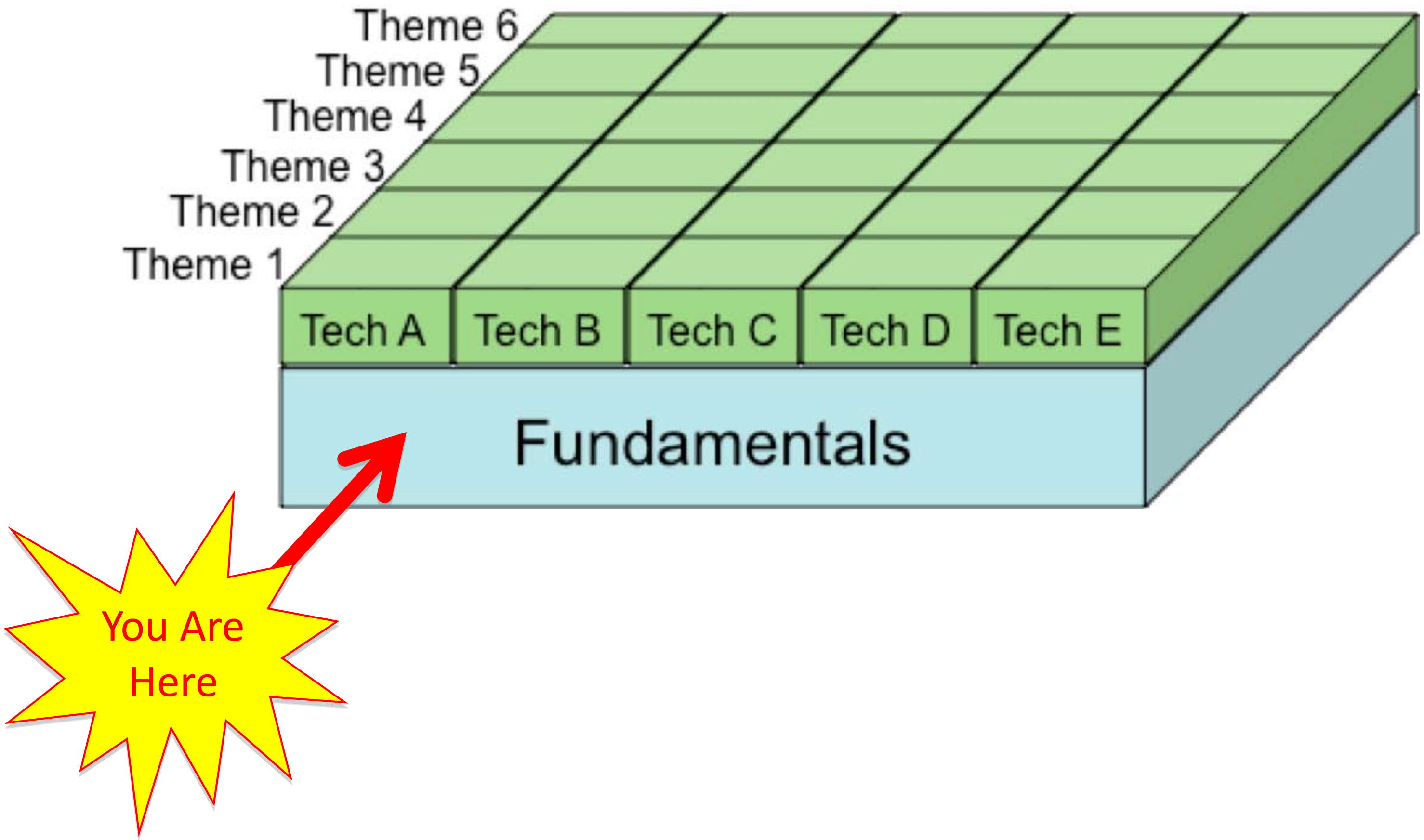
Charge Extraction

Lecture 9 – 10/06/2011

MIT Fundamentals of Photovoltaics
2.626/2.627 – Fall 2011

Prof. Tonio Buonassisi

2.626/2.627 Roadmap



2.626/2.627: Fundamentals

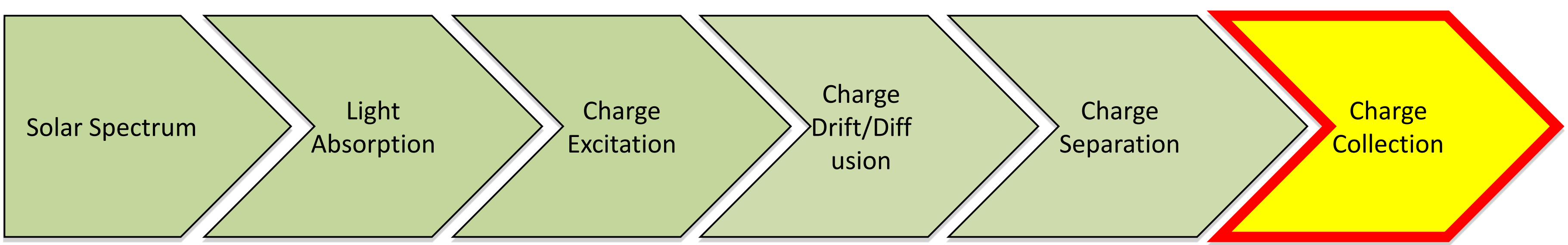
<u>Every</u> photovoltaic device must obey:

$$\text{Conversion Efficiency } (\eta) \equiv \frac{\text{Output Energy}}{\text{Input Energy}}$$

For most solar cells, this breaks down into:

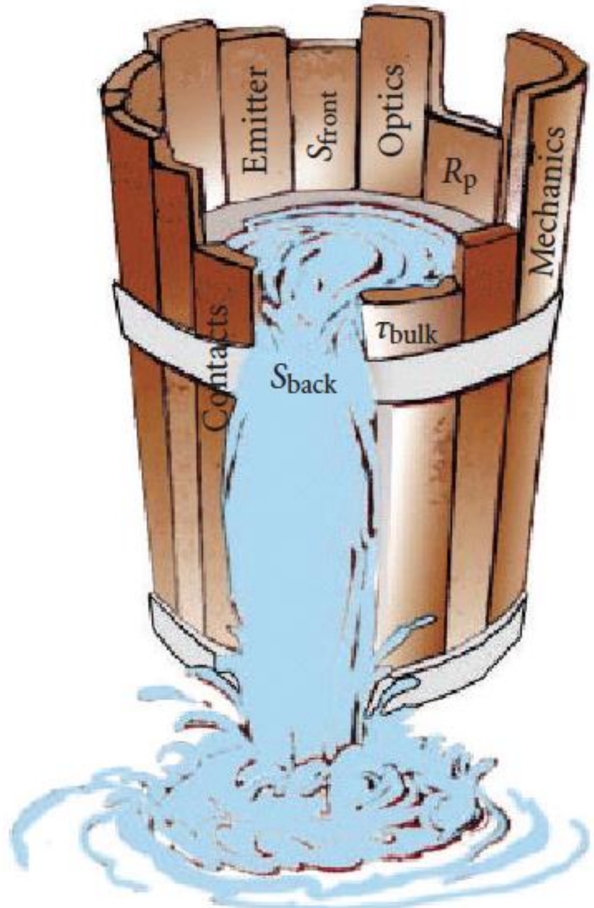
Inputs

Outputs



$$\eta_{\text{total}} = \eta_{\text{absorption}} \times \eta_{\text{excitation}} \times \eta_{\text{drift/diffusion}} \times \eta_{\text{separation}} \times \eta_{\text{collection}}$$

Liebig's Law of the Minimum



S. Glunz, *Advances in Optoelectronics* 97370 (2007)

$$\eta_{total} = \eta_{absorption} \times \eta_{excitation} \times \eta_{drift/diffusion} \times \eta_{separation} \times \eta_{collection}$$

Learning Objectives: Charge Extraction

1. **Describe the purpose of contacts, and their most common types.**
2. Describe the impact of good and poor contacts on IV characteristics.
3. Sketch the IV characteristics of Schottky and Ohmic contacts.
4. Describe what fundamental material parameters determine the IV characteristics of a contact/semiconductor junction.
5. Sketch common band alignments (Types 1, 2, 3 junctions).
6. Sketch common solar cell device architectures.

Contacts

- …extract carriers from device.
- …prevent back-diffusion of carriers into device.
- …are studied extensively in the semiconductor industry (several good review papers) for “common” semiconductors.
- …are semiconductor-specific: While fundamentals generally apply universally, the devil is in the details, and each material system requires individual optimization.
- … are influenced heavily by surface states (i.e., repeatable surface preparation is a *must*!)

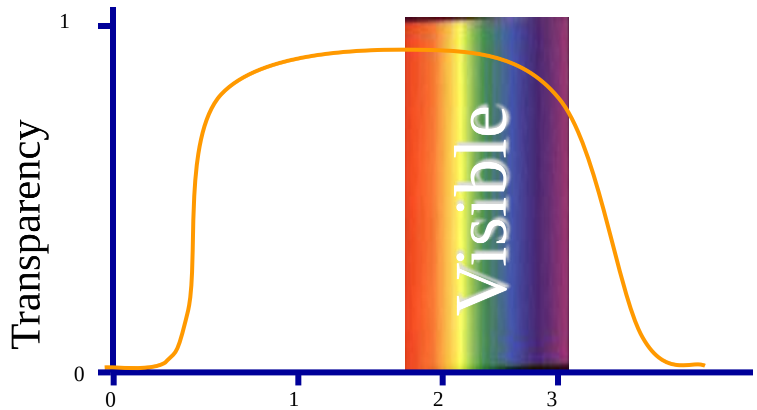
Materials Commonly Used for Contacts

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

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

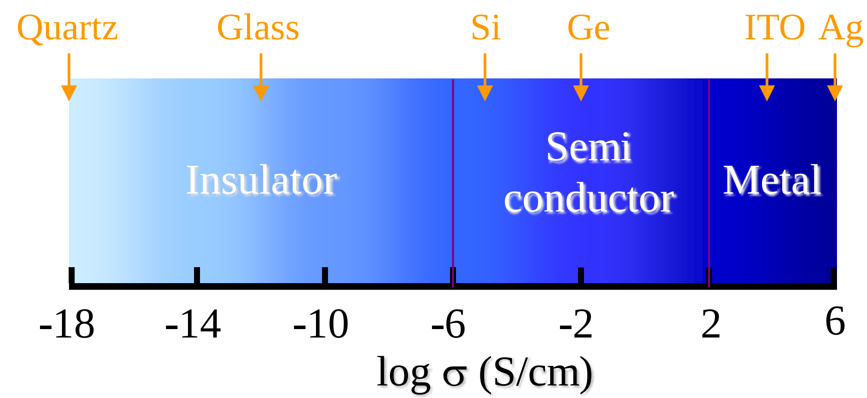
Properties of TCOs

Transparency



- Transmittance: > 80% (Films)
- Range: 400 ~ 700 nm
- Band gap > 3.1eV

Conductivity (σ)



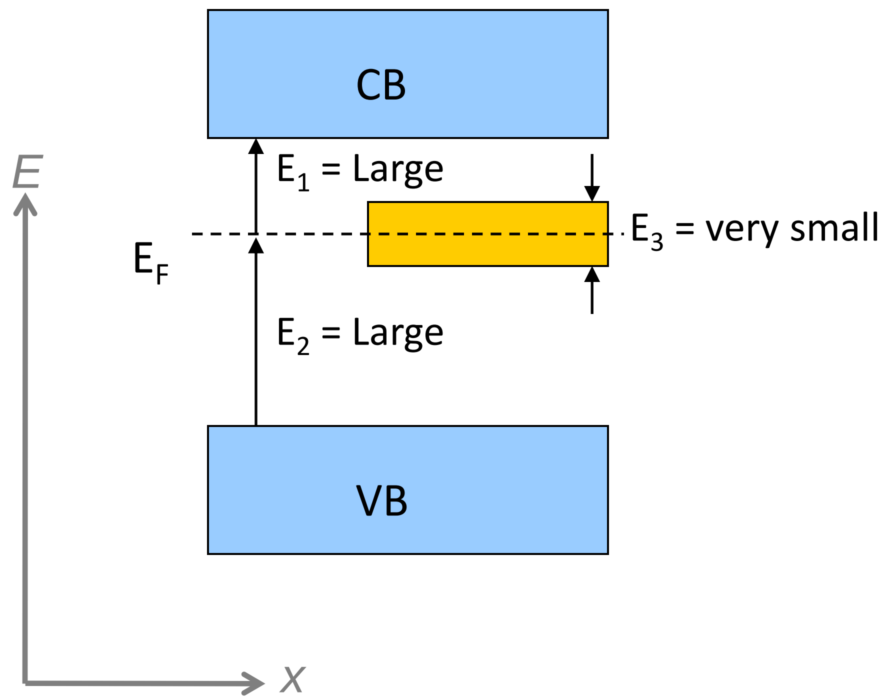
$$\sigma = n \mu e$$

n - carrier conc. (cm^{-3})

μ - mobility (cm^2/Vs)

e - charge per carrier

How TCOs Work



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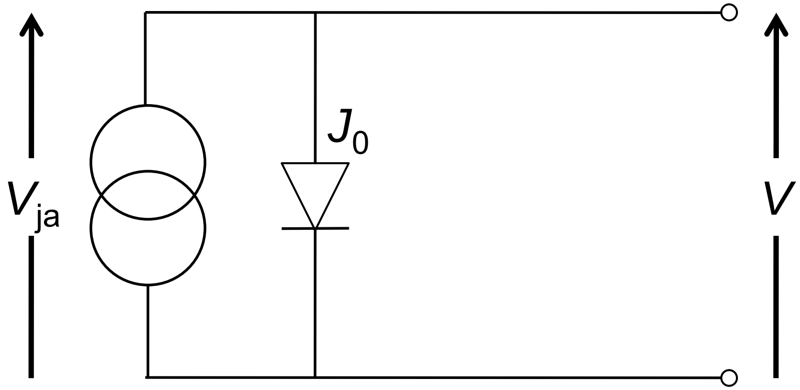
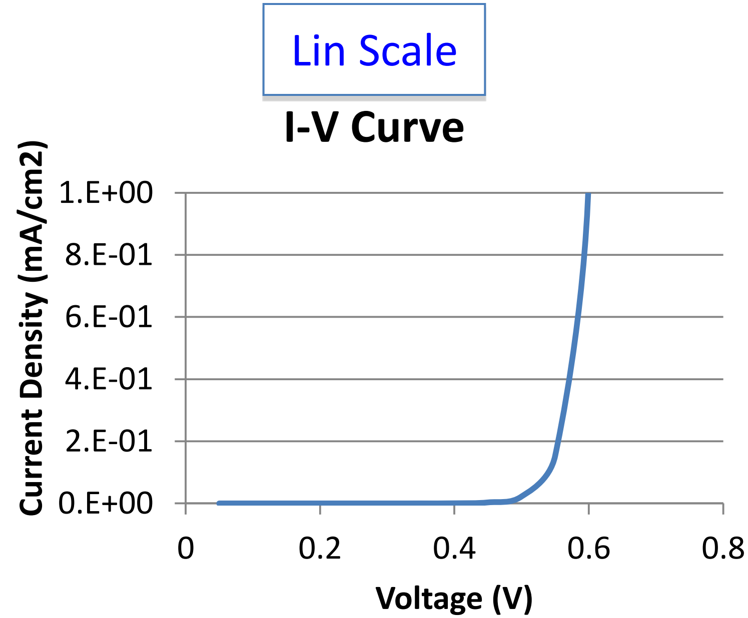
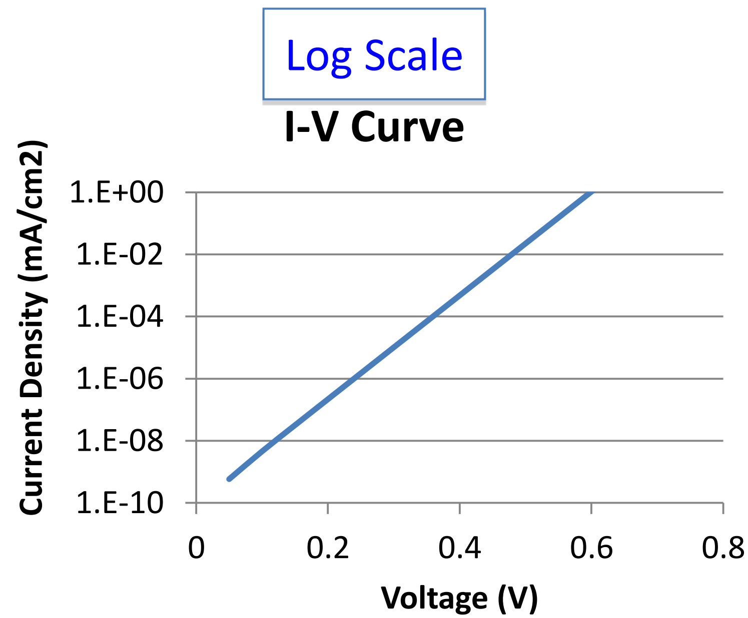
Equivalent Circuit: Simple Case



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





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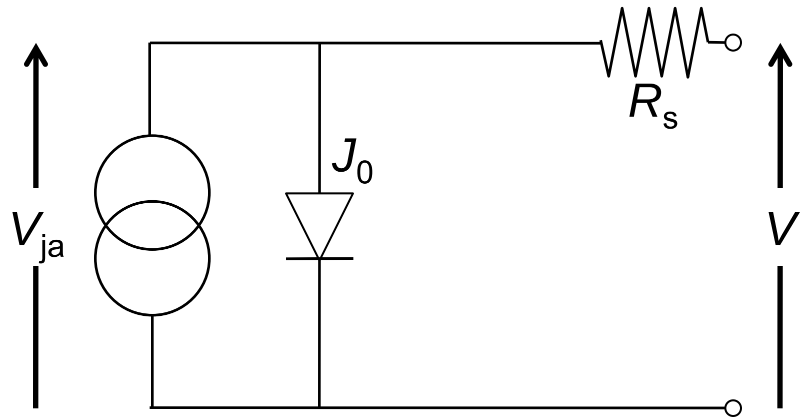
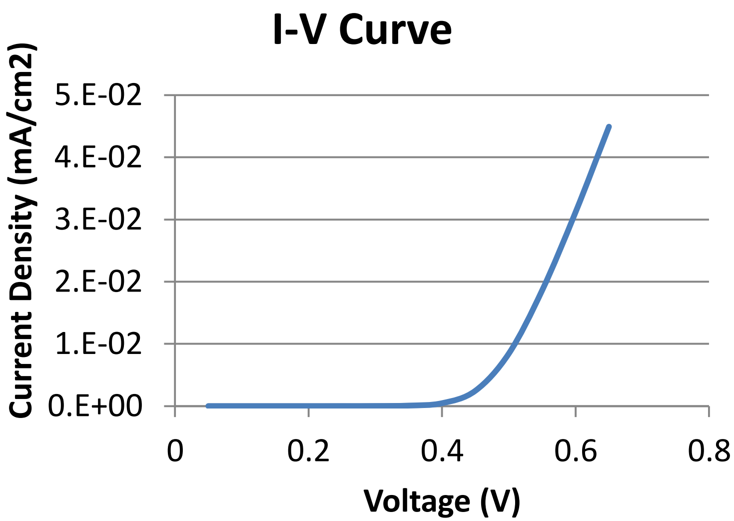
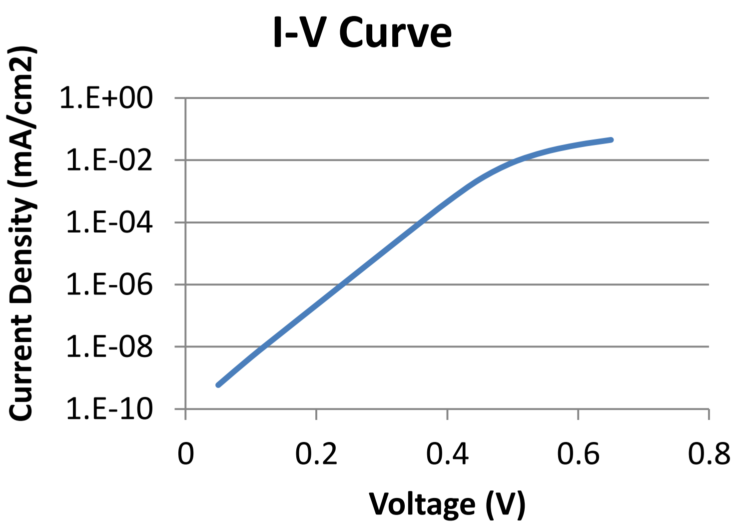
Equivalent Circuit: Simple Case



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





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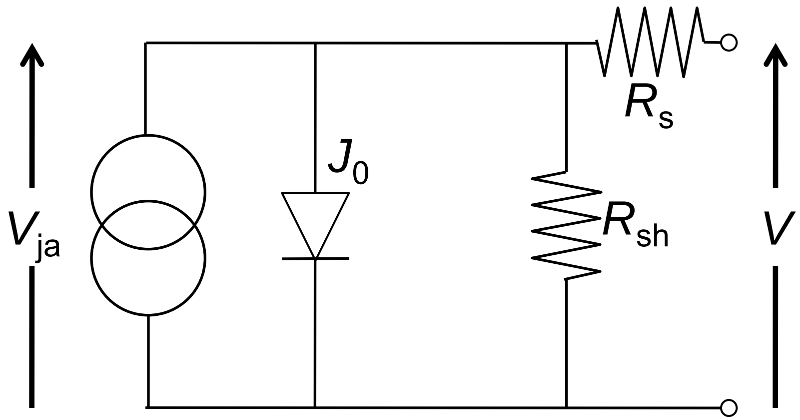
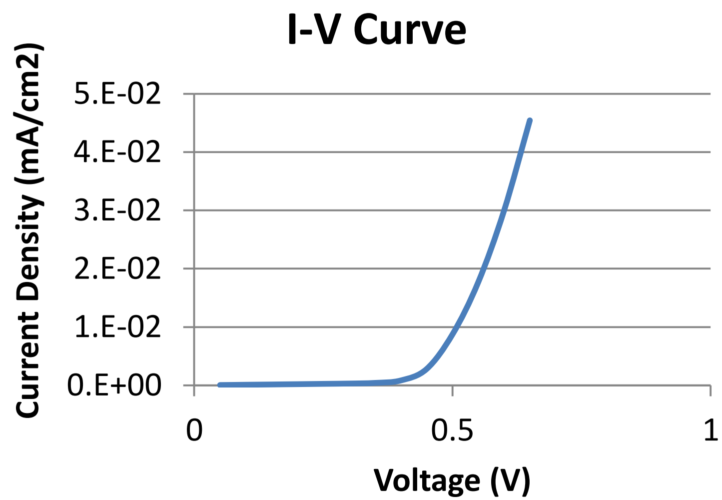
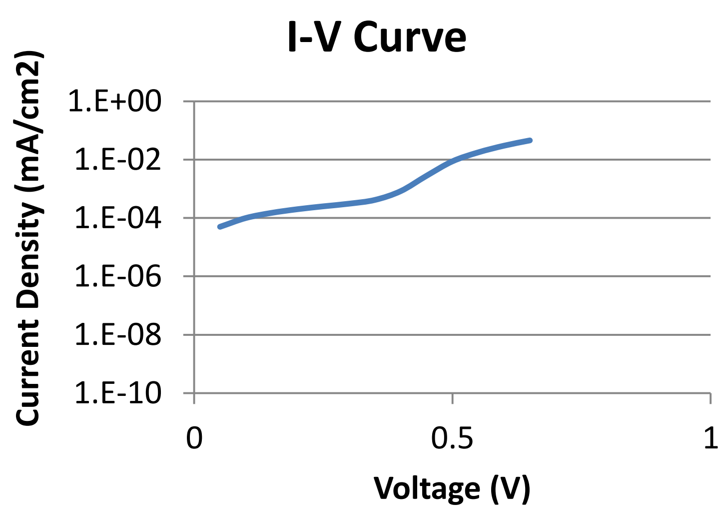
Equivalent Circuit: Simple Case



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





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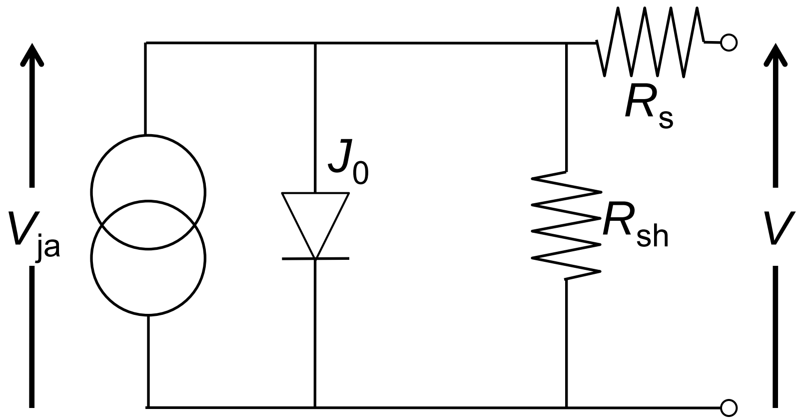

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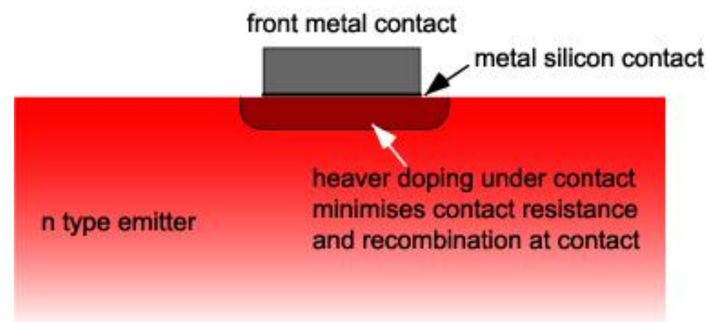


Courtesy of PVCDROM. Used with permission.

Firing contacts? Three possibilities:

1. Contact just right: low R_s, large R_{sh}.
2. “Underfired” contact: Poor contact with Si, large R_s.
3. “Overfired” contact: Metal drives too deep into Si, low R_{sh}.

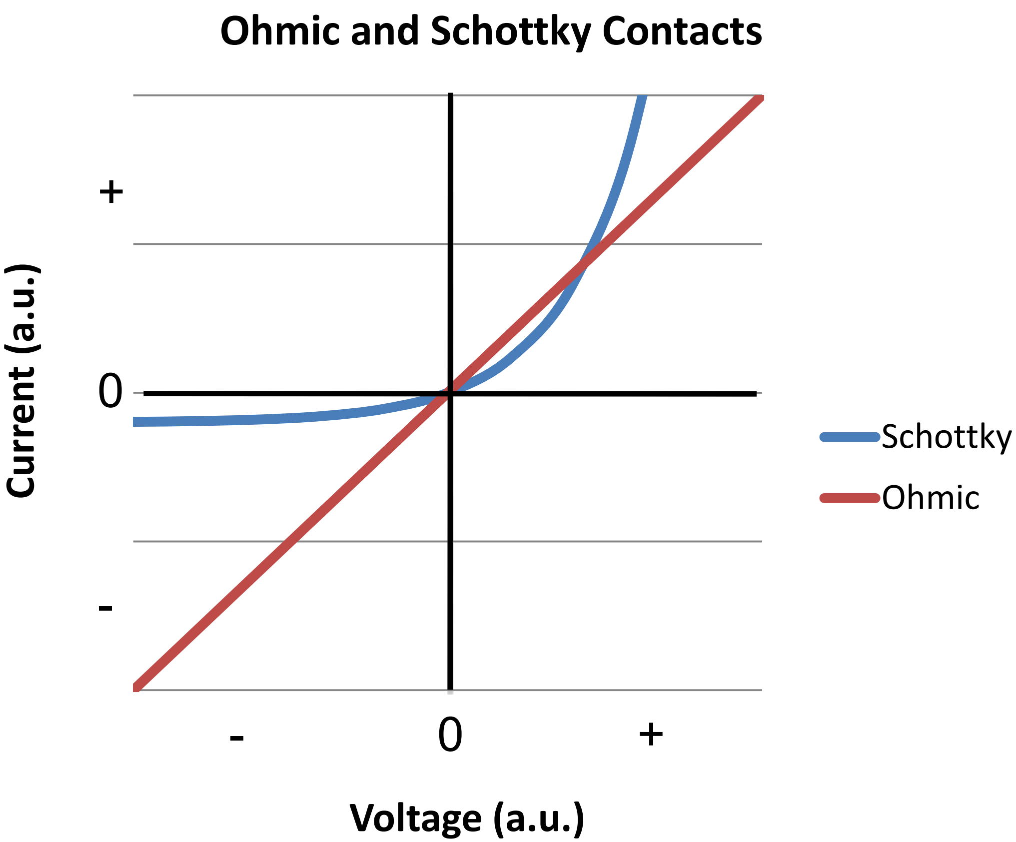
Learning Objectives: Charge Extraction

1. Describe the purpose of contacts, and their most common types.
2. Describe the impact of good and poor contacts on IV characteristics.
3. **Sketch the IV characteristics of Schottky and Ohmic contacts.**
4. Describe what fundamental material parameters determine the IV characteristics of a contact/semiconductor junction.
5. Sketch common band alignments (Type 1, 2, 3, and 4 junctions).
6. Sketch common solar cell device architectures.

Classes of Contacts

- **Ohmic:**
  - Linear I-V curve.
  - Typically used when charge separation is not a goal for metallization.

- **Schottky:**
  - Exponential I-V curve.
  - Used when charge separation is desired.



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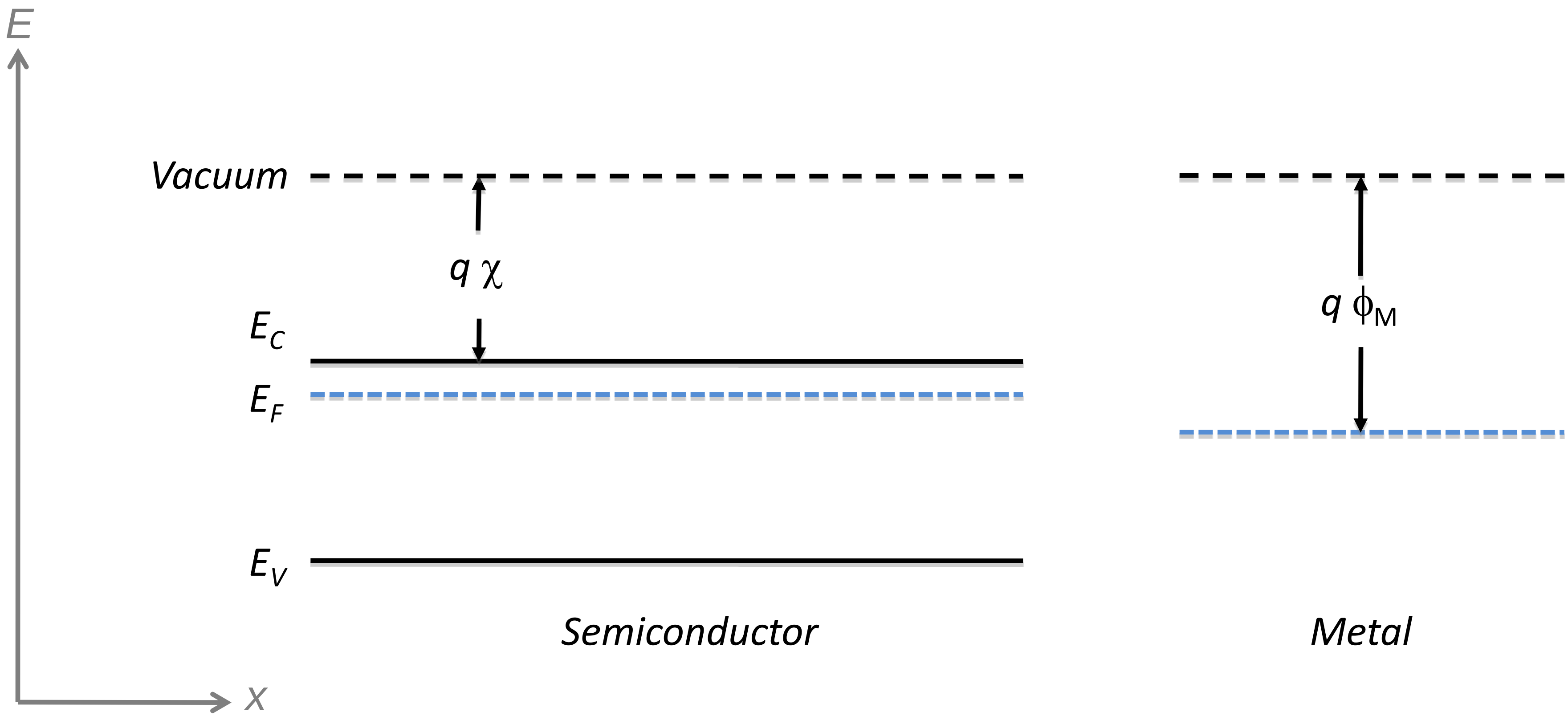
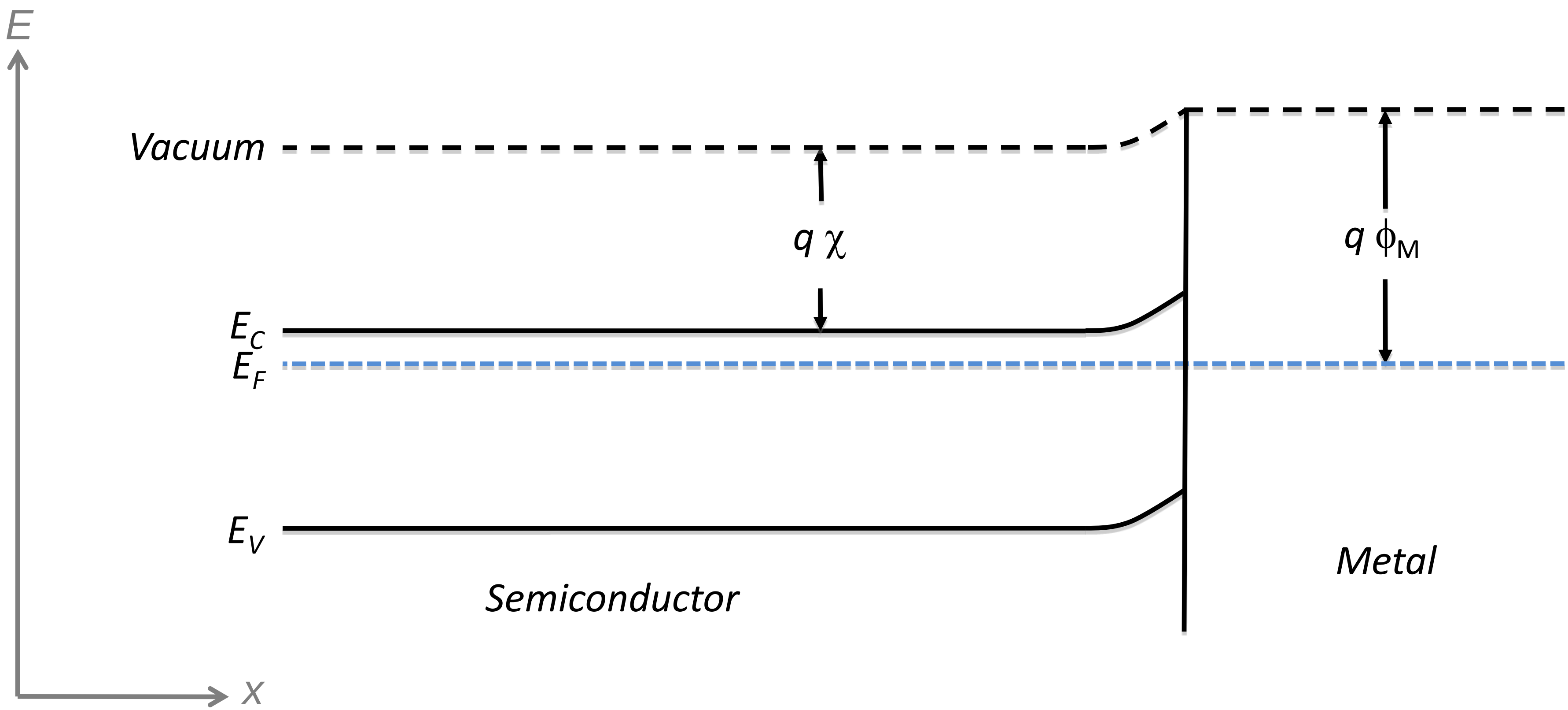
Step #1: Schottky Theory (the ideal case)

Contacts: Schottky Model



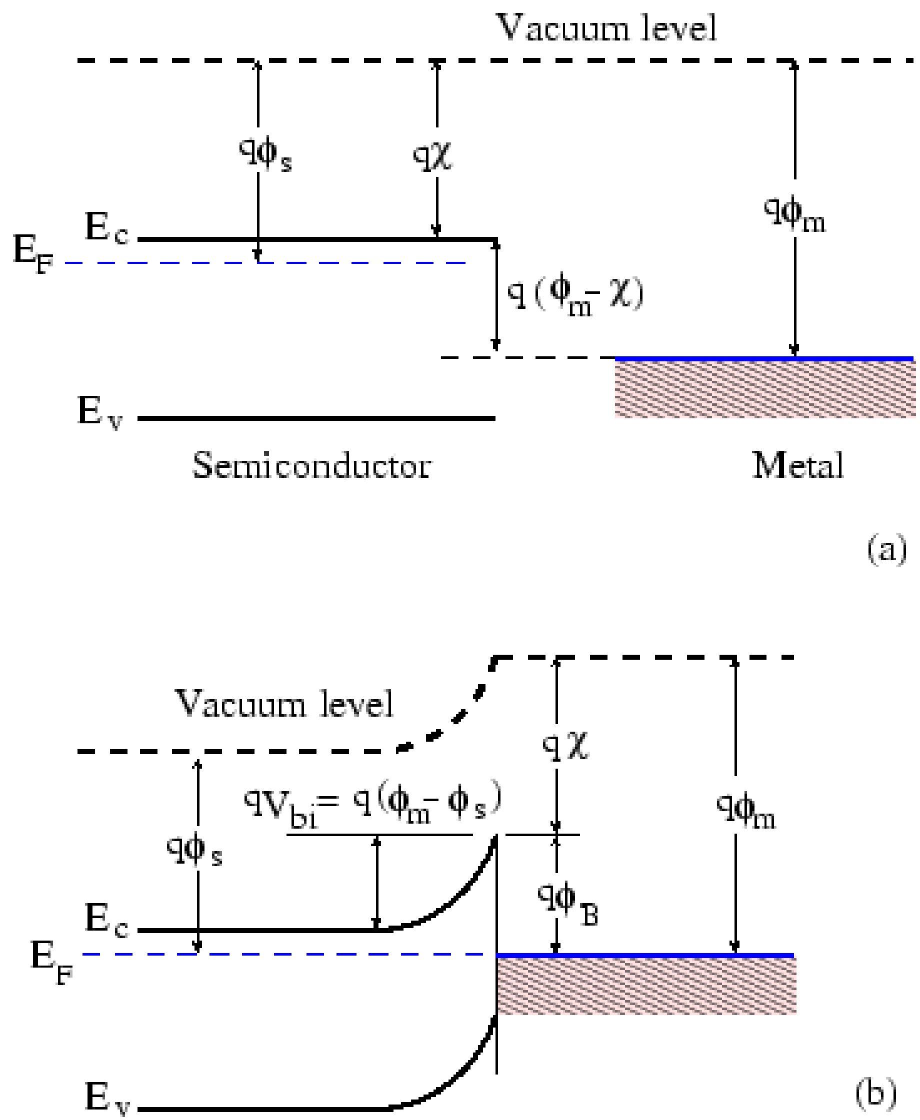
Contacts: Schottky Model



Contacts: Schottky Model

- For Ohmic contact: $\phi_m > \phi_s$
- Barrier Height: $\phi_b = \phi_m - \chi$
- Contact Potential: $V_{bi} = \phi_m - \phi_s$
- Space-charge region width:

$$W = \sqrt{\frac{2\varepsilon_s}{qN_D} V_o}$$



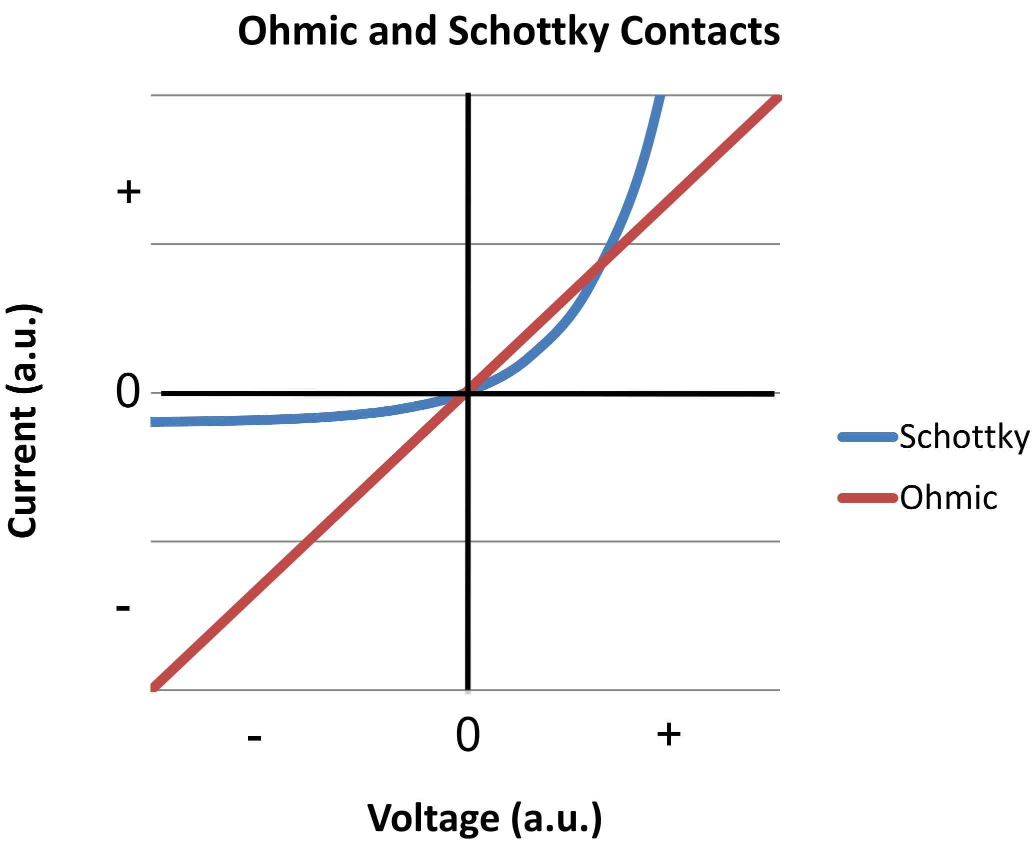
Courtesy of Tesfaye Ayalew. Used with permission.

http://www.iue.tuwien.ac.at/phd/ayalew/node56.html

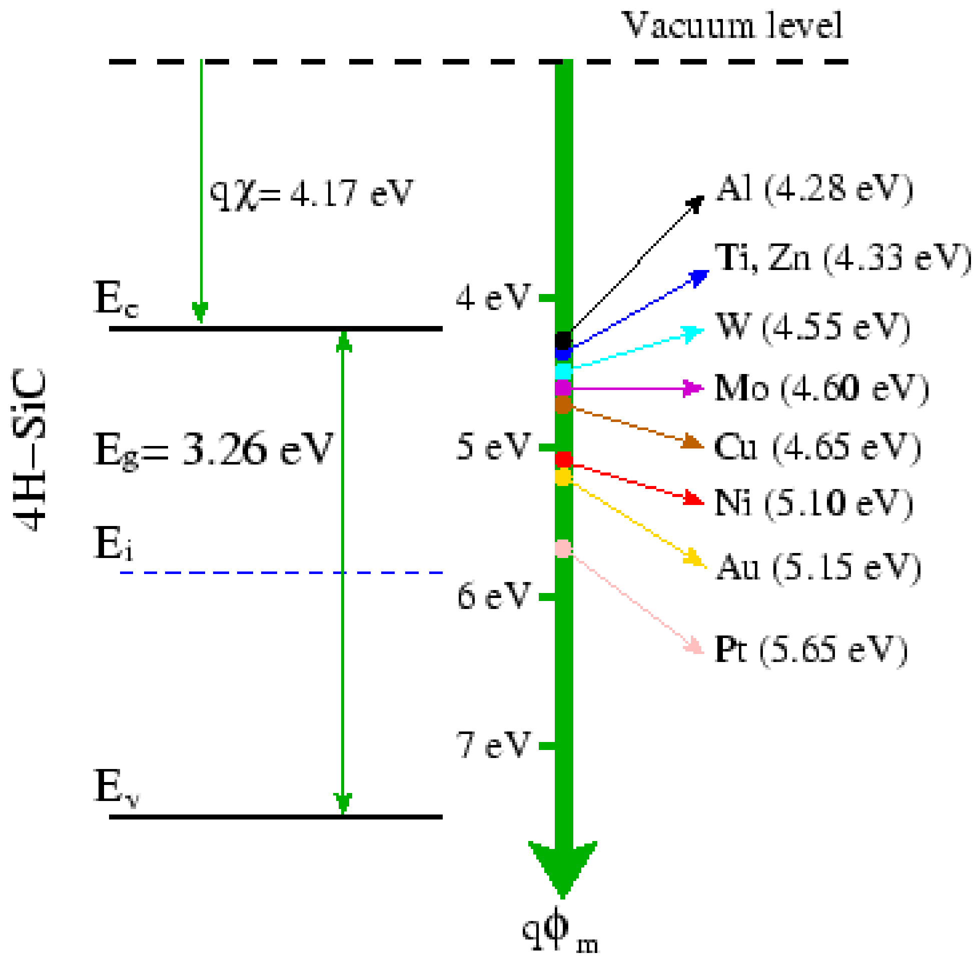
Classes of Contacts

- **Ohmic:**
  - Electron barrier height ≤ 0 (for n-type)
  - Linear I-V curve.
  - Typically used when charge separation is not a goal for metallization.

- **Schottky:**
  - Electron barrier height > 0 (for p-type)
  - Exponential I-V curve.
  - Used when charge separation is desired.



Evaluating Metals for Contacts - Schottky Model



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Reality: Deviations from Schottky theory

- Substantial deviations from Schottky theory are possible, due to interface effects including:
  - Orientation-dependent surface states.
  - Elemental nature of surface termination in binary compounds (*e.g.*, A or B element?).
  - Interface dipoles.
  - *and more…*

Table 3.1: Work function of selected metals and their measured and calculated barrier height on n-type 4H-SiC.

	Al	Ti	Zn	W	Mo	Cu	Ni	Au	Pt
ϕ_m	4.28	4.33	4.33	4.55	4.60	4.65	5.10	5.15	5.65
ϕ_B (Si-face)		1.12					1.69	1.81	
ϕ_B (C-face)		1.25					1.87	2.07	
ϕ_B (calculated)	1.01	1.06	1.06	1.28	1.33	1.38	1.63	1.68	2.08

http://www.iue.tuwien.ac.at/phd/ayalew/node56.html

Role of Surface States

For related visuals, please see the lecture 9 video or the reference below.

D.K. Schroder, IEEE Trans. Electron Dev. **31**, 637 (1984)

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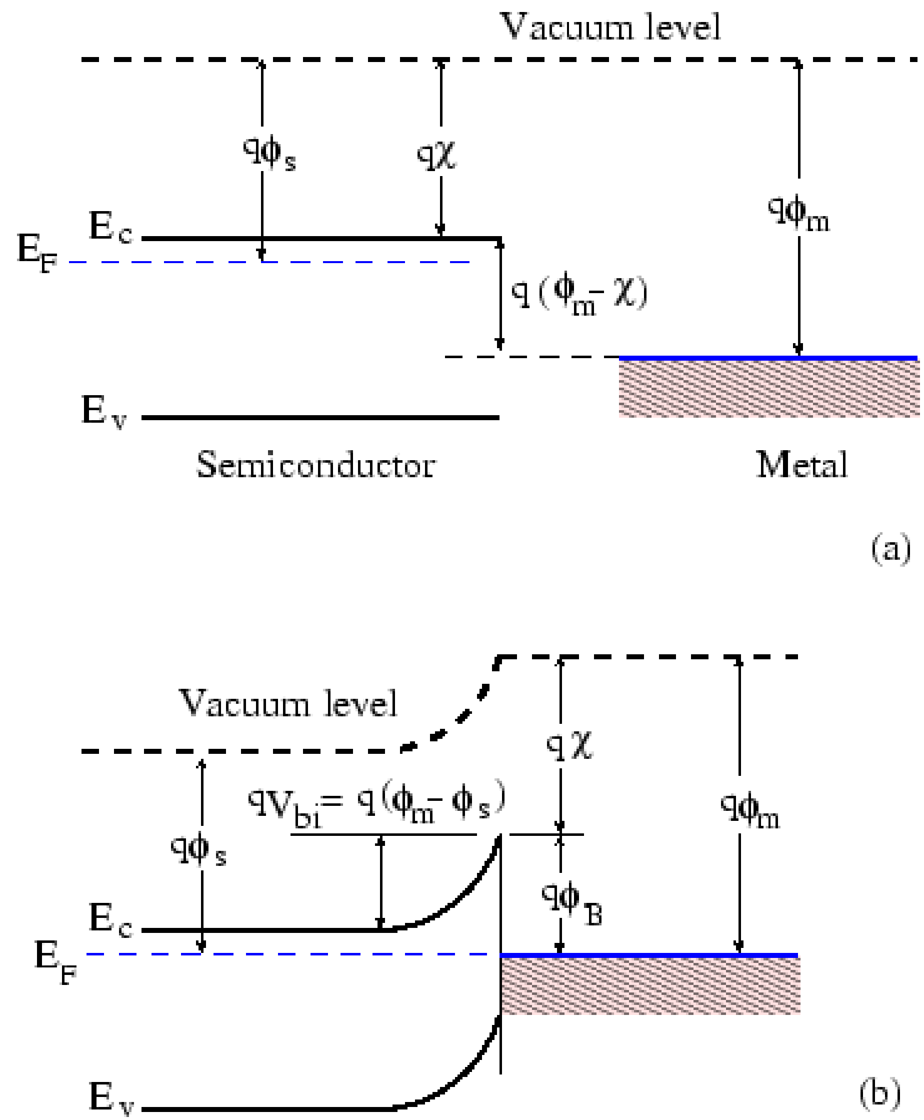

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Thermionic Emission & Field Emission Effects

For related visuals, please see the lecture 9 video or the reference below.

D.K. Schroder, IEEE Trans. Electron Dev. **31**, 637 (1984)

Evaluating Metals for Contacts - Practical

- Sources:
  - Reference books
  - Review articles
  - Scientific articles
  - Trusted websites

https://web.archive.org/web/20130818214213/
http://www.siliconfareast.com/ohmic_table.htm

- NB:
  - Surface states matter!! Be sure you have repeatable surface preparation.

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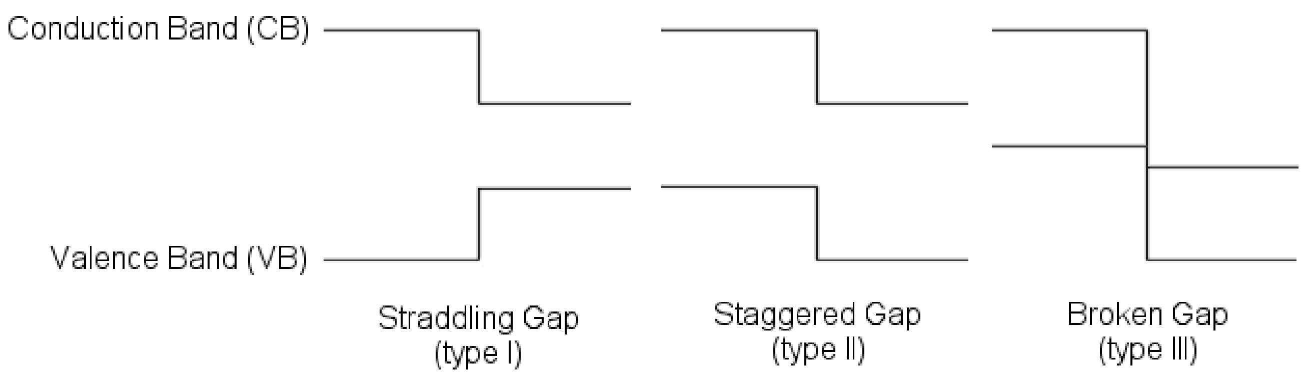
Evaluating Heterojunctions

Not always possible to dope a material both *n*- and *p*-type. Not always possible to find the perfect contact material. Need: heterojunction.

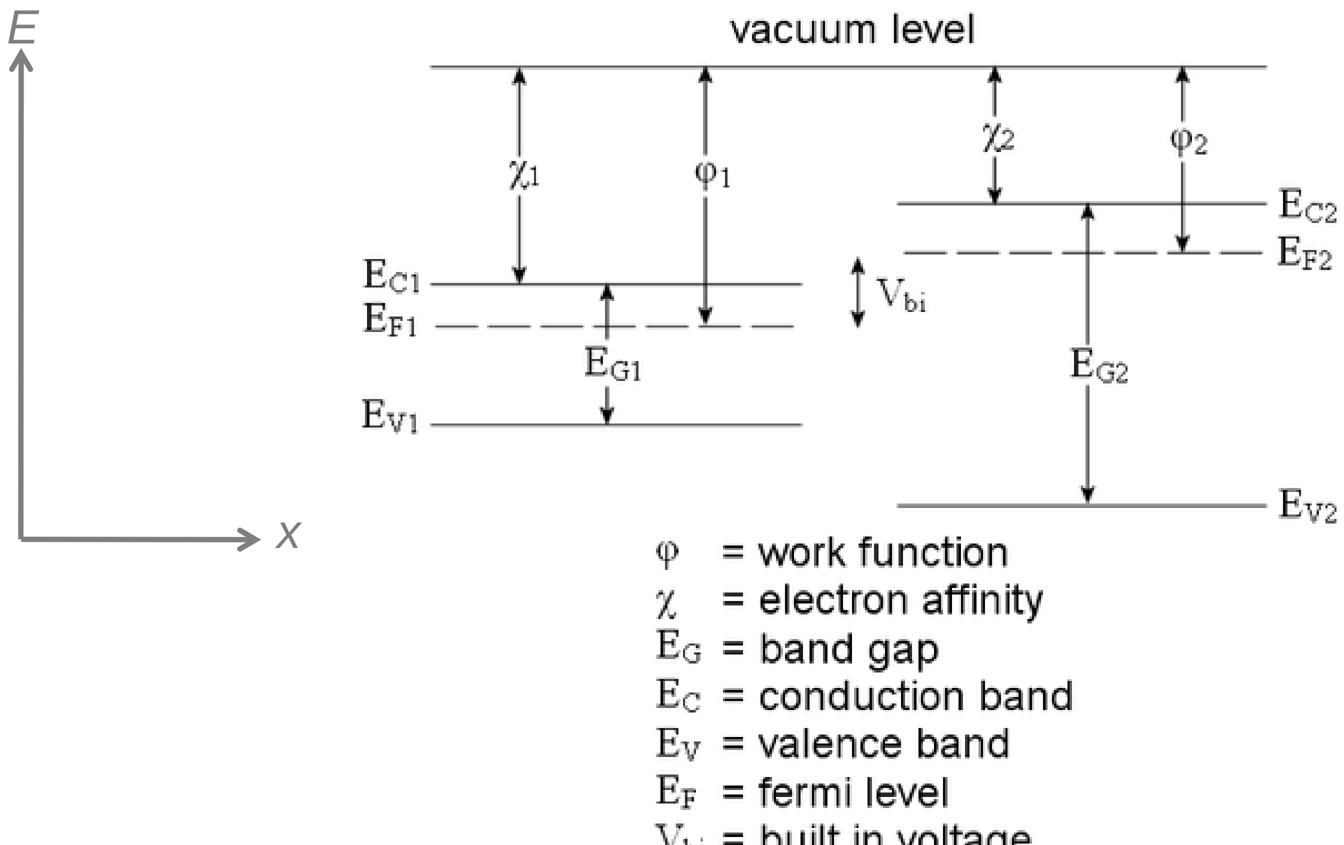
(At least) three types of heterojunction:



What junction will separate charge?

Evaluating Heterojunctions

Simplest case (*analogy to Schottky band alignment for metal-semiconductor contacts*):
1- Set chemical potential equal across entire device.
2- Then, align vacuum levels.
3- Note that VB and CB must follow vacuum levels.



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