Toward a 1D Device Model Part 1: Device Fundamentals

Lecture 7 – 9/29/2011

MIT Fundamentals of Photovoltaics
2.626/2.627 – Fall 2011

Prof. Tonio Buonassisi

Learning Objectives: Toward a 1D Device Model

1. **Describe the difference between "Energy Conversion Efficiency" and "Quantum Efficiency."**
2. Describe common factors that cause solar cell IV curves to deviate from an ideal diode model: shunt & series resistance, recombination currents, and current crowding.
3. Calculate series resistance for a solar cell.
4. Calculate the Fermi Energy of a solar cell as a function of dopant concentration, illumination condition, and temperature.
5. Calculate carrier generation as a function of depth in a solar cell.
6. Calculate how material quality (minority carrier diffusion length) affects QE and solar cell performance.
7. Create a 1D model for solar cell performance based on diffusion length, optical absorption coefficient, surface reflectivity, and series & shunt resistances.

Key Concept:

"Energy conversion efficiency" is not the same thing as "quantum efficiency".

"Quantum efficiency (QE)" is defined as the number of electrons out per incident photon. Note that QE is simply a census: it does not take into consideration the energy of the electron or photon.

QE is generally reported as a function of wavelength. QE is a useful troubleshooting tool to identify why a device is underperforming.

QE values can be quite high (between 60 and 99% for certain wavelengths), and thus can be used by devious individuals to misrepresent the conversion efficiency of their solar cell device.

A Note about "Efficiency"

LETTERS

Solution-processed PbS quantum dot infrared photodetectors and photovoltaics

Under –5 V bias and illumination from a 975 nm laser, our detectors show an internal quantum efficiency of 3%, a ratio of photocurrent to dark current of 630, and a maximum responsivity of 3.1×10^{-3} A W^{-1}. The photovoltaic response under 975 nm excitation results in a maximum open-circuit voltage of 0.36 V, short-circuit current of 350 nA, and short-circuit internal quantum efficiency of 0.006%.

Technical Terms:

- Solar Conversion Efficiency
- External Quantum Efficiency
- Internal Quantum Efficiency

What does this *really* mean?

Solar Conversion Efficiency: Defined in Previous Slides

$$\eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{I_{mp} \cdot V_{mp}}{\Phi} = \frac{FF \cdot I_{sc} \cdot V_{oc}}{\Phi}$$

Typical values are 12–20% for established technologies, <10% for most emerging technologies.

η and Φ_F: Vary with illumination intensity (e.g., 1 Sun)

External Quantum Efficiency

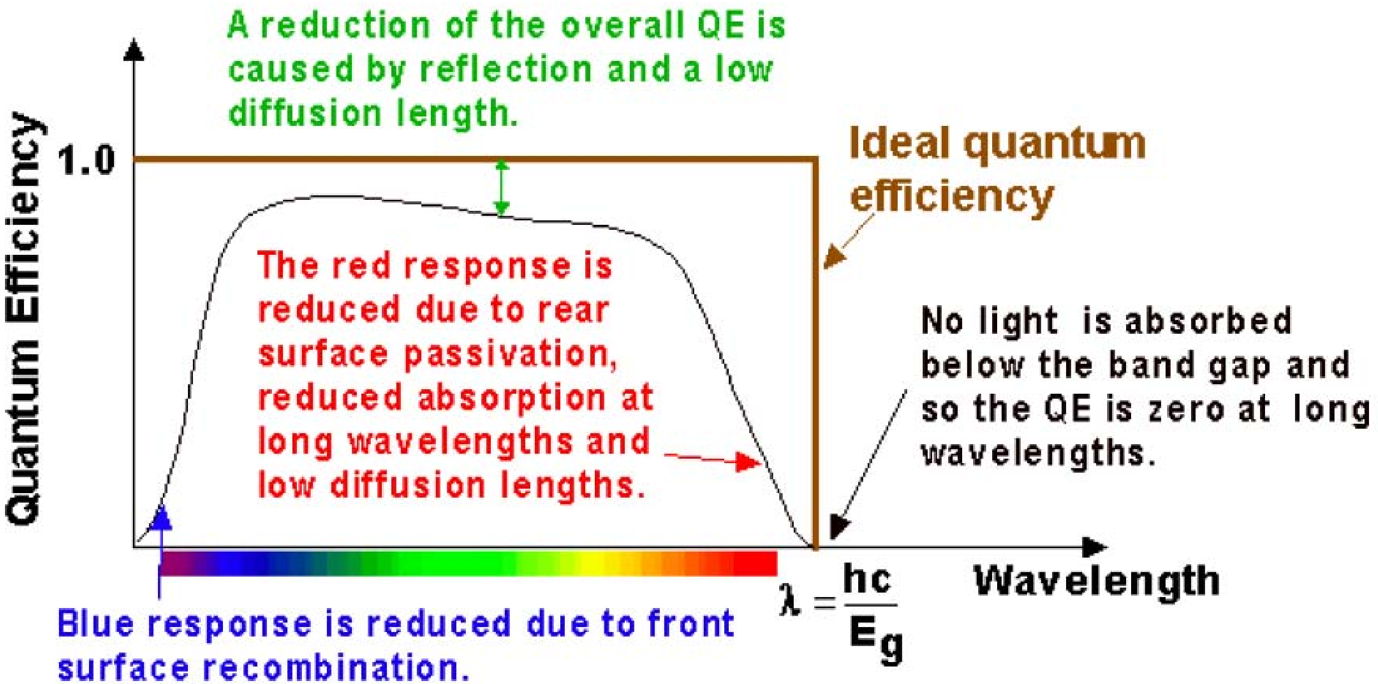
$$\text{EQE} = \frac{\text{Electrons Out}}{\text{Photons In}}$$

Typical peak values are 60–90%, depending on reflectivity, for moderate-efficiency devices.

EQE highly wavelength- and illumination-dependent!

External Quantum Efficiency

Here's an example of a QE spectrum for a solar cell. Note the near-unity (i.e., 100%) QE in the visible wavelengths.



Courtesy of PVCDROM. Used with permission.

from PVCDROM

Internal Quantum Efficiency

$$\text{IQE} = \frac{\text{EQE}}{(1-\text{R})} = \frac{\text{Electrons Out}}{(\text{Photons In})\cdot(1-\text{R})}$$

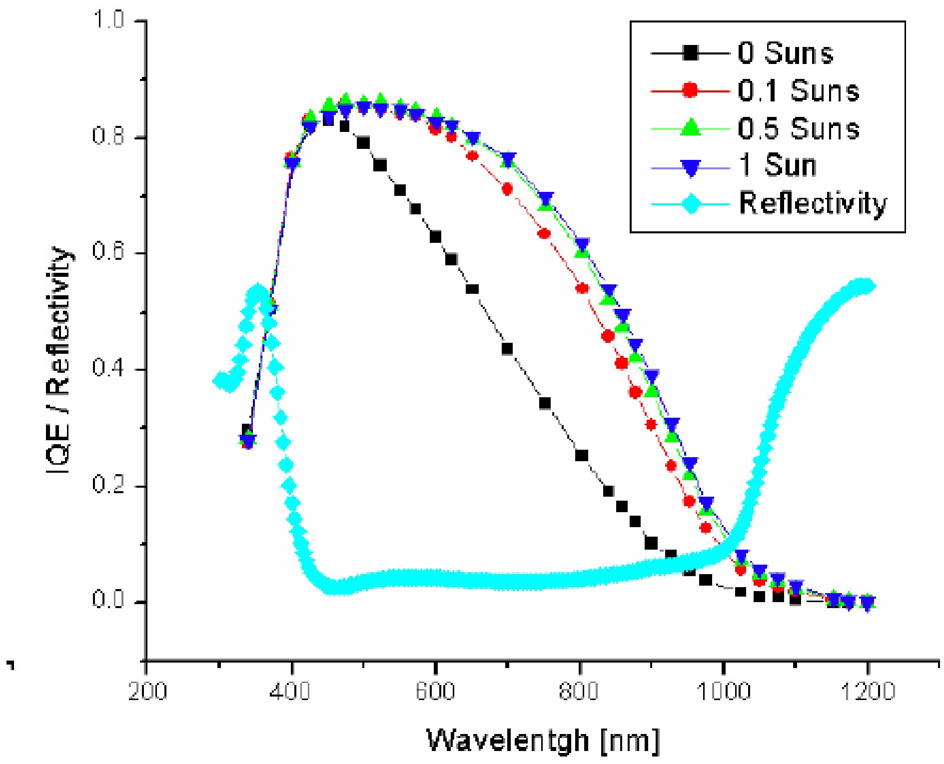
… where R = Reflectivity

Typical peak values between 80–98% for moderate-efficiency devices.

IQE highly wavelength- and illumination-dependent!

Internal Quantum Efficiency

Reflectivity and IQE
(measured with different bias illumination)



Examples of illumination-dependent IQE measurements for a defect-rich multicrystalline silicon solar cell. Minority carrier trapping results in low IQE with low bias illumination.

Approach "efficiency" with a grain of salt:

When an efficiency is quoted, think about:

- What "efficiency" is being measured?
- What is the nature of the light being used?
  - What spectrometer to simulate solar spectrum?
  - If monochromatic, what wavelength?
  - What intensity (photon flux)?

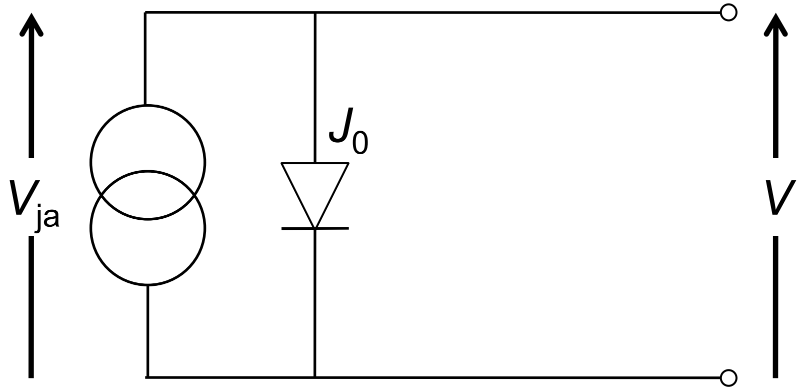
An example of honest efficiency reporting

Please see the abstract from Huynh, W., J. Dittmer et al. "Hybrid Nanorod-Polymer Solar Cells." *Science* 295, no. 5564 (2002): 2425-7.

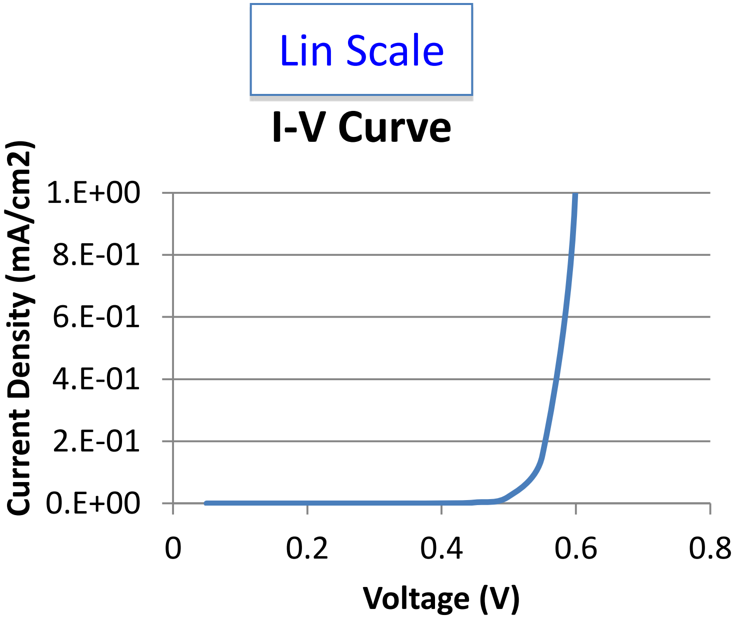
Learning Objectives: Toward a 1D Device Model

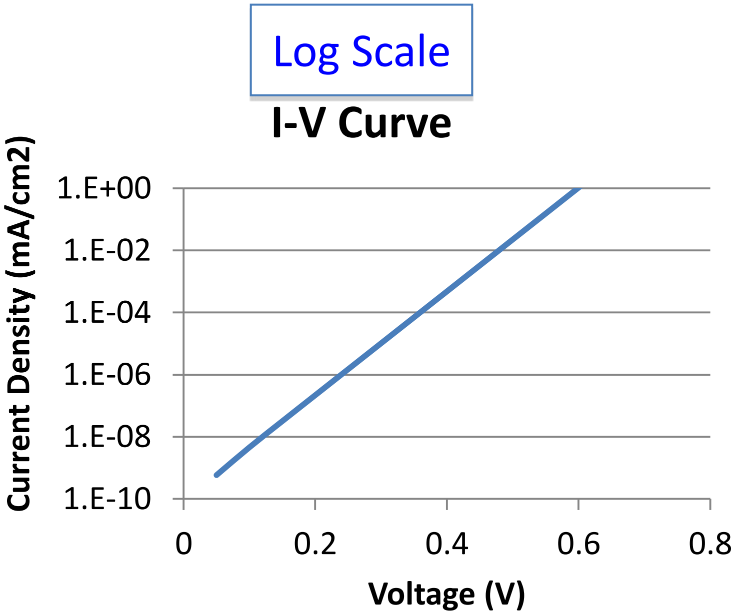
1. Describe the difference between "Energy Conversion Efficiency" and "Quantum Efficiency."
2. **Describe common factors that cause solar cell IV curves to deviate from an ideal diode model: shunt & series resistance, recombination currents, and current crowding.**
3. Calculate series resistance for a solar cell.
4. Calculate the Fermi Energy of a solar cell as a function of dopant concentration, illumination condition, and temperature.
5. Calculate carrier generation as a function of depth in a solar cell.
6. Calculate how material quality (minority carrier diffusion length) affects QE and solar cell performance.
7. Create a 1D model for solar cell performance based on diffusion length, optical absorption coefficient, surface reflectivity, and series & shunt resistances.

Equivalent Circuit: Simple Case



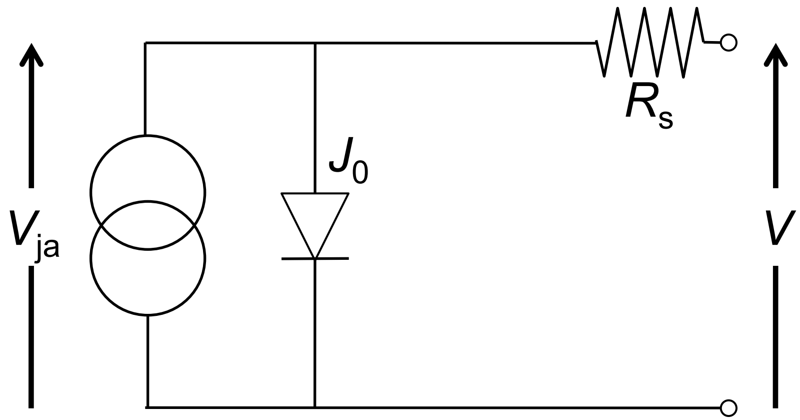
$$J = J_0\left(\exp\left(\frac{qV}{kT}\right)-1\right)-J_L$$



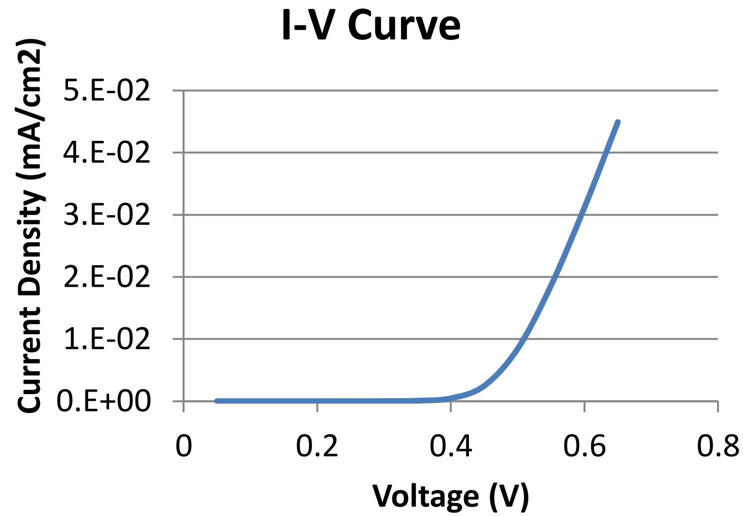


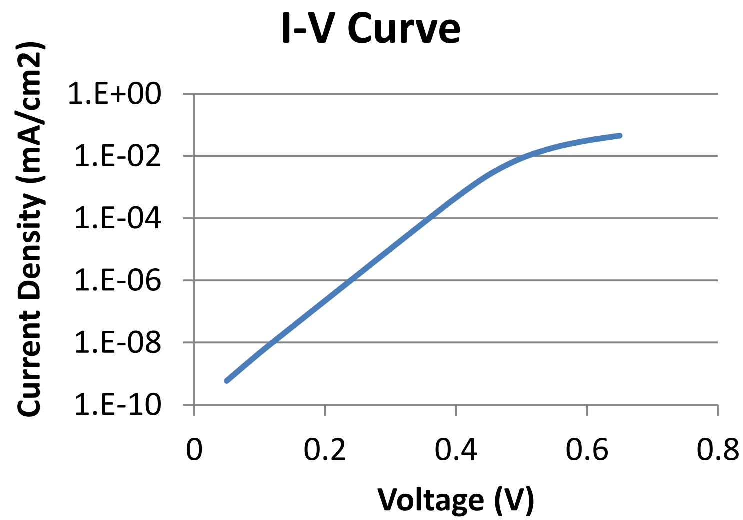
Buonassisi (MIT) 2011

Equivalent Circuit: Simple Case



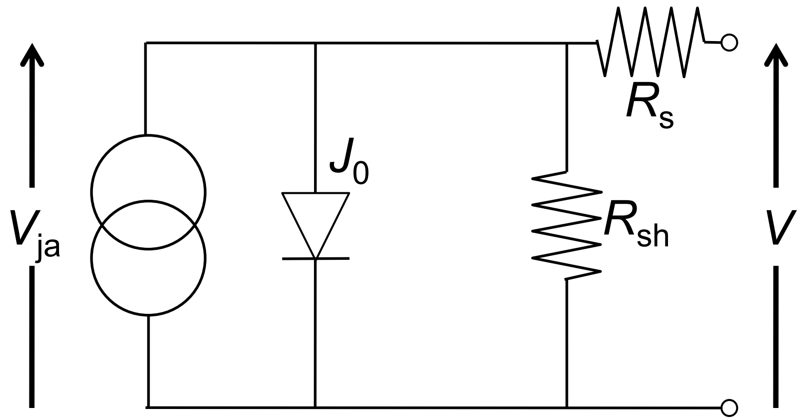
$$J = J_0\left(\exp\left(\frac{q(V - JR_s)}{kT}\right) - 1\right) - J_L$$

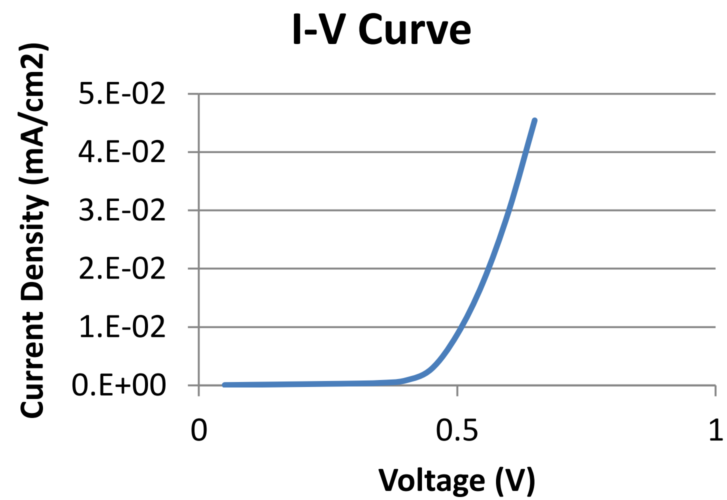




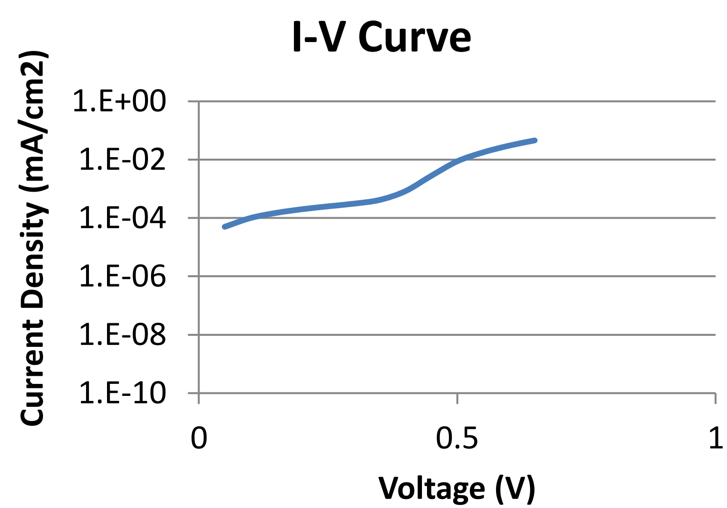
Buonassisi (MIT) 2011

Equivalent Circuit: Simple Case





$$J = J_0\left(\exp\left(\frac{q(V - JR_s)}{kT}\right) - 1\right) + \frac{V - JR_s}{R_{sh}} - J_L$$



Key Concepts:

The ideal diode equation can be enhanced in two key ways:

1) We can add the effects of parallel resistance and series resistance.

2) Advanced Concept: Instead of one saturation current I_o, there are usually two saturation currents contributing to most solar cell devices: (a) one resulting from carrier recombination in the space-charge region (dominant at lower forward bias voltages) and (b) one resulting from carrier recombination in the bulk (dominant at higher forward bias voltages). The "two-diode model" takes both saturation currents into account.

$$J = J_{01}\exp\left(\frac{q(V - JR_s)}{n_1 kT}\right) + J_{02}\exp\left(\frac{q(V - JR_s)}{n_2 kT}\right) + \frac{V - JR_s}{R_{sh}} - J_L$$

Further Reading:

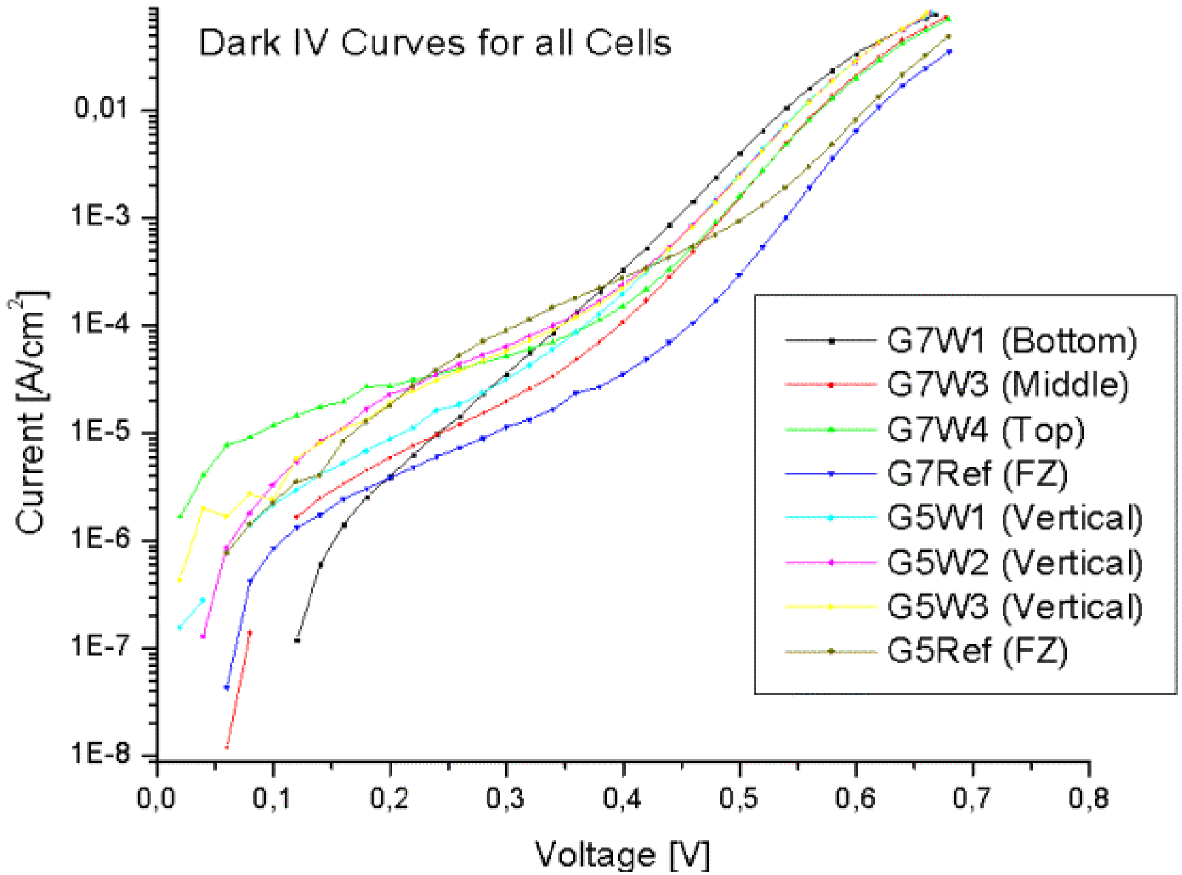
Green, Chapter 5

PVCDROM, Chapter 4: *Solar Cell Operation*http://www.pveducation.org/pvcdrom/solar-cell-operation/solar-cell-structure

K. McIntosh: "Lumps, Humps and Bumps: Three Detrimental Effects in the Current-Voltage Curve of Silicon Solar Cells," Ph.D. Thesis, UNSW, Sydney, 2001

IV Curve Measurements

Several IV curves for real solar cells, illustrating a variety of IV responses!

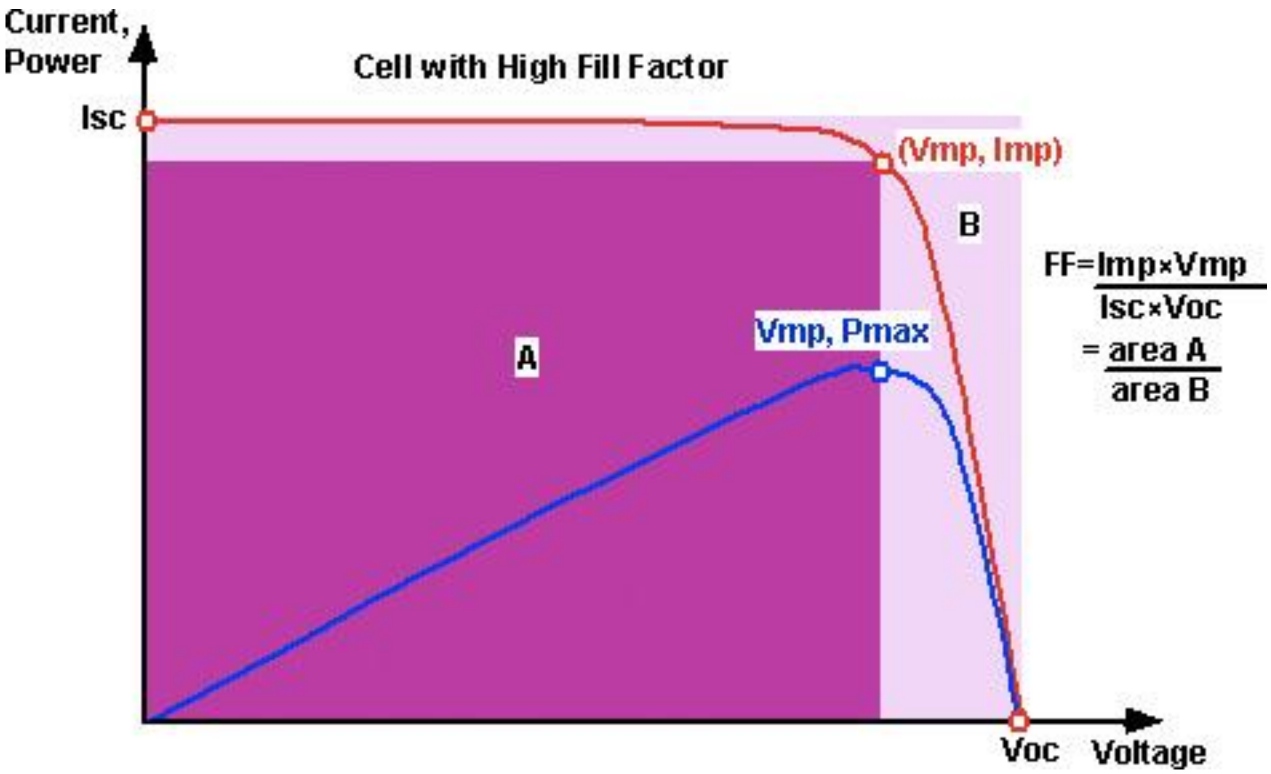


#14
#100
#124
FZ, e.s.r. 79-87 Ω/sq.
#9
#14
#100
FZ, e.s.r. 85-101 Ω/sq.

Fill Factor

Why Fill Factor (FF) Matters:

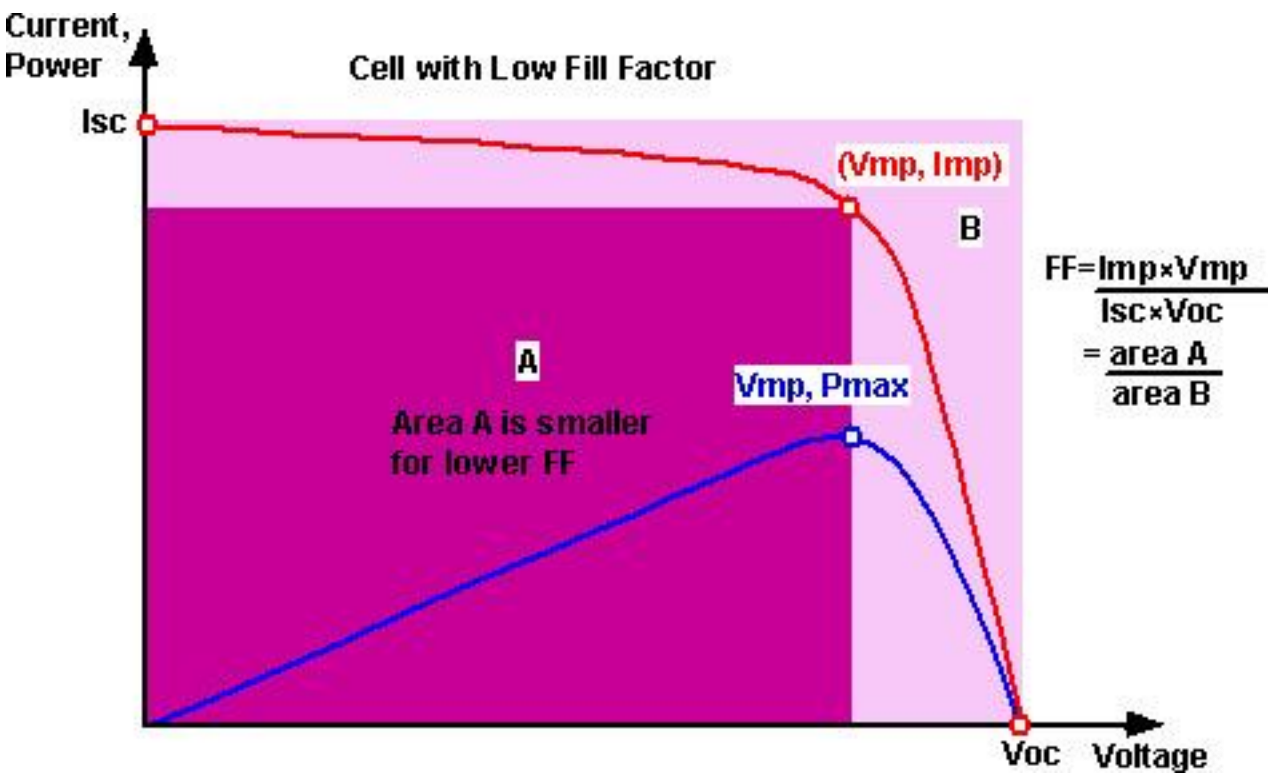
This is a sample IV curve for a high-efficiency solar cell: High FF.



Courtesy of PVCDROM. Used with permission.

Why Fill Factor (FF) Matters:

This is a sample IV curve for a low-efficiency solar cell (same I_{sc} and V_{oc}, but lower FF).

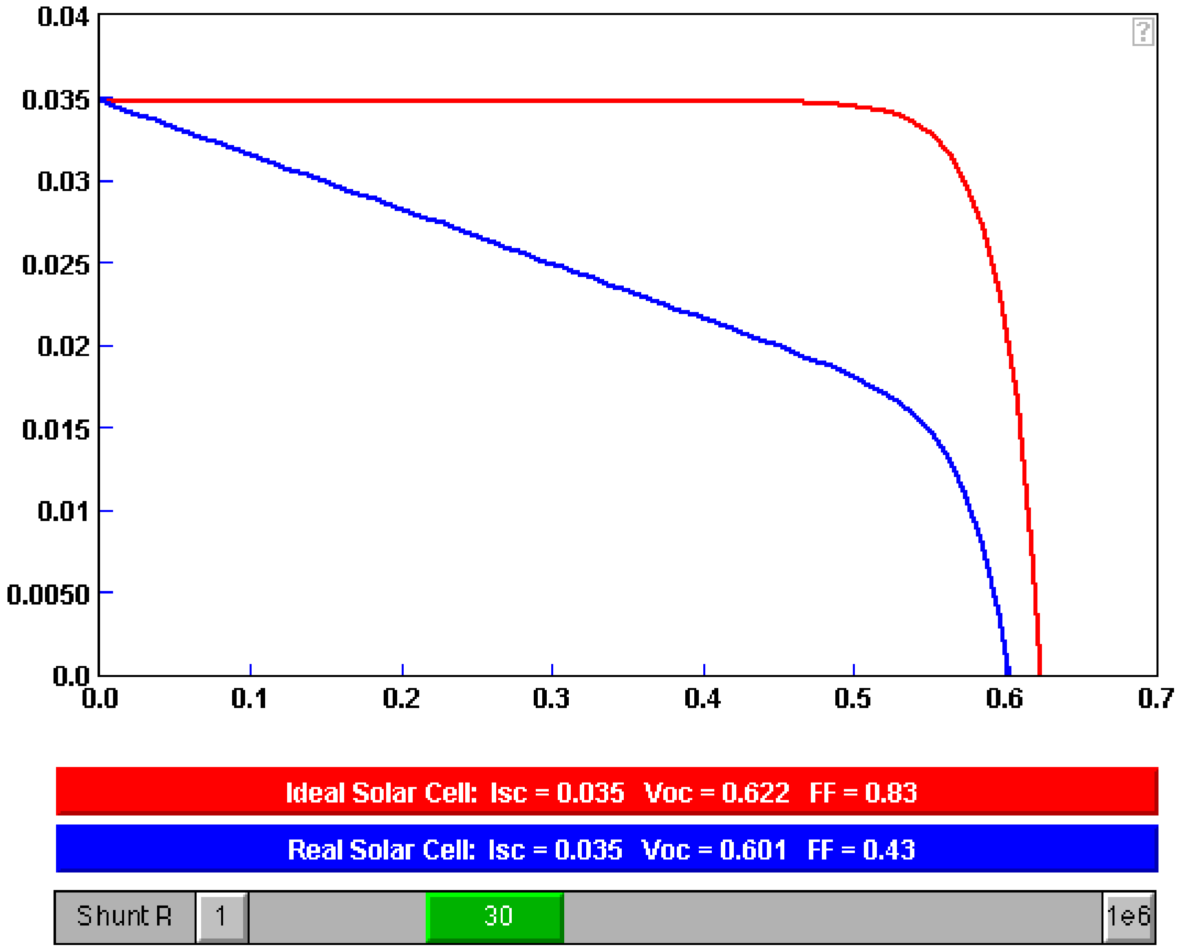


Courtesy of PVCDROM. Used with permission.

Effect of ***Low*** Shunt Resistance (R_{sh})

$$J = J_L - J_0 \exp\left(\frac{q(V+JR_s)}{nkT}\right) - \frac{V+JR_s}{R_{shunt}}$$

Source: http://www.pveducation.org/pvcdrom/solar-cell-operation/shunt-resistance



Courtesy of PVCDROM. Used with permission.

Physical Causes of Shunt Resistance (R_{sh})

Paths for electrons to flow from the emitter into the base. Can be caused by physical defects (scratches), improper emitter formation, metallization over-firing, or material defects (esp. those that traverse the space-charge region).

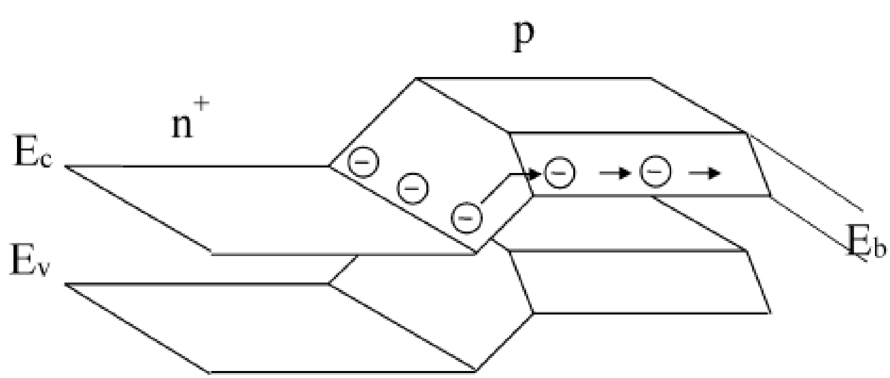


Fig. 6. Schematic 2-dimensional potential distribution on a positively charged surface (in front) crossing an n^+p-junction. E_c: conduction band edge, E_v: valence band edge, E_b: surface potential barrier height.

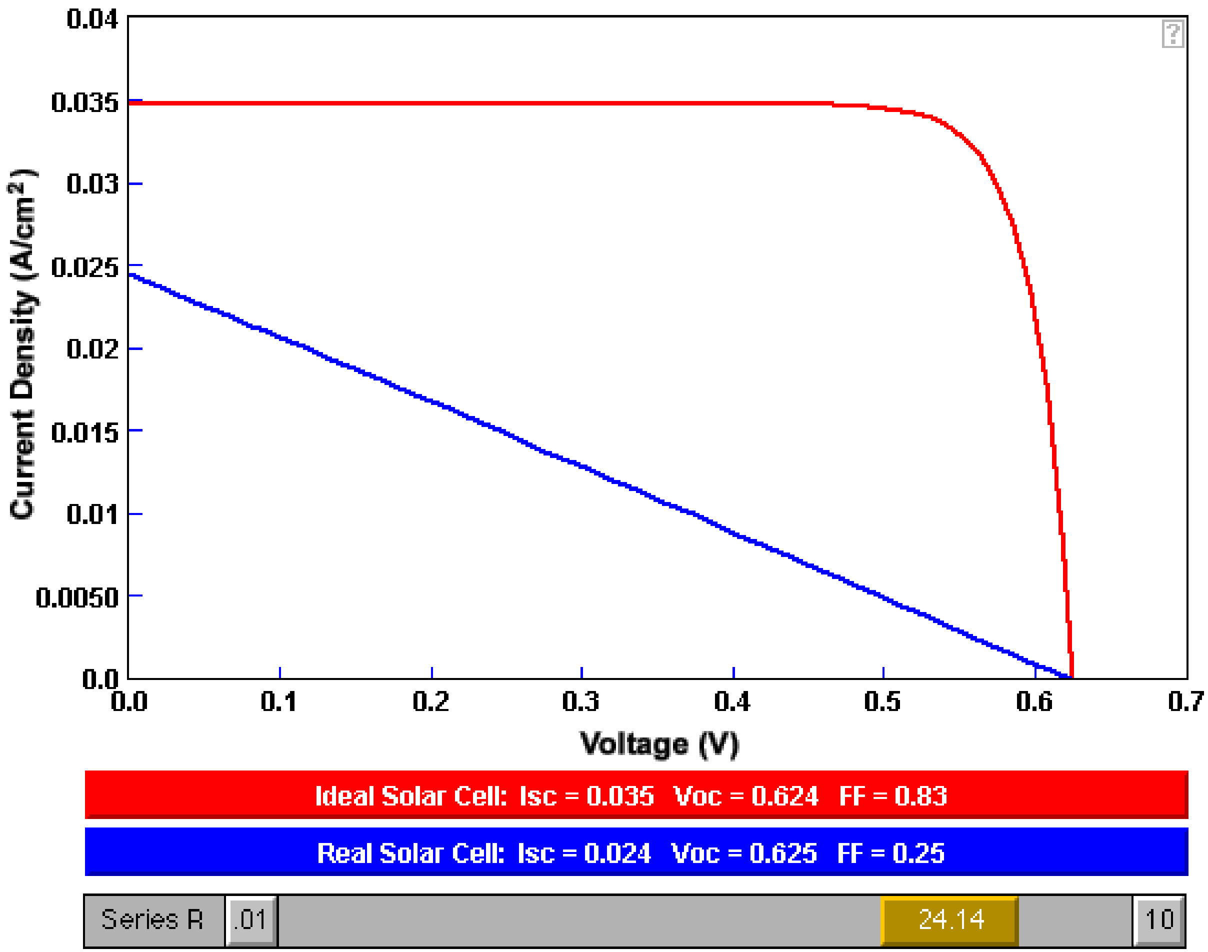
For more information: See publications by Dr. Otwin Breitenstein (Max-Planck Institute in Halle, Germany) on use of lock-in thermography for shunt detection and classification in solar cells.

Effect of ***High*** Series Resistance (R_s)

$$J = J_L - J_0 \exp\left(\frac{q(V + JR_s)}{nkT}\right) - \frac{V + JR_s}{R_{shunt}}$$

NB: IV curve flipped!

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

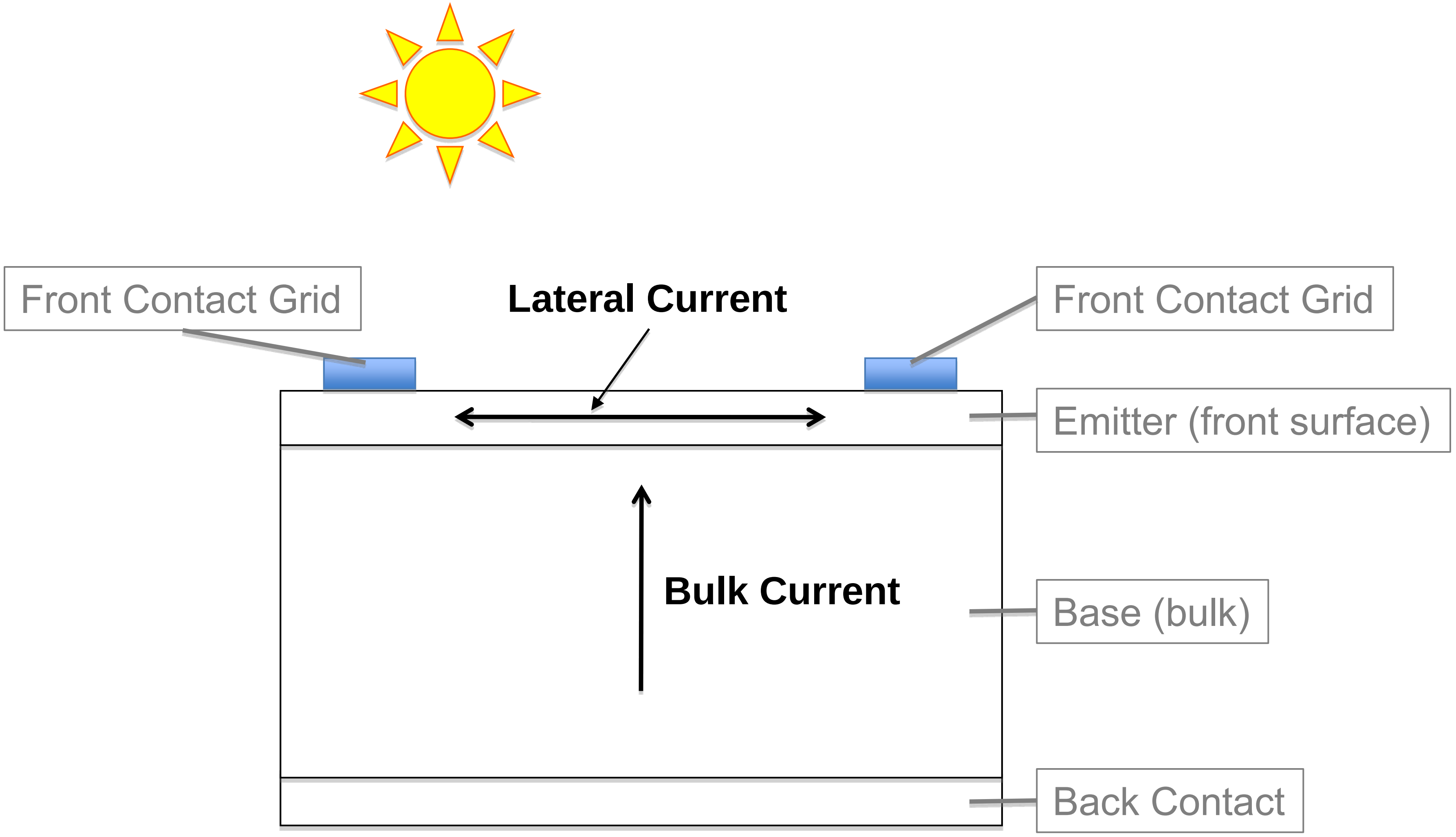


Courtesy of PVCDROM. Used with permission.

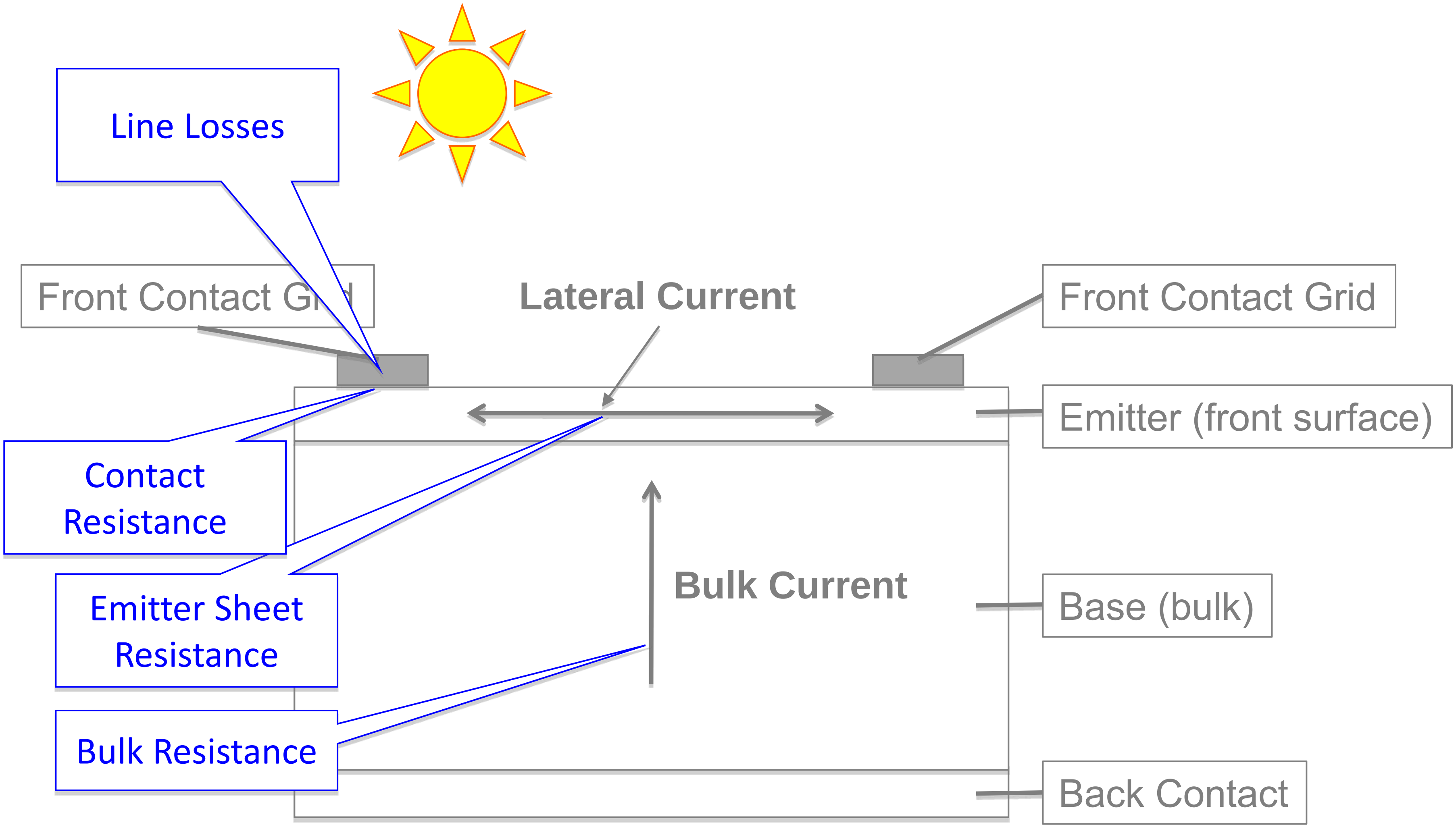
Learning Objectives: Toward a 1D Device Model

1. Describe the difference between "Energy Conversion Efficiency" and "Quantum Efficiency."
2. Describe common factors that cause solar cell IV curves to deviate from an ideal diode model: shunt & series resistance, recombination currents, and current crowding.
3. **Calculate series resistance for a solar cell.**
4. Calculate the Fermi Energy of a solar cell as a function of dopant concentration, illumination condition, and temperature.
5. Calculate carrier generation as a function of depth in a solar cell.
6. Calculate how material quality (minority carrier diffusion length) affects QE and solar cell performance.
7. Create a 1D model for solar cell performance based on diffusion length, optical absorption coefficient, surface reflectivity, and series & shunt resistances.

Components of Series Resistance



Components of Series Resistance

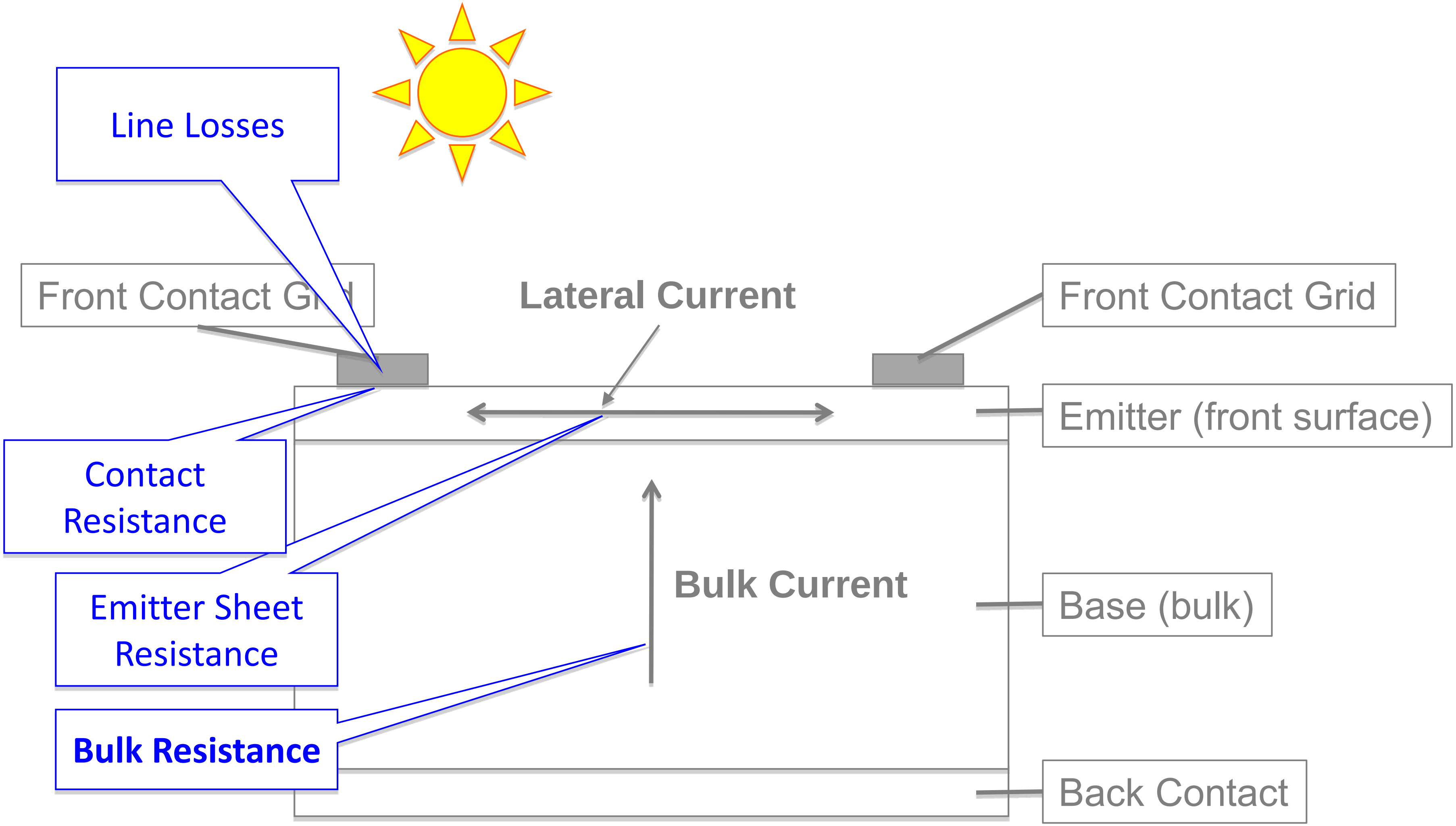


Buonassisi (MIT) 2011

Components of R_s: Bulk Resistance

(i.e., How to choose absorber thickness)

Components of Series Resistance



Bulk (Base) Resistance

Resistivity: $$\rho = \frac{1}{qn\mu}$$

- q = charge
- n = carrier density
- μ = carrier mobility

Base Resistance: $$R_b = \rho \frac{l}{A}$$

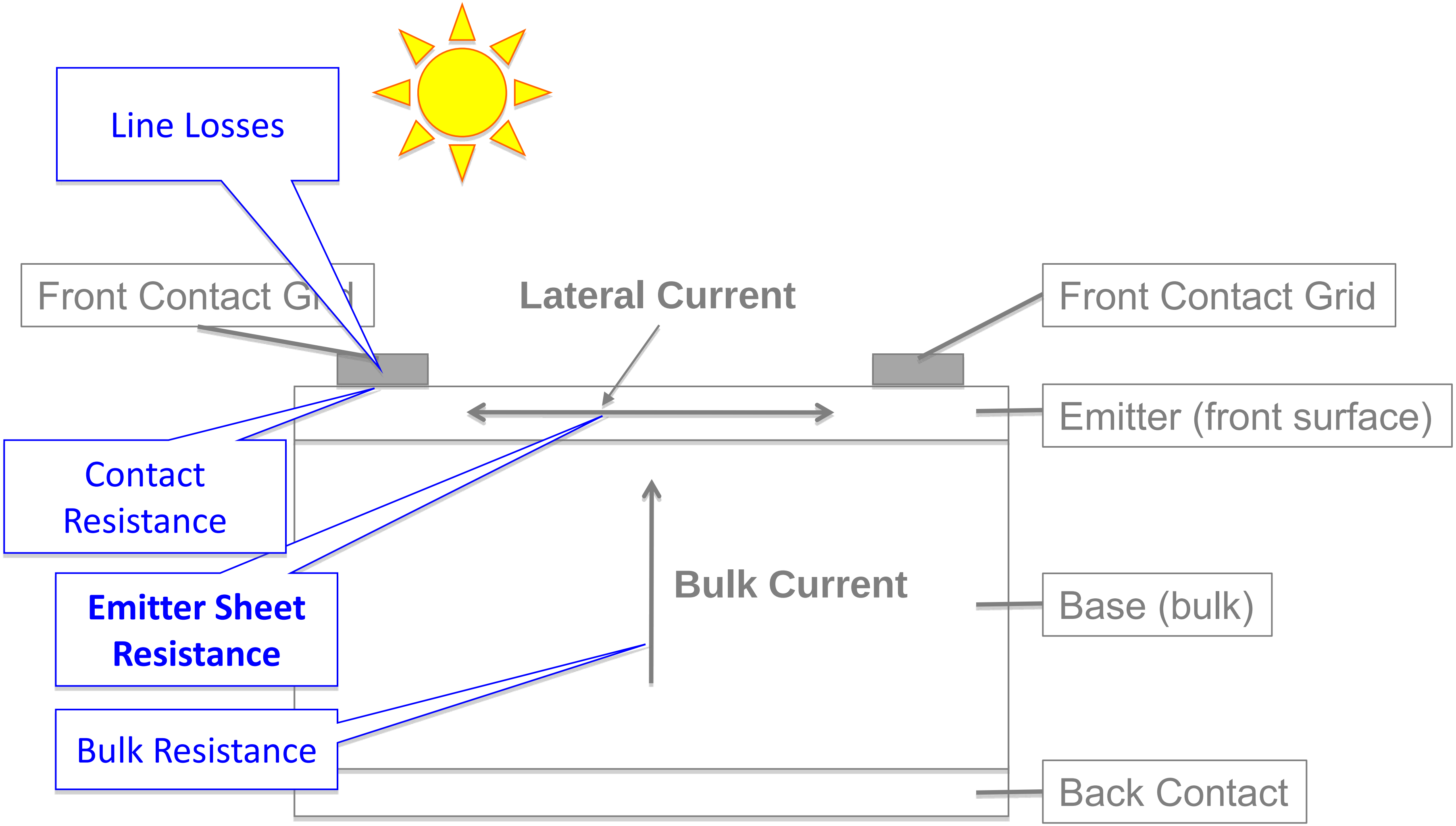
- l = length of conductive path
- A = Area of current flow
- ρ = base resistivity

NB: Beware of non-linearities! (e.g., dependence of μ on n).

Components of R_s: Emitter Sheet Resistance

(i.e., How to design front contact metallization)

Components of Series Resistance



Emitter Sheet Resistance

Bulk Resistivity is defined according to the following expression:

$$\rho = \frac{1}{q \cdot \mu \cdot N}$$

ρ = resistivity
μ = carrier mobility
N = Carrier concentration (dopant concentration)

Units of ρ: Ω-cm

For a thin layer, a "sheet resistance" can be described:

$$\rho_s = \frac{1}{q \int_0^t \mu_e(x) \cdot N_D(x) dx}$$

x = layer thickness

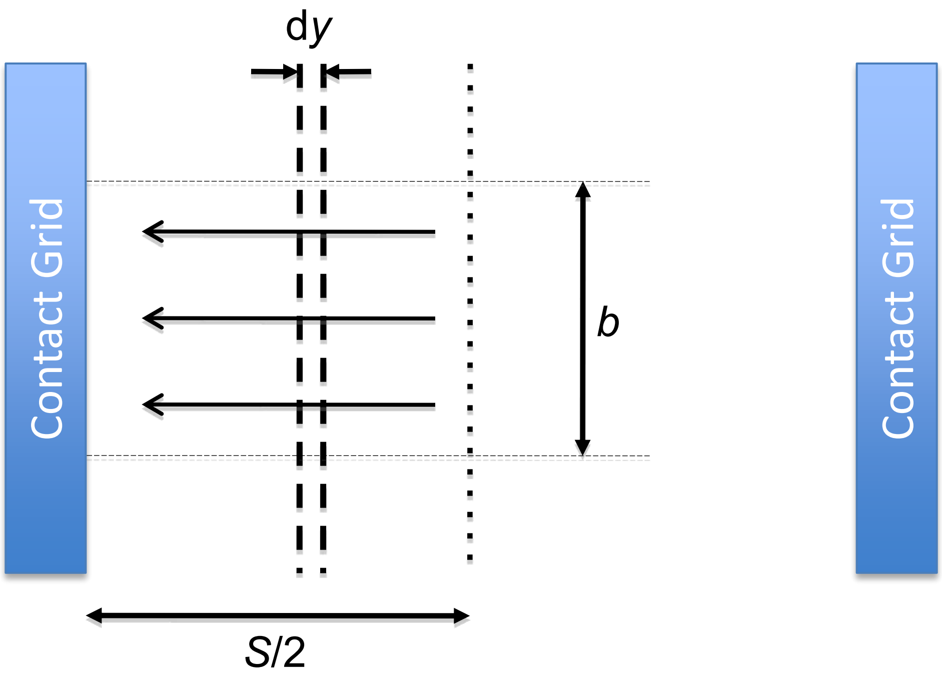
Units of ρ_s: Ω , or Ω/□

For uniform layers, a simplification:

$$\rho_s = \frac{1}{q \cdot \mu \cdot N \cdot t}$$

Sheet Resistance Losses

bird's eye view of solar cell device

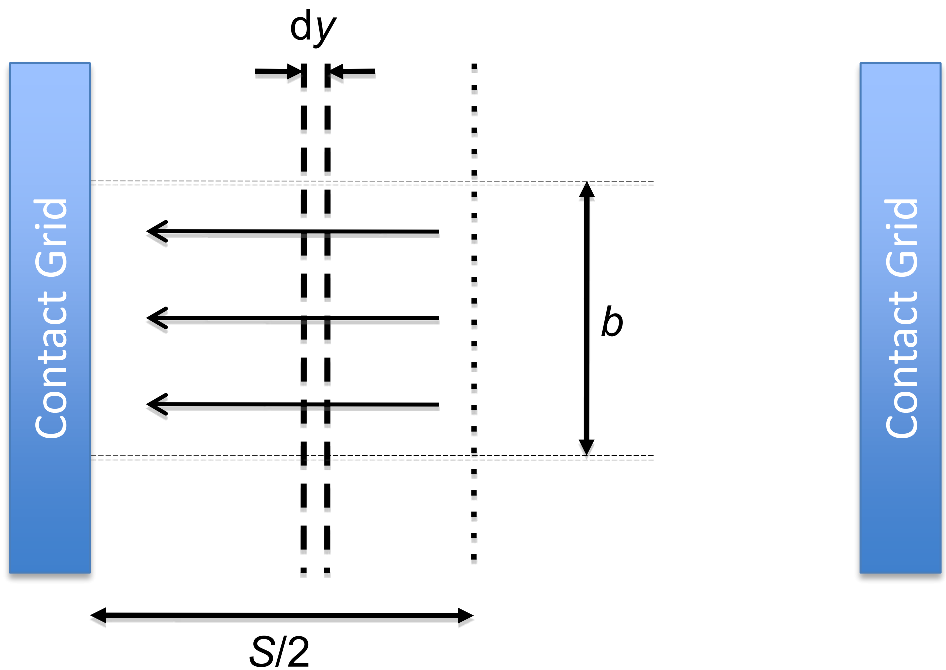


The total power loss is thus:

$$P_{\text{loss}} = \int I^2 dR = \int_0^{S/2} \frac{J^2 b^2 y^2 \rho_s}{b} dy = \frac{J^2 b \rho_s S^3}{24}$$

Sheet Resistance Losses

bird's eye view of solar cell device

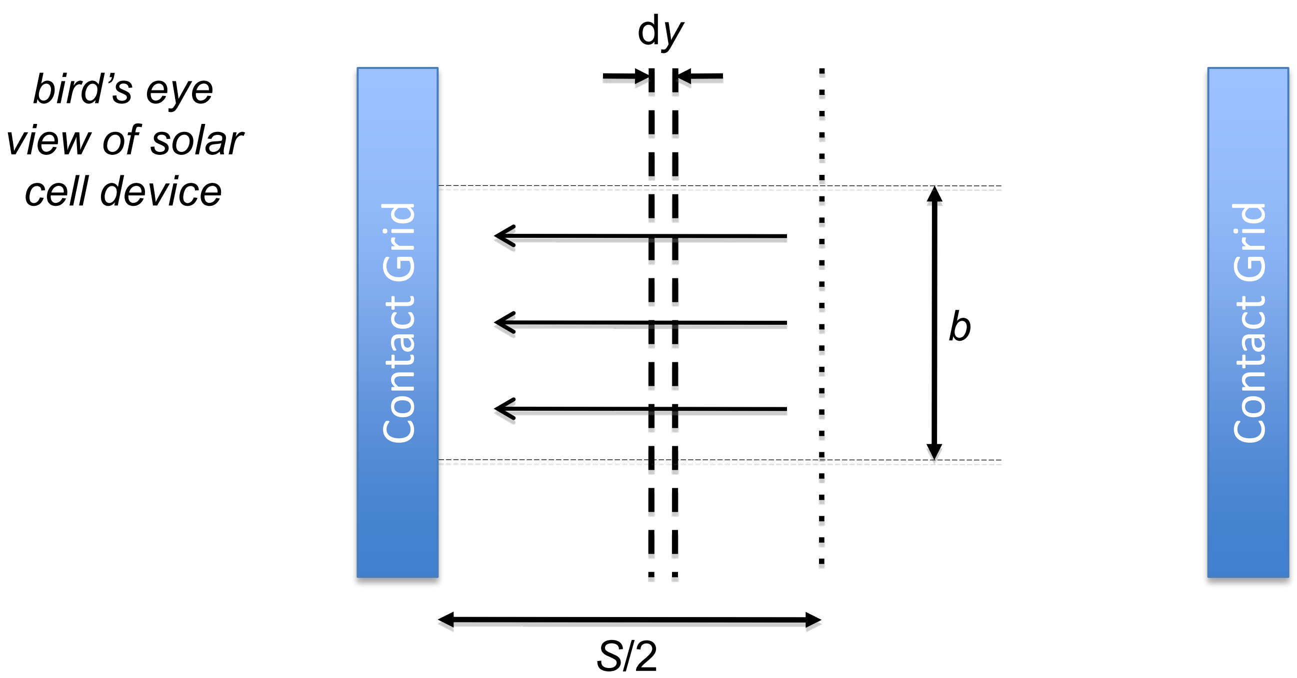


At the maximum power point, the generated power in the emitter ROI is: $V_{mp} J_{mp} b \, {}^{S}\!/_{2}$

Hence, the fractional power loss at the maximum power point (MPP) is:

$$p = \frac{P_{\text{loss}}}{P_{\text{mpp}}} = \frac{\rho_s S^2 J_{\text{mp}}}{12 V_{\text{mp}}}$$

Sheet Resistance Losses



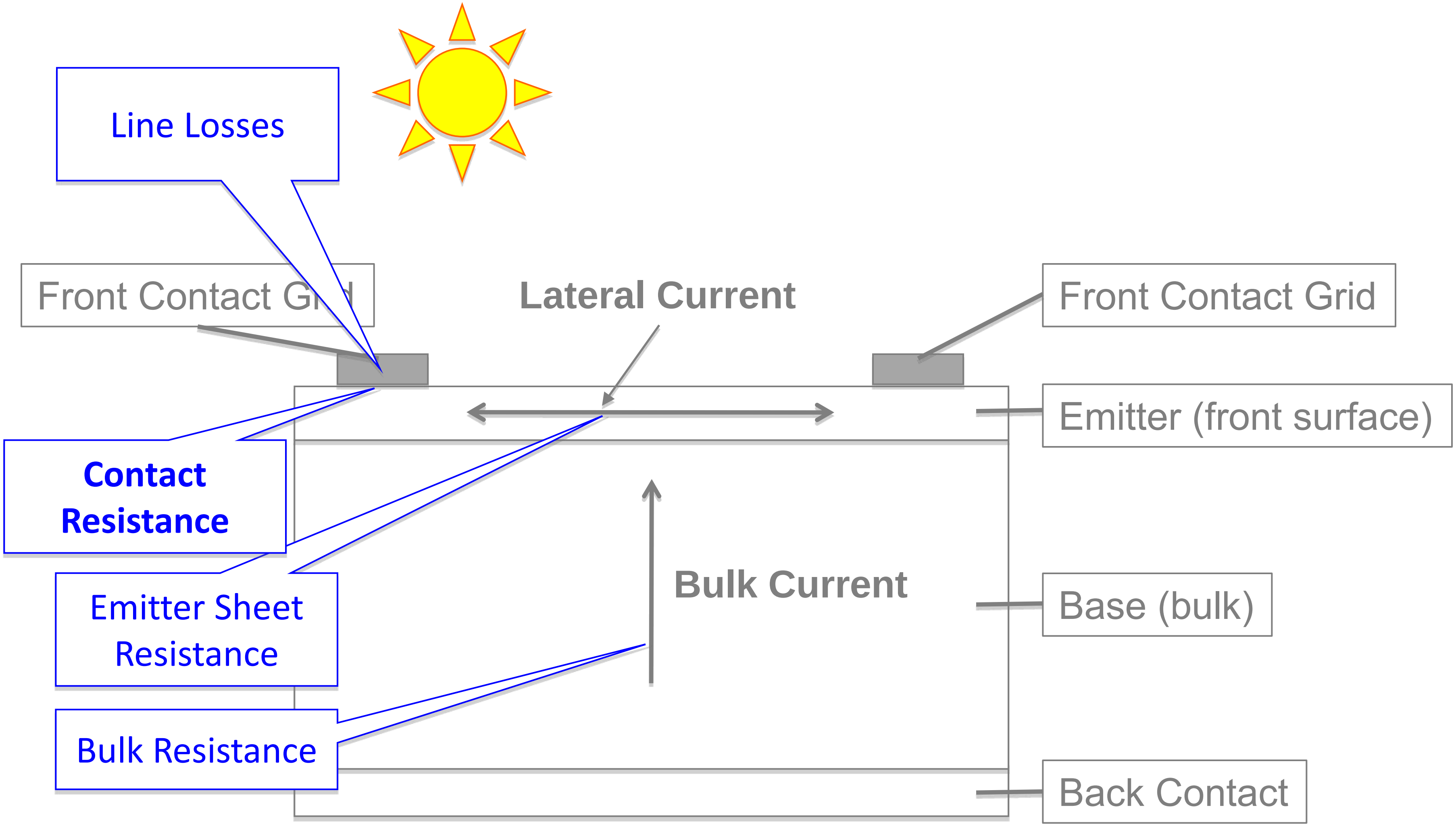
Consider a solar cell with ρ_s = 40 Ω/□, J_{mp} = 30 mA/cm², and V_{mp} = 450 mV. If we want less than a 4% power loss (i.e., $p < 0.04$) through the emitter, then

$$S < \sqrt{\frac{12 p V_{\mathrm{mp}}}{\rho_s J_{\mathrm{mp}}}} = 4 \text{ mm}$$

Agrees with finger spacing in commercial solar cells!

Components of R_s: Contact Resistance

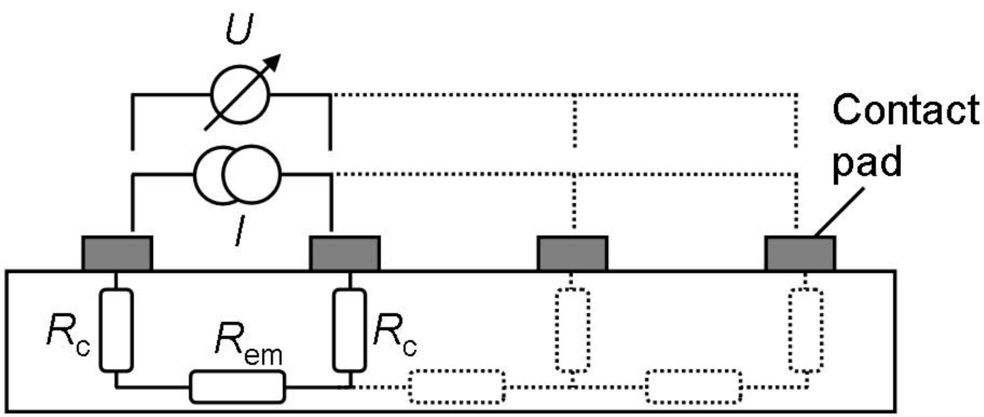
Components of Series Resistance



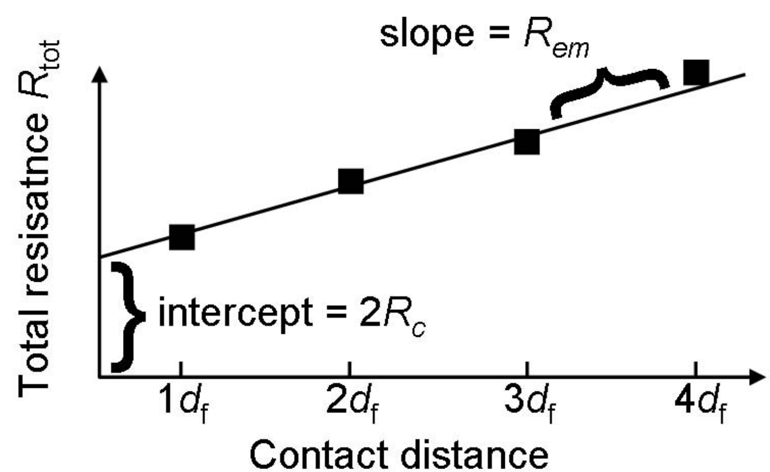
Buonassisi (MIT) 2011

Method to Measure Contact Resistance (TLM Method)

Sequential measurements of resistance between reference finger and measured finger.



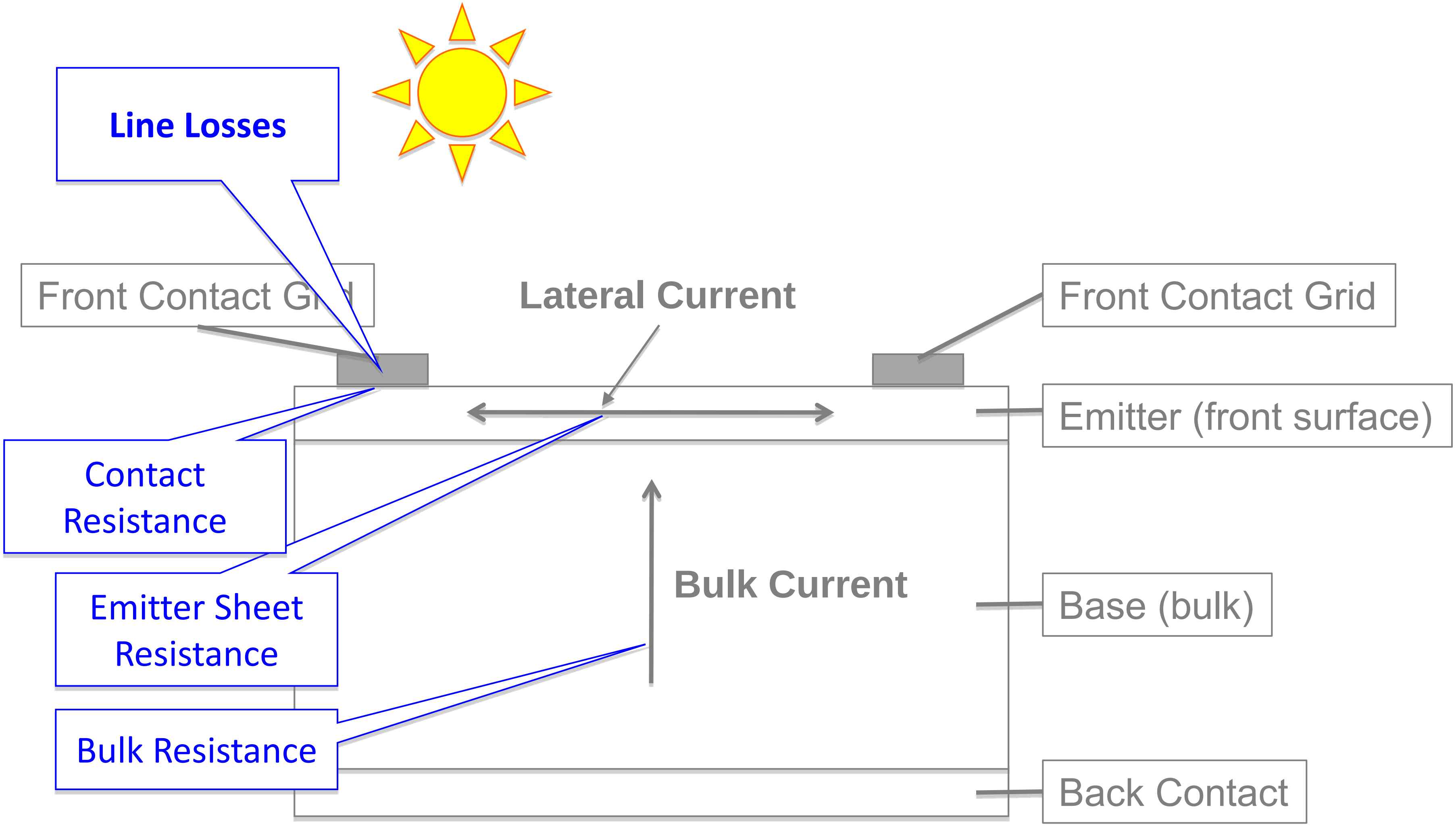
R_c = contact resistance



Figures courtesy of Stefan Kontermann

Components of R_s: Line Losses

Components of Series Resistance

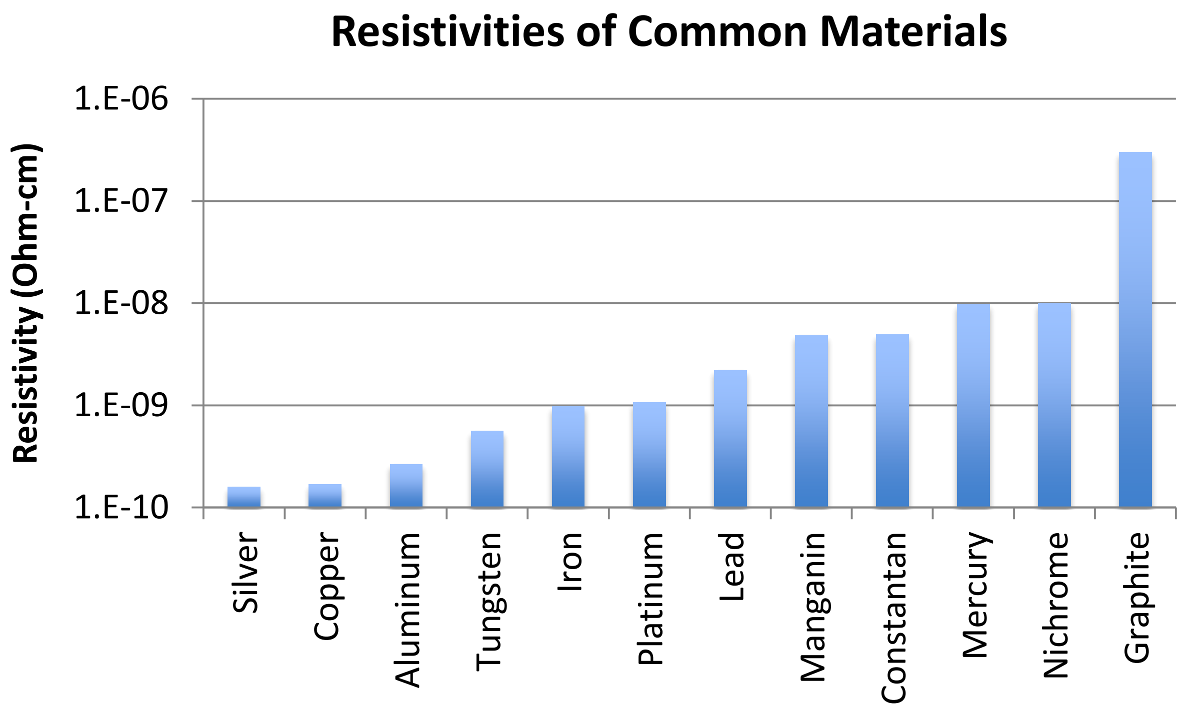


Buonassisi (MIT) 2011

Line Losses

Line Resistance: $$R_b = \rho \frac{l}{A}$$

- l = length of conductive path
- A = Area of current flow
- ρ = metal resistivity



Learning Objectives: Toward a 1D Device Model

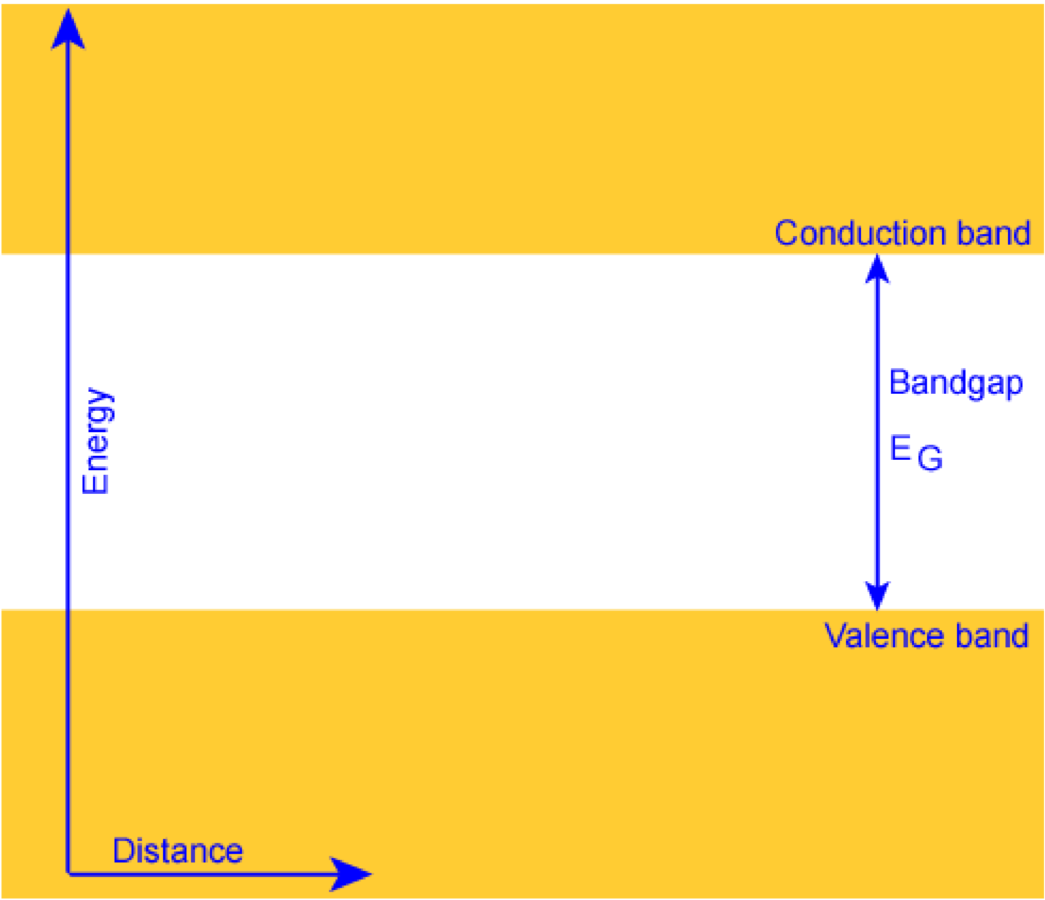
1. Describe the difference between "Energy Conversion Efficiency" and "Quantum Efficiency."
2. Describe common factors that cause solar cell IV curves to deviate from an ideal diode model: shunt & series resistance, recombination currents, and current crowding.
3. Calculate series resistance for a solar cell.
4. **Calculate the Fermi Energy of a solar cell as a function of dopant concentration, illumination condition, and temperature.**
5. Calculate carrier generation as a function of depth in a solar cell.
6. Calculate how material quality (minority carrier diffusion length) affects QE and solar cell performance.
7. Create a 1D model for solar cell performance based on diffusion length, optical absorption coefficient, surface reflectivity, and series & shunt resistances.

Question: When I illuminate my device, do I perturb the band structure or Fermi energy?

Calculate Fermi Energy (function of dopant + illumination + temperature)

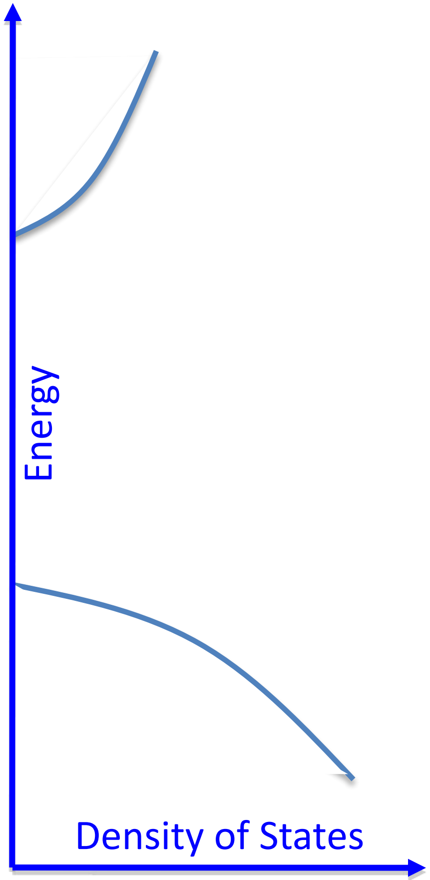
Conductivity

Band Diagram (E vs. x)



Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.
http://pvcdrom.pveducation.org/

Density of States

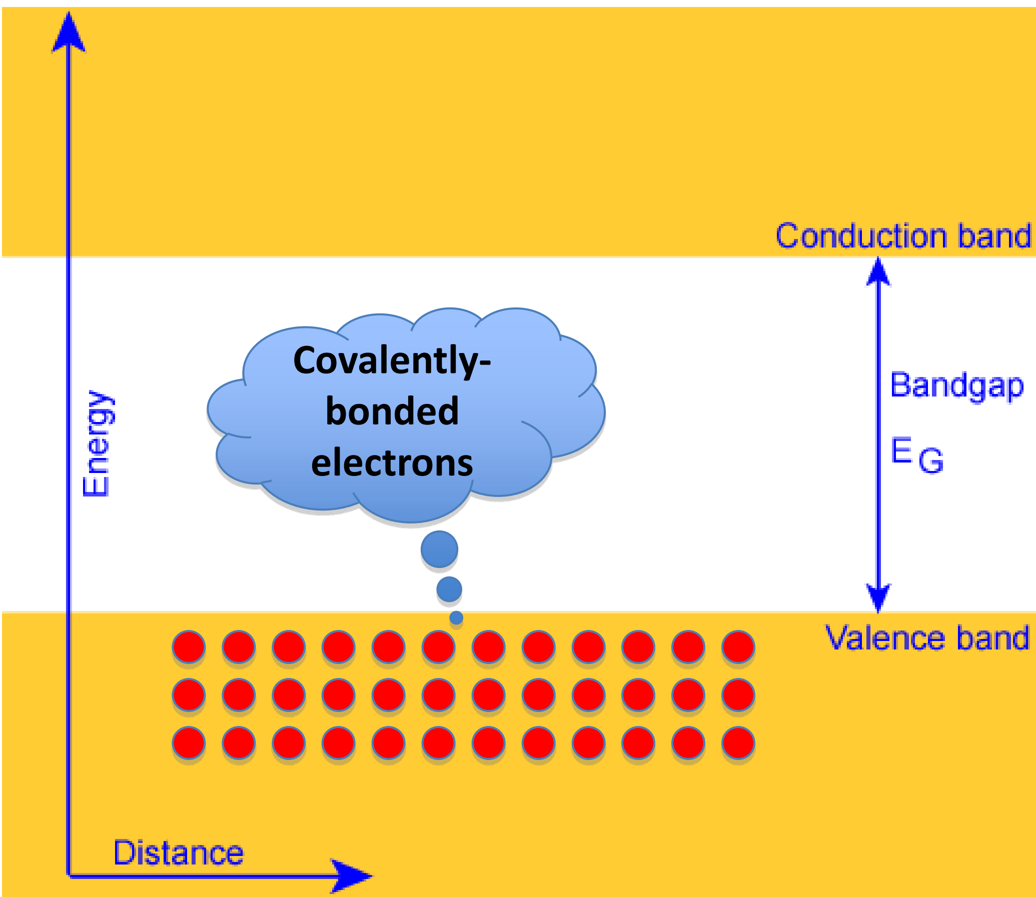


Buonassisi (MIT) 2011

Conductivity: Dependence on Temperature

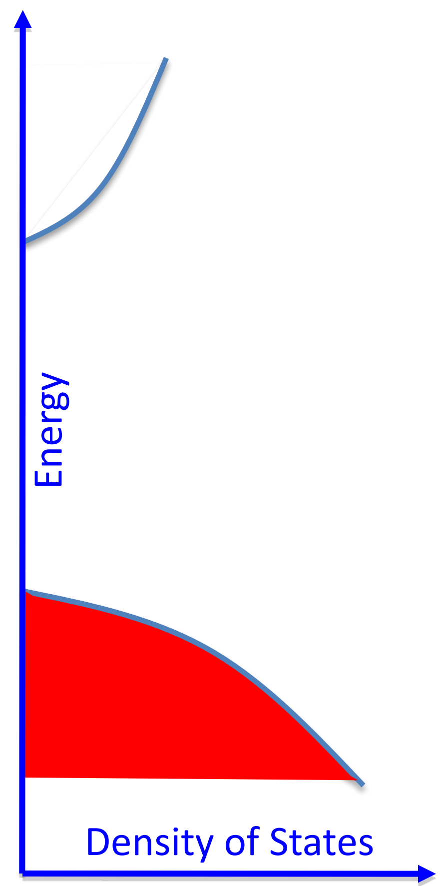
At absolute zero, no conductivity (perfect insulator).

Band Diagram (E vs. x)



Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

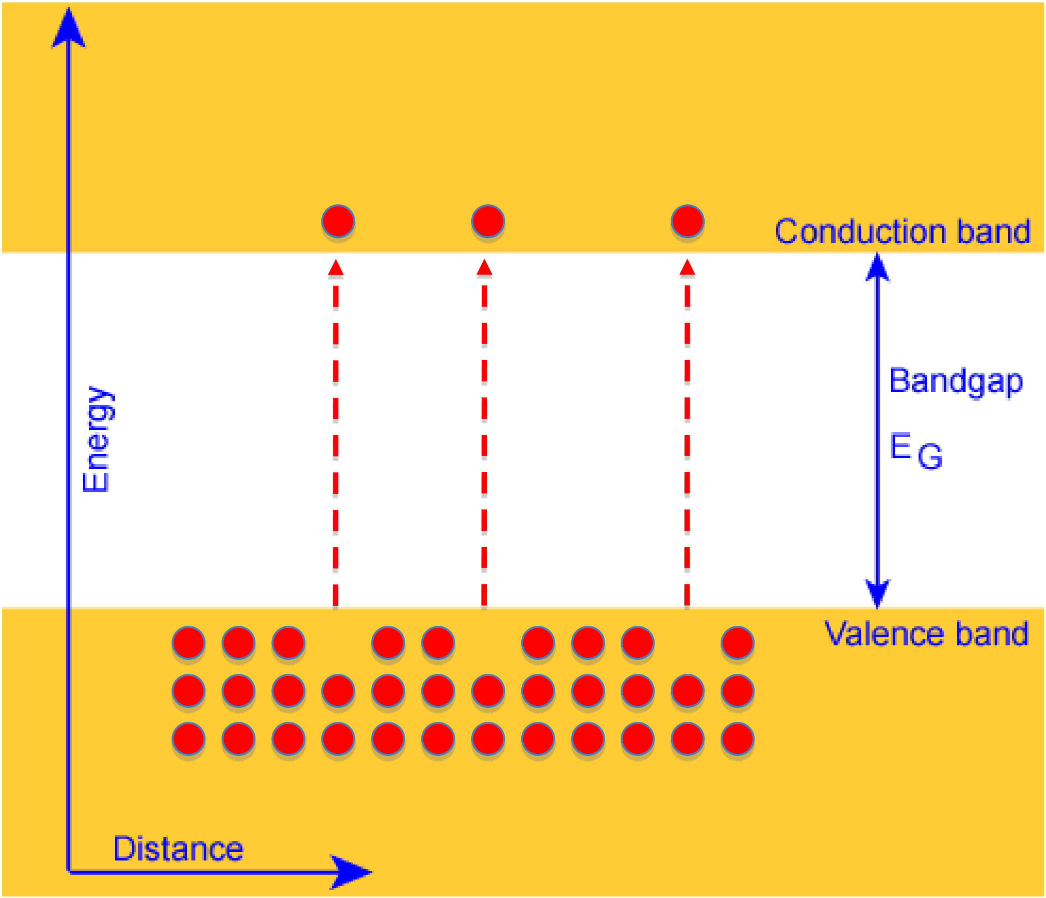
Density of States



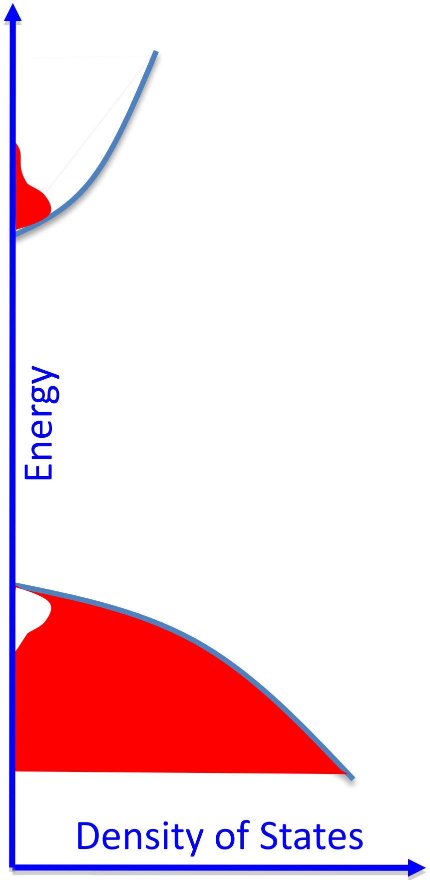
Conductivity: Dependence on Temperature

At T > 0 K, some carriers are thermally excited across the bandgap.

Band Diagram (E vs. x)

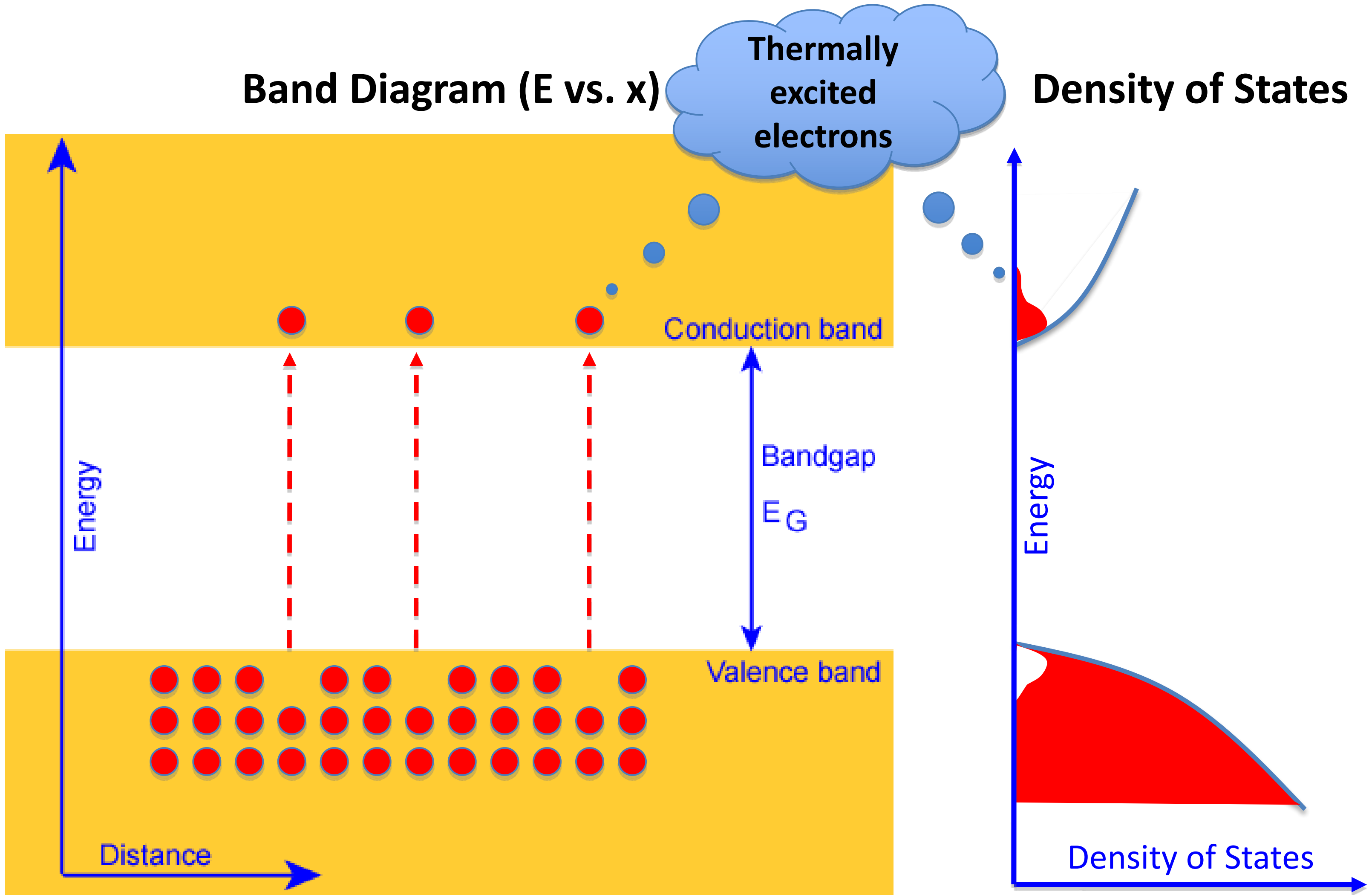


Density of States



Conductivity: Dependence on Temperature

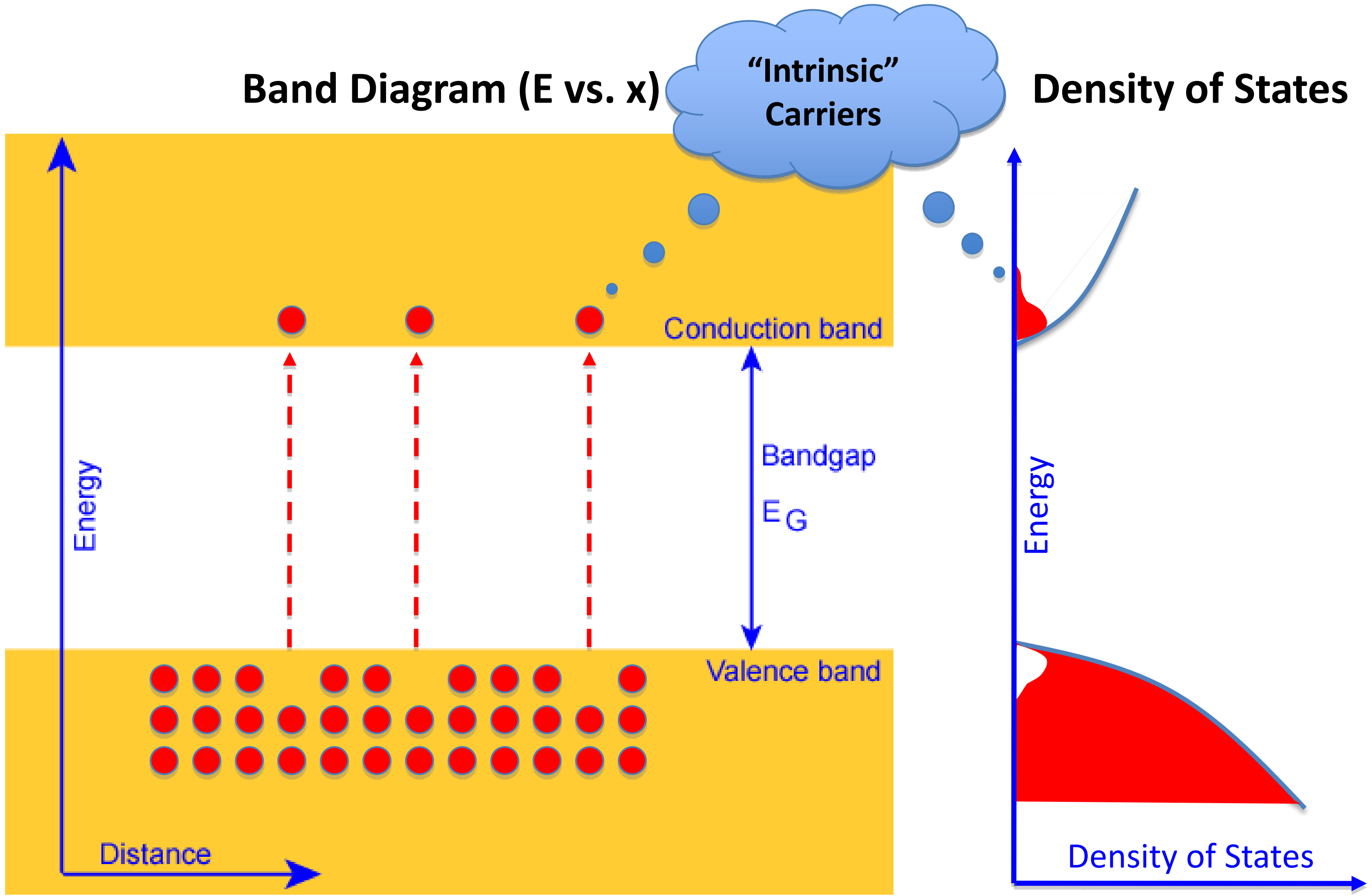
At T > 0 K, some carriers are thermally excited across the bandgap.



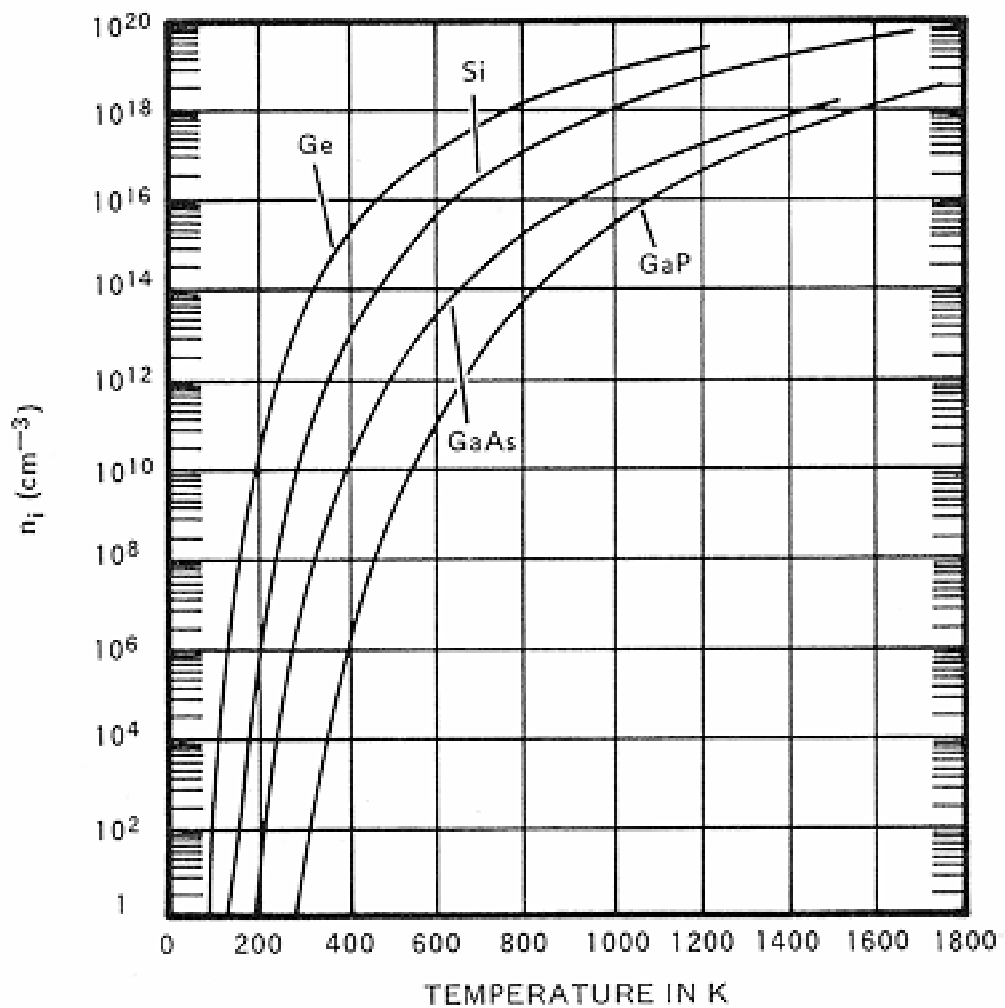
Buonassisi (MIT) 2011

Conductivity: Dependence on Temperature

At T > 0 K, some carriers are thermally excited across the bandgap.



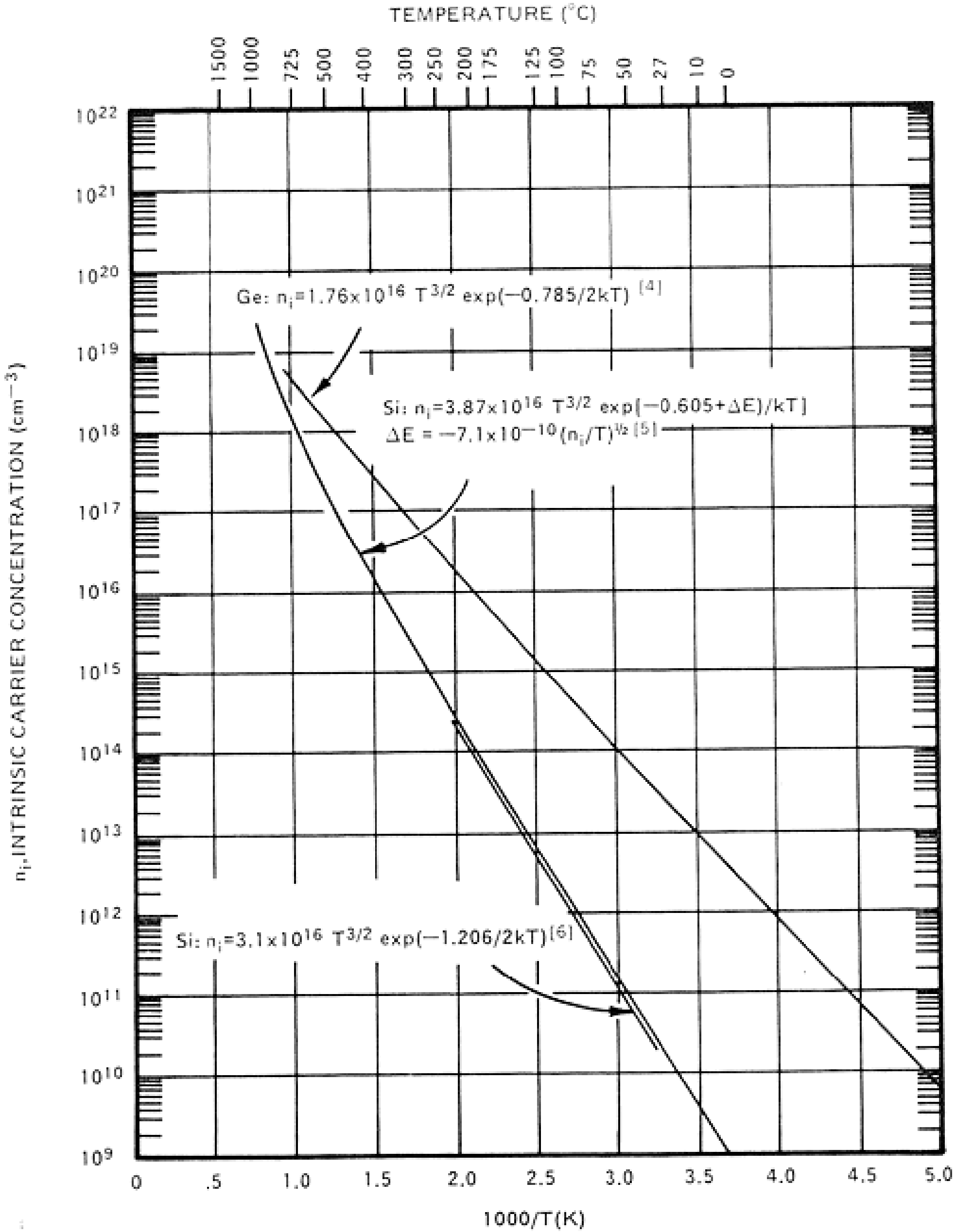
Temperature Dependence of Intrinsic Carrier Concentration



Arrhenius Equation, generic form:

$$N = N_o \cdot \exp\left[-E_A / k_b T\right]$$

Temperature Dependence of Intrinsic Carrier Concentration



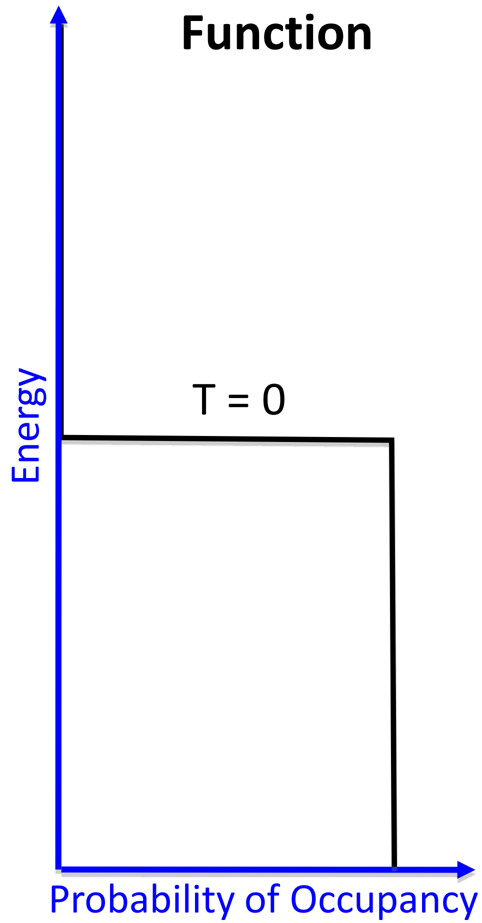
Arrhenius Equation, generic form:

$$N = N_o \cdot \exp\left[-E_A / k_b T\right]$$

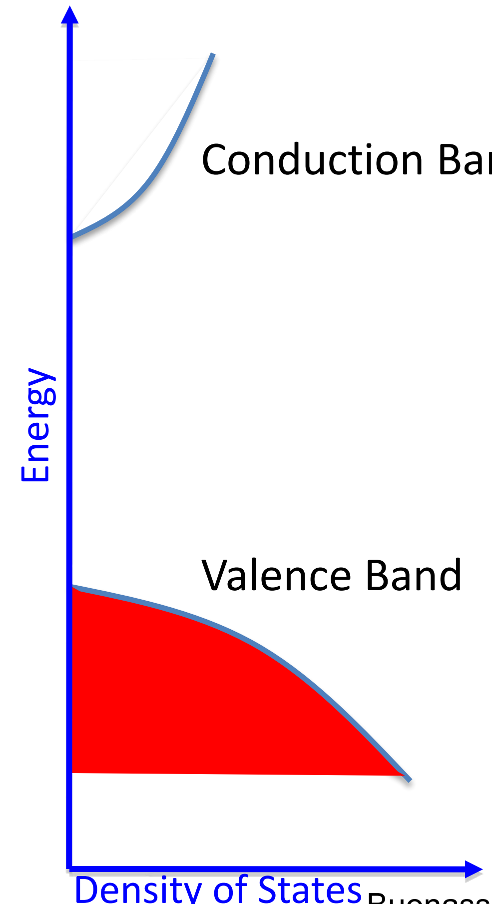
Conductivity: Dependence on Temperature

At absolute zero, no conductivity (perfect insulator).

Probability Distribution Function

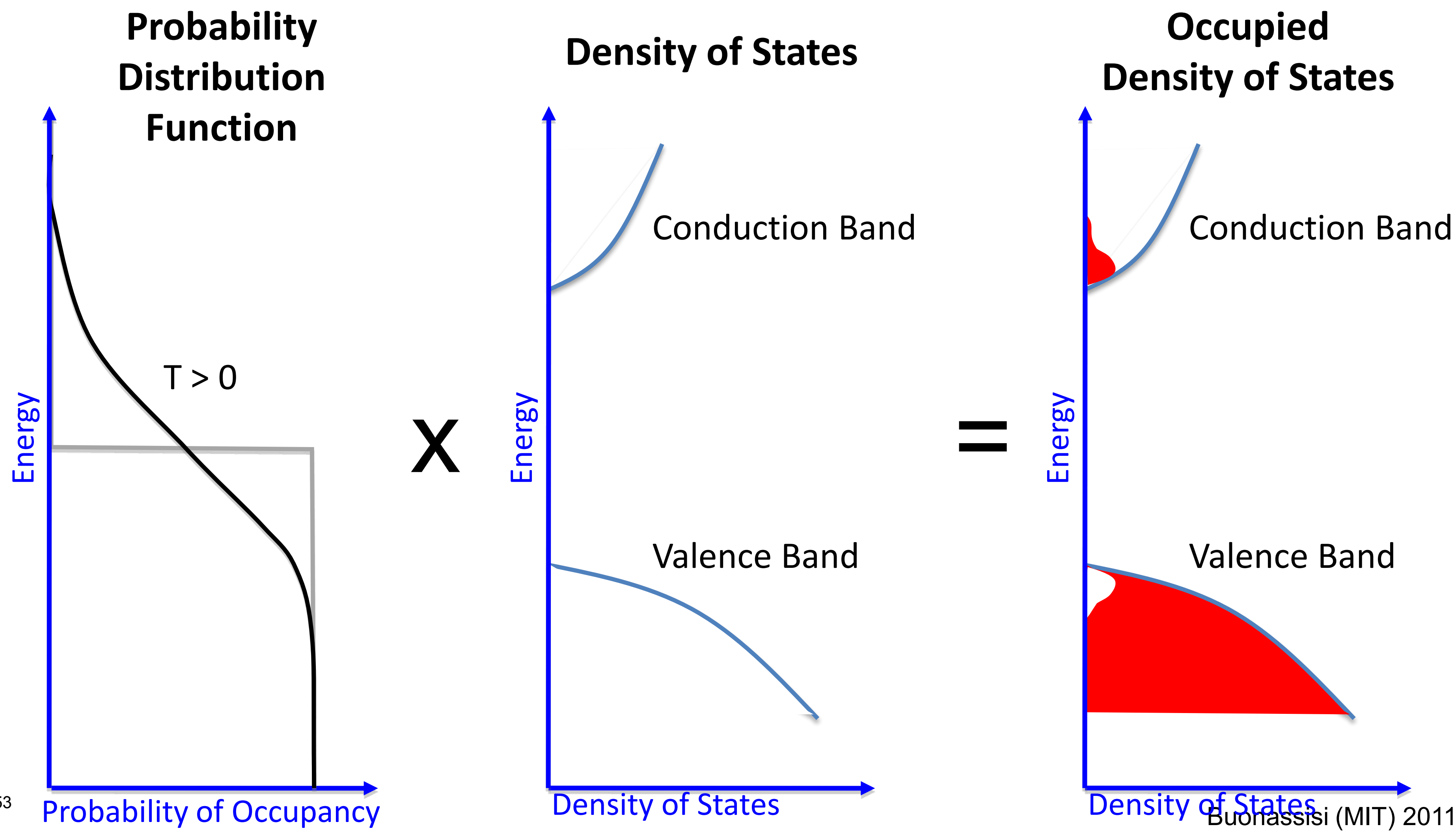


Density of States



Conductivity: Dependence on Temperature

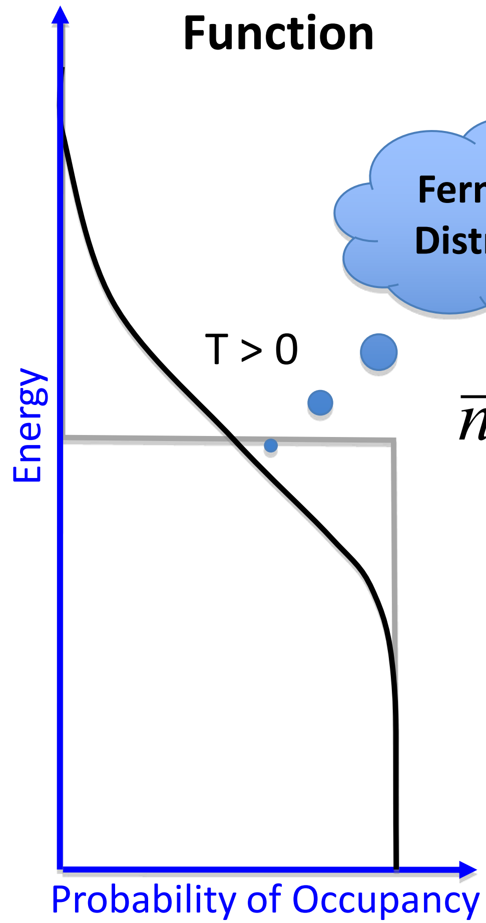
At a finite temperature, finite conductivity (current can flow).

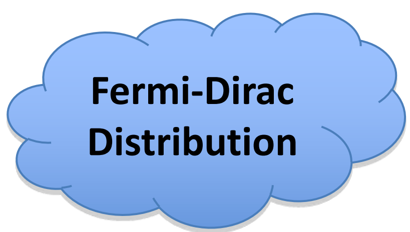


Conductivity: Dependence on Temperature

At a finite temperature, finite conductivity (current can flow).

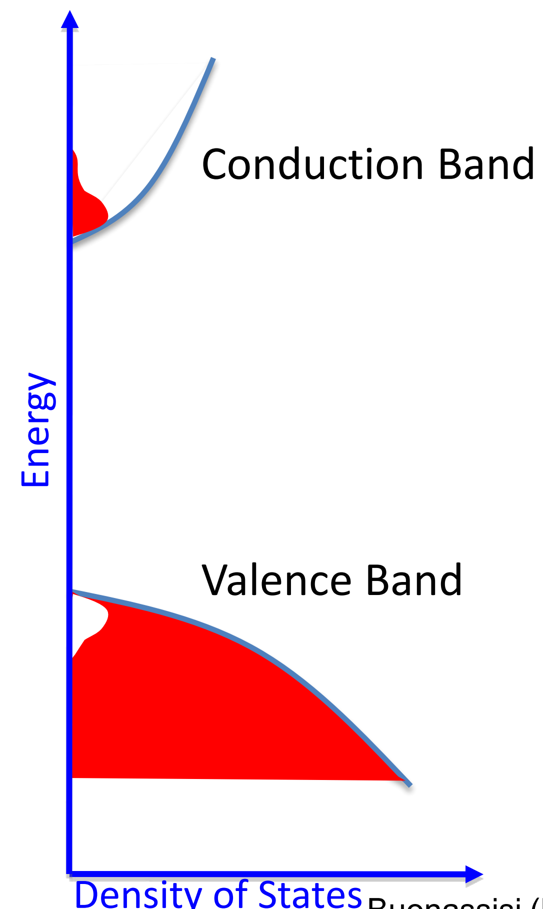
Probability Distribution Function





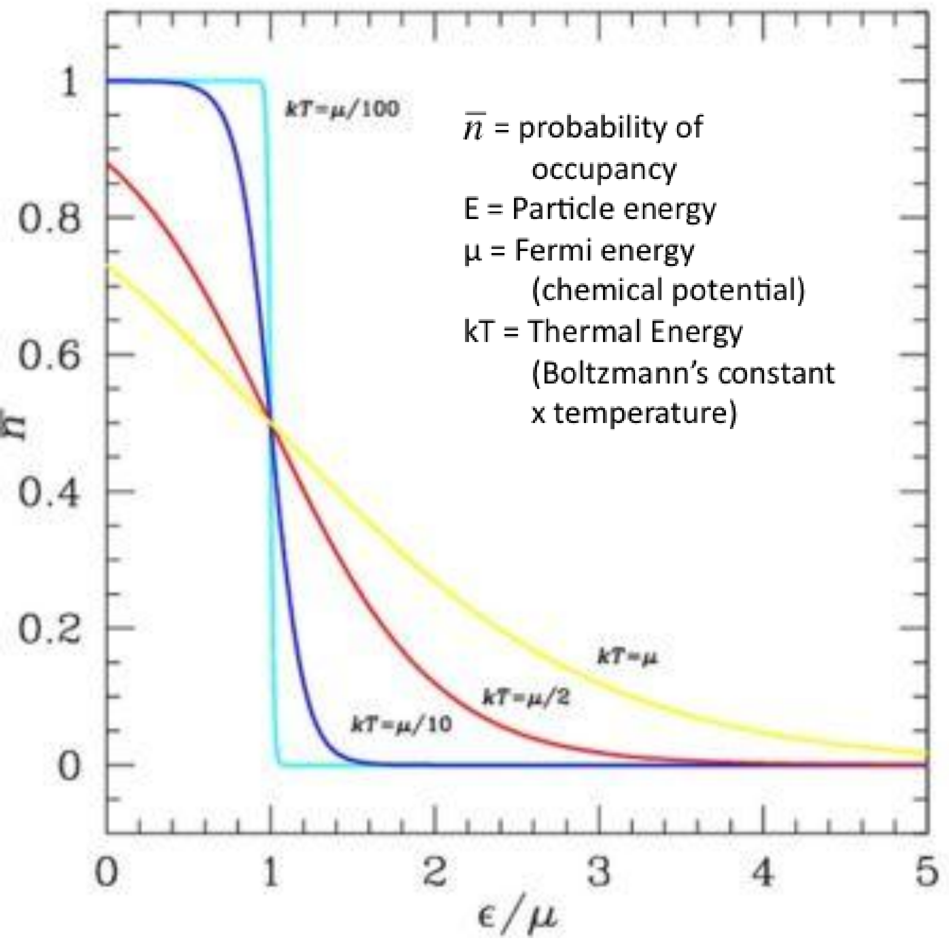
$$\overline{n} = \frac{1}{e^{(E-E_F)/k_b T} + 1}$$

Occupied Density of States



To reduce noise in a Si CCD camera, should you increase or decrease temperature?

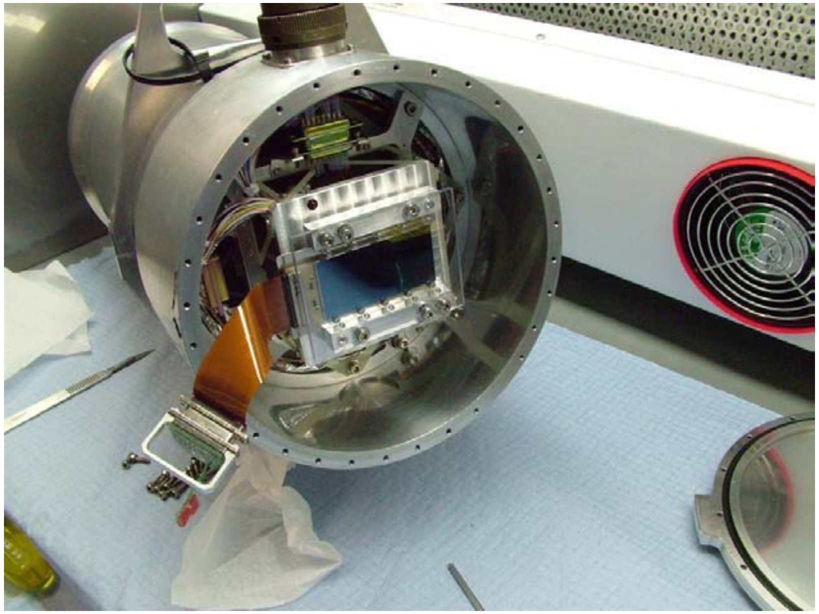
Lower Temperature = Lower Intrinsic Carrier Concentration



Public domain image (Source: Wikimedia Commons).

http://www.answers.com/topic/semiconductor

CCD inside a LN dewar

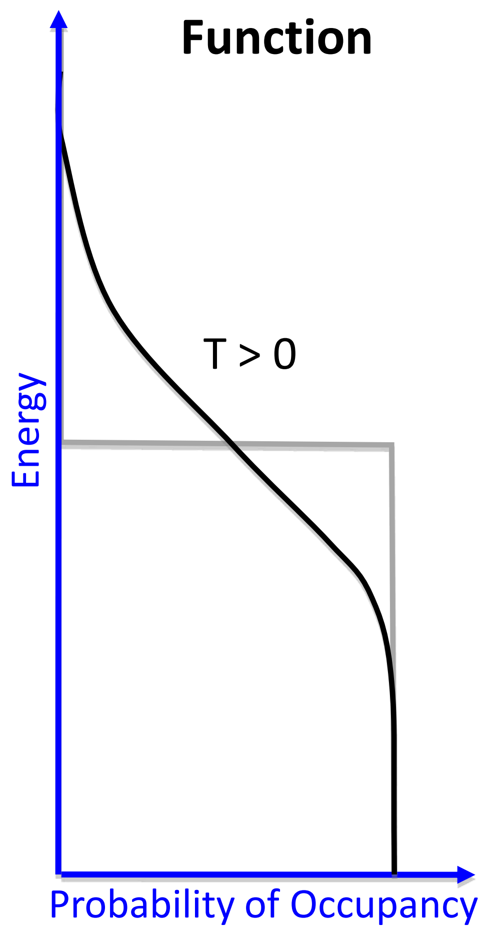


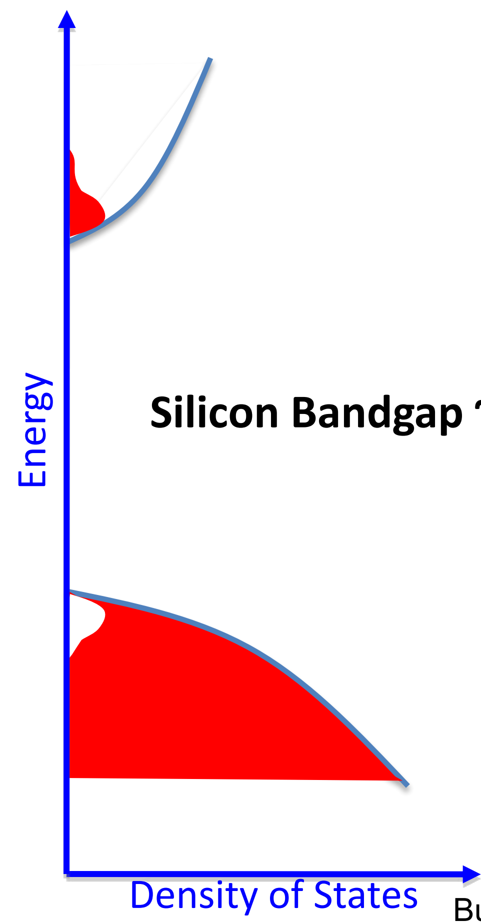
http://msowww.anu.edu.au/observing/detectors/wfi.php

Question: Transistors made from which semiconductor material experience greater electronic noise at room temperature: Germanium or Silicon?

Intrinsic Conductivity: Dependence on Bandgap

At a finite temperature, finite conductivity (current can flow).

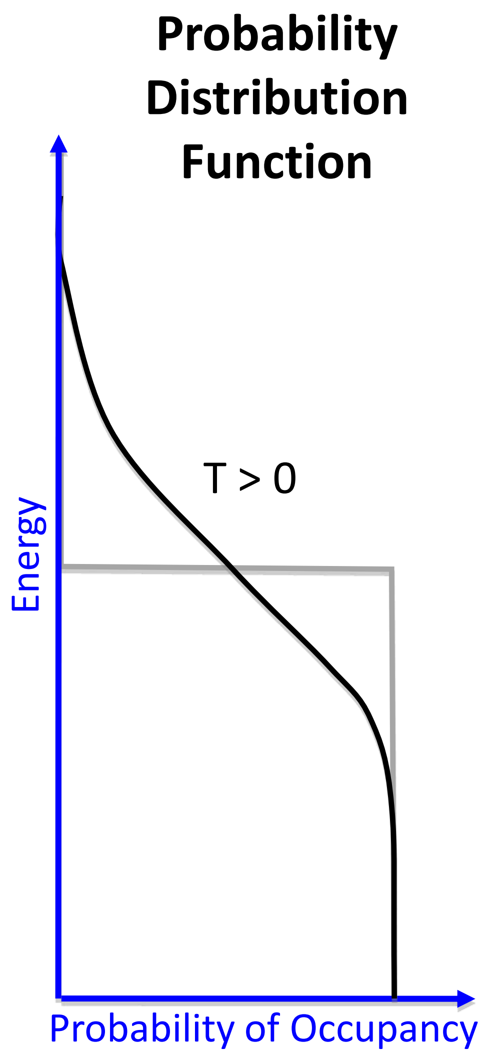


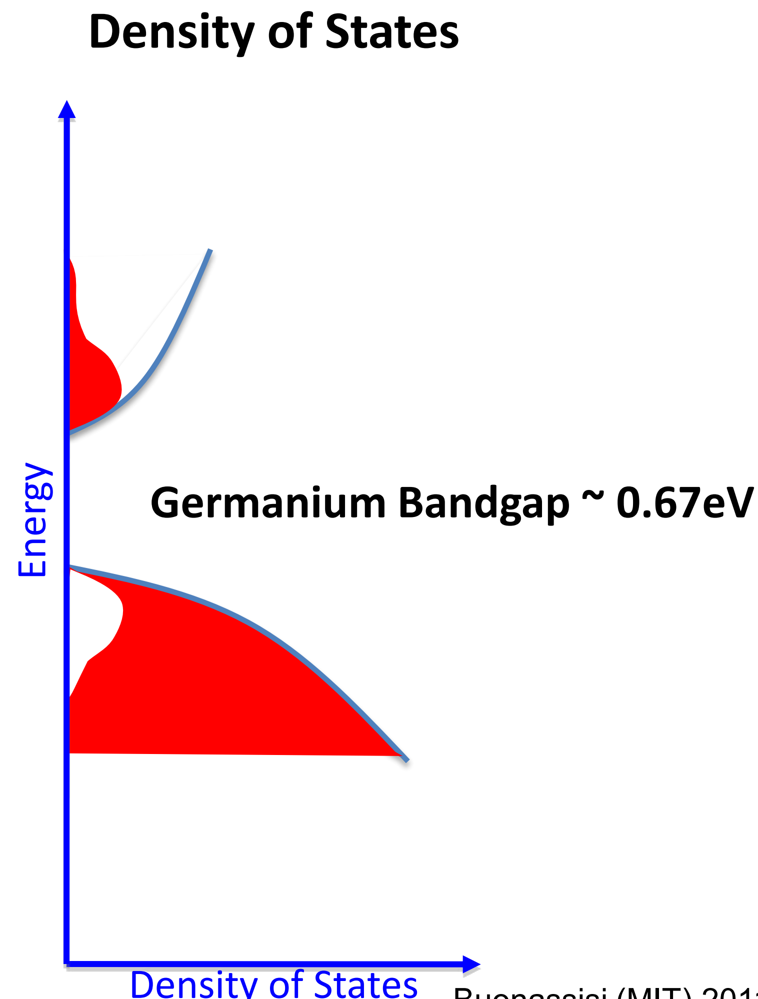


Buonassisi (MIT) 2011

Intrinsic Conductivity: Dependence on Bandgap

At a finite temperature, finite conductivity (current can flow).





Intrinsic Conductivity: Dependence on Bandgap

Please see table at https://web.archive.org/web/20130818190346/http://www.siliconfareast.com/sigegaas.htm