2.626 Fundamentals of Photovoltaics
Fall 2008

Quiz #1 Review: Fundamentals

Lecture 8 – 2.626

Tonio Buonassisi

General Matters

- Practice Exam:
  - Take 10 minutes to think about how you would solve the problems. Write notes.
  - *Then, we'll solve it together during today's review.*

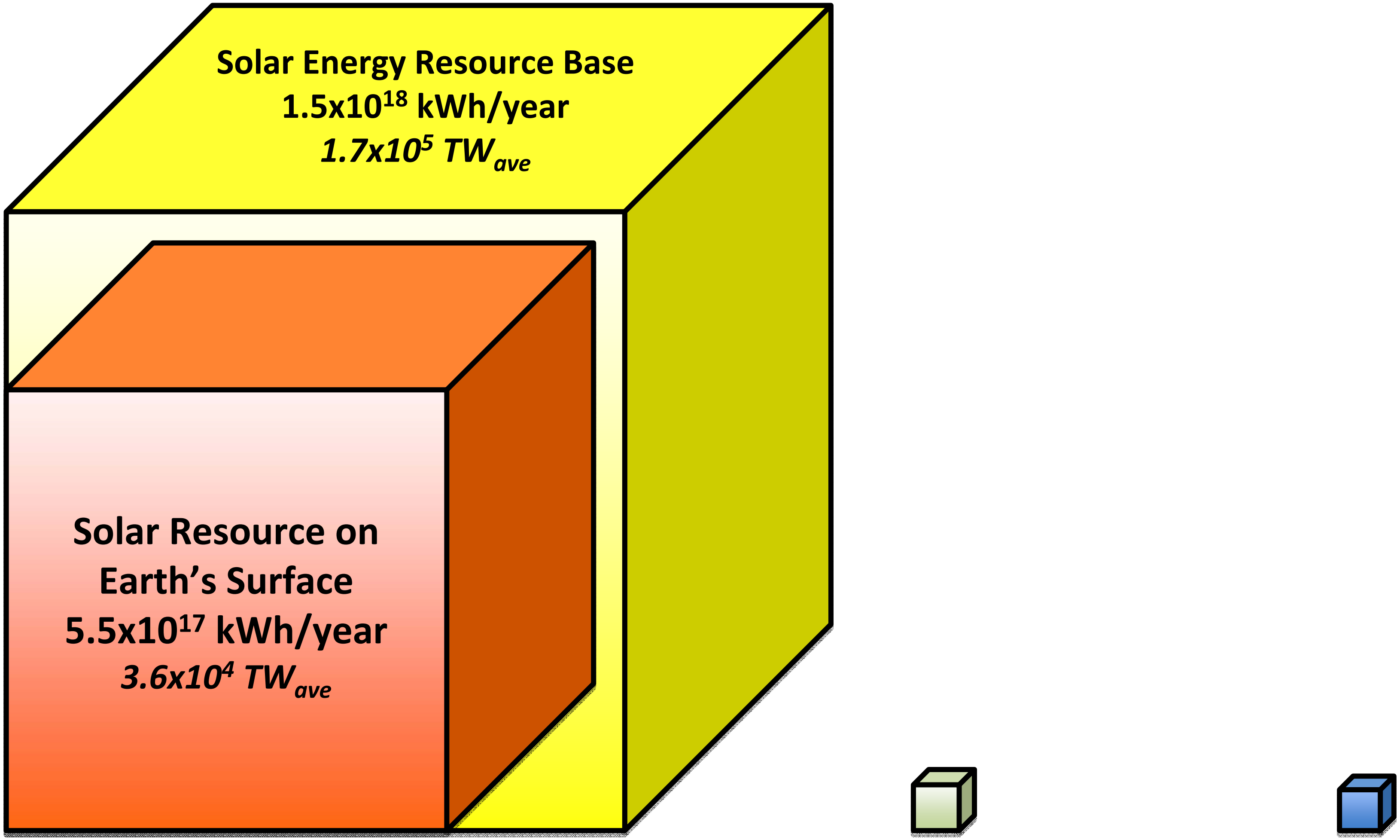
Fundamentals

1. Properties of Sunlight
2. Light Absorption (Charge Excitation and Conduction)
3. Charge Separation
4. Charge Collection

Fundamentals

1. Properties of Sunlight
    1. Resource Base
    2. Solar Spectrum
    3. Atmospheric Absorption
2. Charge Excitation and Conduction
3. Charge Separation
4. Charge Collection

Solar Resource Base = Huge



Solar Energy Resource Base
$1.5\text{x}10^{18}$ kWh/year
$1.7\text{x}10^{5}$ TW$_{ave}$

Solar Resource on Earth's Surface
$5.5\text{x}10^{17}$ kWh/year
$3.6\text{x}10^{4}$ TW$_{ave}$

Wind Energy Resource Base
$6\text{x}10^{14}$ kWh/year
72 TW$_{ave}$

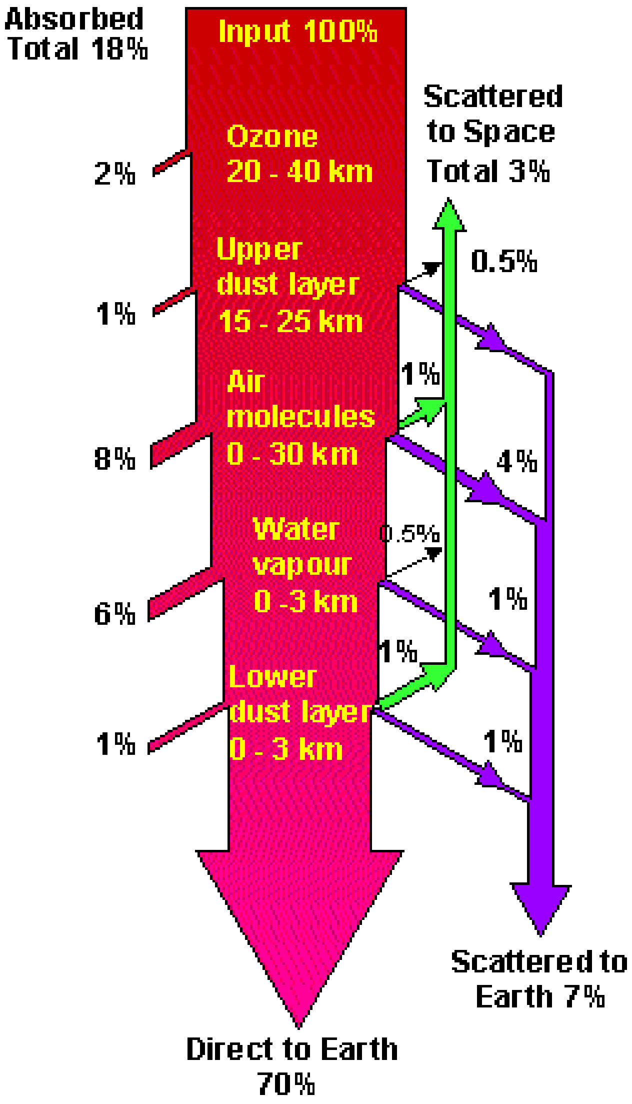
Human Energy Use (mid- to late-century)
$4\text{x}10^{14}$ kWh/year
50 TW$_{ave}$

References:
Wind Energy: C.L. Archer and M.Z. Jacobson, *J. Geophys. Res.* **110**, D12110 (2005).

ATMOSPHERIC EFFECTS

Atmospheric effects have several impacts on the solar radiation at the Earth's surface. The major effects for photovoltaic applications are:

- A reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere;
- A change in the spectral content of the solar radiation due to greater absorption or scattering of some wavelengths;
- The introduction of a diffuse or indirect component into the solar radiation; and
- Local variations in the atmosphere (such as water vapor, clouds and pollution) which have additional effects on the incident power, spectrum and directionality.



Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

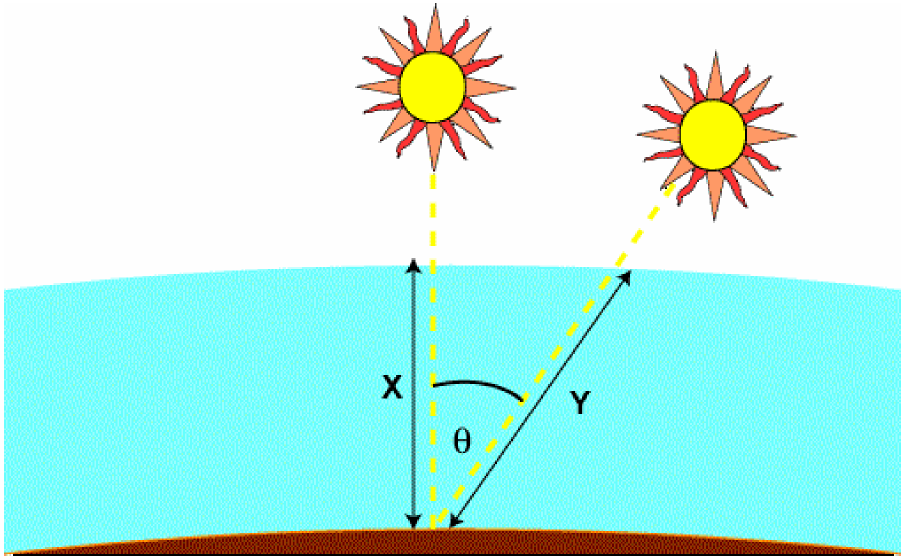
Typical clear sky absorption and scattering of incident sunlight (after Hu and White, 1983).

AIR MASS

The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as:

$$AM = \frac{1}{\cos(\theta)}$$

Valid for small to medium θ



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AM1: Sun directly overhead

AM1.5G: “Conventional”

G (Global): Scattered and direct sunlight

D (Direct): Direct sunlight only

AM0: Just above atmosphere (space applications)

Estimating System Output from Insolation Maps

Q: Let’s say I have a 2.2 kW_p photovoltaic array. How much energy will it produce in a year?

A: Let’s say our location receives, on average, 4 kWh/m²/day from the Sun. The calculation is then straightf

System size

Insolation at site of installation

$$\text{Energy Output} = \frac{\boxed{\left(2200\ \text{W}_p\right)} \times \boxed{\left(4.0\ \text{kWh/m}^2\text{/day}\right)}}{\boxed{1000\ \text{W}_p\text{/m}^2}} = 8.8\ \text{kWh/day} \approx 3200\ \text{kWh/year}$$

AM 1.5G

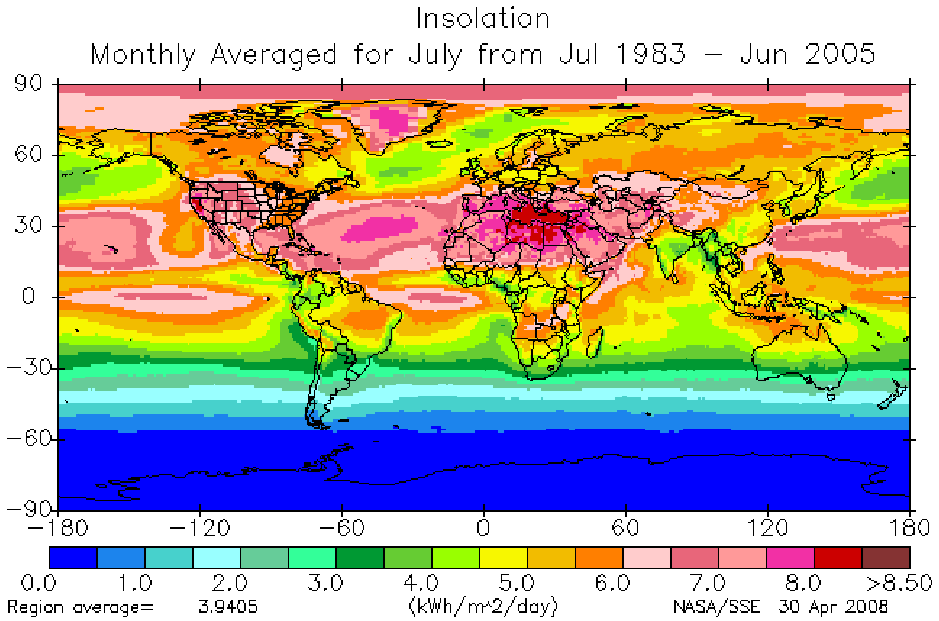


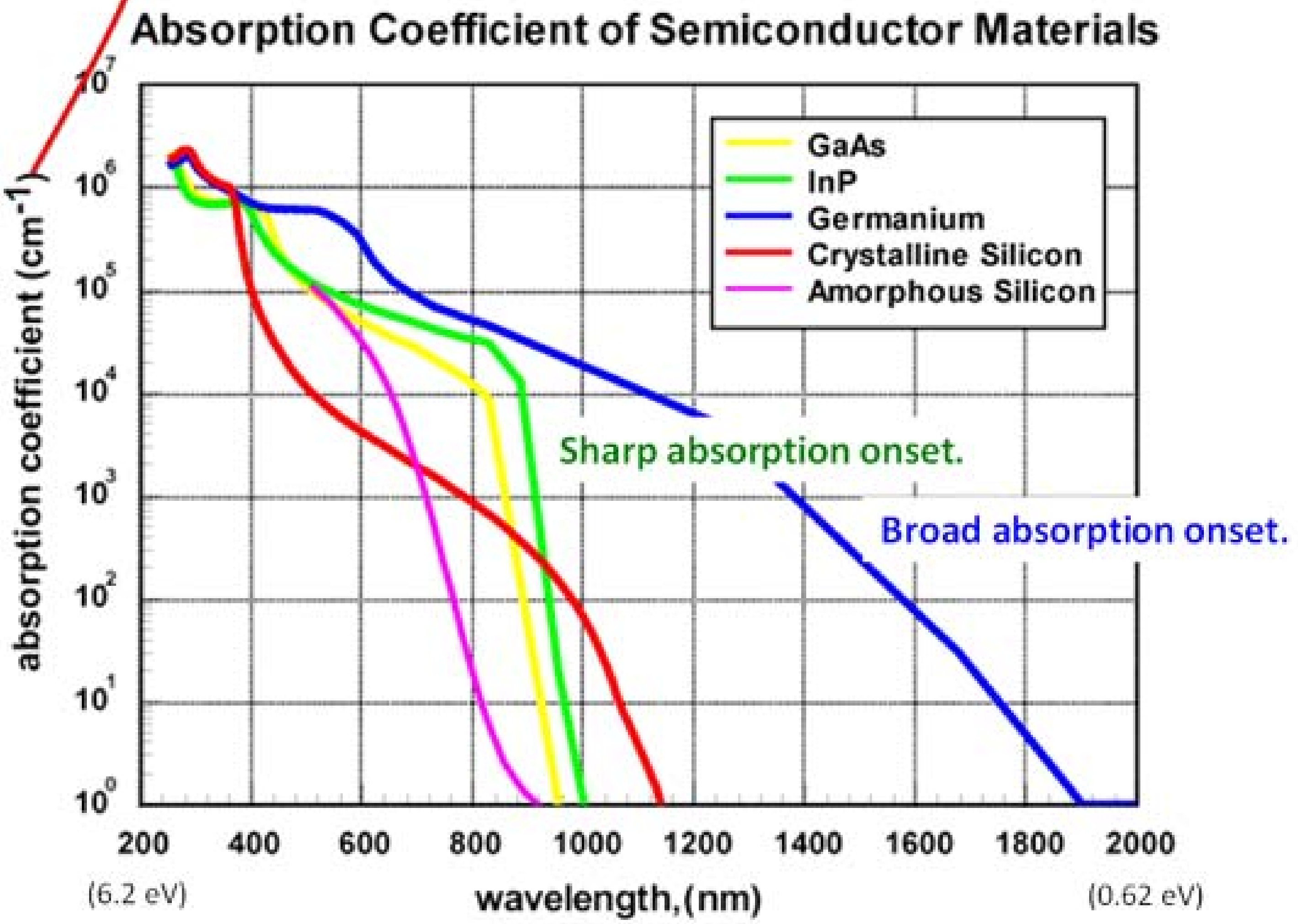
Image courtesy NASA Earth Observatory.

Fundamentals

1. Properties of Sunlight
2. Charge Excitation and Conduction
    a. Optical Absorption
    b. Bandgap
3. Charge Separation
4. Charge Collection

Absorption Coefficient (α) for different materials

$$I = I_o \cdot e^{-\alpha \cdot l}$$



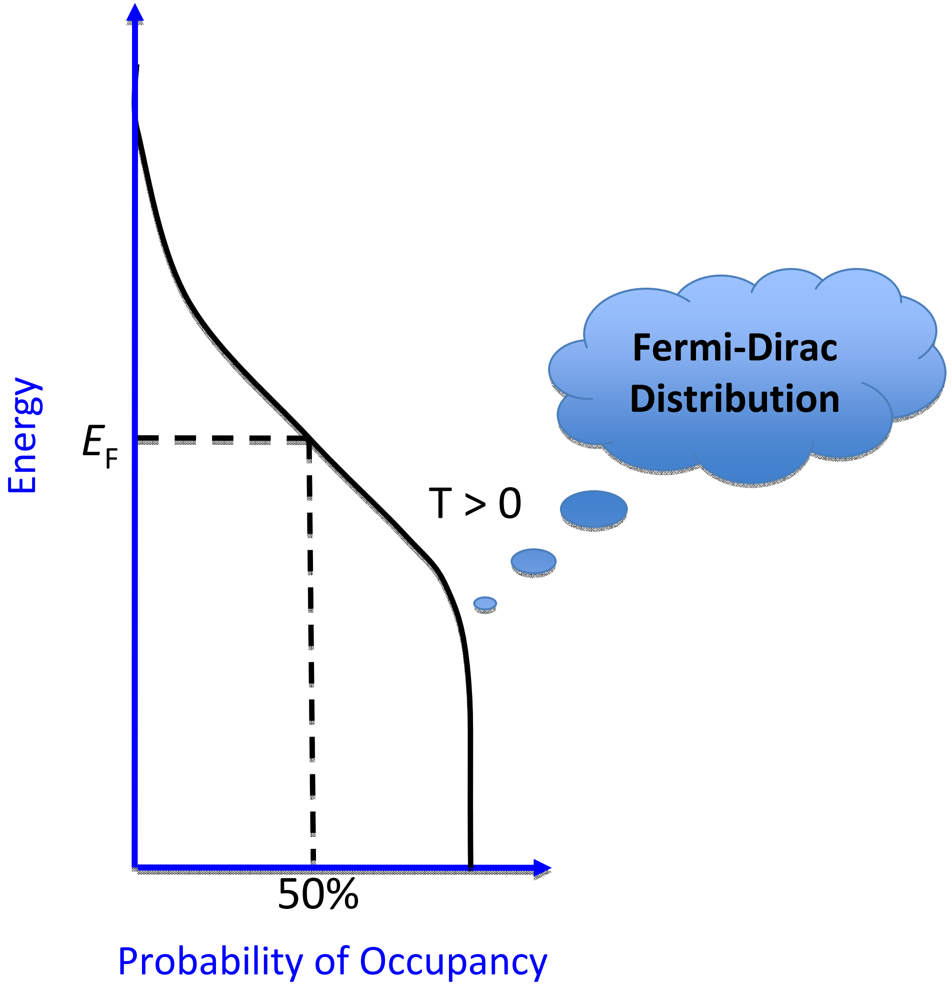
Sharp absorption onset.

Broad absorption onset.

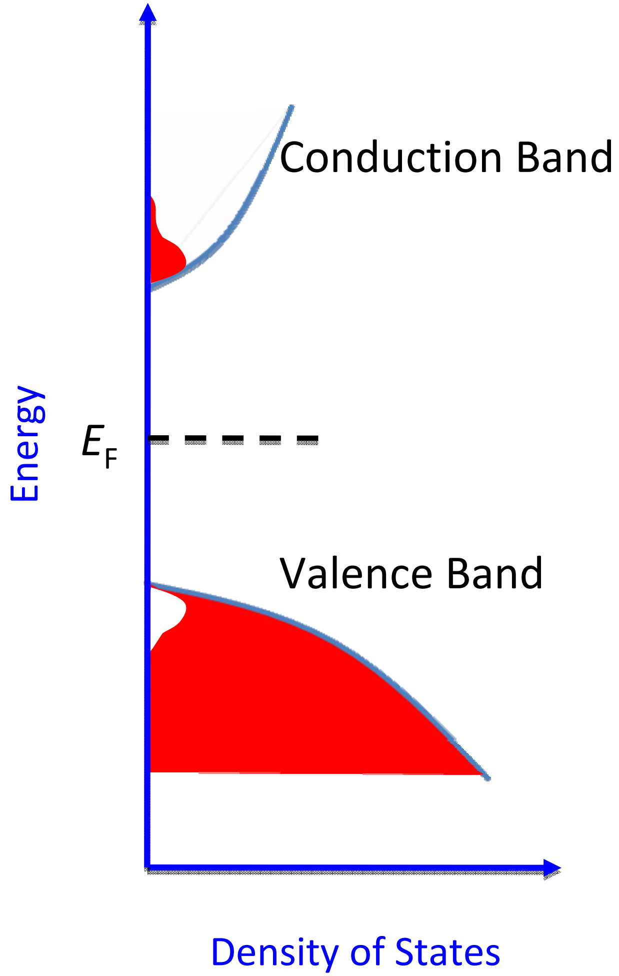
Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

Defining the “Fermi Level”

Fermi-Dirac Probability Distribution Function at T > 0.



Density of States



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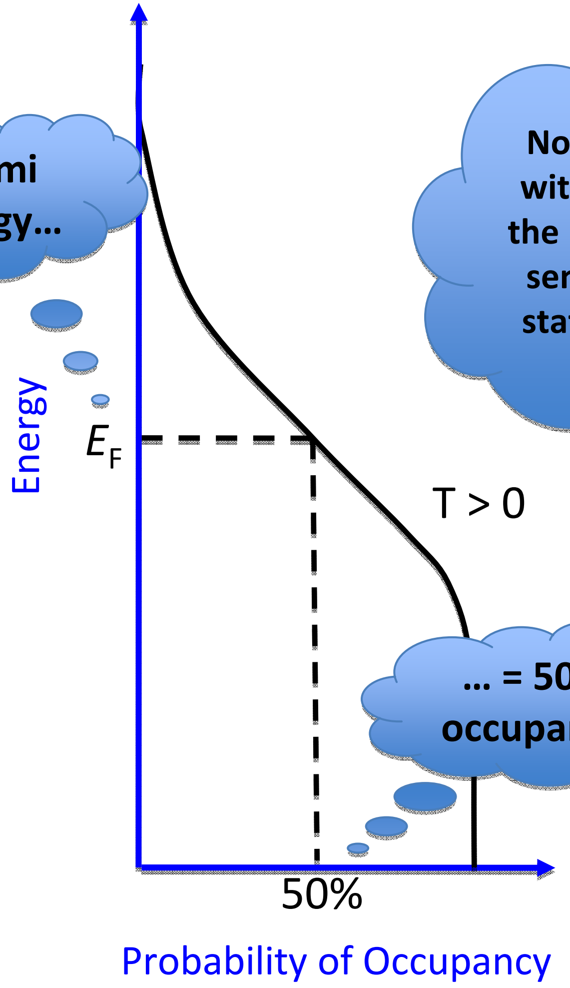
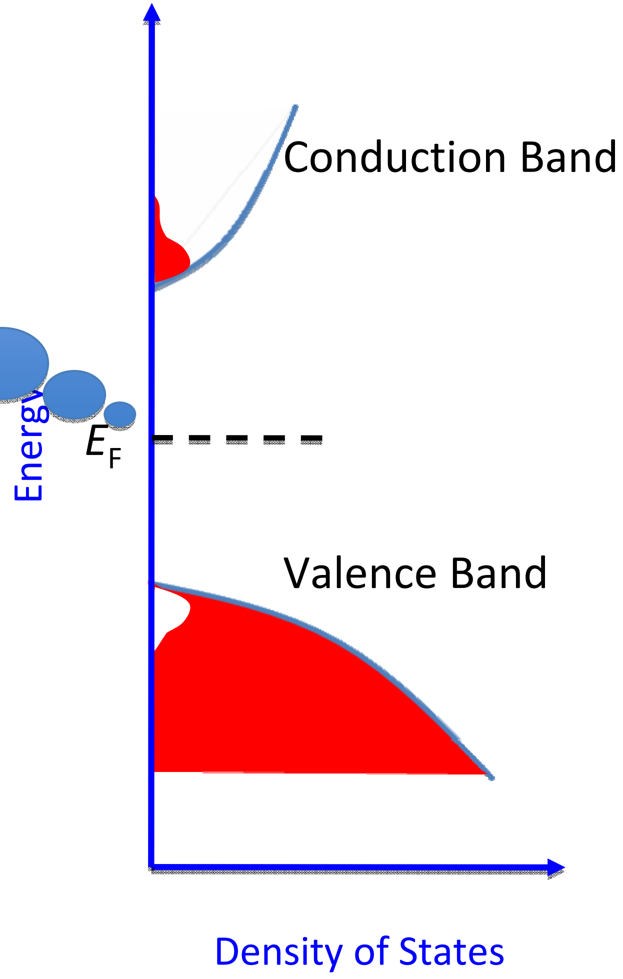


Fermi Energy…

… = 50% occupancy

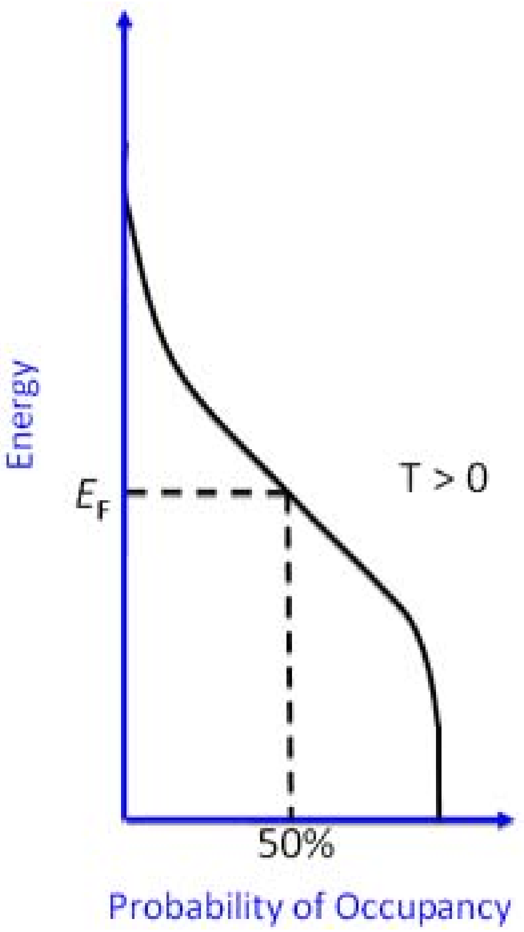
No states can exist within the band. So the Fermi Energy in a semiconductor is a statistical quantity.

Density of States

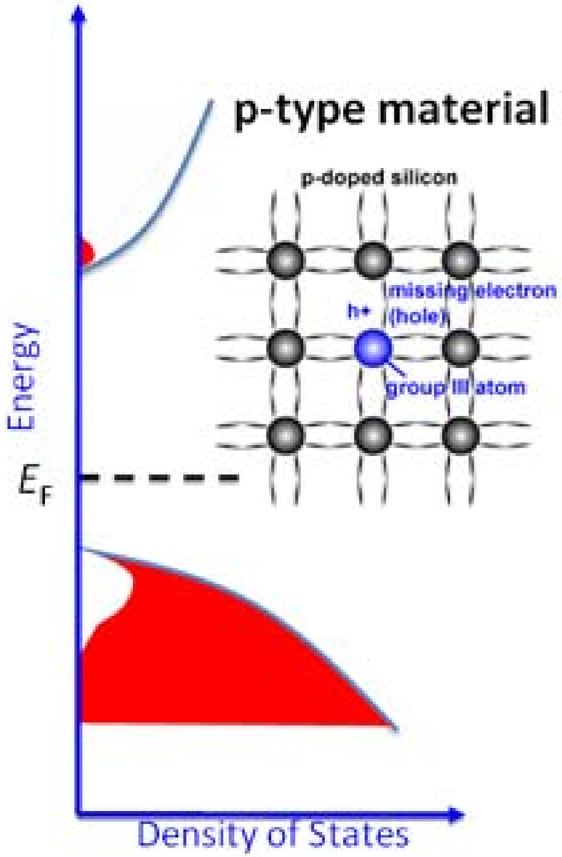


Fermi Level in p-type Material

Fermi-Dirac Probability Distribution Function at T > 0.



Density of States



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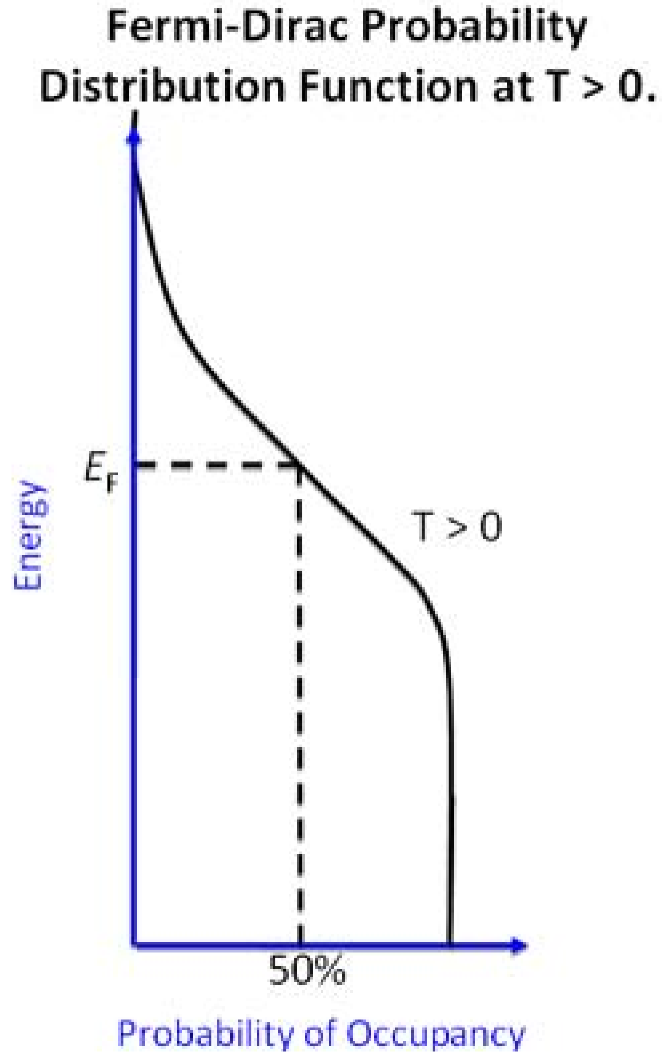
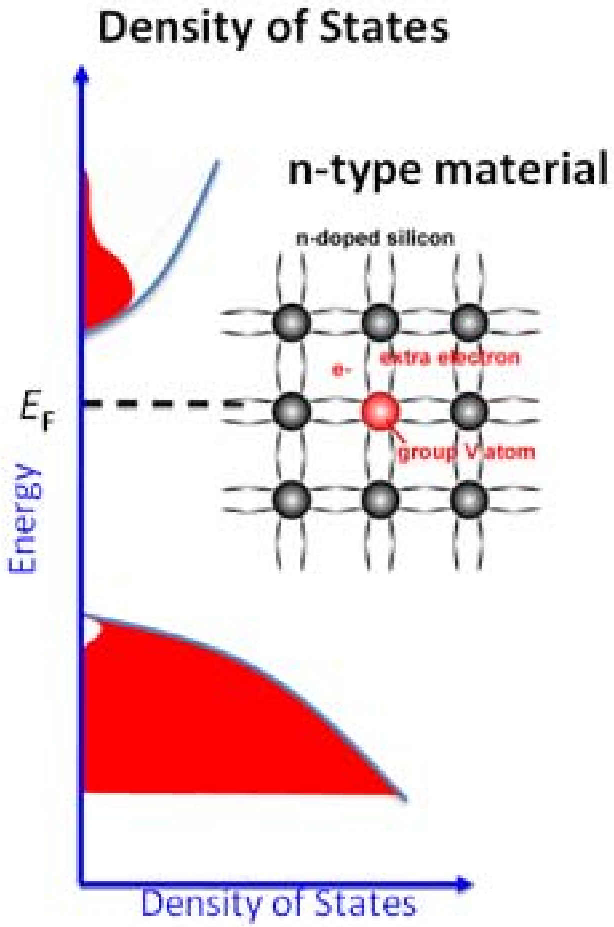
Fermi Level in n-type Material



Fermi-Dirac Probability Distribution Function at T > 0.



Density of States

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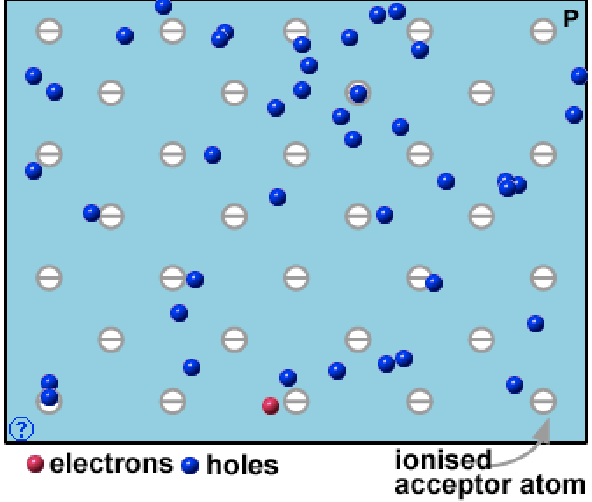

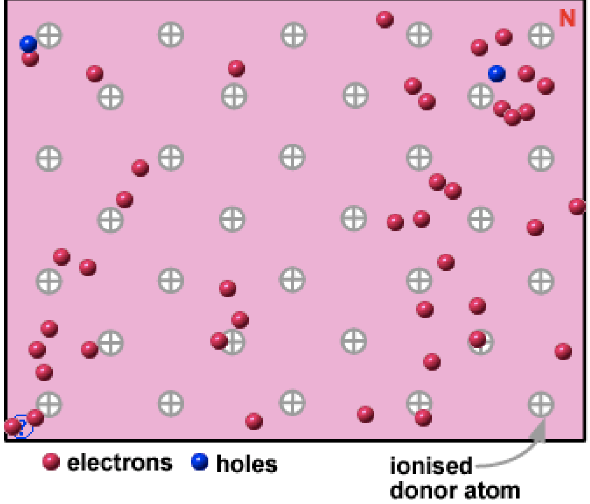

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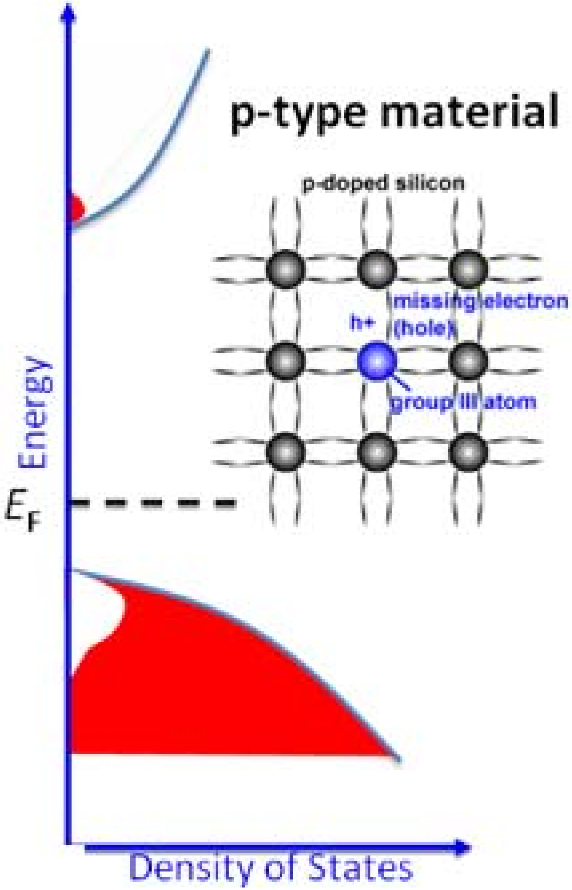

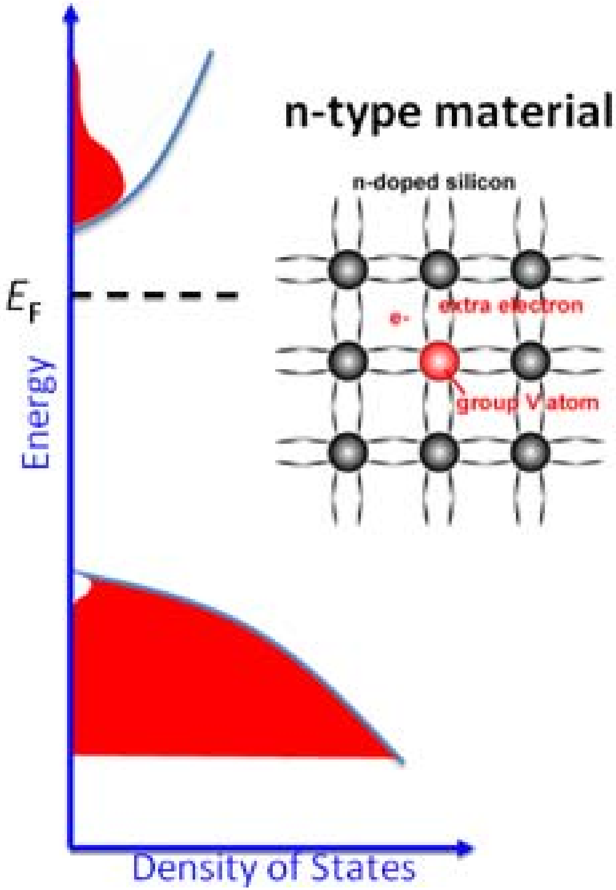

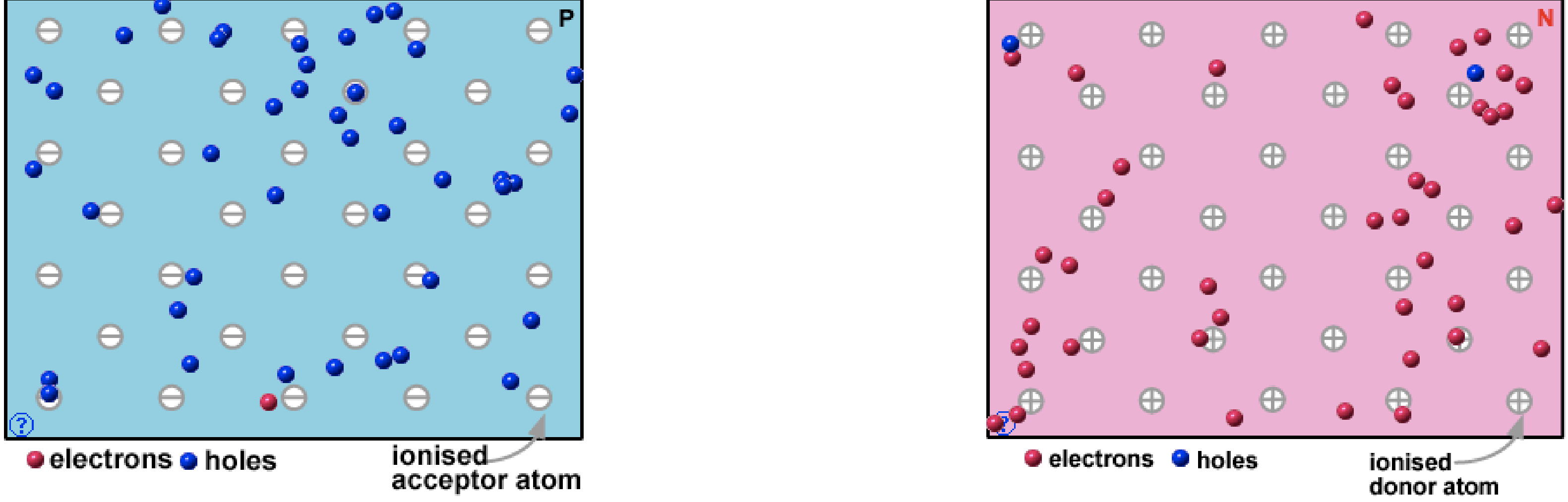

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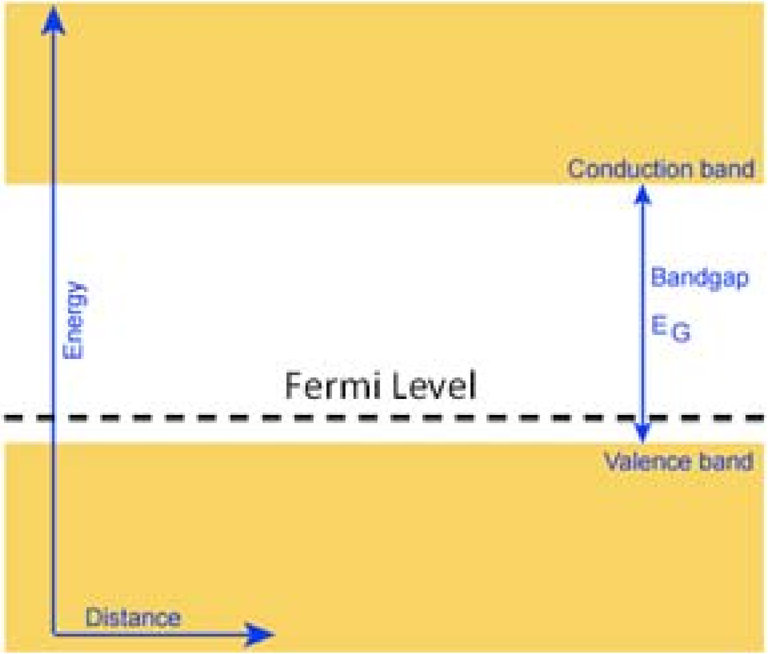
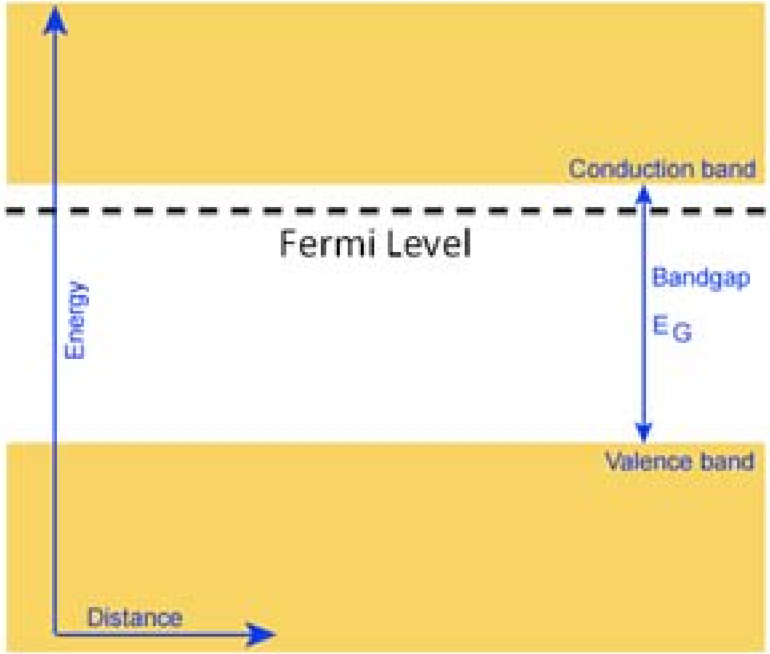
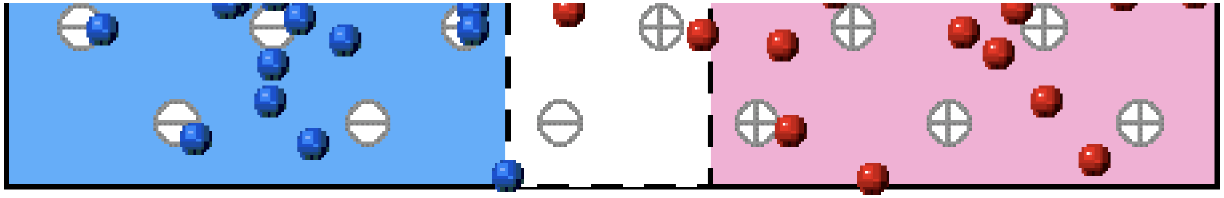




Fundamentals

1. Properties of Sunlight
2. Charge Excitation and Conduction
3. Charge Separation
    a. Excitons
    b. pn junction & IV curve
    c. p-i-n junction
4. Charge Collection

How a pn-junction comes into being



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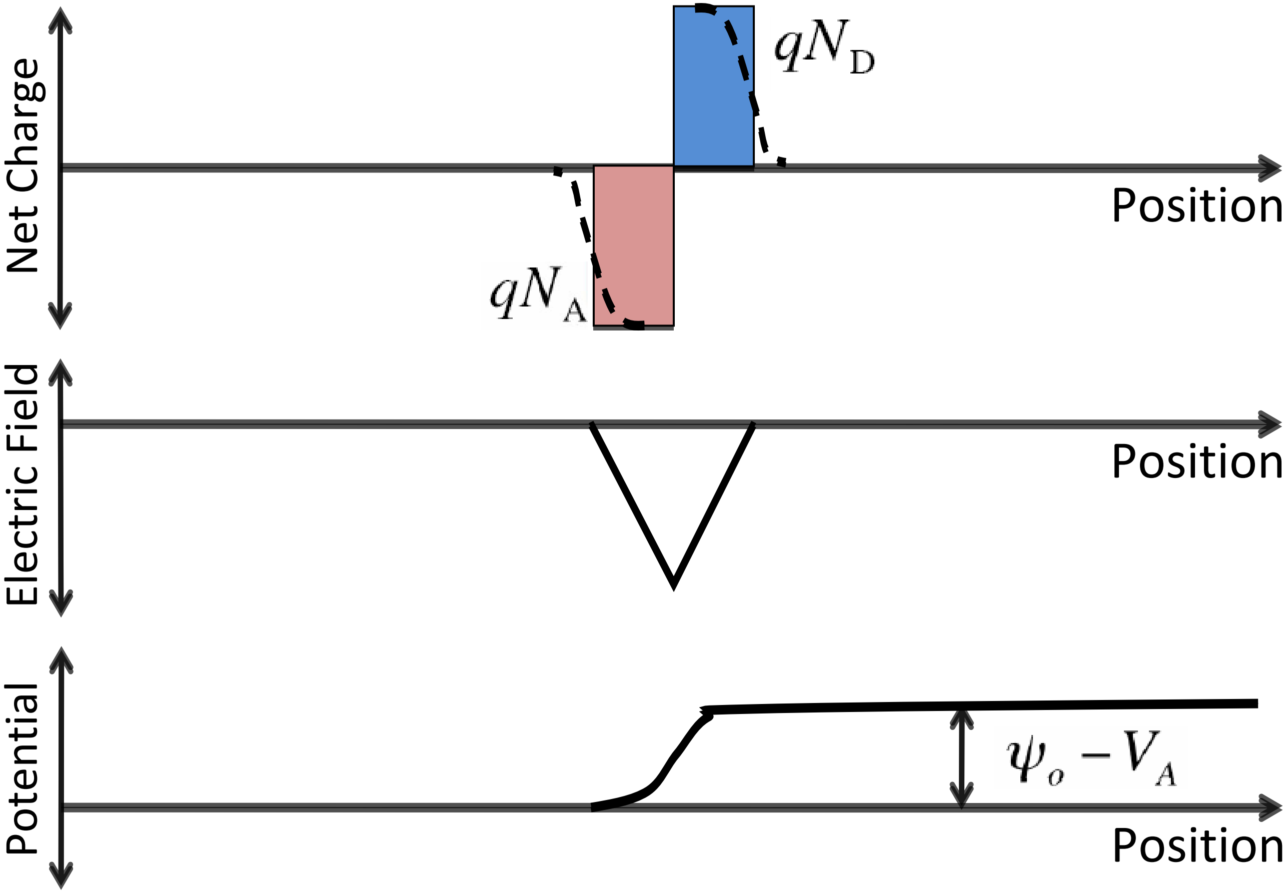

$$\frac{d\xi}{dx} = \frac{\rho}{\varepsilon}$$

$$\frac{d\psi}{dx} = -\xi$$

Dark Diodes: Forward and Reverse Bias

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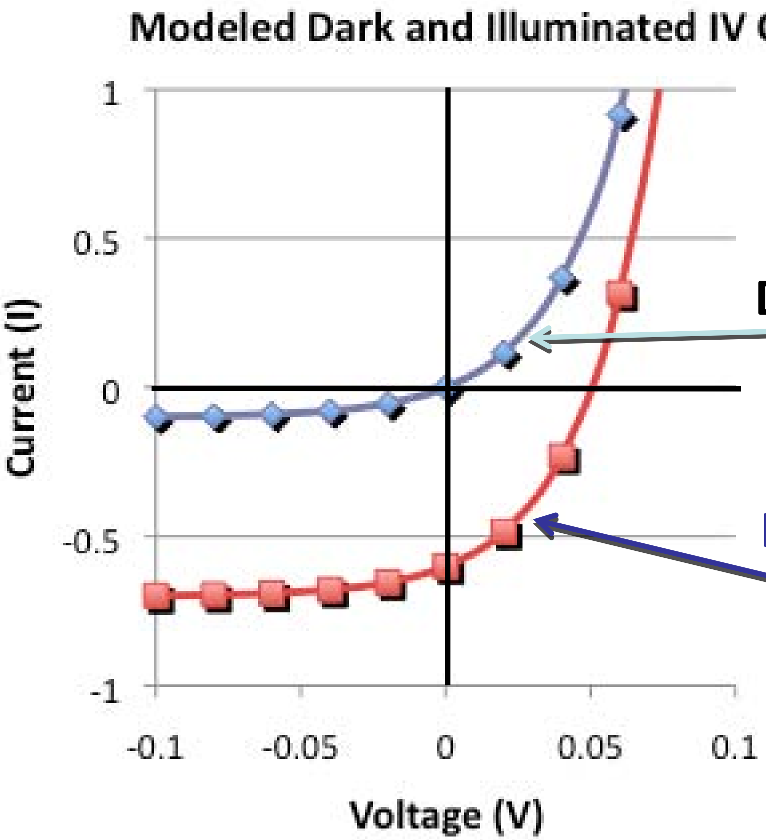
http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/pn_junction/junc_dyn_1b.jpg.
http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/pn_junction/junc_dyn_1a.jpg.
http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/pn_junction/junc_dyn_1c.jpg.

Study Tip: Read pp. 63, 65, 79 in Green, and the PVCDROM.

http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/pn_junction/pn_junction.html

Ideal Diode Equation



Dark

$$I = I_o\left(e^{qV/kT} - 1\right)$$

Illuminated

$$I = I_o\left(e^{qV/kT} - 1\right) - I_L$$

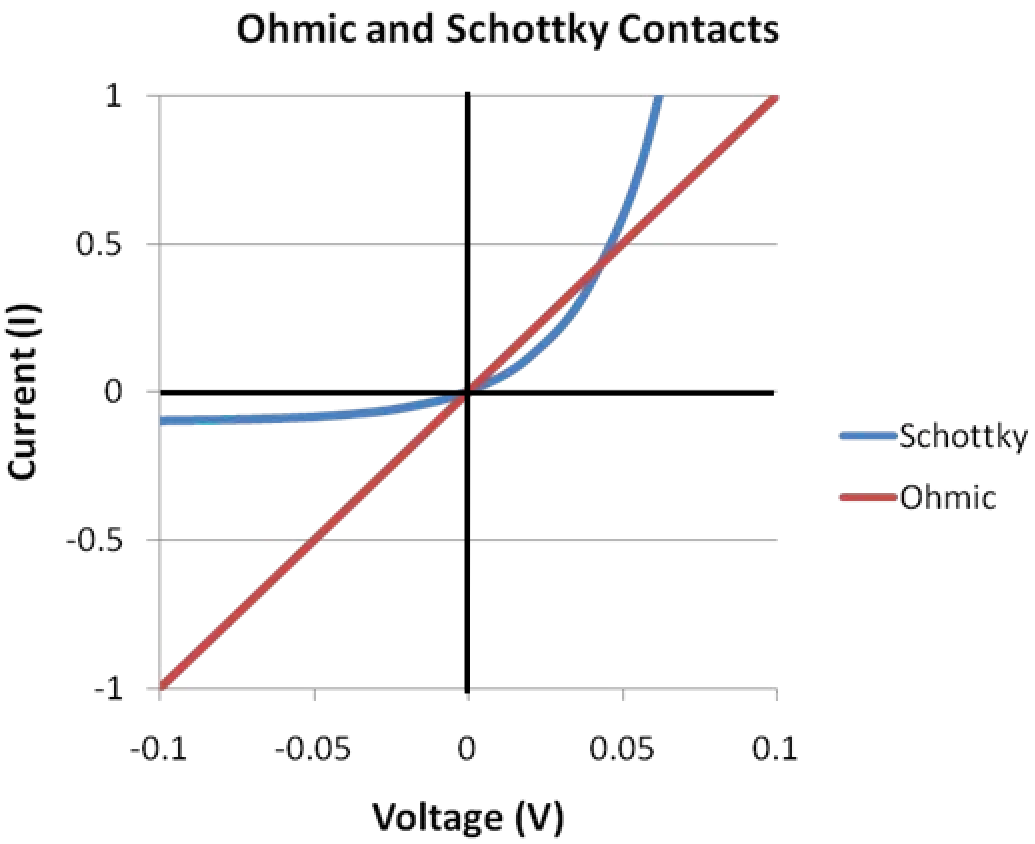
Curves designed using ideal diode equation, with I_o = 0.1 (a.u.), and I_L = 0.6 (a.u.).

Fundamentals

1. Properties of Sunlight
2. Charge Excitation and Conduction
3. Charge Separation
4. Charge Collection
    1. Types
    2. Losses

Classes of Contacts

- **Ohmic:**
  - Electron barrier height ≤ 0.
  - Linear I-V curve.
  - Typically used when charge separation is not a goal for metallization.
- **Schottky:**
  - Electron barrier height > 0.
  - Exponential I-V curve.
  - Used when charge separation is desired.



Materials Commonly Used for Contacts

- **Metals**
  - Optically opaque.
  - Electrically conductive.

- **Transparent Conducting Oxides (TCOs)**
  - Optically transparent.
  - Electrically conductive.

Evaluating Metals for Contacts - Theoretical

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Fundamentals

1. Properties of Sunlight
   a. Solar Spectrum
   b. Atmospheric Absorption
2. Charge Excitation and Conduction
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4. Charge Collection
   a. Types
   b. Losses

General Matters

- Practice Exam
- Concept Quiz Results