetScale/i x,0,10, TestWave
•
•TestWave = Gauss(x,5,1)+gnoise(.01)
```

StatsCircularTwoSampleT
StatsCMSSDCDF
StatsCochranTest
StatsContingencyTable
StatsCorrelation
StatsDExpCDF
StatsDExpPDF
StatsDIPTest
StatsDunnettTest
StatsErlangCDF
StatsErlangPDF
StatsErrorPDF
StatsEValueCDF
StatsEValuePDF
StatsExpCDF
StatsExpPDF
StatsFCDF
StatsFPDF
StatsFriedmanCDF

StatsCorrelation(*waveA* [, *waveB*])

The StatsCorrelation function computes Pearson's correlation coefficient between two real valued arrays of data of the same length. Pearson r is give by:

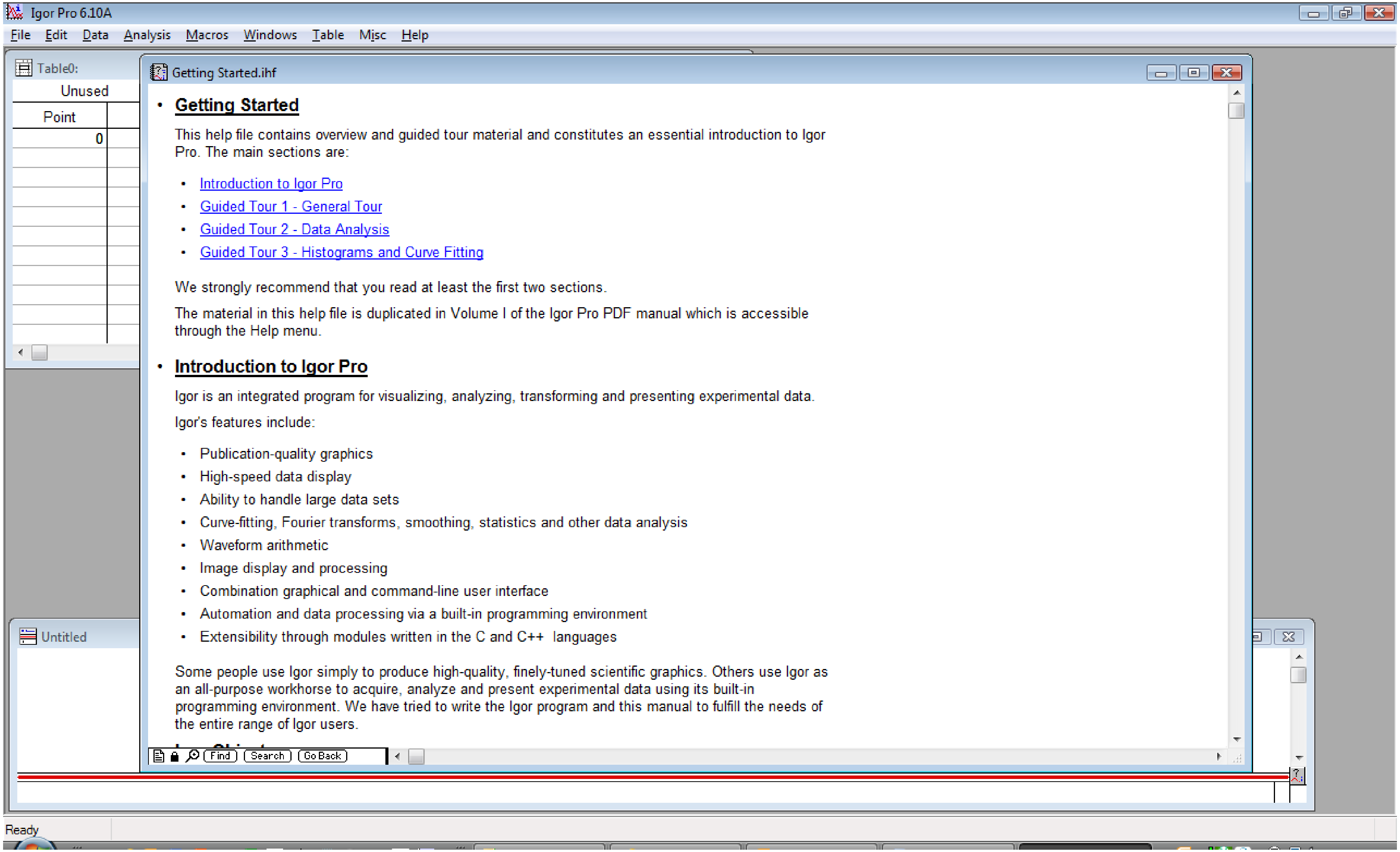
$$r=\frac{\sum_{i=0}^{n-1}(waveA[i]-A)(waveB[i]-B)}{\sqrt{\sum_{i=0}^{n-1}(waveA[i]-A)^{2}\sum_{i=0}^{n-1}(waveA[i]-A)^{2}}}.$$

Here *A* is the average of the elements in *waveA*, *B* is the average of the elements of *waveB* and the sum is over all wave elements.

Details

If you use both *waveA* and *waveB* then the two waves must have the same number of points

Igor Pro 6.1 (www.wavemetrics.com)



- **Getting Started**

This help file contains overview and guided tour material and constitutes an essential introduction to Igor Pro. The main sections are:

- Introduction to Igor Pro
- Guided Tour 1 - General Tour
- Guided Tour 2 - Data Analysis
- Guided Tour 3 - Histograms and Curve Fitting

We strongly recommend that you read at least the first two sections.

The material in this help file is duplicated in Volume I of the Igor Pro PDF manual which is accessible through the Help menu.

- **Introduction to Igor Pro**

Igor is an integrated program for visualizing, analyzing, transforming and presenting experimental data.

Igor's features include:

- Publication-quality graphics
- High-speed data display
- Ability to handle large data sets
- Curve-fitting, Fourier transforms, smoothing, statistics and other data analysis
- Waveform arithmetic
- Image display and processing
- Combination graphical and command-line user interface
- Automation and data processing via a built-in programming environment
- Extensibility through modules written in the C and C++ languages

Some people use Igor simply to produce high-quality, finely-tuned scientific graphics. Others use Igor as an all-purpose workhorse to acquire, analyze and present experimental data using its built-in programming environment. We have tried to write the Igor program and this manual to fulfill the needs of the entire range of Igor users.

Igor Pro information (please note)

http://www.wavemetrics.com/support/demos.htm

Download the IgorPro Demo (available for either Mac or Windows), and use this information for the S/N and the Activation Key.

Serial Number: (available from instructors)

Activation Key: (available from instructors)

Lab Reports:

Ensure individual reports represents your own words and understanding, even when data is shared.

- Project 269 - Exploration 18 -

This breathtaking organism may have been made for the most nefarious of purposes — but no matter, the scientific achievement shines through. The National Socialists gave birth to the Volkswagen Beetle, yet the hippies saw its beauty. What we have here is LIFE, created by man not god! The German Shakespeare would have understood.

Dare with determin'd will to burst the portals
Past which in terror others fain would steal!
Now is the time, through deeds, to show that mortals
The calm sublimity of gods can feel…

I remember the first time I tried to create life. A failed merger of paramecium and amoeba, all cilia and pseudopods, a paradox in a petri dish. And then the second time, with more primitive methods, heaving and perspiring, nine months of grueling effort for the carrier, culminating in a convulsive expulsion of amniotic fluid. I suppose the output was better that time, although the hybrid had a bit too much of his mother. Parthenogenesis might have been preferable.

But this chimera is something else entirely. The offspring of unconscious evolution and conscious design, marvelous yet dreadful — the very model of a Hegelian synthesis. Never seen anything like it, except of course for that astonishing black-and-tan I poured myself in Heidelberg, 1985. The perfect mingling of two local brews — a dunkel and a weizen — rich chocolaty oligosaccharides fornicating with bitter earthy extracts of humulus lupulus. But where did I put the recipe? I must have taken it from my head before they could, stored it in sequence with the rest of my best ideas.

And now I must perform my own extraction, from the fellow with the hole in his head. Pulling thoughts — substantially more difficult than pulling teeth. The boy is skeptical, but Nietzsche put it best: "I favor any skepsis to which I may reply: 'Let us try it!' But I no longer wish to hear anything of all those things and questions that do not permit any experiment." Now, what was Peter's electrical tolerance? Was it 40, or 80? Oh well, only one way to find out!

GENETIC ANALYZER - SAMPLE # 78 PARASITE

http://www.fringebloggers.com

- Show what you have learned – describe the experiment (background, what is measured, important steps, how things fit together, origins and magnitude of the uncertainties);
- Label your graphs carefully – ensure that the reader knows what is graphed. <u>Include units</u> on each axis label, and on other quantities (refer to syllabus for more detailed info).
- ***Avoid plagiarism***: understand what you read, know the points you want to make, and restate the ideas in your own words. You'll learn more this way, and avoid potentially big problems.

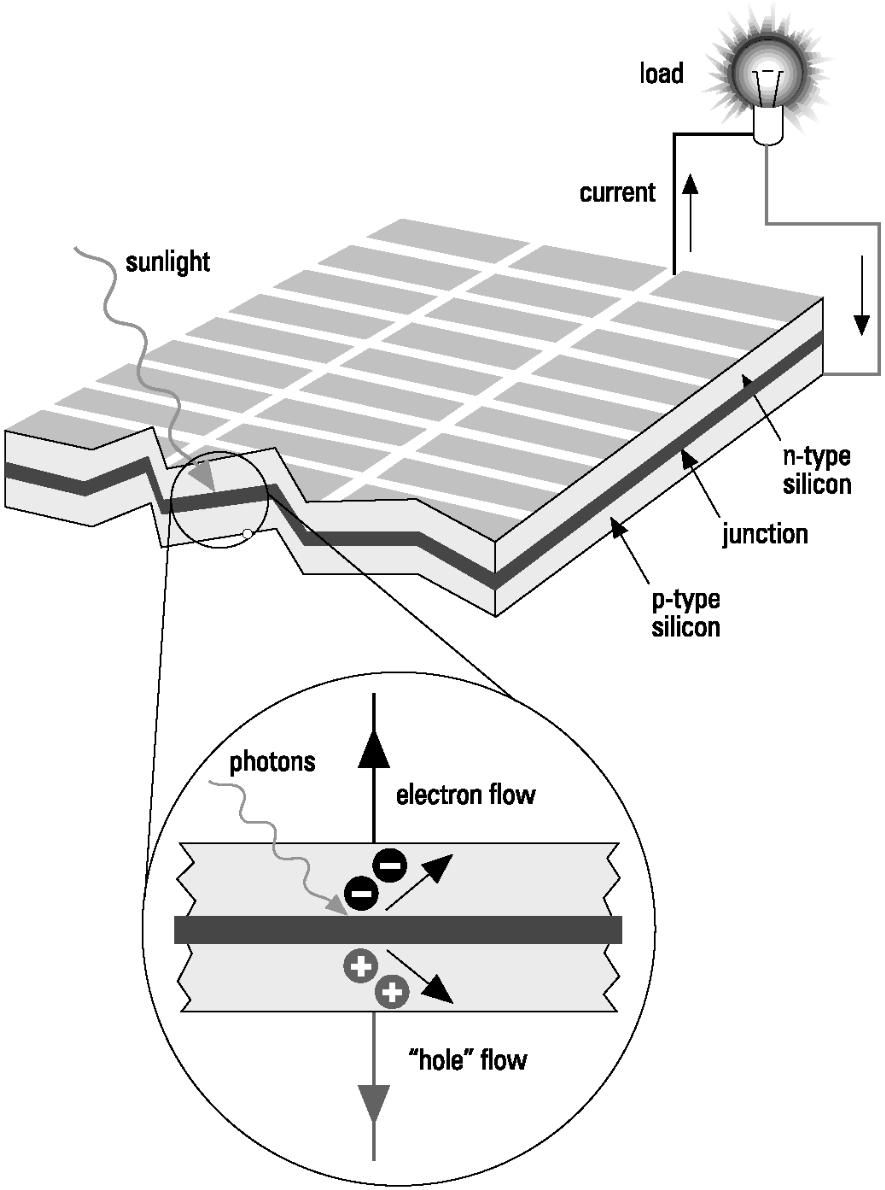
The First Experiment – Intro to Hardware and Software

- Familiarity with the experimental workstation – software and hardware elements
- Opening and running LabVIEW programs; writing simple LV programs
- Using the monochromator and light source
- Light detection using the thermopile detector
- Optical chopping of a steady-state light beam
- Using the DAQ device
- Recording light intensity vs. time data points using LV
- Writing your data to a file
- Fitting a function to your data; extracting meaningful information from the fits.

Basic silicon photovoltaic (solar) cell operation

Key functions of a solar cell

- absorbs sunlight efficiently.
- separates charge (electrons from “holes”).
- Creates electrical current and voltage (*power)* when illuminated.
- Acts like a battery under sunlight.



http://www.emeraldinsight.com/fig/0870210205001.png

CdTe Device Technology

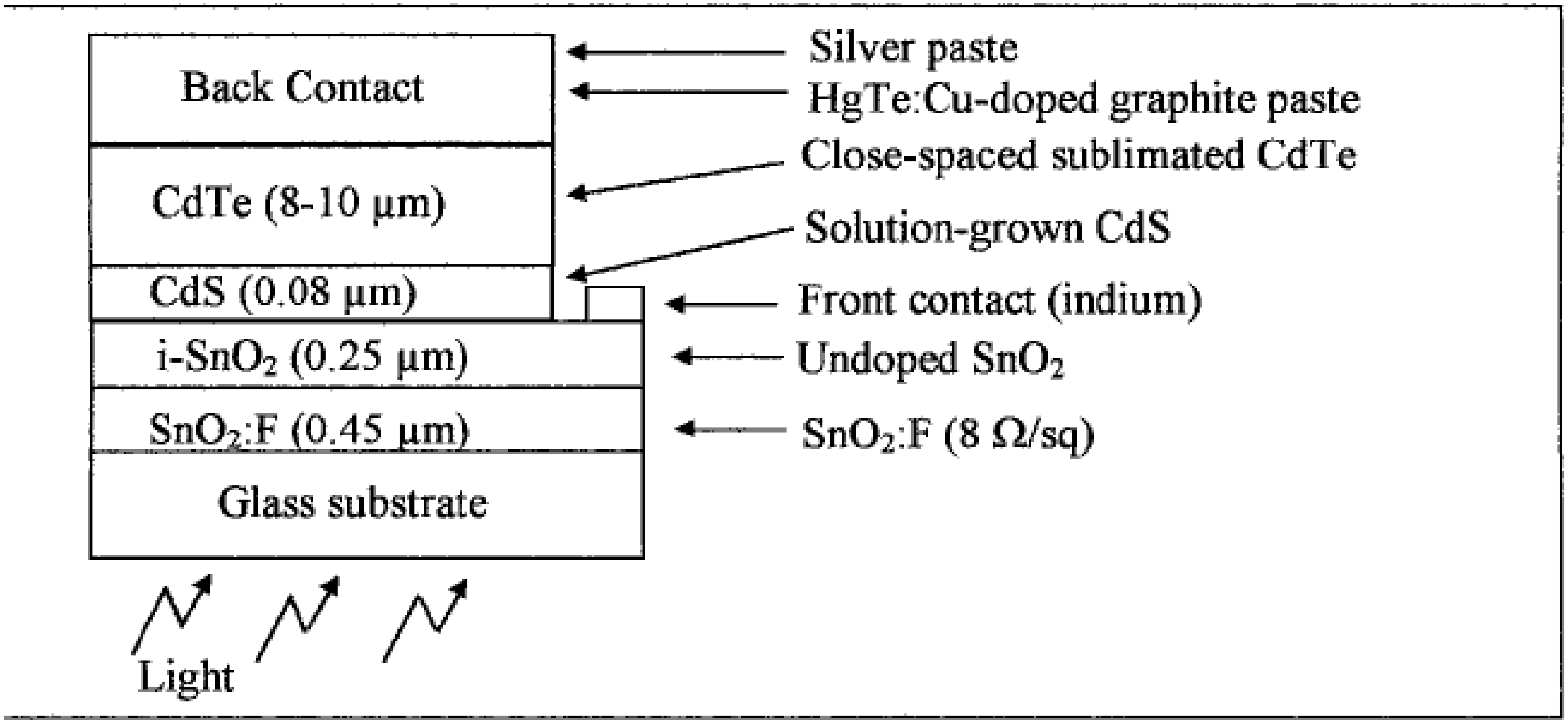
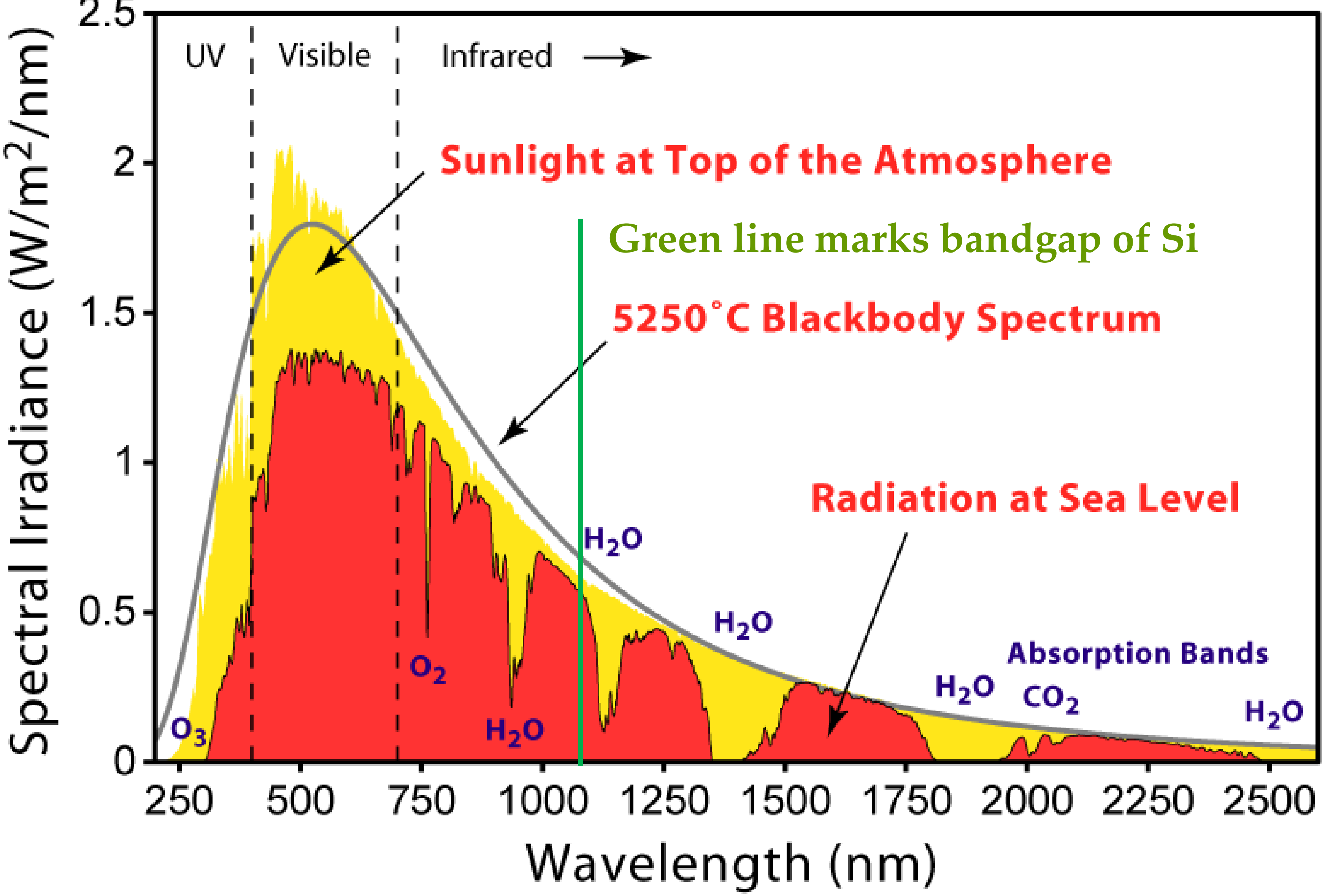


Figure 1. Solar cell device structure

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. **7**, 331–340 (1999)

Solar Radiation Spectrum



Green line marks bandgap of Si

Image created by Robert A. Rohde / Global Warming Art

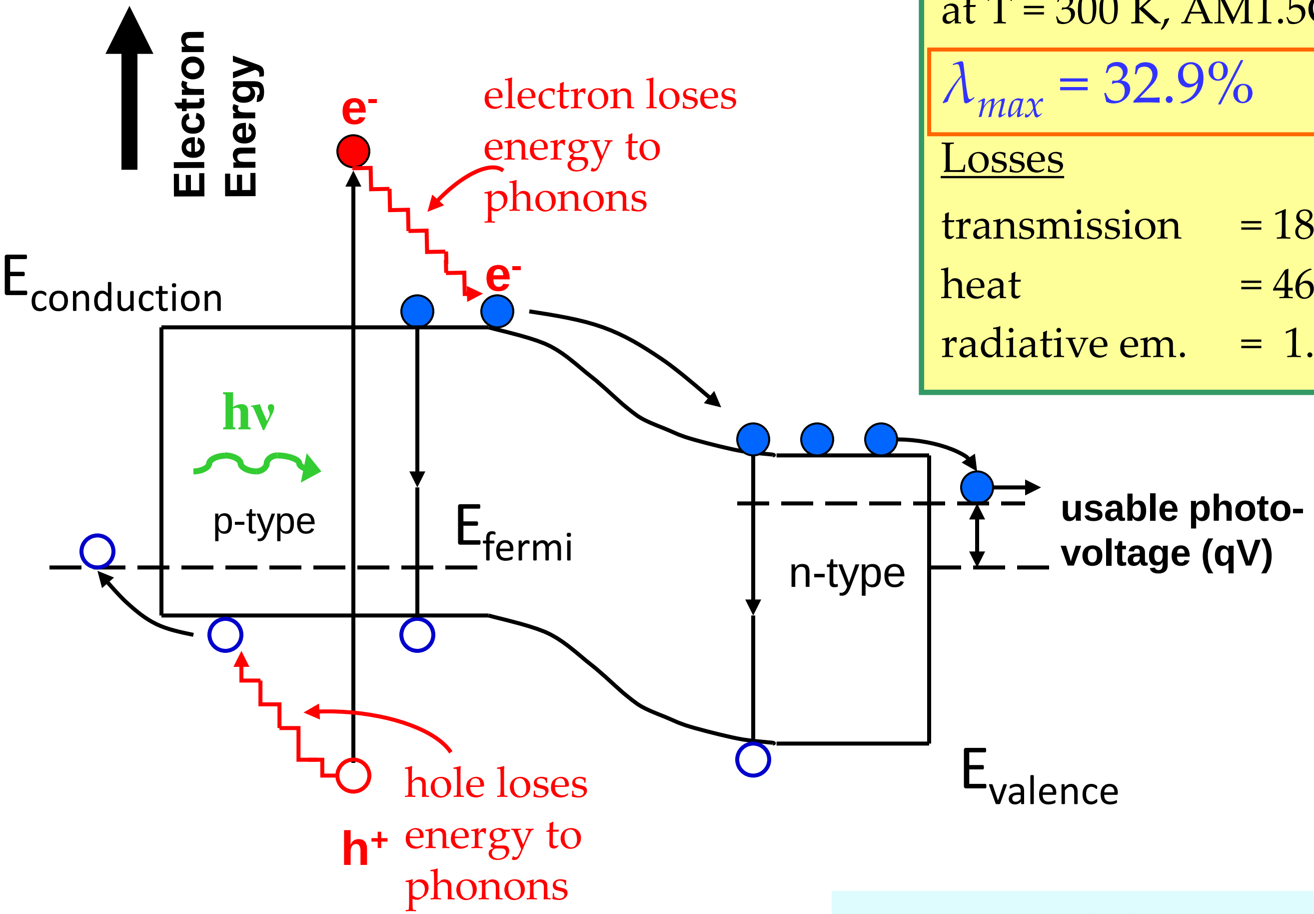
Conventional p-n junction photovoltaic cell

For Si (E_g = 1.1 eV)
at T = 300 K, AM1.5G

λ_{max} = 32.9%

<u>Losses</u>

transmission = 18.7%
heat = 46.8%
radiative em. = 1.6%



1 *e*⁻-*h*⁺ pair/photon

External and internal quantum efficiency

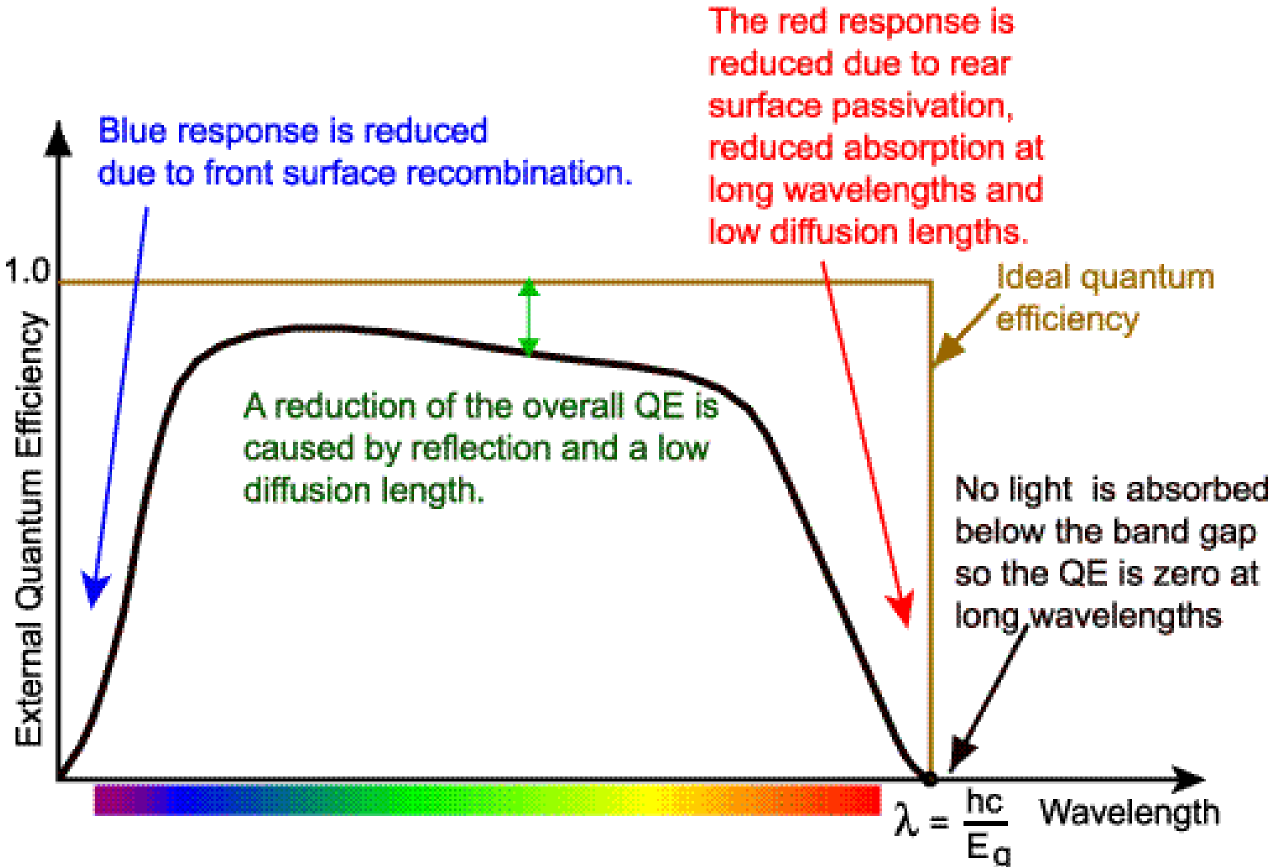
Two different kinds, both a functions of wavelenth:

External quantum efficiency (EQE):

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

Internal quantum efficiency (QE):

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



Blue response is reduced due to front surface recombination.

The red response is reduced due to rear surface passivation, reduced absorption at long wavelengths and low diffusion lengths.

A reduction of the overall QE is caused by reflection and a low diffusion length.

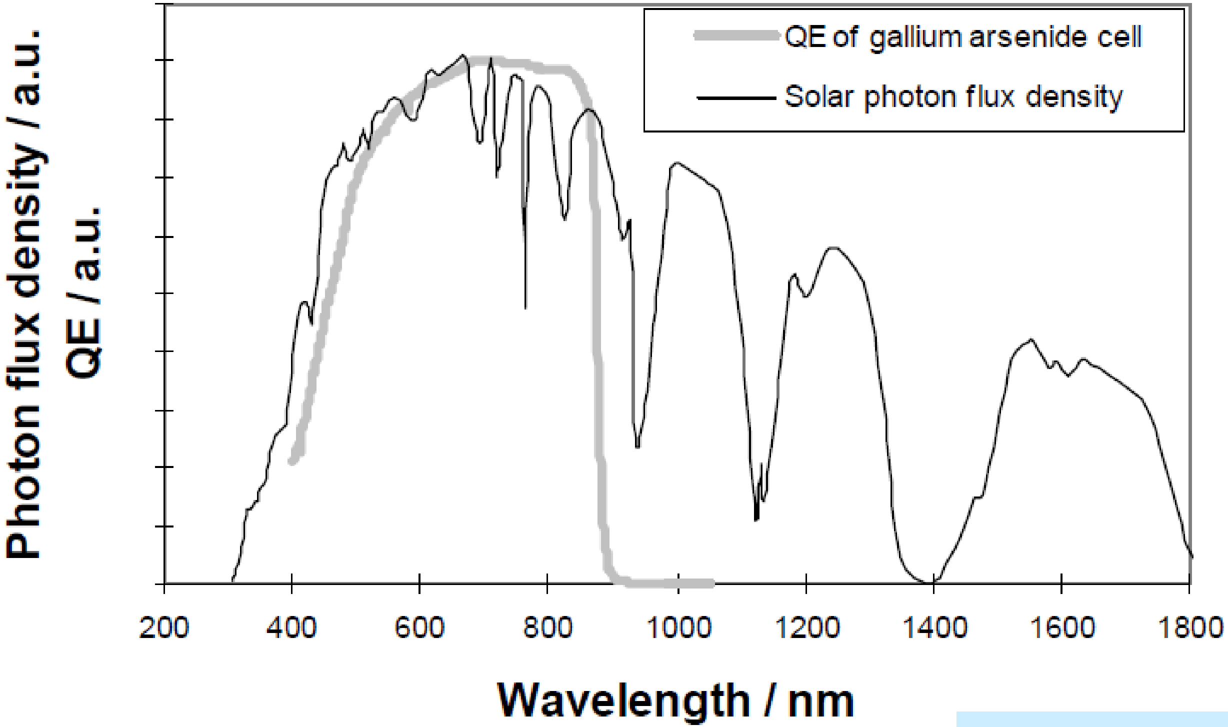
No light is absorbed below the band gap so the QE is zero at long wavelengths

PVEDUCATION.ORG

Relationship between QE and J_{sc}

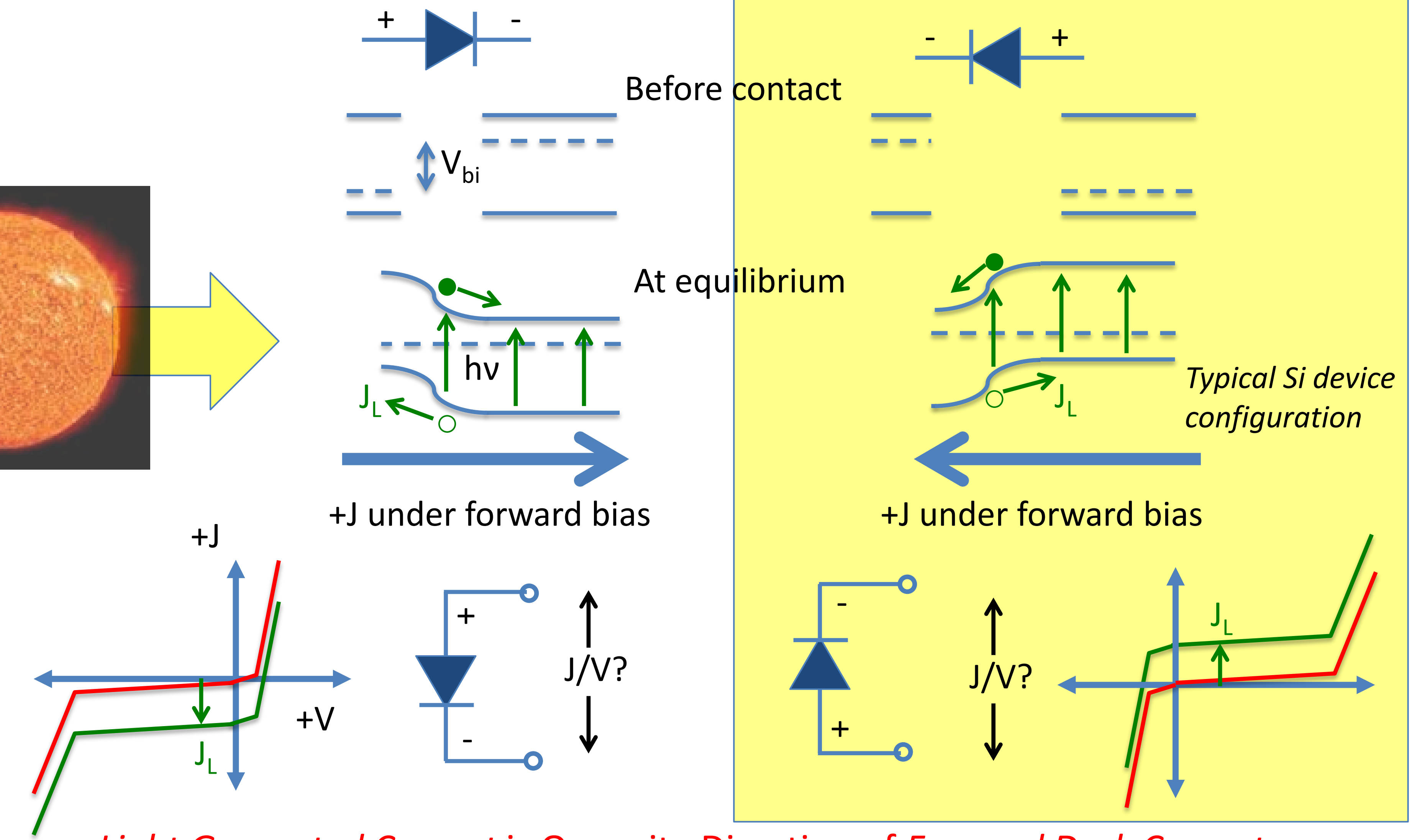
$$J_{SC} = q\int b_s(E)QE(E)dE$$

Where q is the electronic charge, $b_s(E)$ is the incident photon flux density as a function of energy, i.e. the number of photons in the energy range E to $E + dE$ which are incident on unit area in unit time, The Quantum Efficiency (QE) depends upon the absorption coefficient of the solar cell materials, the efficiency of charge separation, and the efficiency of charge collection in the device; but it does not depend on the incident spectrum.



"The Physics of Solar Cells", J. Nelson

Homojunction solar cell (e.g., Silicon)



p-type emitter (window)
n-type base (absorber)

n-type emitter (window)
p-type base (absorber)

Before contact

At equilibrium

Typical Si device configuration

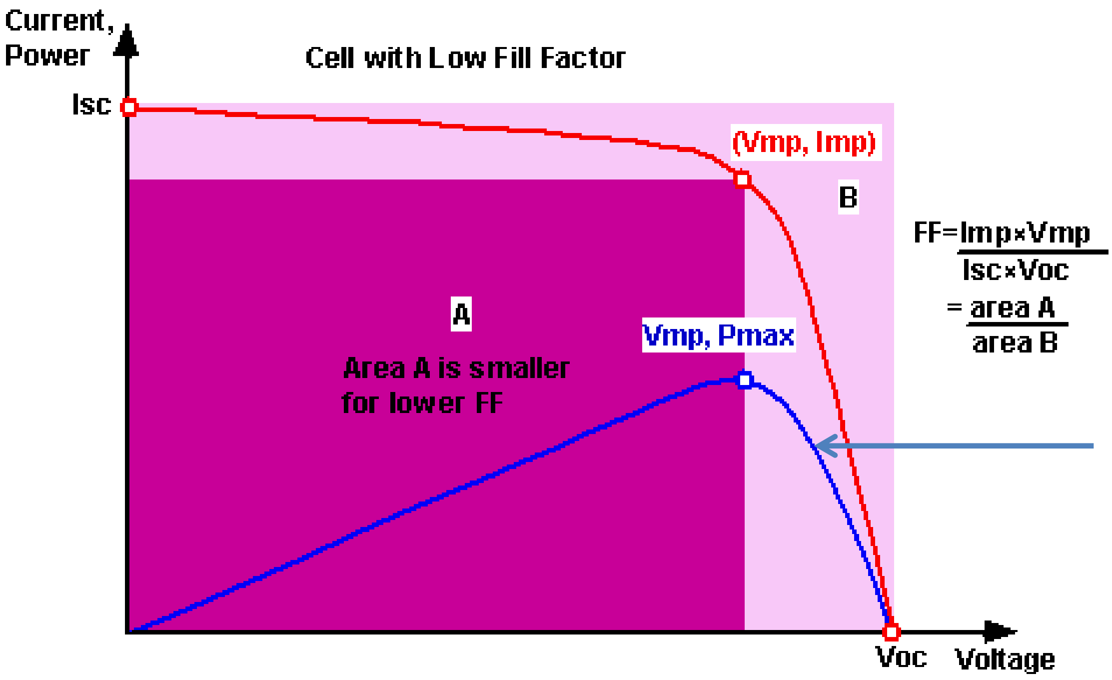
+J under forward bias

+J under forward bias

Light Generated Current is Opposite Direction of *Forward Dark Current*

Solar cell fill factor (FF) and Max Power Point (mpp)

At both of the operating points corresponding to I_{SC} and 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 solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated below:



$P_{out} = I * V$

$dP/dV = 0$

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 (sometimes known as the power conversion efficiency, or PCE, and also 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:

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

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.

Power in AM1.5G spectrum is 1kW/m^2 , or 100 mW/cm^2

For a 10 x 10 cm^2 cell, the input power (AM1.5G) is 100 mW/cm^2 x 100 cm^2 = 10 W.