Understanding the collection of electrical carriers (separation of electrons and holes) and Connections Used to Distribute Current

P-N Homojunctions, Metal-Semiconductor Junctions, Heterojunctions, and Insulator-Semiconductor Junctions

Reading:

Notes

Some images from Anderson and Anderson text and Dr. Fred Schubert Webpage at RPI

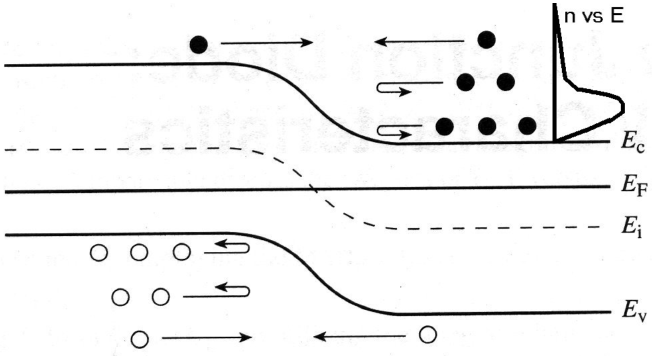
Basic Collecting Junctions

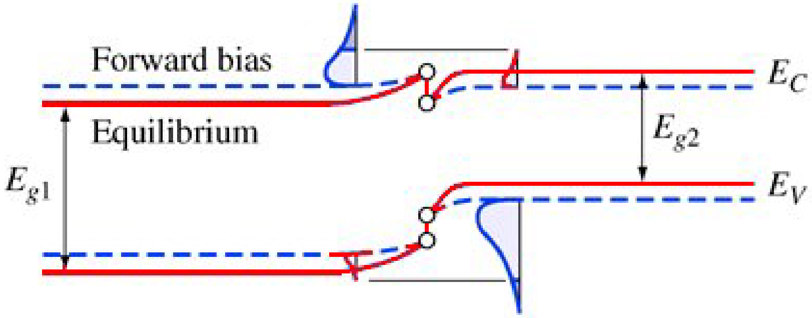
Intro and Comparisons

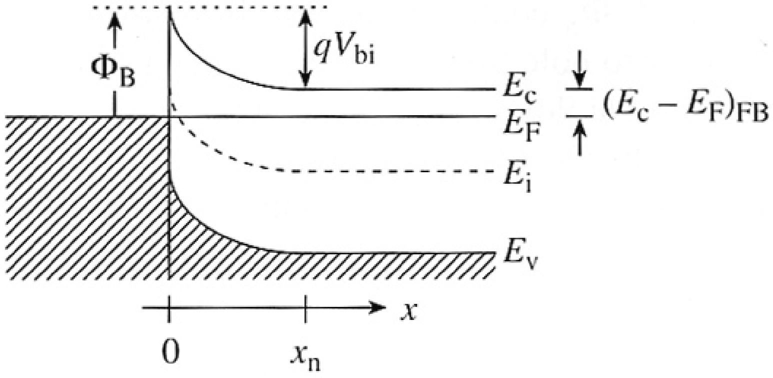
Role of the collecting junction:
It is the role of the collecting junction to separate the electron and hole pairs and force them to "collect" in spatially different regions of the device, thus creating a voltage and facilitating a current.

Basic Collecting Junctions

Intro and Comparisons







p-n Homojunctions:
The main collecting junction used in photovoltaics. "Simple" but proper implementation in PV requires carful attention to details. Other devices are more forgiving than PV

Heterojunctions:
The main collecting junction for advanced, high performance compound semiconductor devices. Makes more efficient use of the energy spectrum of the sun.

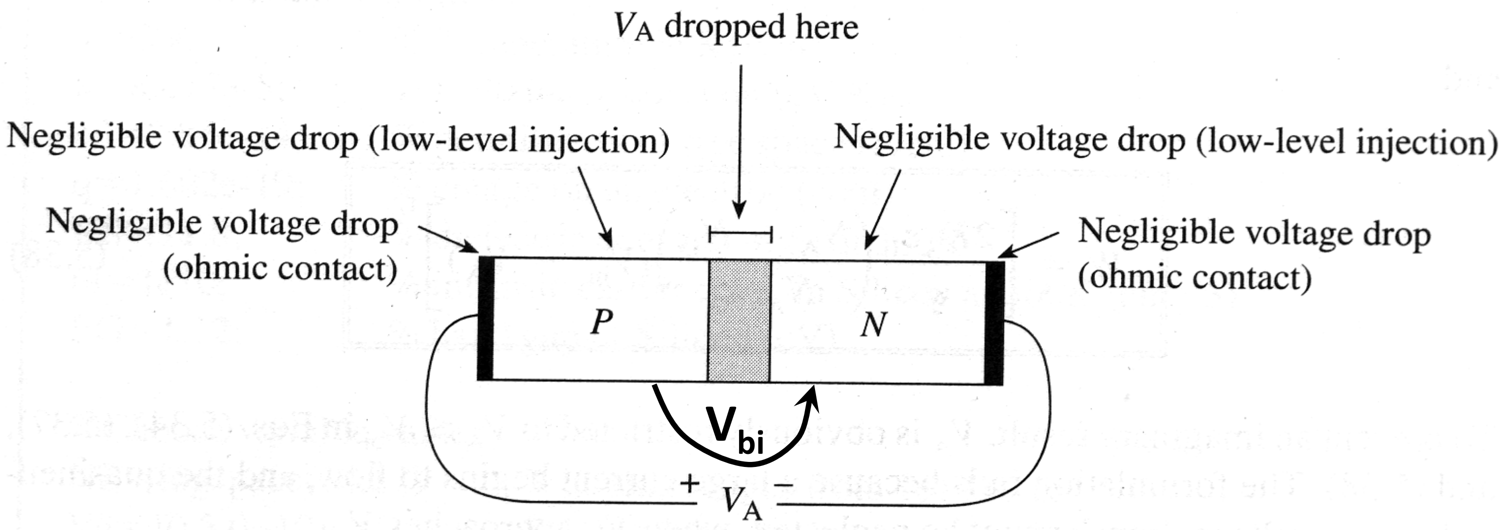
Schottky Junctions (Diodes):
Rarely intentionally used in PV due to inherently lower voltage than those above. However, many metal-semiconductor junctions can only be made as Schottky Diodes.

Basic Collecting Junction

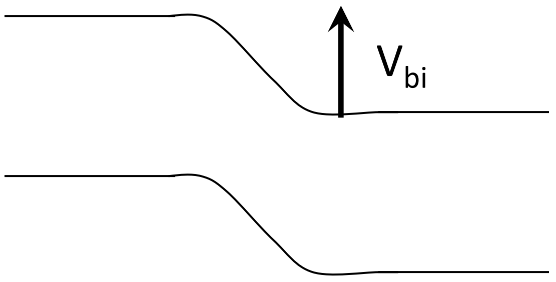
p-n Homojunction Example

Movement of electrons and holes under Bias (electrical or light)

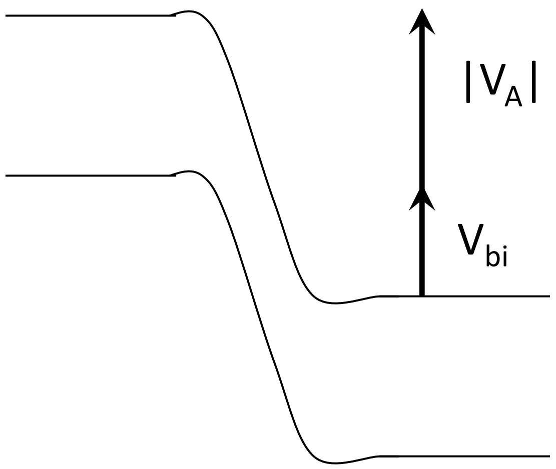
Voltage Bias



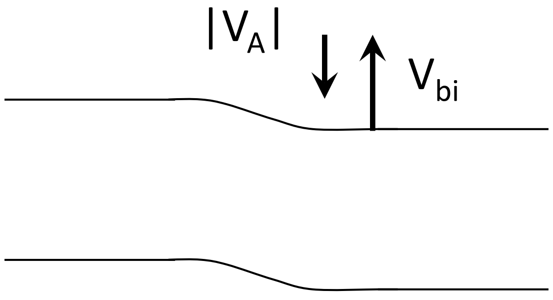
$V_A=0$: No Bias



$V_A<0$: Reverse Bias



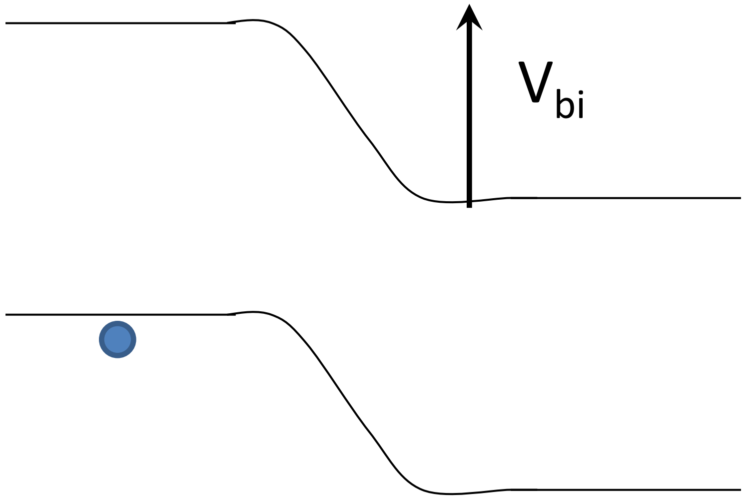
$V_A>0$: Forward Bias



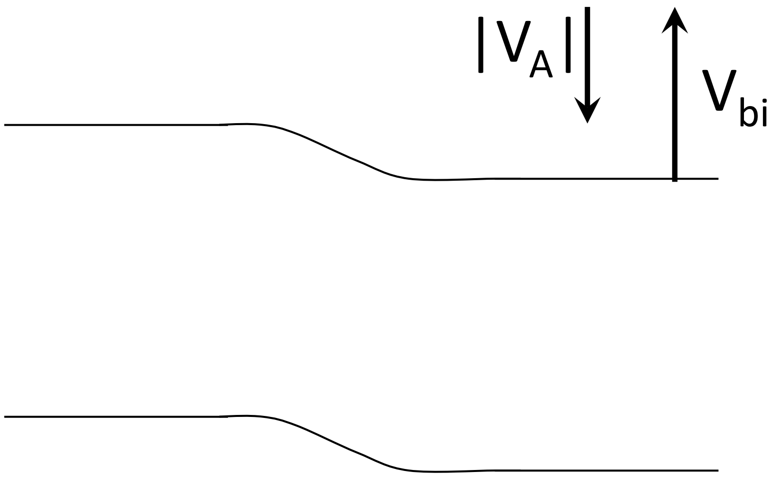
Movement of electrons and holes under Bias (electrical or light)

Light Bias

$V_A=0$: No Bias (no light)



$V_A>0$: Forward Bias due to Light

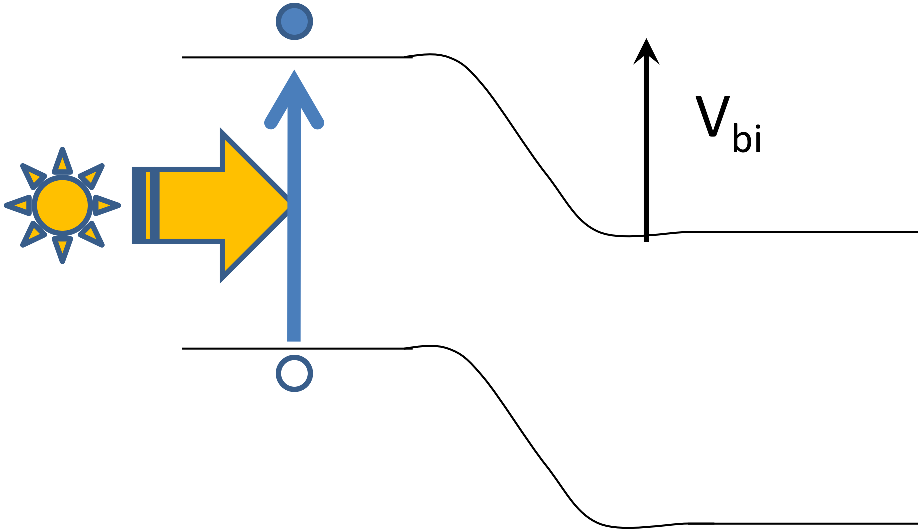


Movement of electrons and holes under Bias (electrical or light)

Light Bias

V_A>0 : Forward Bias due to Light

Voltage drives the charge into the external circuit generating power (V x I)



Excess charge on either side of the junction creates a Voltage: Q=CV

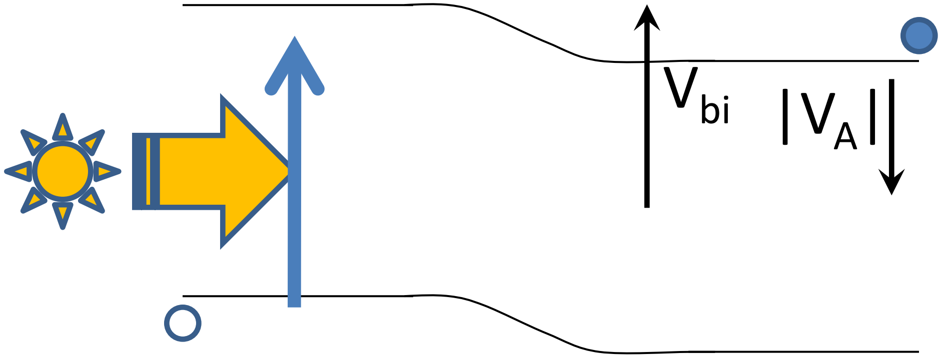
(but in this case C is also a nonlinear function of V)

Movement of electrons and holes under Bias (electrical or light)

Light Bias

$V_A>0$: Forward Bias due to Light

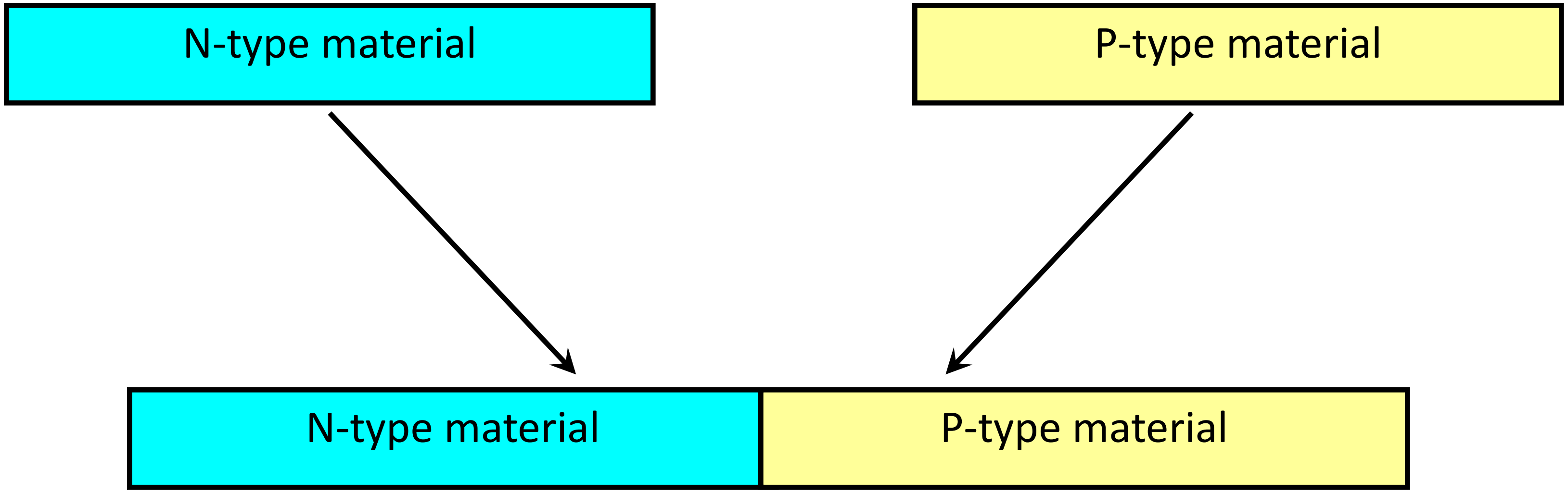
Voltage drives the charge into the external circuit generating power (V x I)



Basic Collecting Junction

p-n Homojunction Description

Our First Device: p-n Junction Diode



N-type material

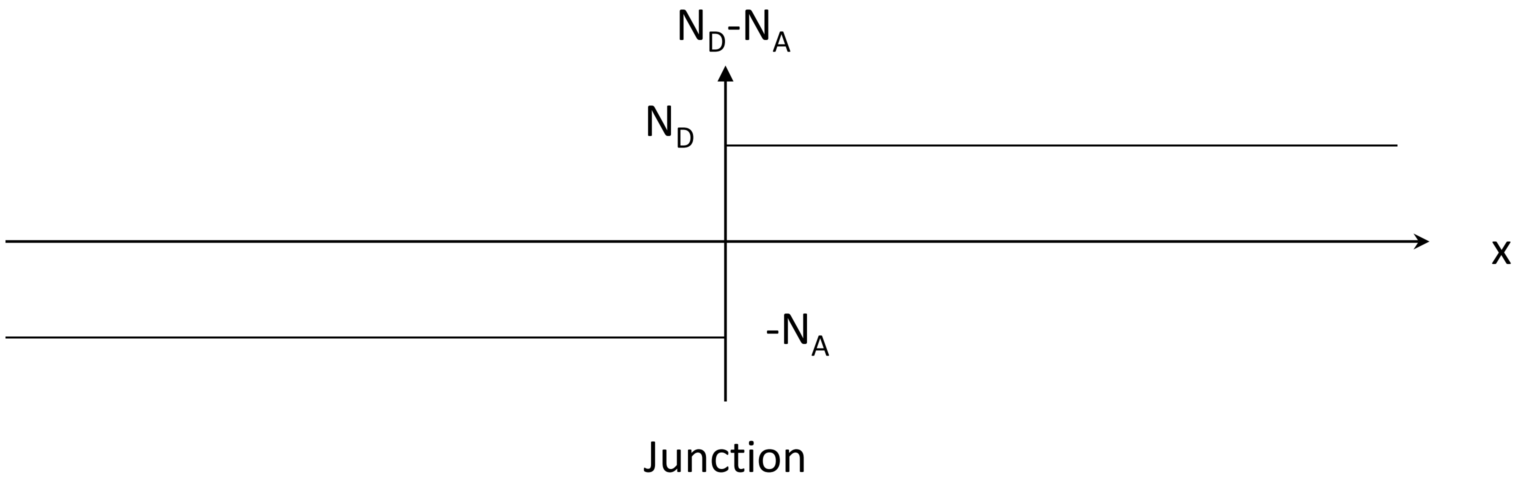
P-type material

N-type material

P-type material

A p-n junction diode is made by forming a p-type region of material directly next to a n-type region.

Our First Device: p-n Junction Diode



In regions far away from the “junction” the band diagram looks like:

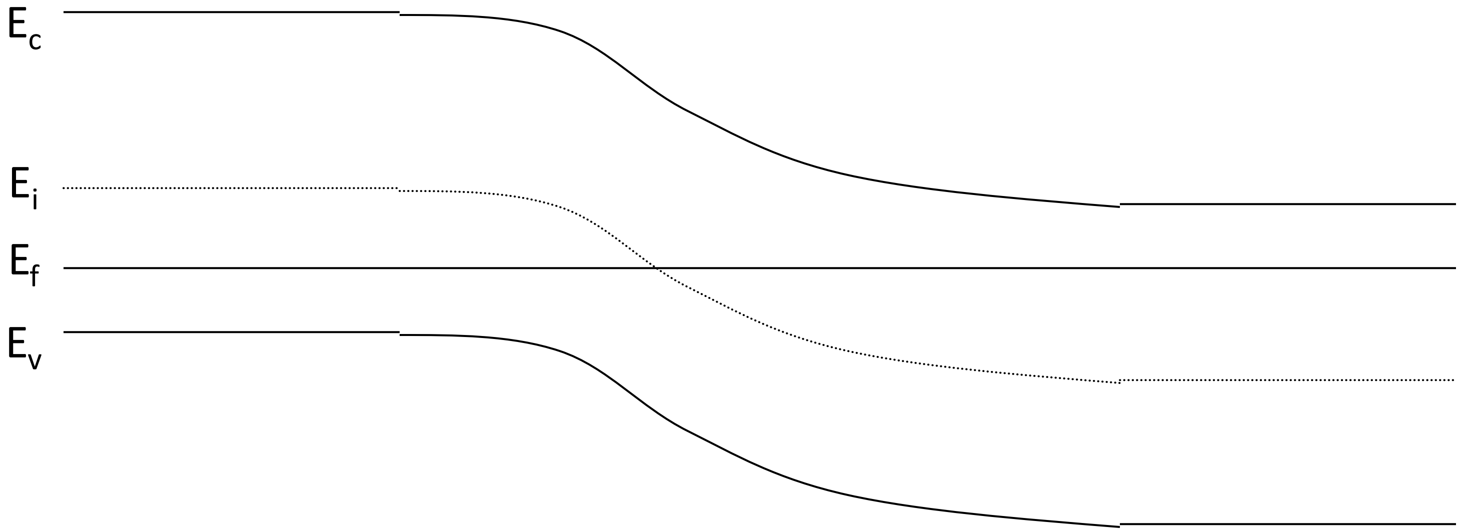
Our First Device: p-n Junction Diode

But when the device has no external applied forces, no current can flow.   Thus, the fermi-level must be flat!

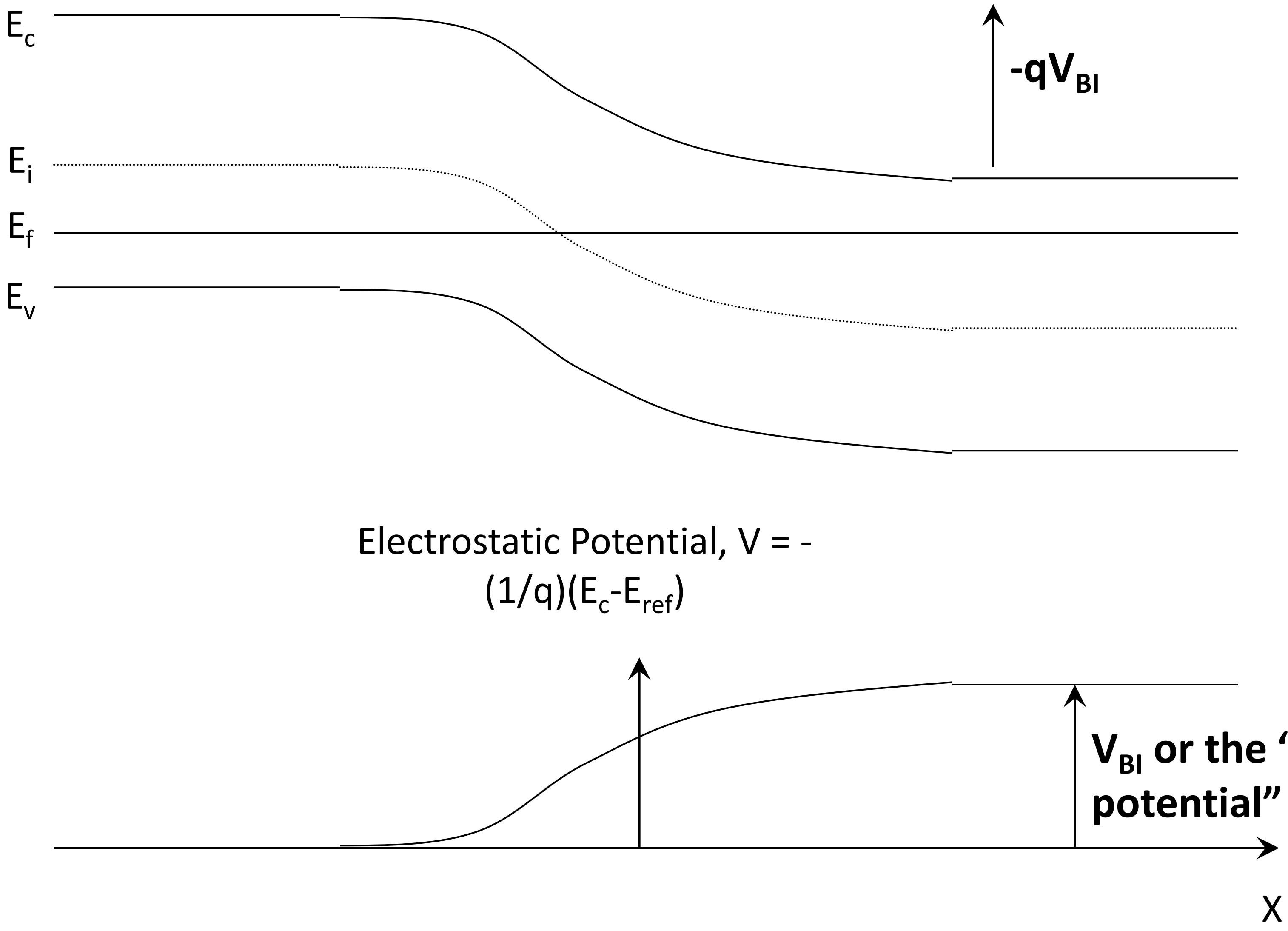
We can then fill in the junction region of the band diagram as:

or…

Our First Device: p-n Junction Diode



Our First Device: p-n Junction Diode

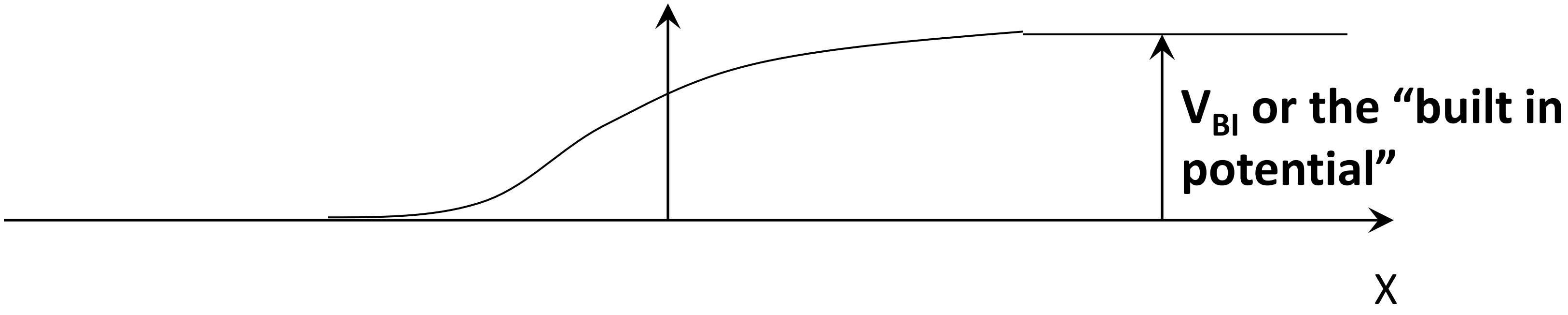


Electrostatic Potential, $V = -(1/q)(E_c-E_{ref})$

V_{BI} or the "built in potential"

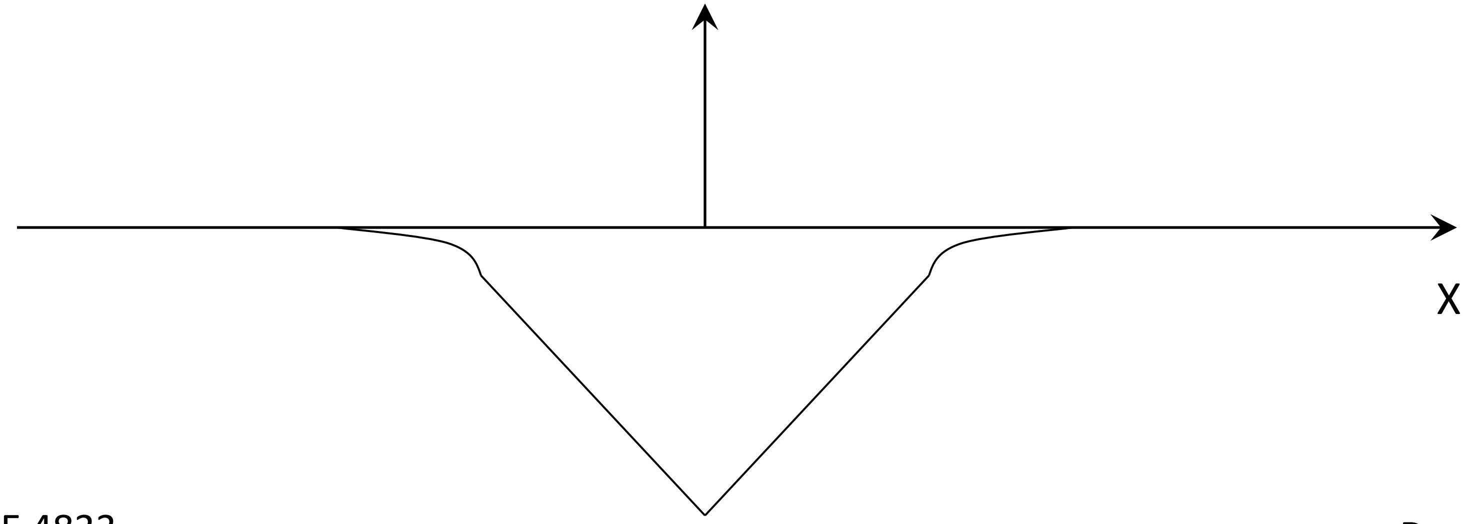
Our First Device: p-n Junction Diode

Electrostatic Potential, $V=-(1/q)(E_c-E_{ref})$



Electric Field

$E=-dV/dx$



Our First Device: p-n Junction Diode

Poisson's Equation:

Electric Field

Charge Density (NOT resistivity)

$$\nabla \bullet E = \frac{\rho}{K_s \varepsilon_o} \quad or\ in\ 1D,\ \frac{dE}{dx} = \frac{\rho}{K_s \varepsilon_o}$$

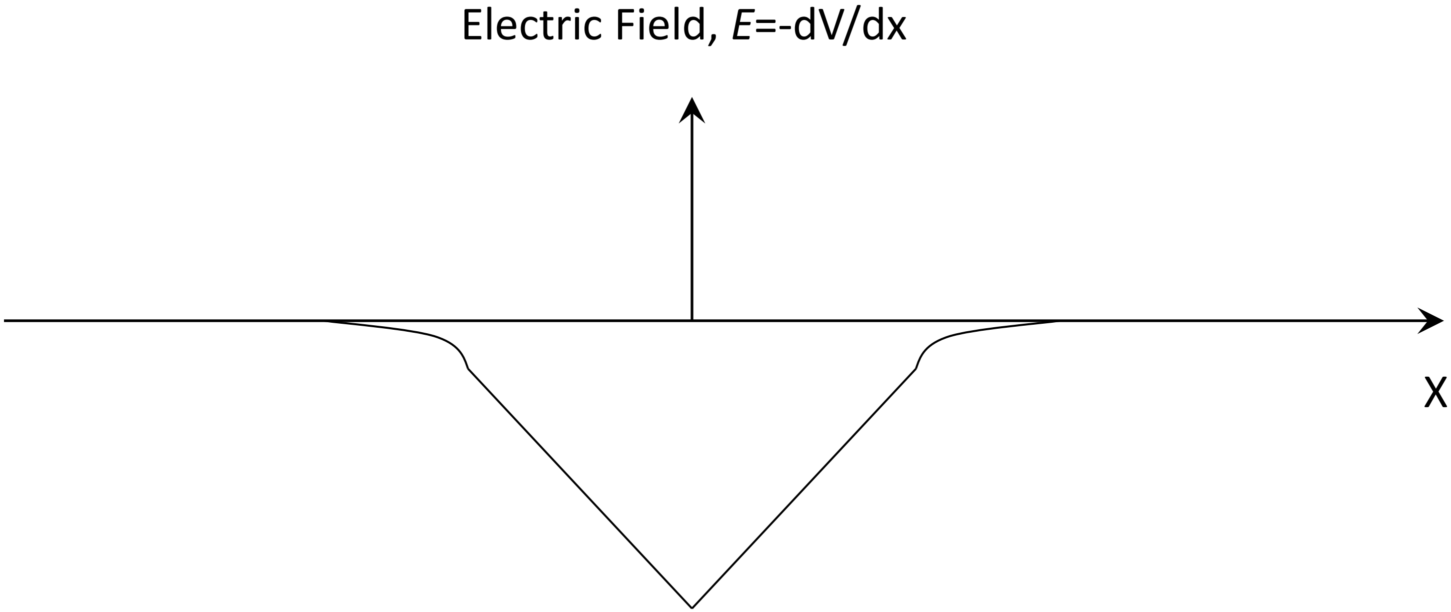
Permittivity of free space

Relative Permittivity of Semiconductor

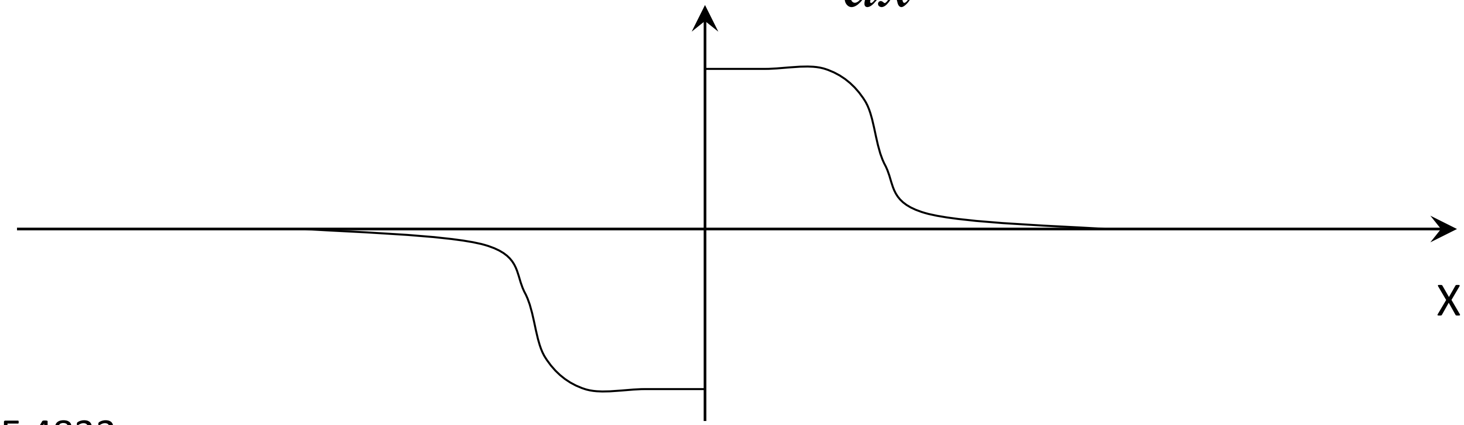
(previously referred to as ε_R)

$\rho = q(\ p - n + N_D - N_A\ )$

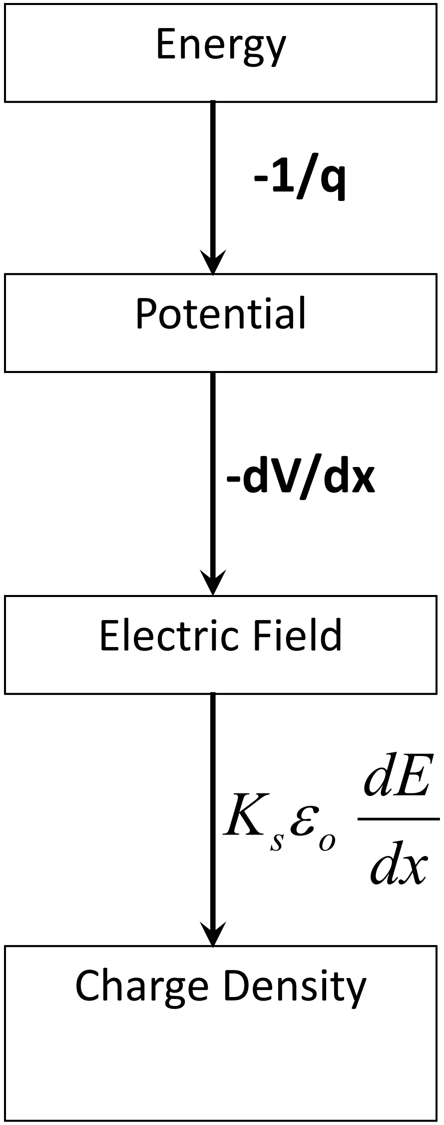
Our First Device: p-n Junction Diode



$$\rho = K_s \varepsilon_o \frac{dE}{dx}$$



Our First Device: p-n Junction Diode



Energy

-1/q

Potential

-dV/dx

Electric Field

$K_s \varepsilon_o \frac{dE}{dx}$

Charge Density

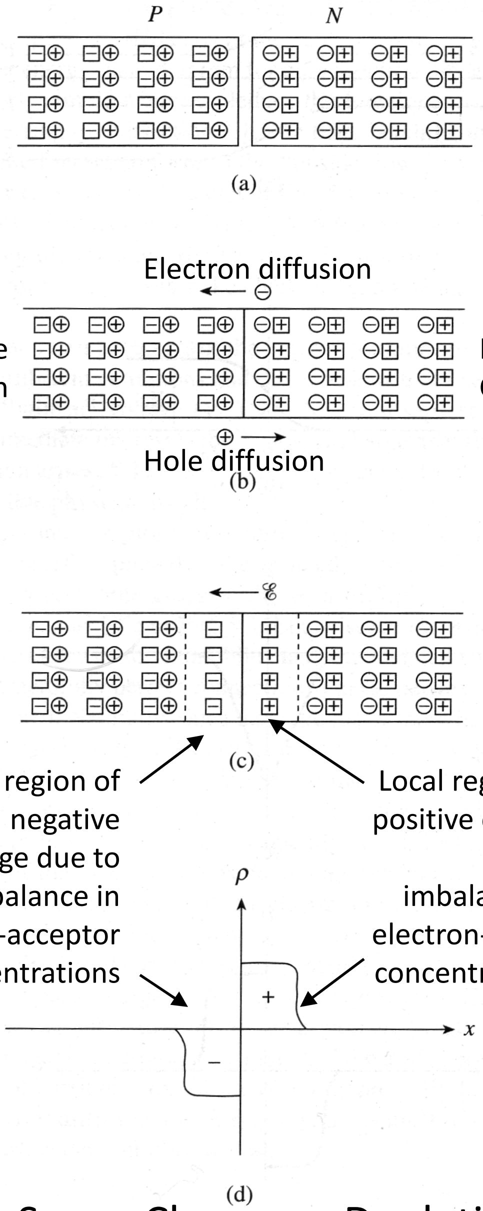
P-N Junction Diodes: Part 2

How do they work? (A little bit of math)

Movement of electrons and holes when forming the junction

○ Circles are charges free to move (electrons and holes)

☐ Squares are charges NOT free to move (ionized donor or acceptor atoms)



Electron diffusion

High hole Concentration

High electron Concentration

Hole diffusion

Local region of negative charge due to imbalance in hole-acceptor concentrations

Local region of positive charge due to imbalance in electron-donor concentrations

Space Charge or Depletion Region

Movement of electrons and holes when forming the junction

$E = -\, dV/dx$

$-E\,dx = dV$

$$-\int_{-x_p}^{x_n} E\,dx = \int_{V(-x_p)}^{V(x_n)} dV \quad = \quad V(x_n) - V(-x_p) = V_{bi}$$

but...

$$J_N = q\mu_n n E + q D_N \frac{dn}{dx} = 0 \longleftarrow$$

No net current flow in equilibrium

$$E = -\frac{D_N}{\mu_n}\frac{\frac{dn}{dx}}{n} = -\frac{kT}{q}\frac{\frac{dn}{dx}}{n}$$

thus...

$$V_{bi} = -\int_{-x_p}^{x_n} E\,dx = \frac{kT}{q}\int_{n(-x_p)}^{n(x_n)} \frac{\frac{dn}{dx}}{n}dx = \frac{kT}{q}\ln\left[\frac{n(x_n)}{n(-x_p)}\right]$$

Movement of electrons and holes when forming the junction

$$V_{bi} = \frac{kT}{q}\ln\left[\frac{n(x_n)}{n(-x_p)}\right] = \frac{kT}{q}\ln\left[\frac{N_D}{n_i^2 / N_A}\right]$$

$$\boxed{V_{bi} = \frac{kT}{q}\ln\left[\frac{N_A N_D}{n_i^2}\right]}$$

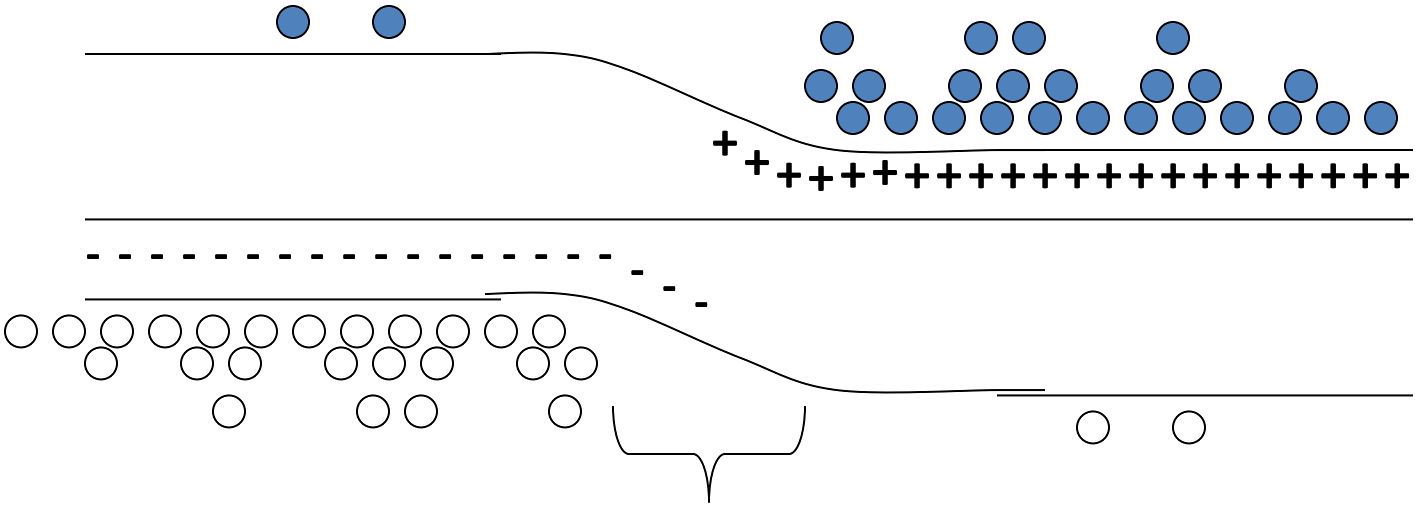
For $N_A=N_D=10^{15}/\text{cm}^{-3}$ in silicon at room temperature, V_{bi}~0.6 V*

For a non-degenerate semiconductor, $|-qV_{bi}|<|E_g|$

*Note to those familiar with a diode turn on voltage: This is not the diode turn on voltage! This is the voltage required to reach a flat band diagram and sets an upper limit (typically an overestimate) for the voltage that can be applied to a diode before it burns itself up.

Movement of electrons and holes when forming the junction

Depletion Region Approximation



Depletion Region Approximation states that approximately no free carriers exist in the space charge region and no net charge exists outside of the depletion region (known as the quasi-neutral region). Thus,

$$\frac{dE}{dx}=\frac{\rho}{K_S\varepsilon_o}=\frac{q}{K_S\varepsilon_o}(p-n+N_D-N_A)=0 \quad \textit{within the quasi-neutral region}$$

becomes...

$$\frac{dE}{dx}=\frac{q}{K_S\varepsilon_o}(N_D-N_A) \quad \textit{within the space charge region}$$

Depletion Region Approximation: Step Junction Solution

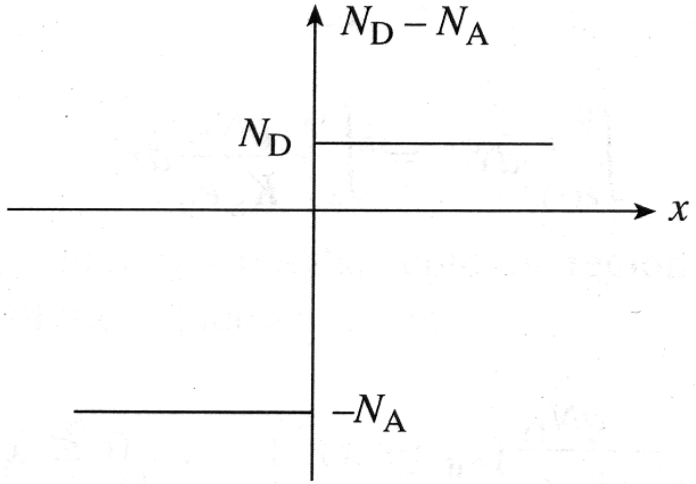
$$\rho = \begin{cases} -qN_A & for\ -x_p \le x \le 0 \\ qN_D & for\ 0 \le x \le x_n \\ 0 & for\ x \le -x_p\ \ and\ \ x \ge x_n \end{cases}$$

thus,

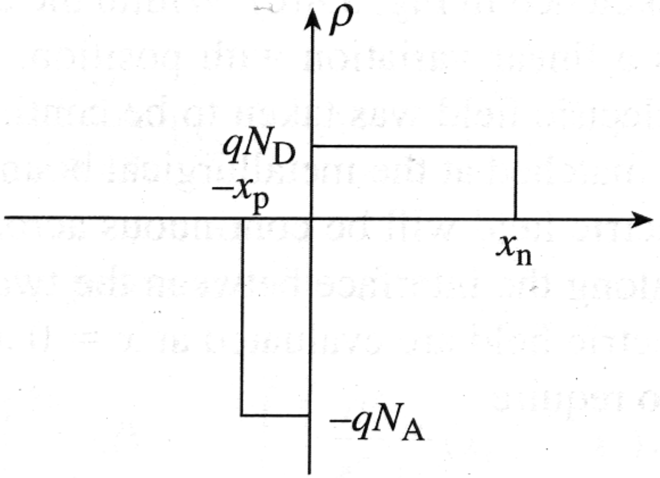
$$\frac{dE}{dx} = \begin{cases} \dfrac{-qN_A}{K_S\varepsilon_o} & for\ -x_p \le x \le 0 \\ \dfrac{qN_D}{K_S\varepsilon_o} & for\ 0 \le x \le x_n \\ 0 & for\ x \le -x_p\ \ and\ \ x \ge x_n \end{cases}$$

Where we have used:

$$\frac{dE}{dx} = \frac{\rho}{K_S\varepsilon_o}$$



(a)



Movement of electrons and holes when forming the junction

Depletion Region Approximation: Step Junction Solution

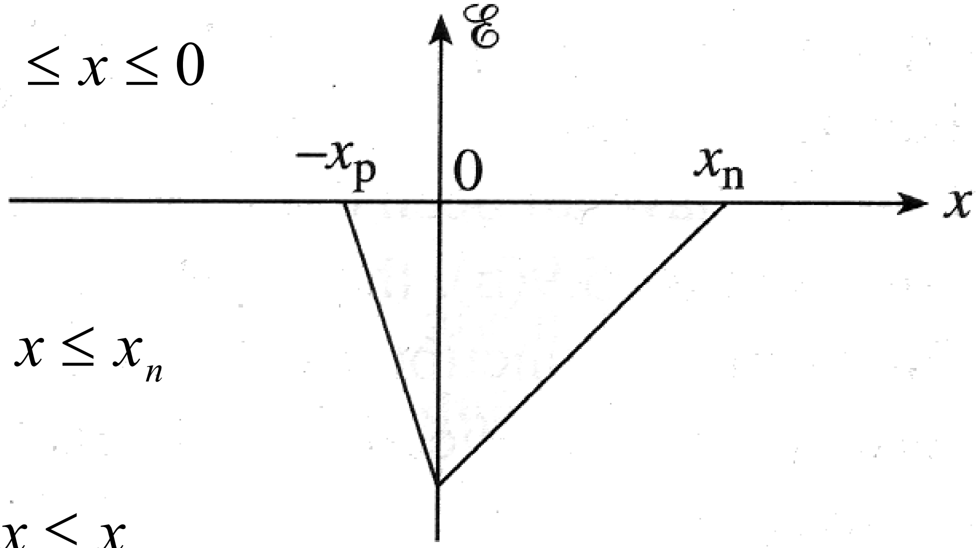
$$\int_0^{E(x)} dE' = \int_{-x_p}^{x} \frac{-qN_A}{K_S\varepsilon_o} dx' \quad for \; -x_p \le x \le 0$$

$$E(x) = \frac{-qN_A}{K_S\varepsilon_o}\left(x + x_p\right) \quad for \; -x_p \le x \le 0$$

and

$$\int_{E(x)}^{0} dE' = \int_{x}^{x_n} \frac{qN_D}{K_S\varepsilon_o} dx' \quad for \; 0 \le x \le x_n$$

$$E(x) = \frac{-qN_D}{K_S\varepsilon_o}\left(x_n - x\right) \quad for \; 0 \le x \le x_n$$



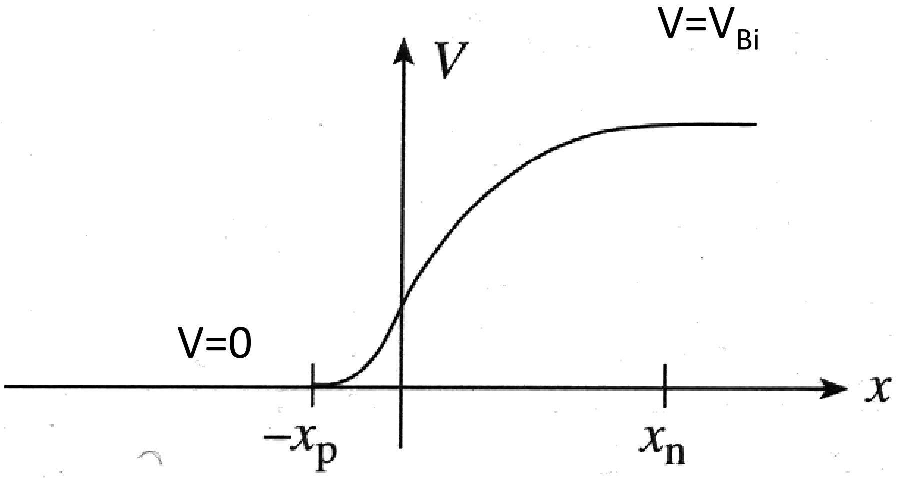
Since $E(x=0^-)=E(x=0^+)$

$$\boxed{N_A x_p = N_D x_n}$$

Movement of electrons and holes when forming the junction

Depletion Region Approximation: Step Junction Solution

$$E = -\frac{dV}{dx}$$



$$\frac{dV}{dx} = \begin{cases} \frac{qN_A}{K_S\varepsilon_o}\left(x_p + x\right) & for\ -x_p \le x \le 0 \\ \frac{qN_D}{K_S\varepsilon_o}\left(x_n - x\right) & for\ 0 \le x \le x_n \end{cases}$$

$or,$

$$\int_0^{V(x)} dV' = \int_{-x_p}^{x} \frac{qN_A}{K_S\varepsilon_o}\left(x_p + x'\right)dx' \quad for\ -x_p \le x \le 0$$

$$\int_{V(x)}^{V_{Bi}} dV' = \int_{x}^{x_n} \frac{qN_D}{K_S\varepsilon_o}\left(x_n - x'\right)dx' \quad for\ 0 \le x \le x_n$$

$$V(x) = \begin{cases} \frac{qN_A}{2K_S\varepsilon_o}\left(x_p + x\right)^2 & for\ -x_p \le x \le 0 \\ V_{bi} - \frac{qN_D}{2K_S\varepsilon_o}\left(x_n - x\right)^2 & for\ 0 \le x \le x_n \end{cases}$$

Movement of electrons and holes when forming the junction

Depletion Region Approximation: Step Junction Solution

At x=0,

$$\frac{qN_A}{2K_S\varepsilon_o}\left(x_p\right)^2 = V_{bi} - \frac{qN_D}{2K_S\varepsilon_o}\left(x_n\right)^2$$

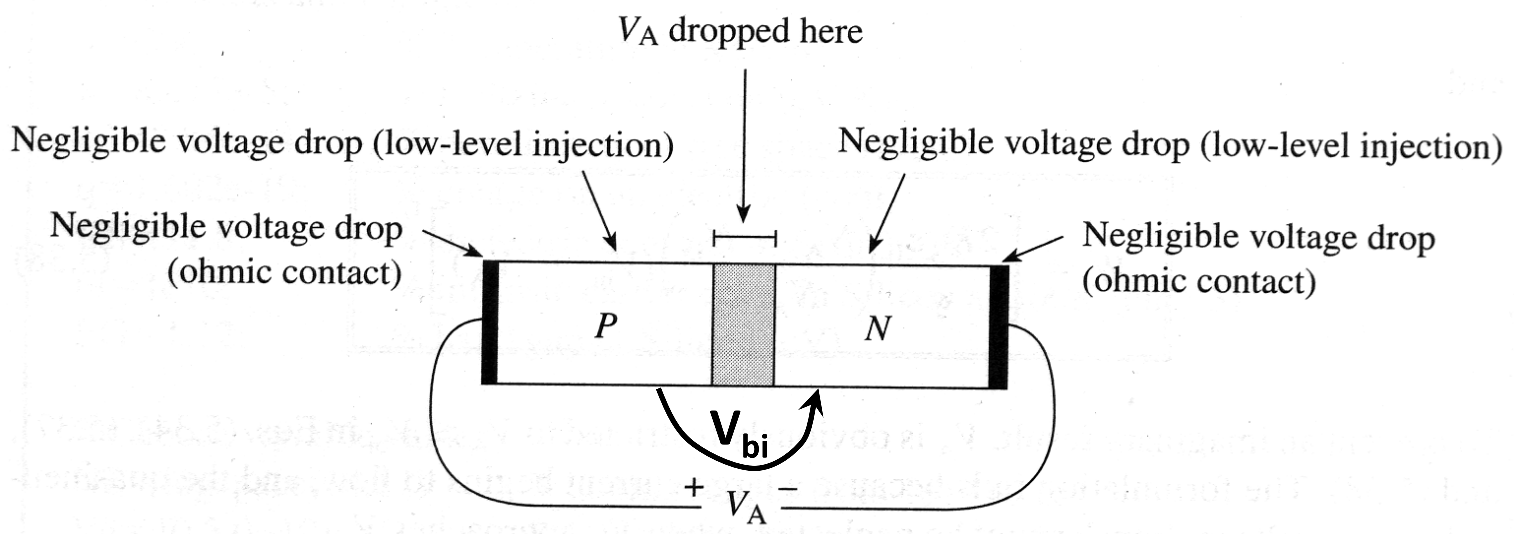
$$U\sin g,\ x_p = \left(x_nN_D\right)\Big/ N_A$$

$$x_n = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{N_A}{N_D\left(N_A+N_D\right)}V_{bi}} \quad and \quad x_p = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{N_D}{N_A\left(N_A+N_D\right)}V_{bi}}$$

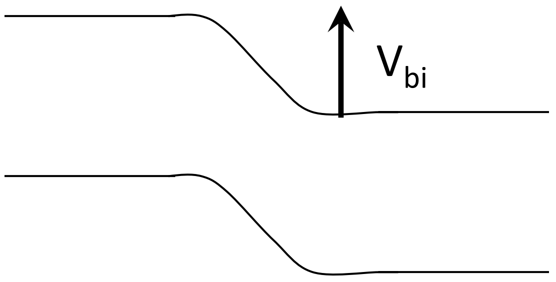
$$W = x_p + x_n = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{\left(N_A+N_D\right)}{N_AN_D}V_{bi}}$$

Movement of electrons and holes when forming the junction

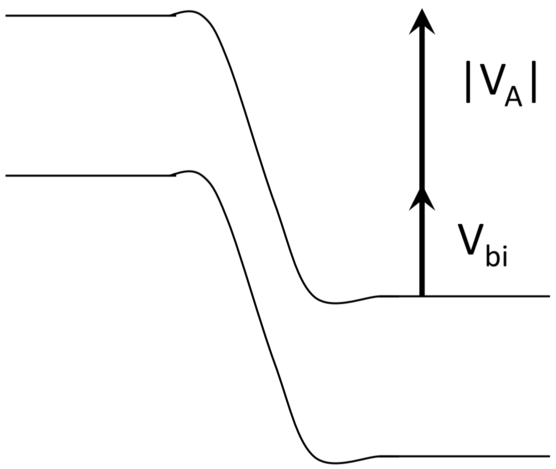
Depletion Region Approximation: Step Junction Solution



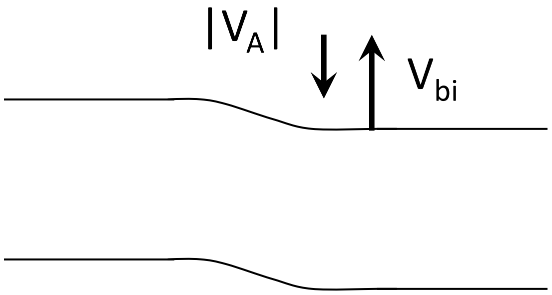
V_A=0 : No Bias



V_A<0 : Reverse Bias



V_A>0 : Forward Bias



Movement of electrons and holes when forming the junction

Depletion Region Approximation: Step Junction Solution

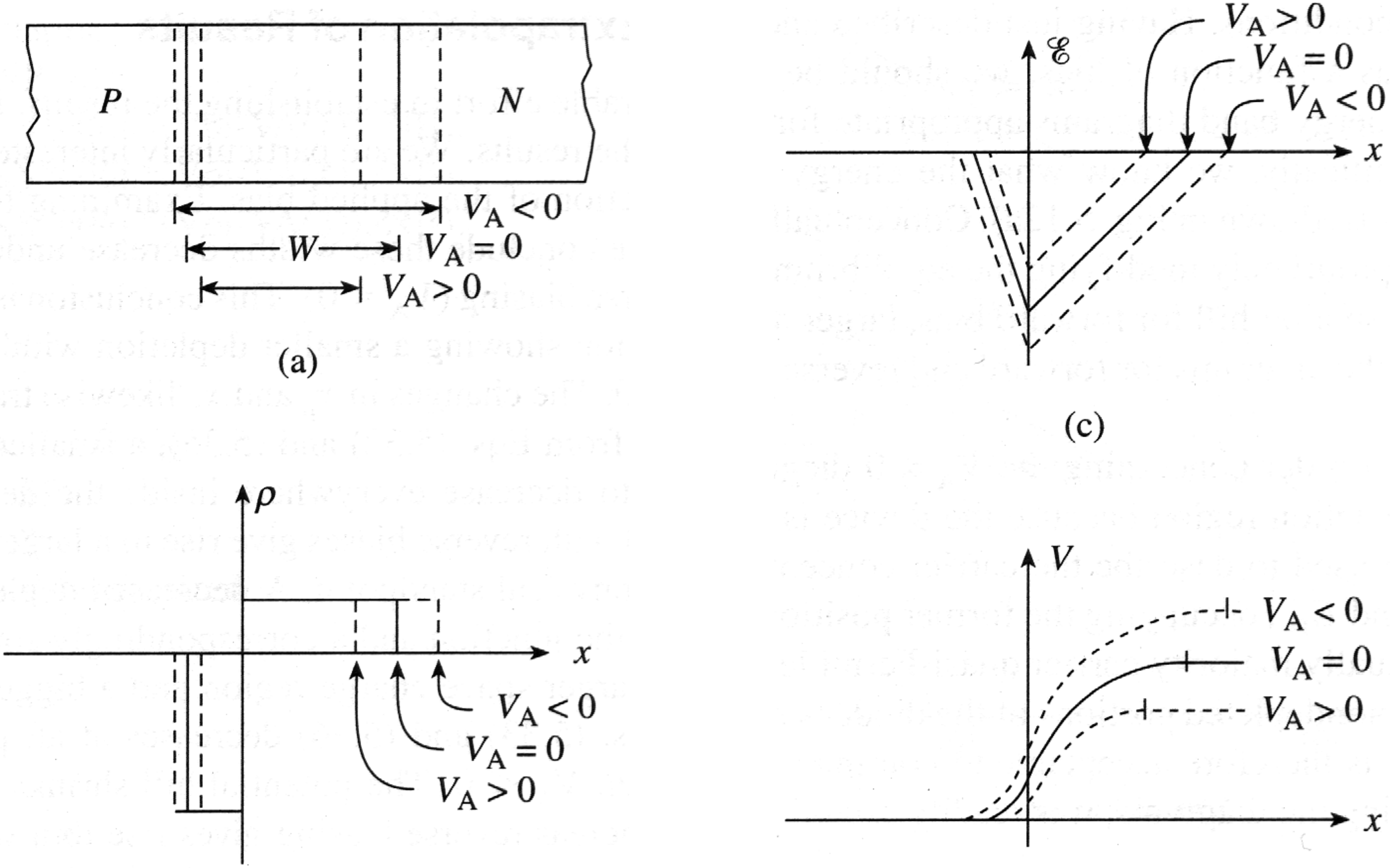
Thus, only the boundary conditions change resulting in direct replacement of V_{bi} with $(V_{bi}-V_A)$

$$x_n = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{N_A}{N_D\left(N_A+N_D\right)}\left(V_{bi}-V_A\right)} \quad and \quad x_p = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{N_D}{N_A\left(N_A+N_D\right)}\left(V_{bi}-V_A\right)}$$

$$\boxed{W = x_p + x_n = \sqrt{\frac{2K_S\varepsilon_o}{q}\frac{\left(N_A+N_D\right)}{N_A N_D}\left(V_{bi}-V_A\right)}}$$

Step Junction Solution: What does it mean?

Consider a p^{+} -n junction (heavily doped p-side, normal or lightly doped n side).



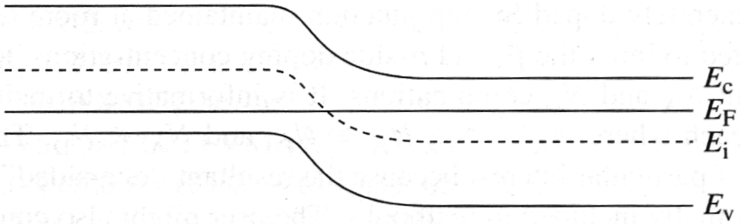
(a)

(c)

Movement of electrons and holes when forming the junction

Step Junction Solution: What does it mean?

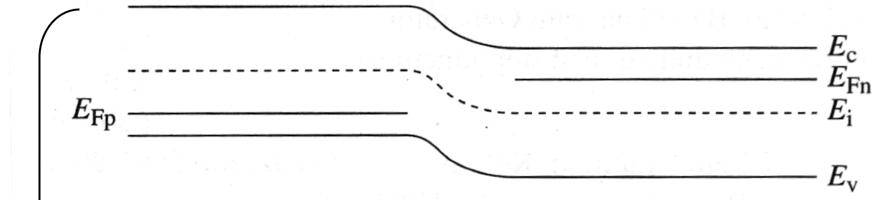
Fermi-level only applies to equilibrium (no current flowing)



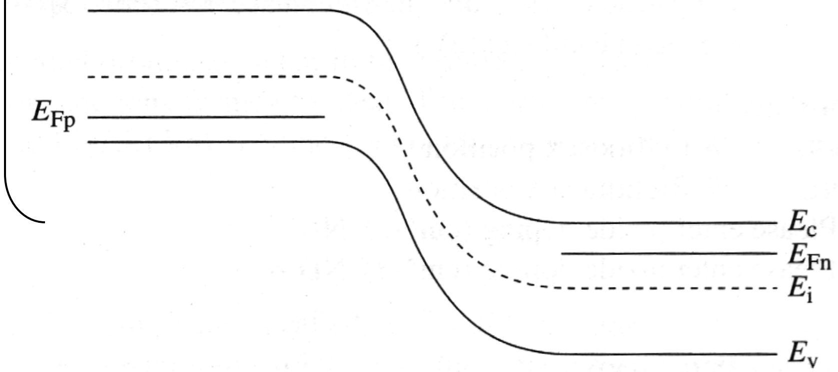
(a) Equilibrium ($V_A = 0$)

Majority carrier Quasi-fermi levels

$$\underbrace{\phantom{E_{fp}-E_{fn}}}_{}\ E_{fp}-E_{fn}=-qV_A$$



(b) Forward bias ($V_A > 0$)



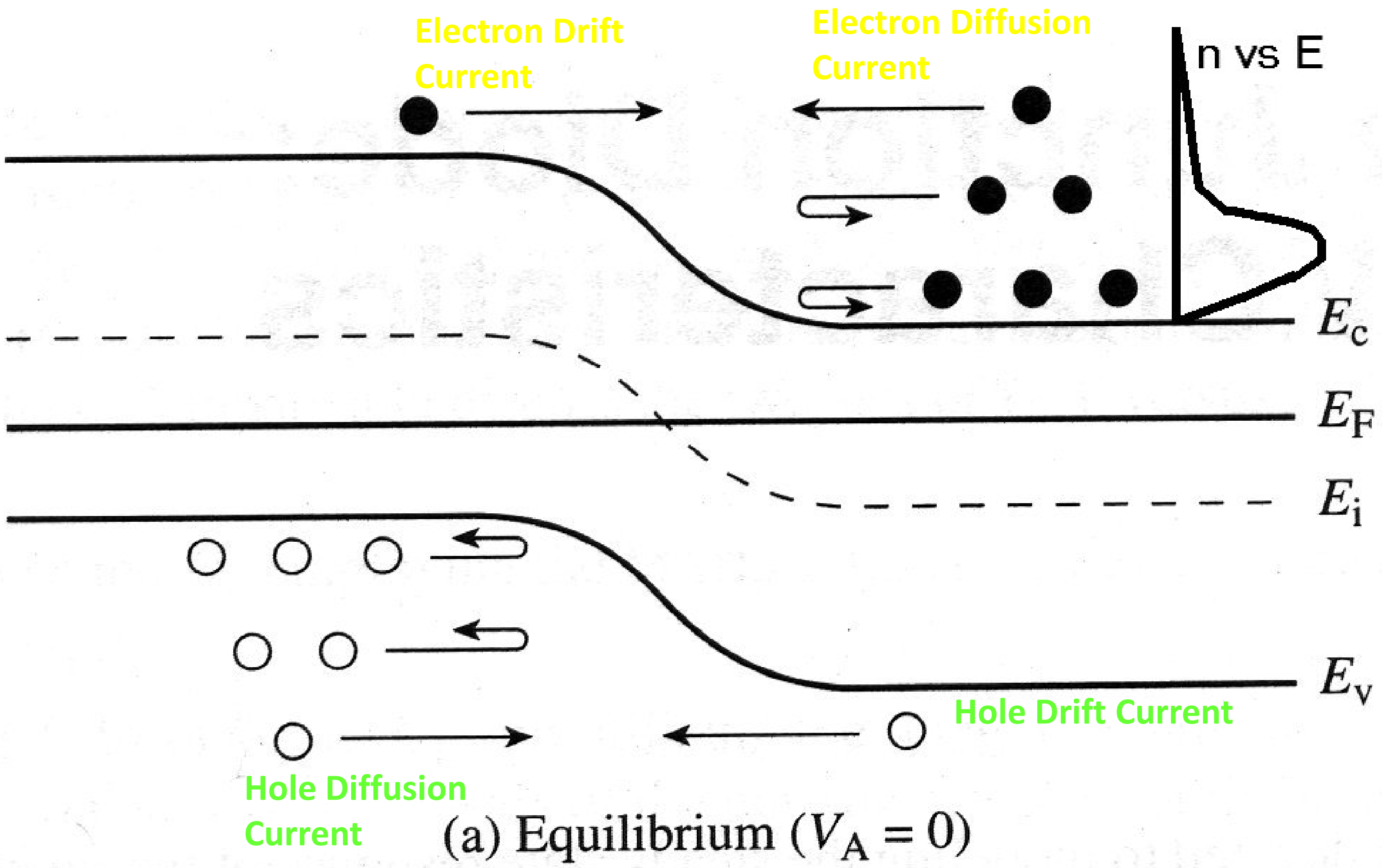
(c) Reverse bias ($V_A < 0$)

P-N Junction Diodes: Part 3

Current Flowing through a Diode

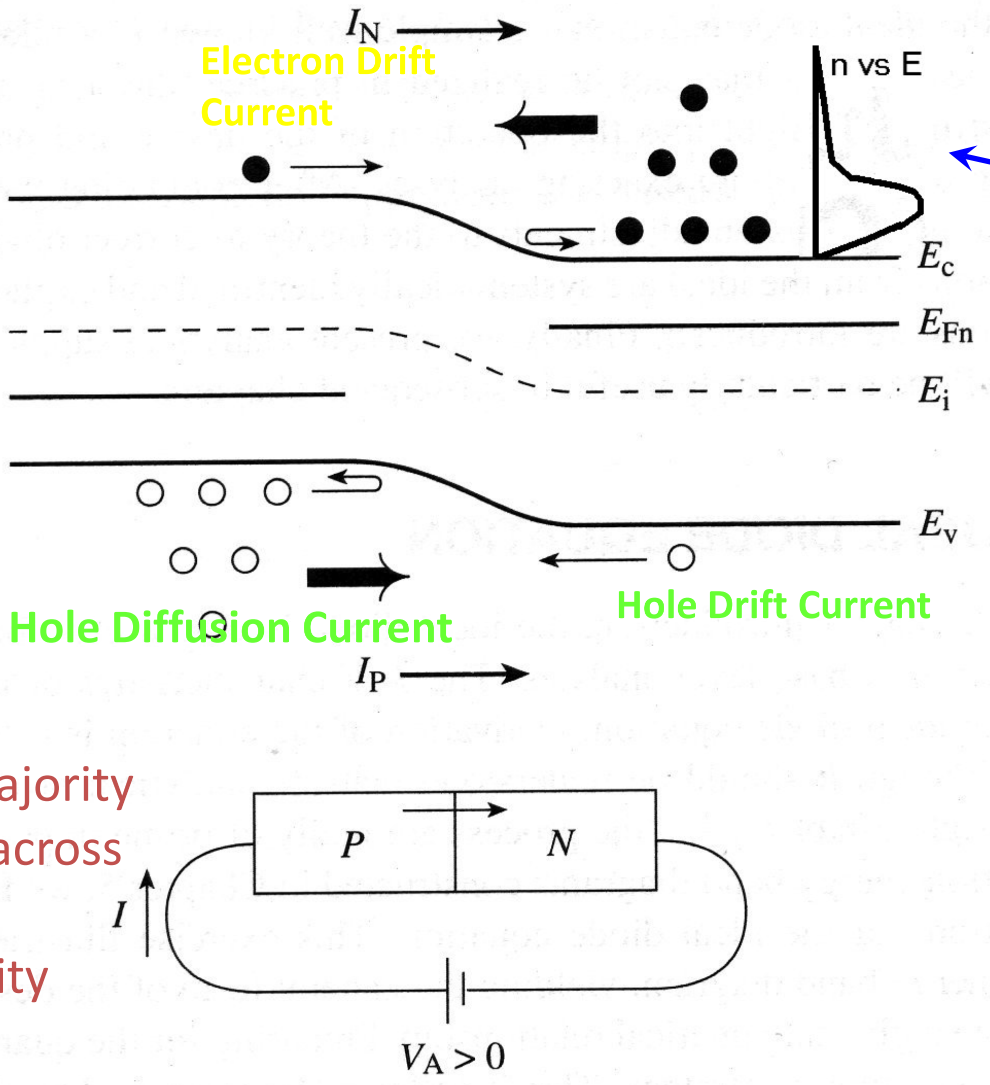
p-n Junction I-V Characteristics: Equilibrium

In Equilibrium, the Total current balances due to the sum of the individual components



(a) Equilibrium ($V_A = 0$)

p-n Junction I-V Characteristics: Forward Electrical Bias



Electron Diffusion Current

Electron Drift Current

Hole Diffusion Current

Hole Drift Current

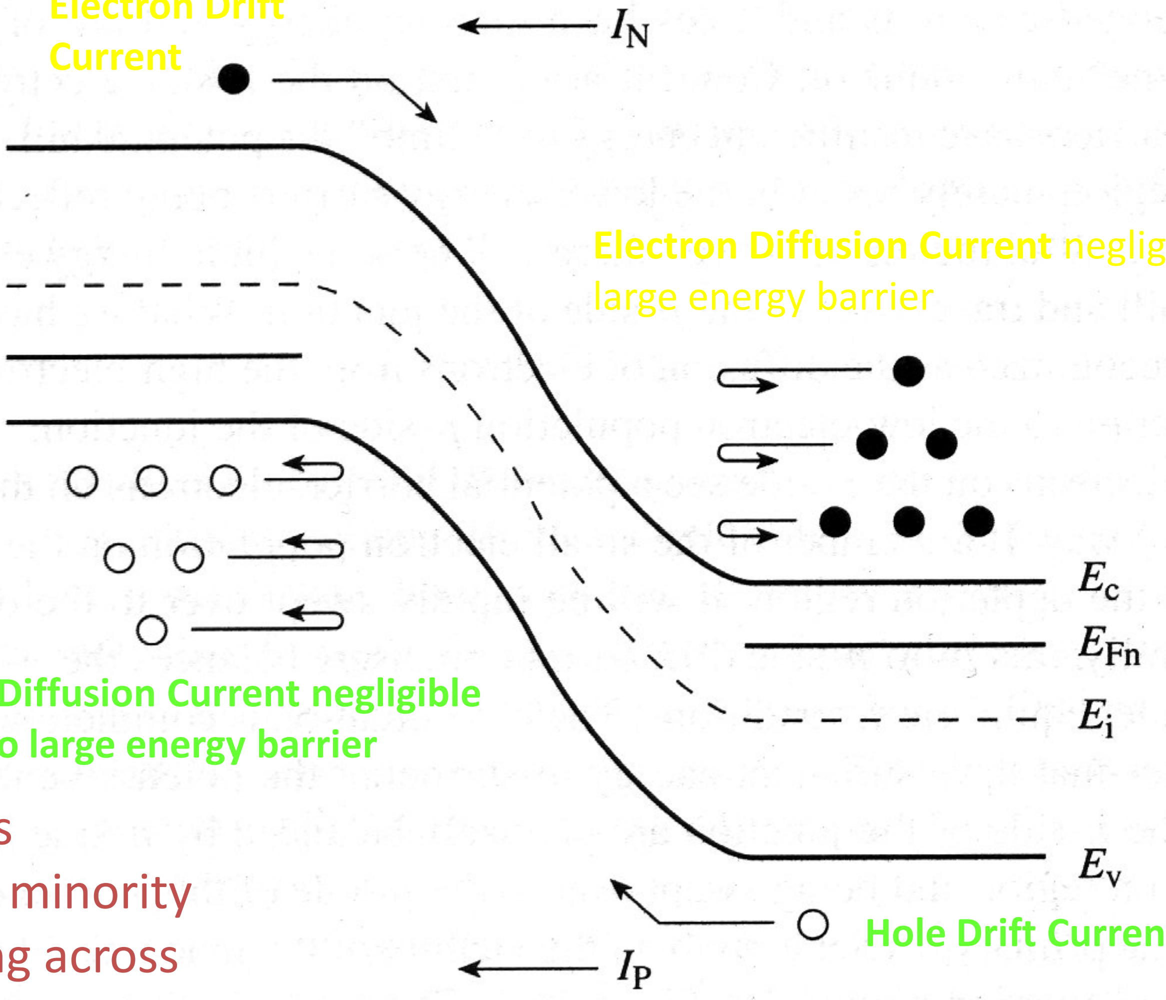
(b) Forward bias ($V_A > 0$)

Current flow is proportional to $e^{(Va/Vref)}$ due to the exponential decay of carriers into the majority carrier bands

Current flow is dominated by majority carriers flowing across the junction and becoming minority carriers

p-n Junction I-V Characteristics: Reverse Electrical Bias

Current flow is constant due to thermally generated carriers swept out by E-fields in the depletion region



Electron Drift Current

Electron Diffusion Current negligible due to large energy barrier

Hole Diffusion Current negligible due to large energy barrier

Hole Drift Current

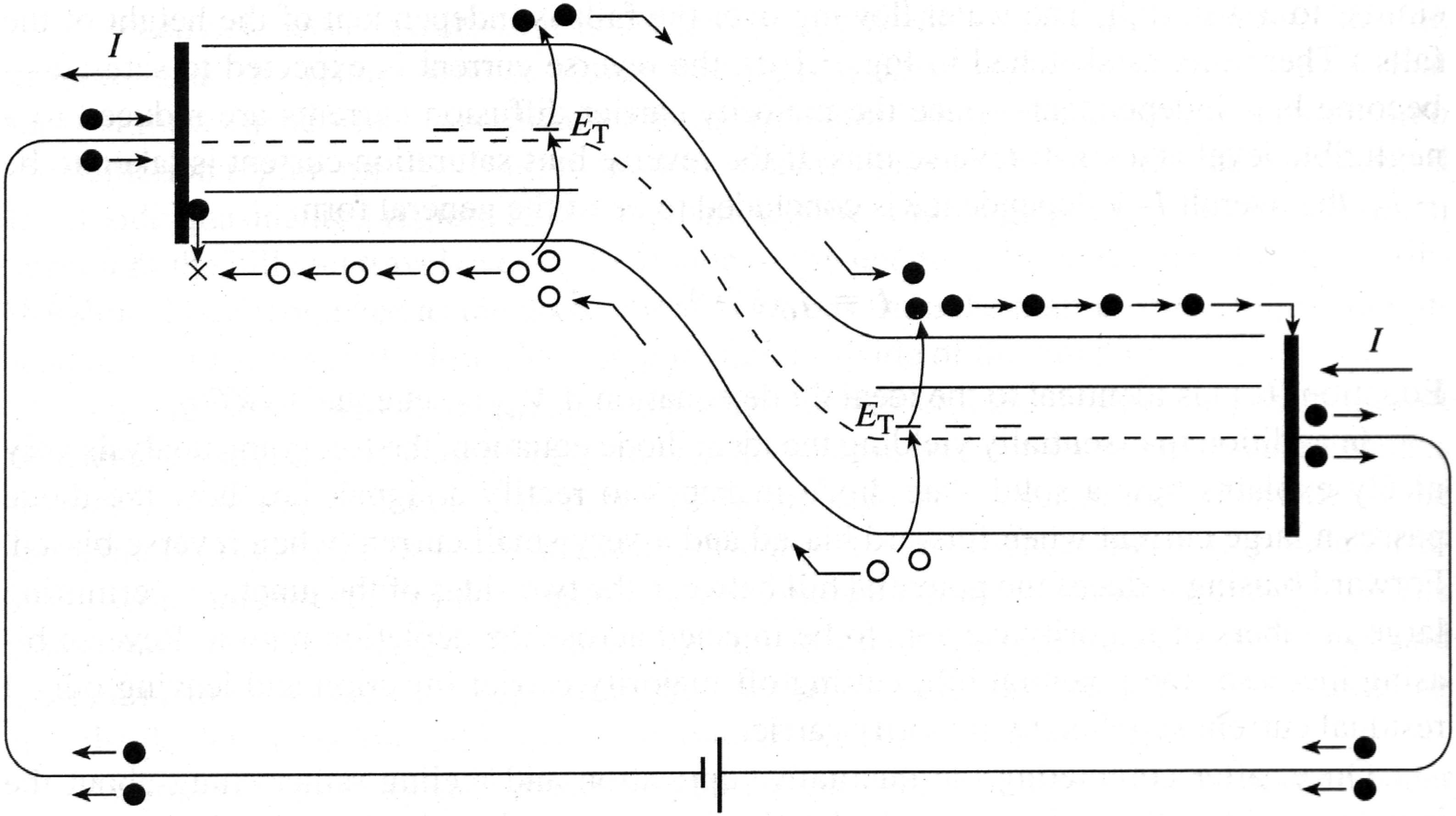
(c) Reverse bias ($V_A < 0$)

Current flow is dominated by minority carriers flowing across the junction and becoming majority carriers

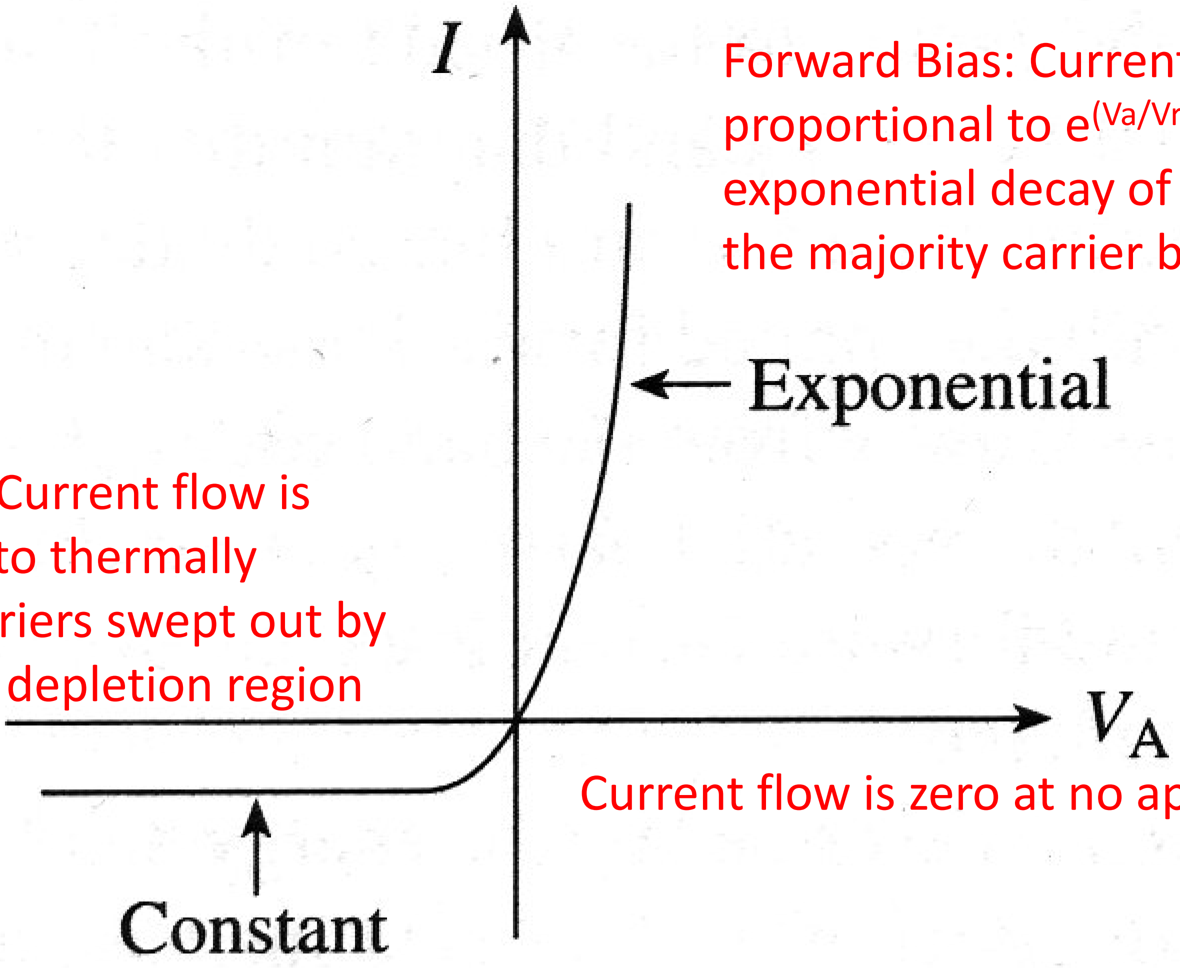
QuickTime Movie

p-n Junction I-V Characteristics: Reverse Electrical Bias

Where does the reverse bias current come from? Generation near the depletion region edges "replenishes" the current source.



p-n Junction I-V Characteristics
Putting it all together



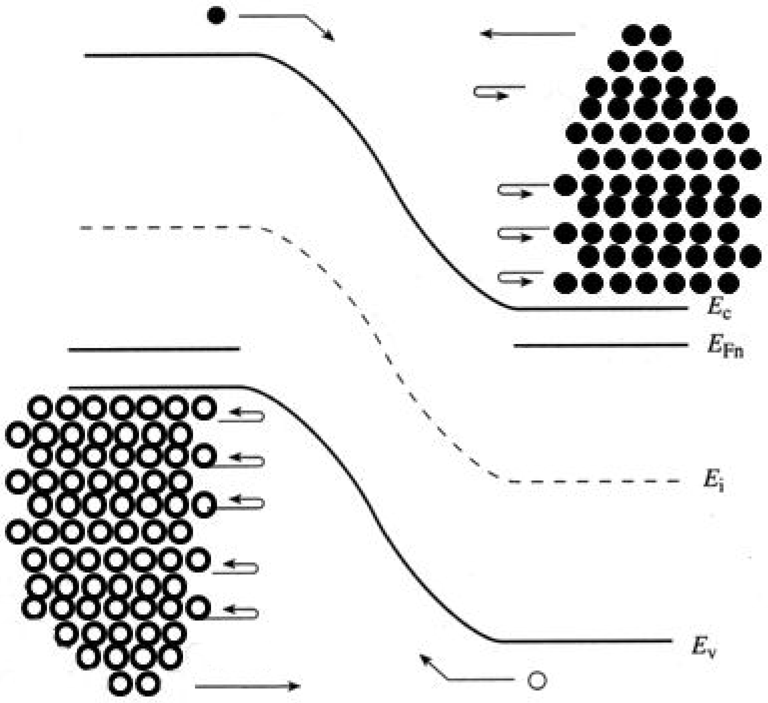
Forward Bias: Current flow is proportional to $e^{(Va/Vref)}$ due to the exponential decay of carriers into the majority carrier bands

Reverse Bias: Current flow is constant due to thermally generated carriers swept out by E-fields in the depletion region

Current flow is zero at no applied voltage

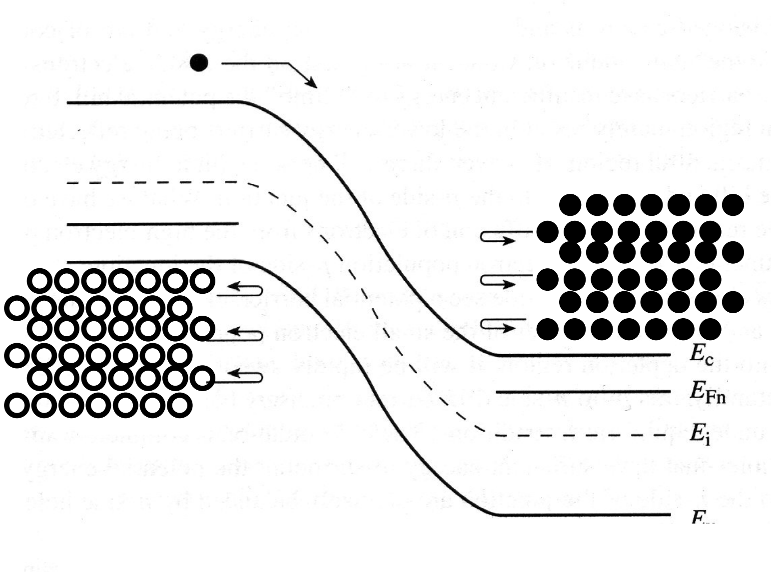
$$I=I_o(e^{Va/Vref} - 1)$$

The Difference in a Photodiode and a Solar Cell: Equilibrium

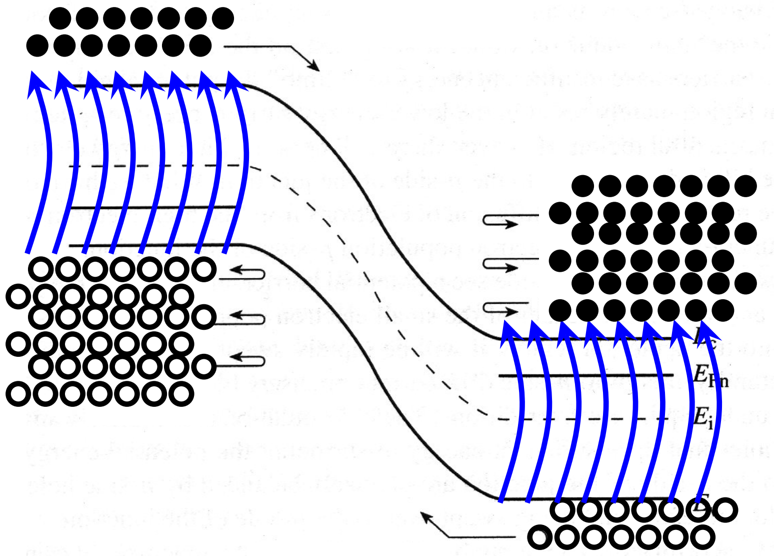


Zero Bias (Equilibrium) Diode with no light illumination has equal amounts of Drift and Diffusion current resulting in no net current flow.

The Difference in a Photodiode and a Solar Cell: Photodiode=Electrically Reverse Biased Diode

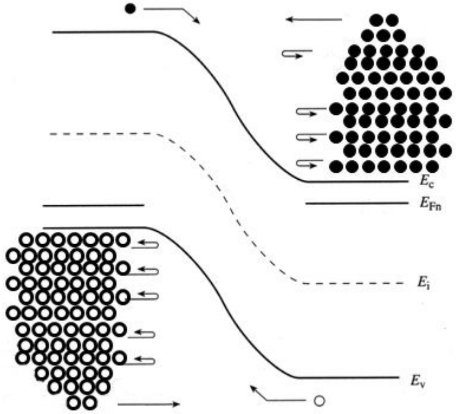


- Photodiodes are Reversed Biased Diodes. Case shown with no light illumination.
- Diffusion current is practically zero due to enormous energy barriers preventing diffusion.
- Drift current is small but finite due to minority carriers accelerated by the large electric fields.

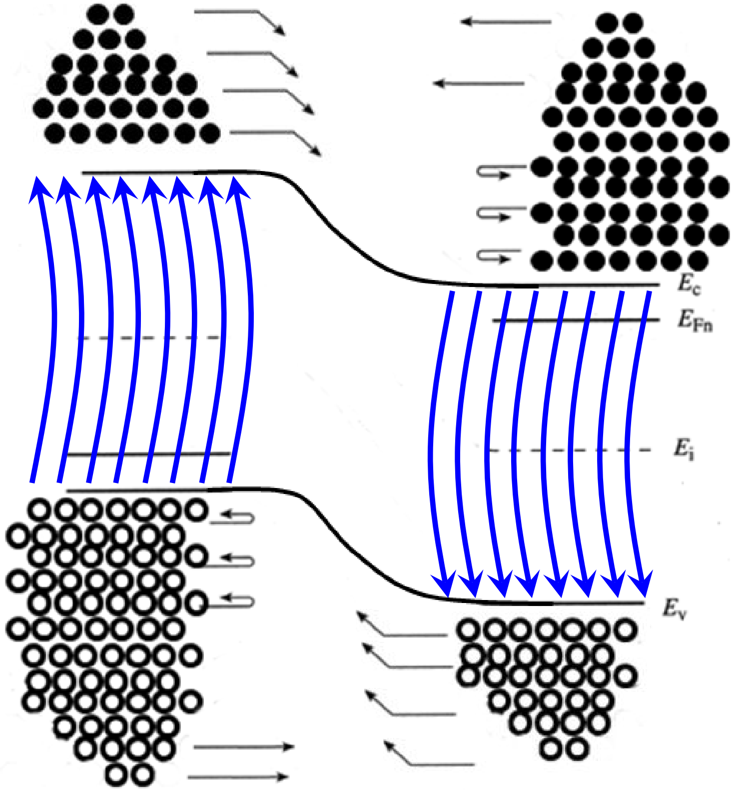


- Case Shown: Reversed Bias Diode(photodiode) WITH light illumination
- Again, Diffusion current is practically zero due to enormous energy barriers preventing diffusion.
- Extra photogenerated ehp's that can reach the junction are collected as "extra" drift current

The Difference in a Photodiode and a Solar Cell:
Solar Cell: No applied Electrical Bias but Forward biased due to Light



- Zero Bias (Equilibrium) Diode with no light illumination has equal amounts of Drift and Diffusion current resulting in no net current flow.



- Solar Cell: Forward Biased (due to light)
- Diode results in “extra” drift current due to photogenerated ehp’s (just like a photodiode) that can reach the junction and be collected.
- This extra collected charge flattens the bands resulting forward bias and partial offsetting by diffusion current.

The Difference in a Photodiode and a Solar Cell: Current – Voltage Characteristics – Photodiode Case

$$I_{total} = I_{dark} + I_{Due\ to\ Light}$$

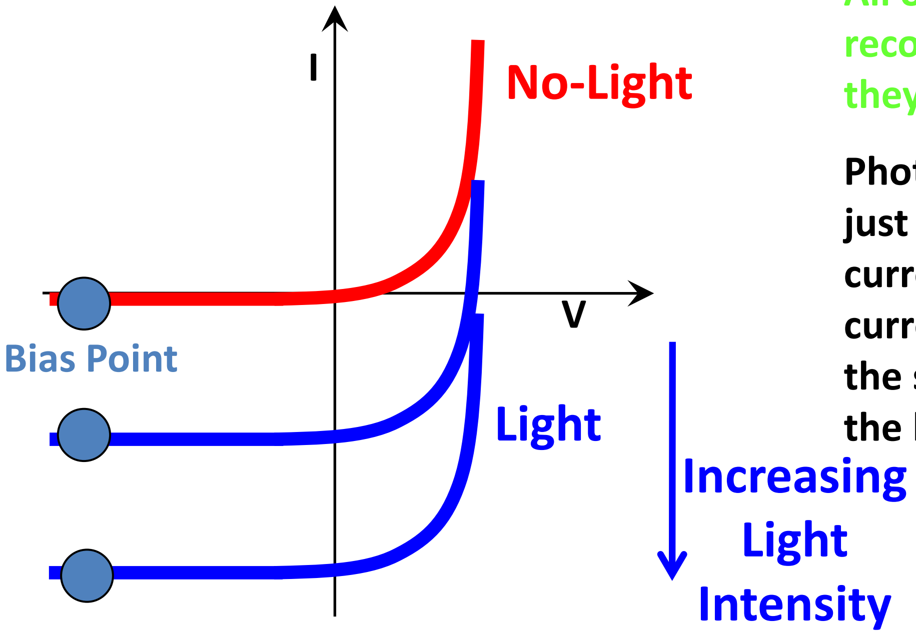
$$I_{total} = I_o\left(e^{\left(V_D/V_T\right)} - 1\right) + I_{Due\ to\ Light}$$

$$I_{total} = \underbrace{\left(I_o e^{\left(V_D/V_T\right)} - I_o\right)}_{\text{No-Light}} + \underbrace{(-qA)\overbrace{(L_N + W + L_P)}G_L}_{\text{Light}}$$

Every EHP created within the depletion region (W) and within a diffusion length away from the depletion region is collected (swept across the junction by the electric field) as photocurrent (current resulting from light). All other EHP’s recombine before they can be collected.

Photodiode current, just like leakage current is Drift current and thus is in the same direction as the leakage current.

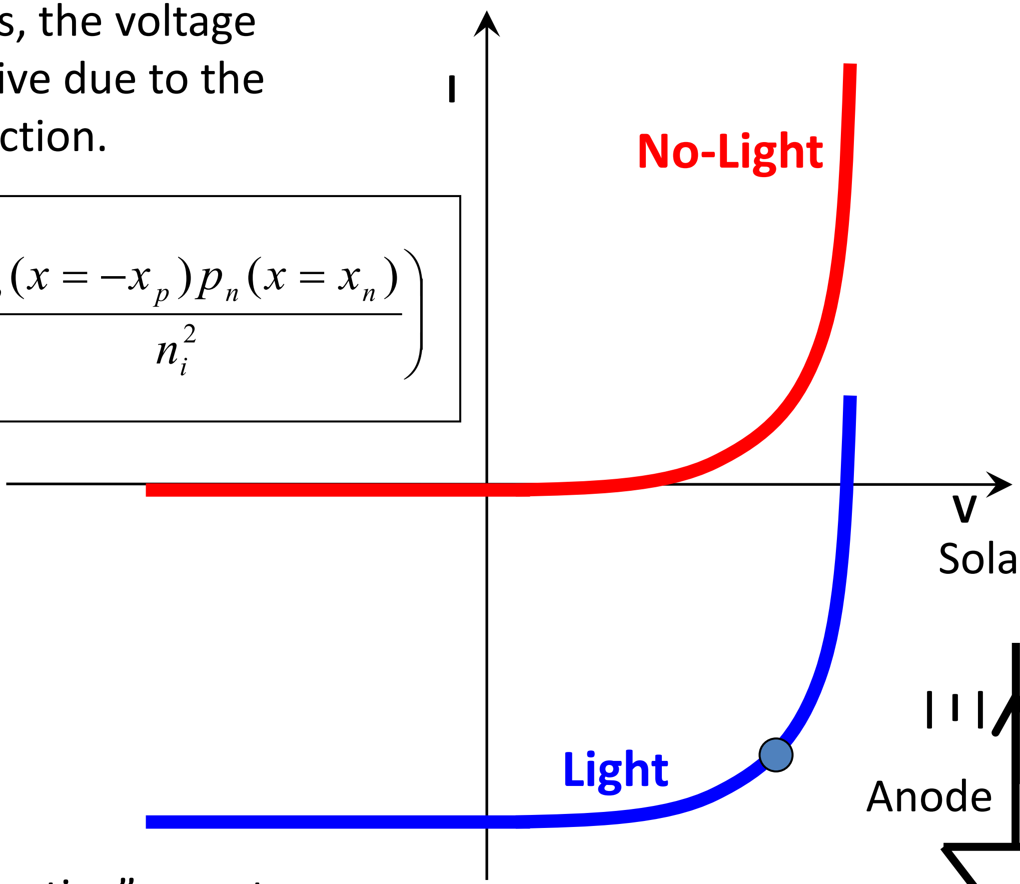
Explanation of these curves: The IV curve is found by sweeping all voltages and measuring the resulting currents. During operation, the device is held at one operating voltage call the bias point.



Solar Cell = No applied electrical bias, but Light induced Forward bias Diode: Voltage

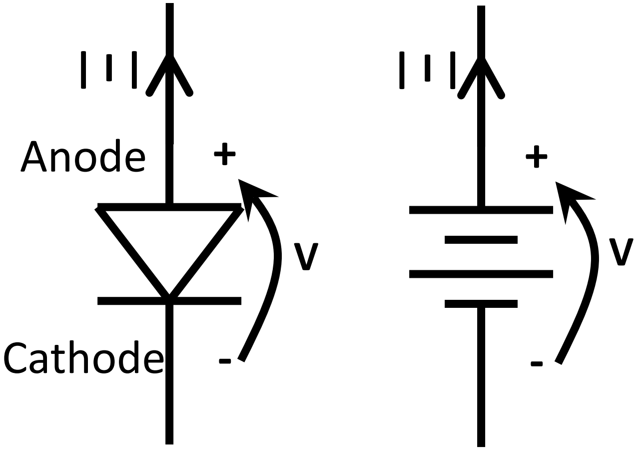
Since $n_p>n_o$ and $p_n>p_o$ at the junction edges, the voltage must be positive due to the law of the junction.

$$V_A = \frac{kT}{q}\ln\left(\frac{n_p(x=-x_p)\,p_n(x=x_n)}{n_i^2}\right)$$



Current is "negative" or out of the p-type side (anode)

Solar Cell acts as a battery producing power



Solar Cell = No applied electrical bias, but Light induced Forward bias Diode: Current

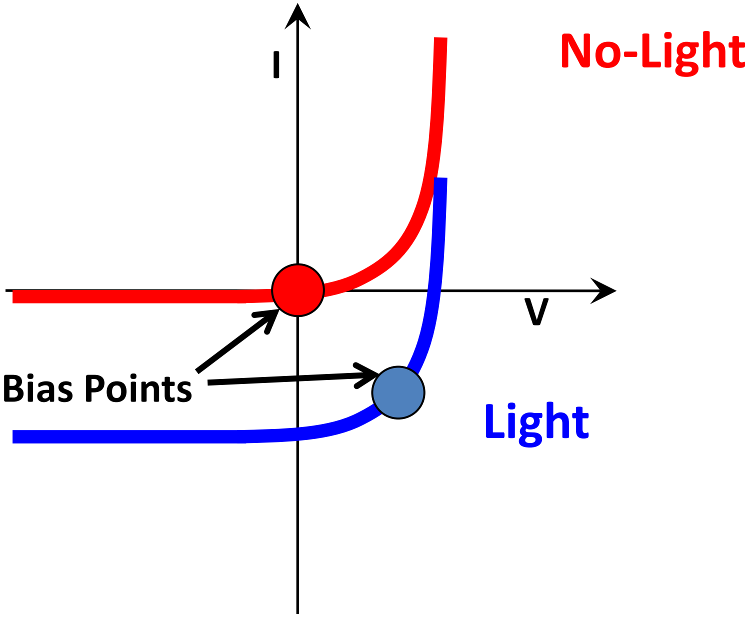
$$I_{total} = I_{dark} + I_{Due\ to\ Light}$$

$$I_{total} = I_o\left(e^{\left(V_D/V_T\right)} - 1\right) + I_{Due\ to\ Light}$$

$$I_{total} = \underbrace{\left(I_o e^{\left(V_D/V_T\right)} - I_o\right)}_{\text{No-Light}} + \underbrace{(-qA)\overbrace{(L_N + W + L_P)}G_L}_{\text{Light}}$$

Every EHP created within the depletion region (W) and within a diffusion length away from the depletion region is collected (swept across the junction by the electric field) as photocurrent (current resulting from light). All other EHP's recombine before they can be collected.

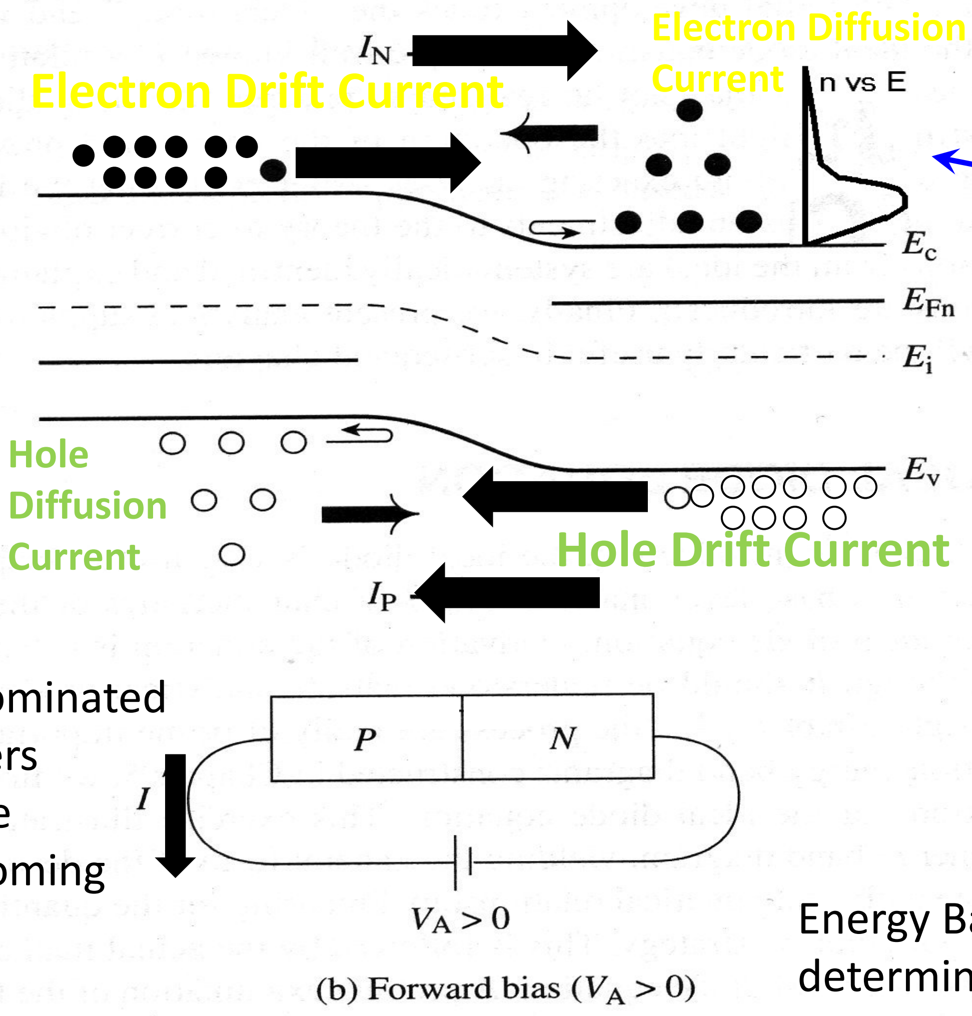
Note: without a reverse bias, W is substantially smaller for a solar cell than for a photodiode.



Photodiode current, just like leakage current is Drift current and thus is in the same direction as the leakage current.

Current is "negative" or out of the p-type side (anode)

Under Optical Forward Bias, the total current is unbalanced due to a greatly enhanced drift current (due to more minority carriers) that is only partially offset by an exponentially larger Diffusion current. Net current flows from N to P (generating power). Energy bands flatten.



(b) Forward bias ($V_A > 0$)

Current flow is initially linear with illumination but dies off exponentially as Diffusion current increases at higher forward bias (flatter bands).

Current flow is dominated by <u>minority</u> carriers flowing across the junction and becoming <u>majority</u> carriers

Energy Band Bending is determined by the Law of the Junction

Other types of Collecting Junctions

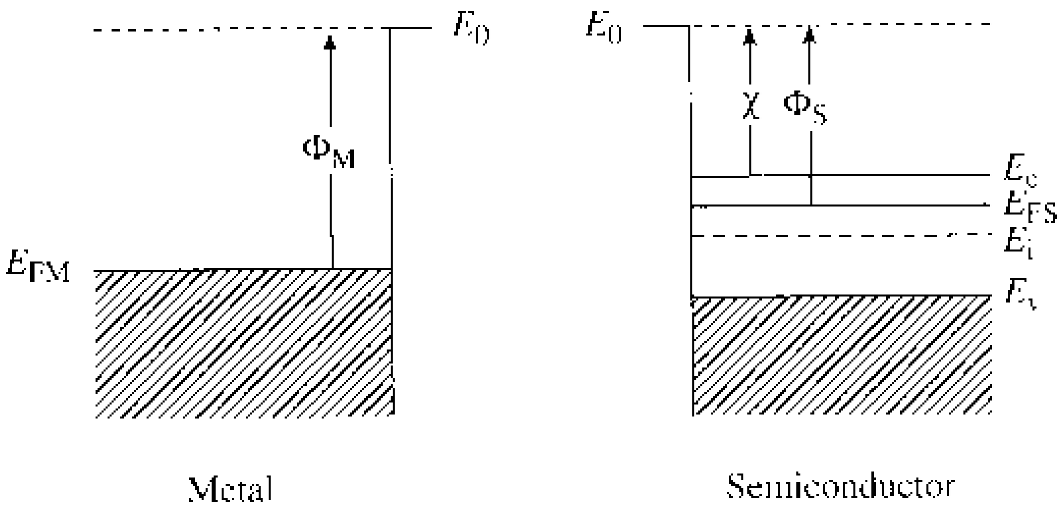
Metal Semiconductor Junctions (Ohmic and Schottky)

- Why a Schottky Diode or Schottky Solar Cell?
    - Cheap, Cheap, Cheap!
    - Many attempts to have “ohmic contacts” are often thwarted by mother nature. Schottky contacts are all that can be formed in some cases
    - Minority Carrier Charge storage in p-n junctions tends to limit the switching times of p-n junction diodes
        - Turn off times limited by minority carrier lifetimes
    - Schottky Diodes have little (no) minority carrier stored charge and thus have application in fast switching applications (solar invertors, motors, etc…)
    - Cheaper
    - Collecting junction is optimally placed at the surface of the solar cell where most of the generation occurs.
- Disadvantages:
    - Inherently low V_{oc}
    - Full metal coverage creates reflection issues
    - Generally higher leakage currents
    - Generally lower breakdown voltages imply higher shunting of the junction

Metal-semiconductor (MS) junctions

- P-N junctions formed depletion regions by bringing together two materials with dissimilar fermi energies, allowing charge transfer and subsequent alignment of the energy bands.
- Several other combinations of such materials can also form “useful junctions”.
  - Schottky Diodes (metal-semiconductor junction)
  - Ohmic contacts (metal-semiconductor junction)
  - Thermocouples (metal-metal junction)

Ideal Metal-Semiconductor Contacts



Assumptions - Ideal MS contacts

- Metal (M) and Semiconductor (S) are in intimate contact, on atomic scale
- No oxides or charges at the interface (very bad assumption in some cases – some interfaces are dominated by interfacial oxides or interface charge).
- No intermixing at the interface (in some cases, it is impossible to put a metal on a semiconductor without some exchange of atoms – intermixing- occurring)
- These assumptions require ultra-clean interfaces otherwise non-ideal behavior results (fermi-level pinning of III-V compounds is common for example)

Definitions

- **Vacuum level, E_0** - corresponds to energy of free electrons in vacuum.
- The difference between vacuum level and Fermi-level is called workfunction, Φ of materials.
  - **Workfunction, Φ_M** is an invariant property of a given metal. It is the minimum energy required to remove electrons from the metal. (Lowest value is 1.95eV for Cs, 3.66eV for Mg, 5.15eV for Ni, and highest value is 5.7eV for Pt, etc.). Electron density varies with crystallographic orientation so the work function varies with orientation as well.
- However, since the electron concentration depends on doping in a semiconductor, the semiconductor **workfunction, Φ_s,** depends on the doping.

$$\Phi_S = \chi + (E_C - E_F)_{FB}$$

where $\chi = (E_0 - E_C)|_{SURFACE}$ is a a fundamental property of the semiconductor. (Example: χ = 4.0 eV, 4.03 eV and 4.07 eV for Ge, Si and GaAs respectively)

Energy band diagrams for ideal MS contacts

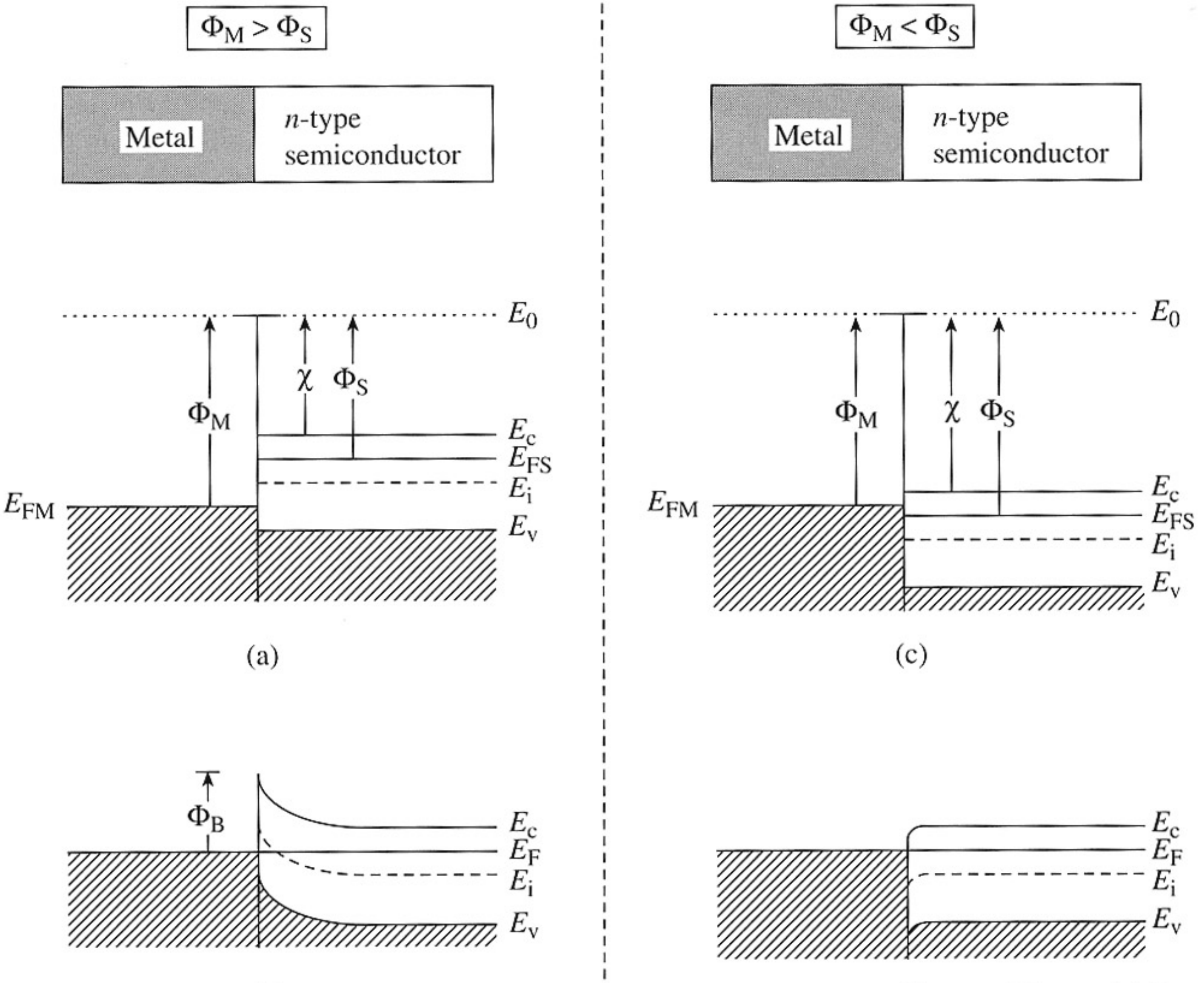


Figure 14.2

An instant after contact formation

Under equilibrium conditions

Schottky

$\Phi_M > \Phi_S$

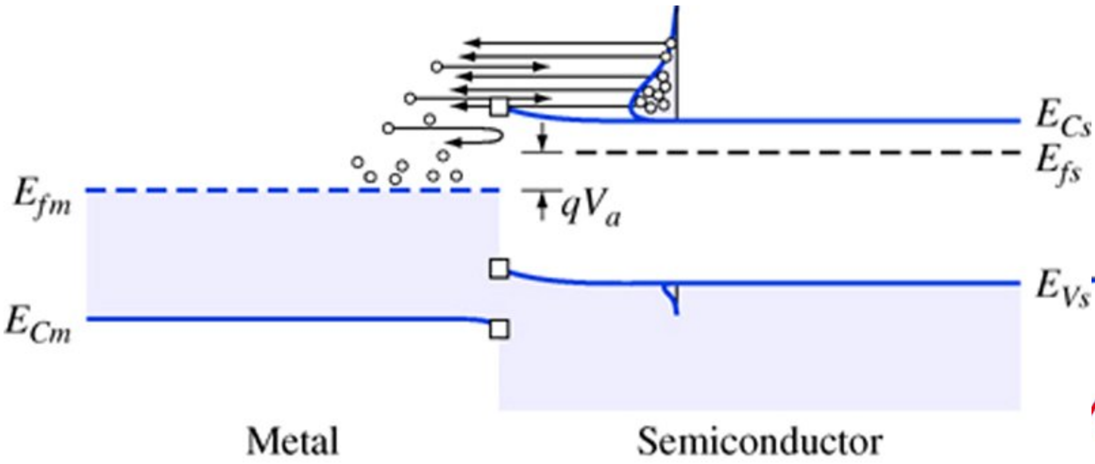
Ohmic

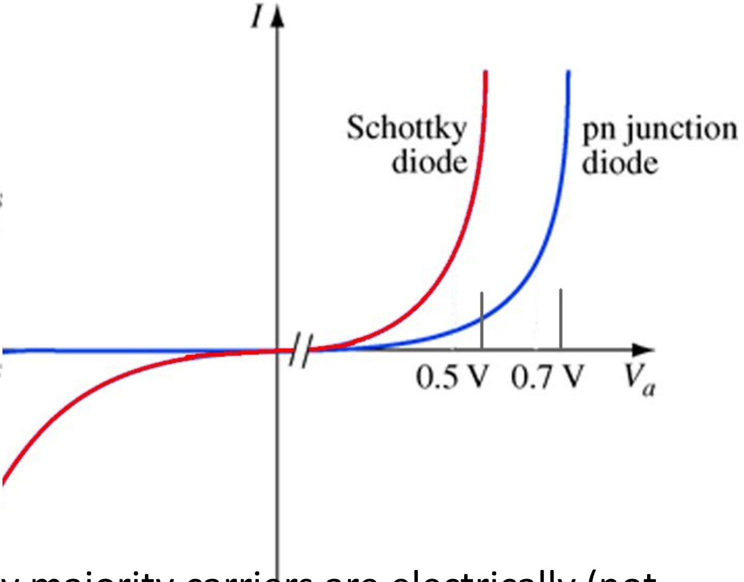
$\Phi_M < \Phi_S$

MS (n-type) contact with $\Phi_M > \Phi_S$

- Soon after the contact formation, electrons will begin to flow from the semiconductor to the metal.
- The removal of electrons from the n-type material leaves behind uncompensated N_d^+ donors, creating a surface depletion layer, and hence a built-in electric field (similar to p^+-n junction).
- Under equilibrium, the Fermi-level will be constant and no energy transfer (current) flows
- A barrier Φ_B forms blocking electron flow from M to S.
- Based on the Electron Affinity Model (EAM), the simplest of models used to describe MS junctions, $\Phi_B = \Phi_M - \chi$ … ideal MS (n-type) contact. Φ_B is called the "barrier height".
- Electrons in a semiconductor will encounter an energy barrier equal to $\Phi_M - \Phi_S$ while flowing from S to M.

I-V Characteristics



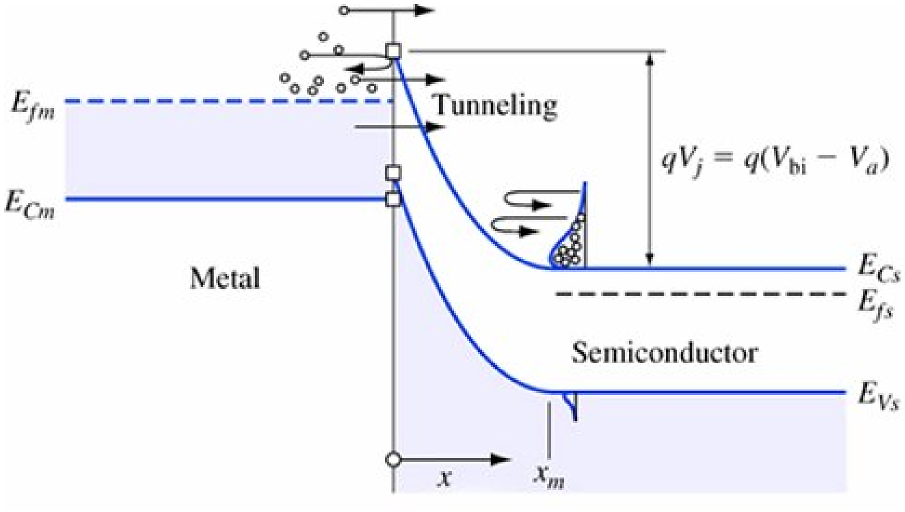


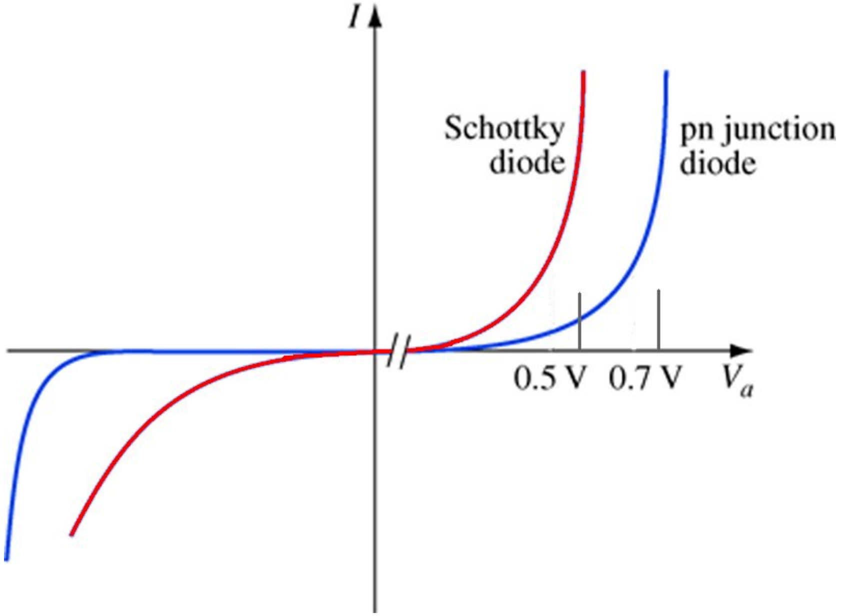
Since MS Schottky diode is a majority carrier device (i.e only majority carriers are electrically (not necessarily optically) injected from semiconductor to the metal) and thus has no minority carrier storage, the frequency response of the device is much higher than that of equivalent p^+ n diode. Thus, Schottky diodes are often used in “fast switching” applications.

The “turn on voltage” of a Schottky diode is typically smaller than a comparable p-n junction since the barrier to forward current flow (Φ_m-Φ_s) is typically small. This “turn on” voltage can be as small as 0.3 Volts in some Si Schottky diodes. This limits the open Circuit voltage.

This makes a Schottky diode the best choice for power switch protection in inductive load applications (motors, solenoids, coils, etc…) and in high frequency rectification but not a good choice when low leakage or high breakdown voltage is required (solar cells). However, some metal-semiconductor contacts can only be made with a Schottky diode. We will see how to handle this situation later.

I-V Characteristics





Leakage in a Schottky diode is dominated by:

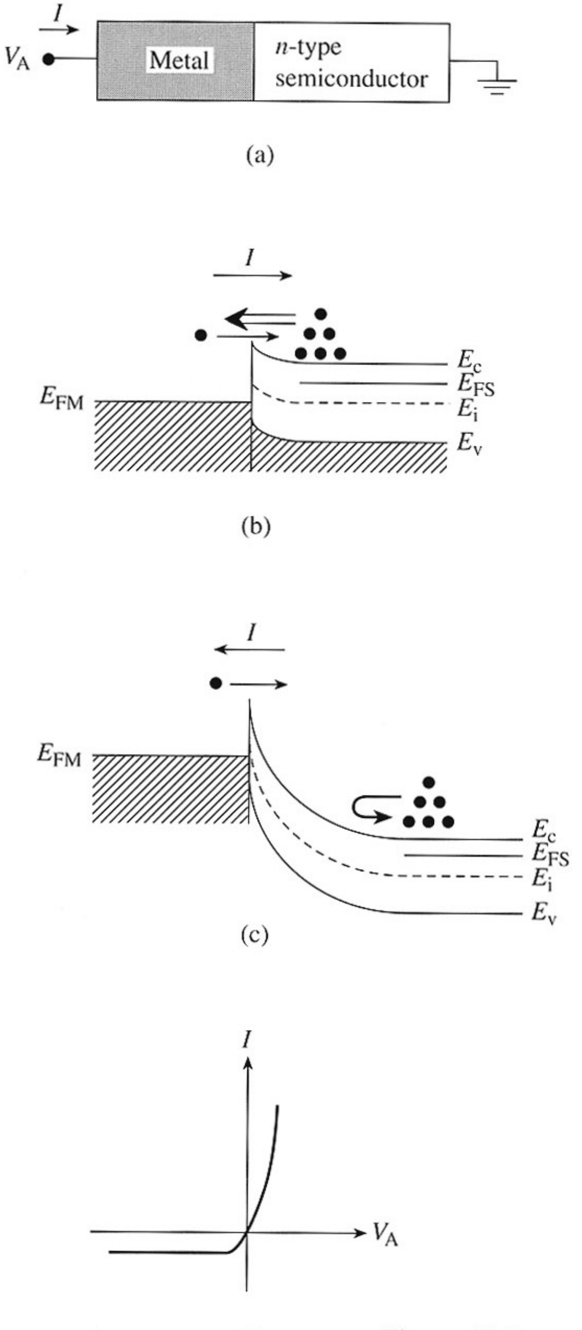
1) "Thermionic Emission" (metal electrons emitted over the barrier – not likely)
2) "Thermionic Field Emission" (metal electrons of higher energy tunneling through the barrier – more likely)
3) "Direct tunneling" (metal electrons tunneling through the barrier – most likely in higher doped semiconductors).

Since generation does not require the entire bandgap energy to be surmounted, the reverse leakage current for a Schottky diode is generally much larger than that for a p^+n diode. Likewise, breakdown (for the same reason) is generally at smaller voltages. All of this leads to low voltages and low shunt resistances in solar cells.

MS (n-type) contact with $\Phi_M > \Phi_S$

A forward bias will reduce the barrier height unbalancing the electron current flow, resulting in a huge forward current that increases exponentially with applied voltage

A reverse bias will increase the barrier height resulting in a small “reverse current” flow that will be dominated by tunneling currents for high doped semiconductors and/or thermally assisted field emission for moderate/low doped semiconductors.



(a)

(b)

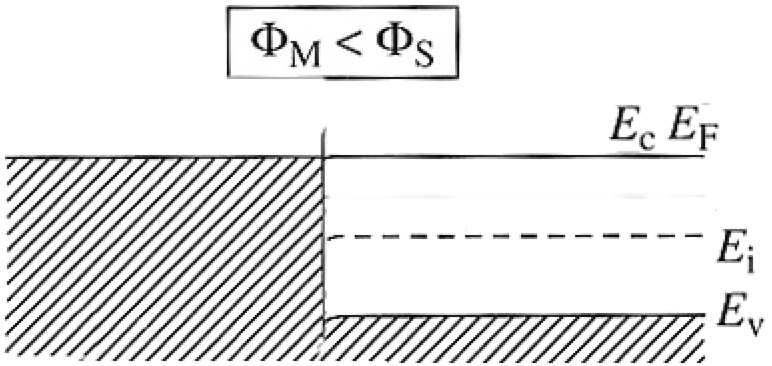
(c)

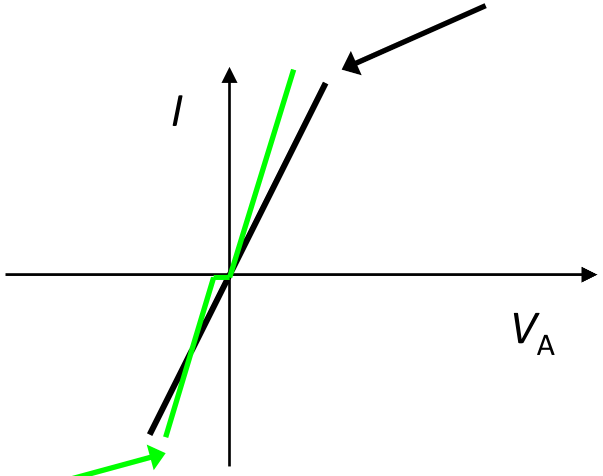
(d)

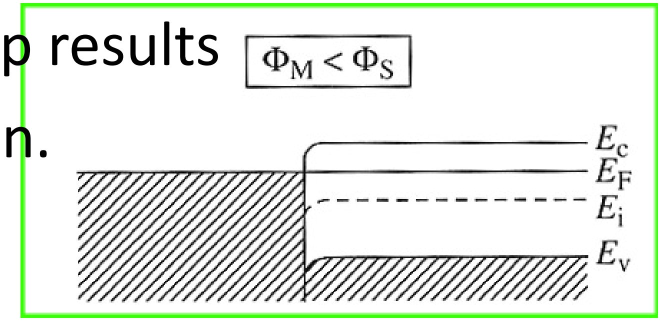
Figure 14.3

Ohmic Contacts: MS (n-type) contact with $\Phi_M < \Phi_S$

- There is no barrier for electron flow from the semiconductor to the metal. So, even for a small $V_A > 0$ this results in large current.
- The small barrier that exists for electron flow from metal to the semiconductor, all but vanishes when $V_A < 0$ is applied to the metal. Large current flows when $V_A < 0$.
- The MS (n-type) contact when $\Phi_M < \Phi_S$ behaves like an ohmic contact.
- The loss of a bandgap results in instant recombination.







Generalization of Metal Semiconductor Contact Energy Relationships

	n-type	**p-type**
$\Phi_M > \Phi_S$	rectifying	ohmic
$\Phi_M < \Phi_S$	ohmic	rectifying

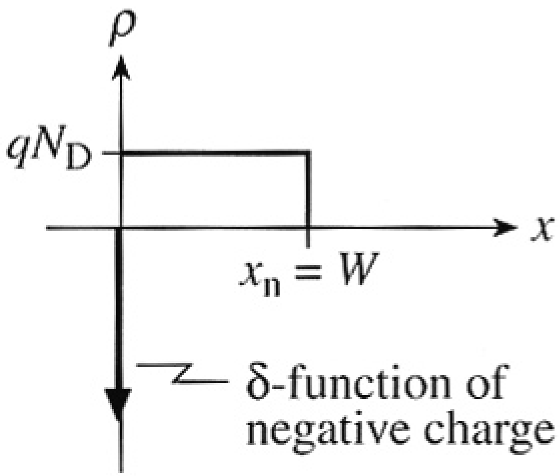
Schottky Diode Electrostatics

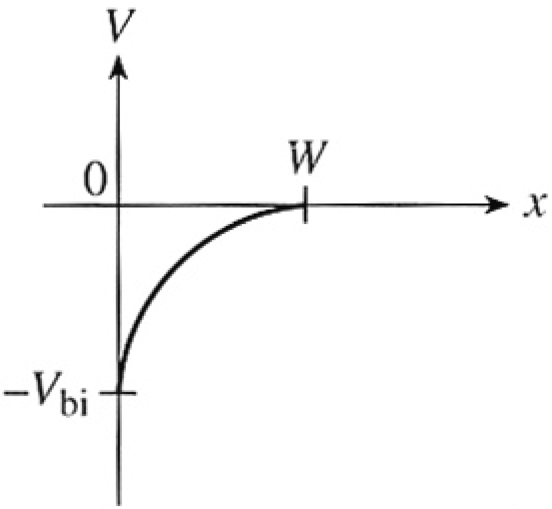
$$V_{\mathrm{bi}} = \frac{1}{q}\left[\Phi_{\mathrm{B}} - (E_{\mathrm{C}} - E_{\mathrm{F}})_{\mathrm{FB}}\right]$$

$$\begin{aligned} \rho &\approx qN_{\mathrm{D}} \quad \text{for } 0 \le x \le W \\ &\approx 0 \quad\quad\;\; \text{for } x > W \end{aligned}$$

$$\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}x} = \frac{\rho}{\varepsilon_{\mathrm{Si}}} = \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}} \quad \text{for} \quad 0 \le x \le W$$

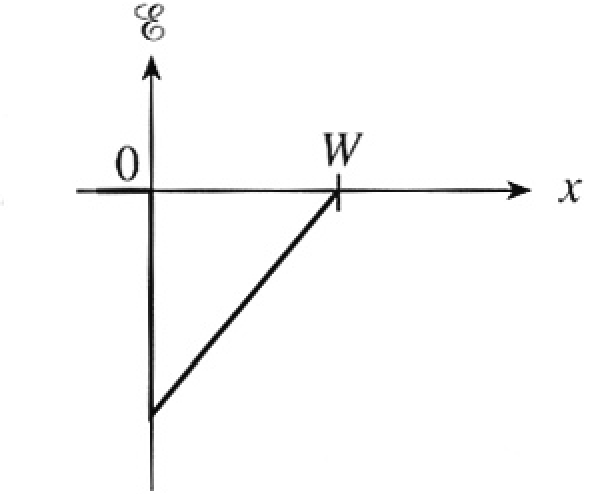
$$\mathbf{E} = \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}}(x - W) \quad \text{for} \quad 0 \le x \le W$$





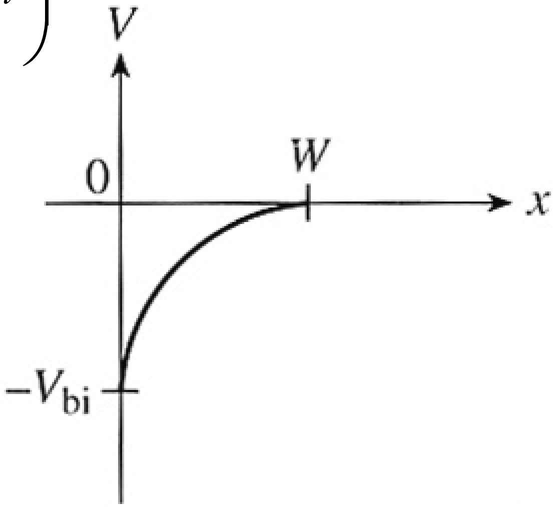
Schottky Diode Electrostatics

$$\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}x} = \frac{\rho}{\varepsilon_{\mathrm{Si}}} = \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}} \quad \text{for} \quad 0 \le x \le W$$



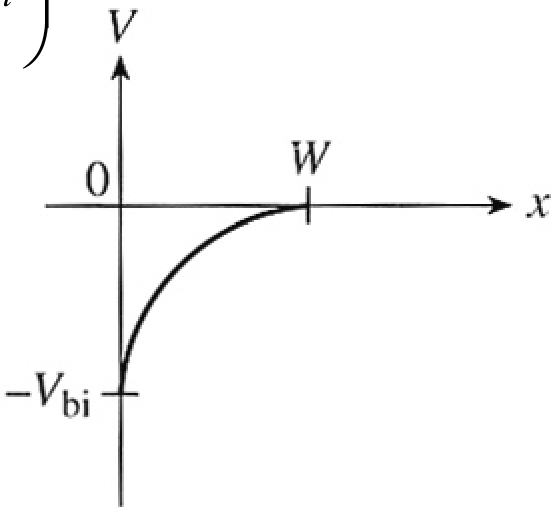
$$\mathbf{E} = \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}}(x - W) \quad \text{for} \quad 0 \le x \le W$$

$$V(x) = \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}}\left(Wx - \frac{1}{2}x^2\right) - \left(\left(\frac{\left(E_c - E_f\right)_{FB}}{q}\right) + V_{bi}\right) \quad \text{for} \quad 0 \le x \le W$$

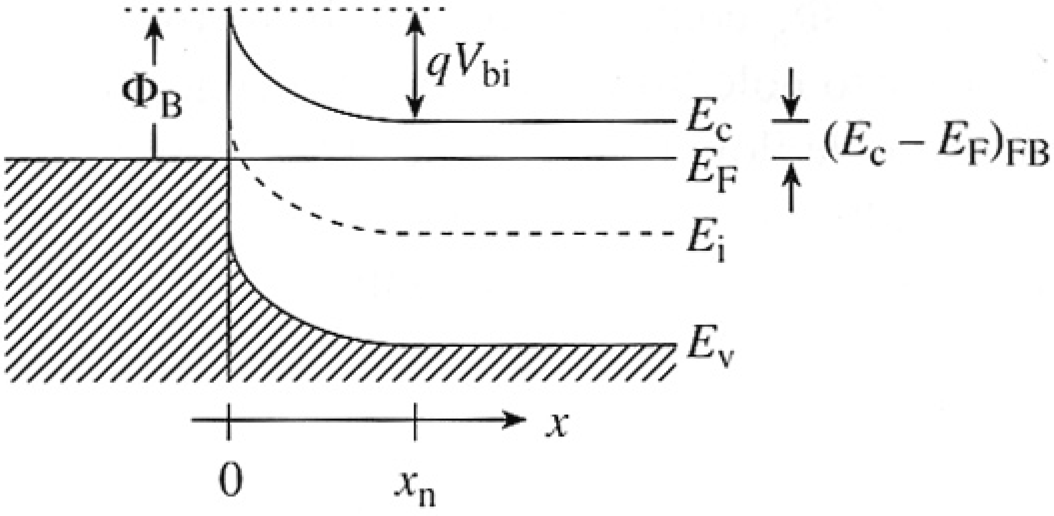


Schottky Diode Electrostatics

$$V(x)=\frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}}\left(Wx-\frac{1}{2}x^{2}\right)-\left(\left(\frac{\left(E_{c}-E_{f}\right)_{FB}}{q}\right)+V_{bi}\right)\quad \text{for}\quad 0\le x\le W$$



$$W=\sqrt{\frac{2\,\varepsilon_{\mathrm{Si}}}{q\,N_{\mathrm{D}}}\left(V_{\mathrm{bi}}-V_{\mathrm{A}}-\frac{\mathrm{kT}}{\mathrm{q}}\right)}$$



Example

Find barrier height, built-in voltage, maximum E-field, and the depletion layer width at equilibrium for W-Si (n-type) contact.
Given: $\Phi_M = 4.55$eV for W; χ(Si) = 4.01eV; Si doping = 10^{16} cm^{-3}
Draw the band diagram at equilibrium.

$$For\ N_D >> N_A\ and\ N_D >> n_i$$

Solution:

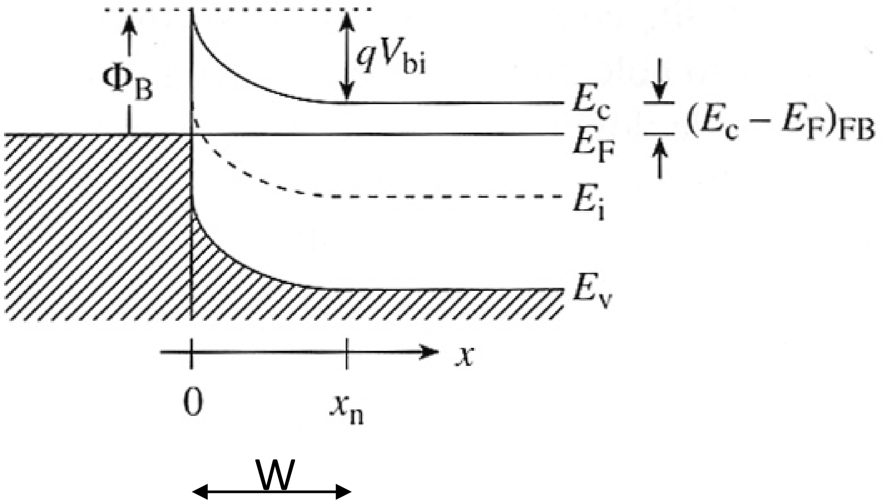
Find $E_F - E_i$ $\quad$ $E_F - E_i = 0.357$eV $\leftarrow$ $E_f - E_i = kT\ln\left(\frac{N_D}{n_i}\right)$

Find $E_C - E_F$ $\quad$ $E_C - E_F = 0.193$eV $\leftarrow$ $n = N_c e^{(E_f - E_c)/kT}$

$\Phi_B = \Phi_M - \chi = 0.54$eV

$$\Phi_S = \chi + (E_C - E_F)_{FB} = 4.203\ \text{eV}$$

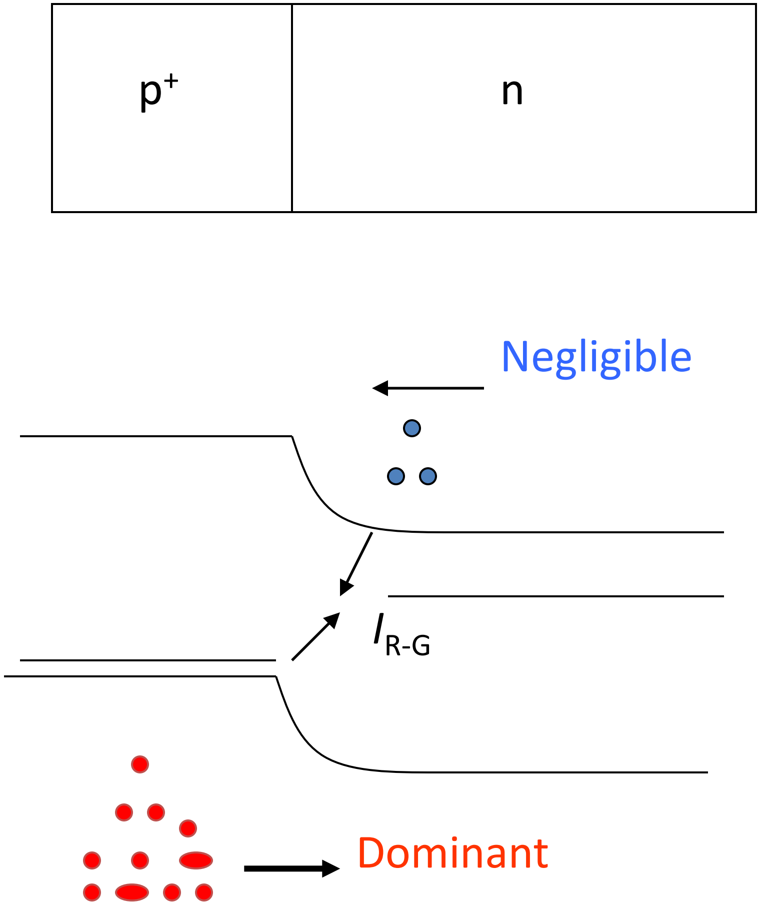
$V_{bi} = \Phi_B - (E_c - E_f) = 0.347$ V
$W = 0.21\ \mu$m
$\mathcal{E}(x = 0) = \mathcal{E}_{max} = 3.4 \times 10^4$ V/cm

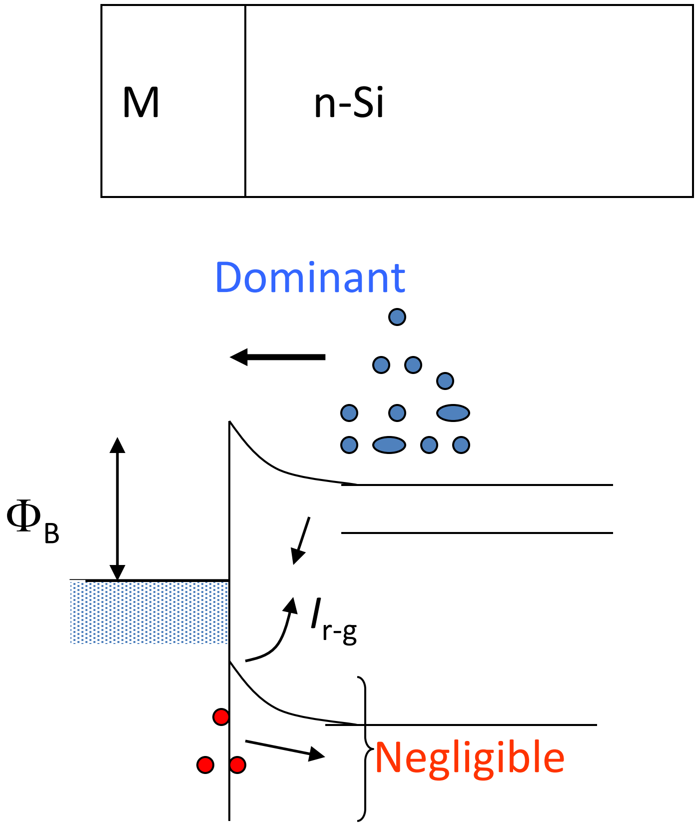


Schottky Diode I-V characteristics

- Schottky diode is a metal-semiconductor (MS) diode
- Historically, Schottky diodes are the oldest diodes
- MS diode electrostatics and the general shape of the MS diode I-V characteristics are similar to p^+n diodes, but the details of current flow are different.
- Dominant currents in a p^+n diode
  - arise from recombination in the depletion layer under small forward bias.
  - arise from hole injection from p^+ side under larger forward bias.
- Dominant currents in a MS Schottky diodes
  - Electron injection from the semiconductor to the metal.

Current Components in a p^+n and MS Schottky Diodes





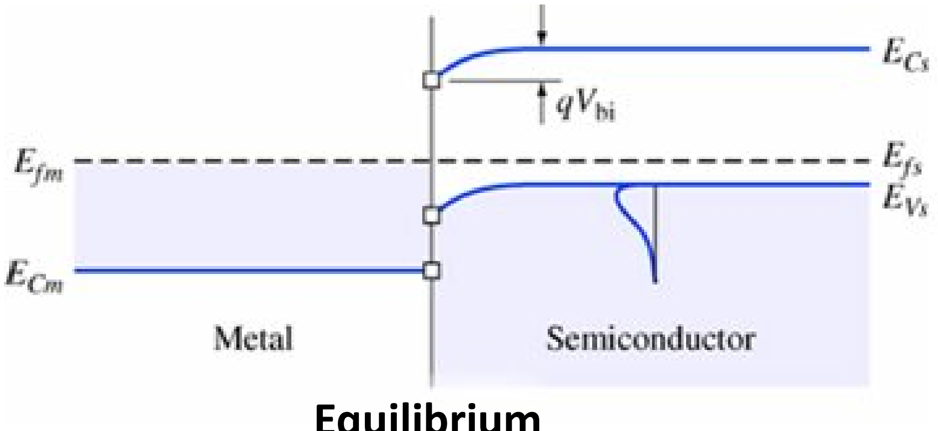
I-V Characteristics

$$I = I_s\left(e^{\frac{qV_A}{kT}} - 1\right) \quad \text{where} \quad I_s = A\mathcal{A}^* T^2 e^{-\frac{\Phi_B}{kT}}$$

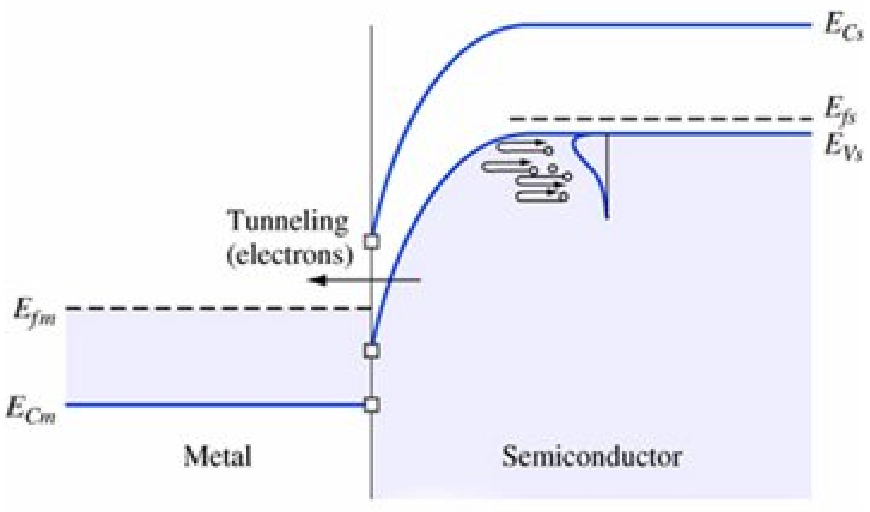
where Φ_B is Schottky barrier height, V_A is applied voltage, A is area, and $\mathcal{A}^*$ is Richardson's constant.

$$\text{where} \quad \mathbf{A}^* = \frac{4\pi q m^* k^2}{h^3} = 120\left[\frac{A}{cm^2 K}\right]$$

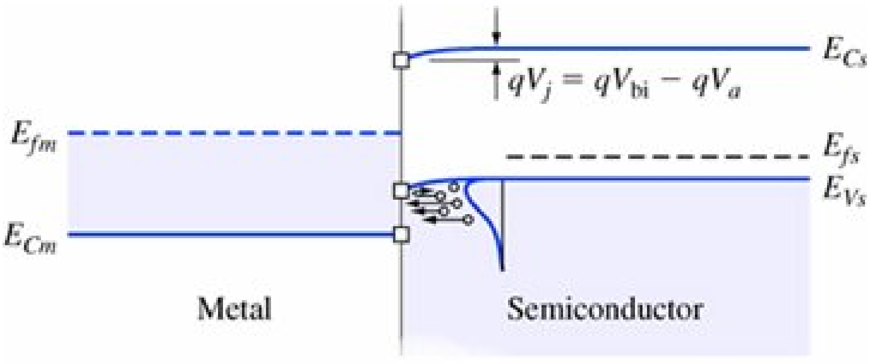
P-type Schottky Diodes



Equilibrium

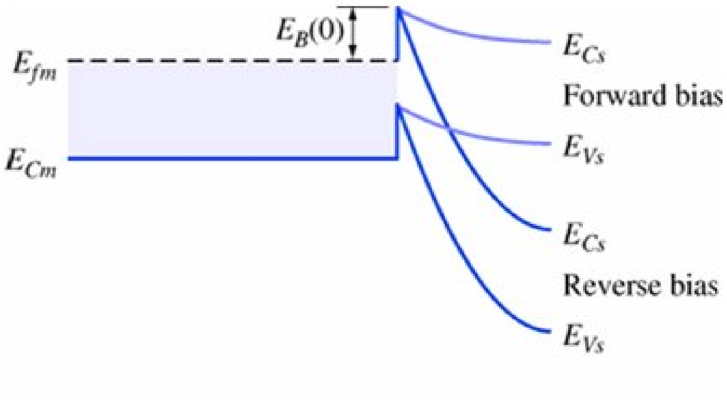


Reverse Bias

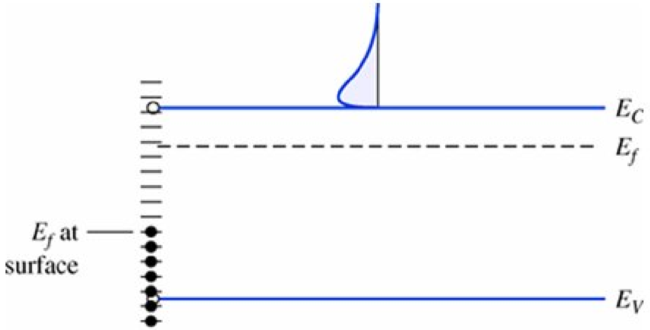


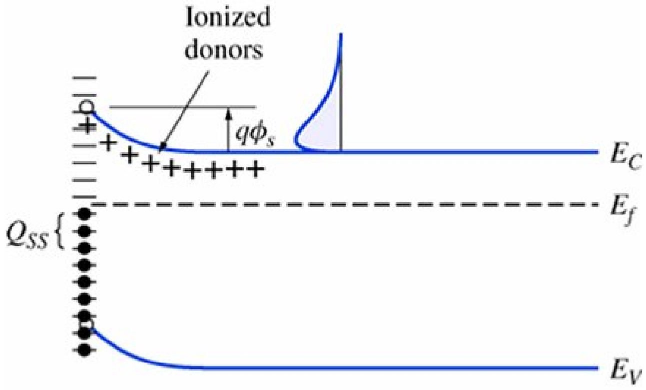
Forward Bias

Details of Schottky Behavior

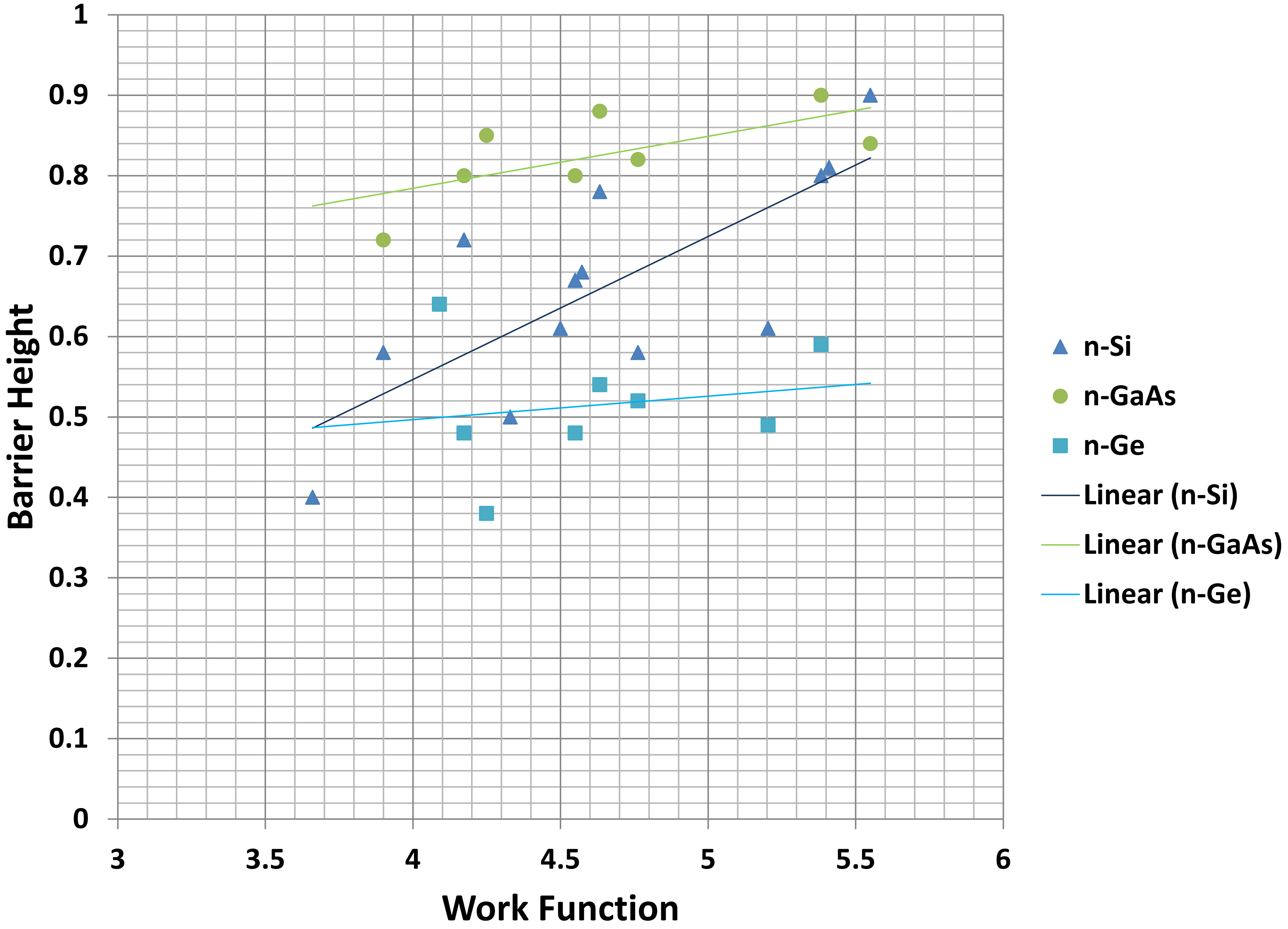


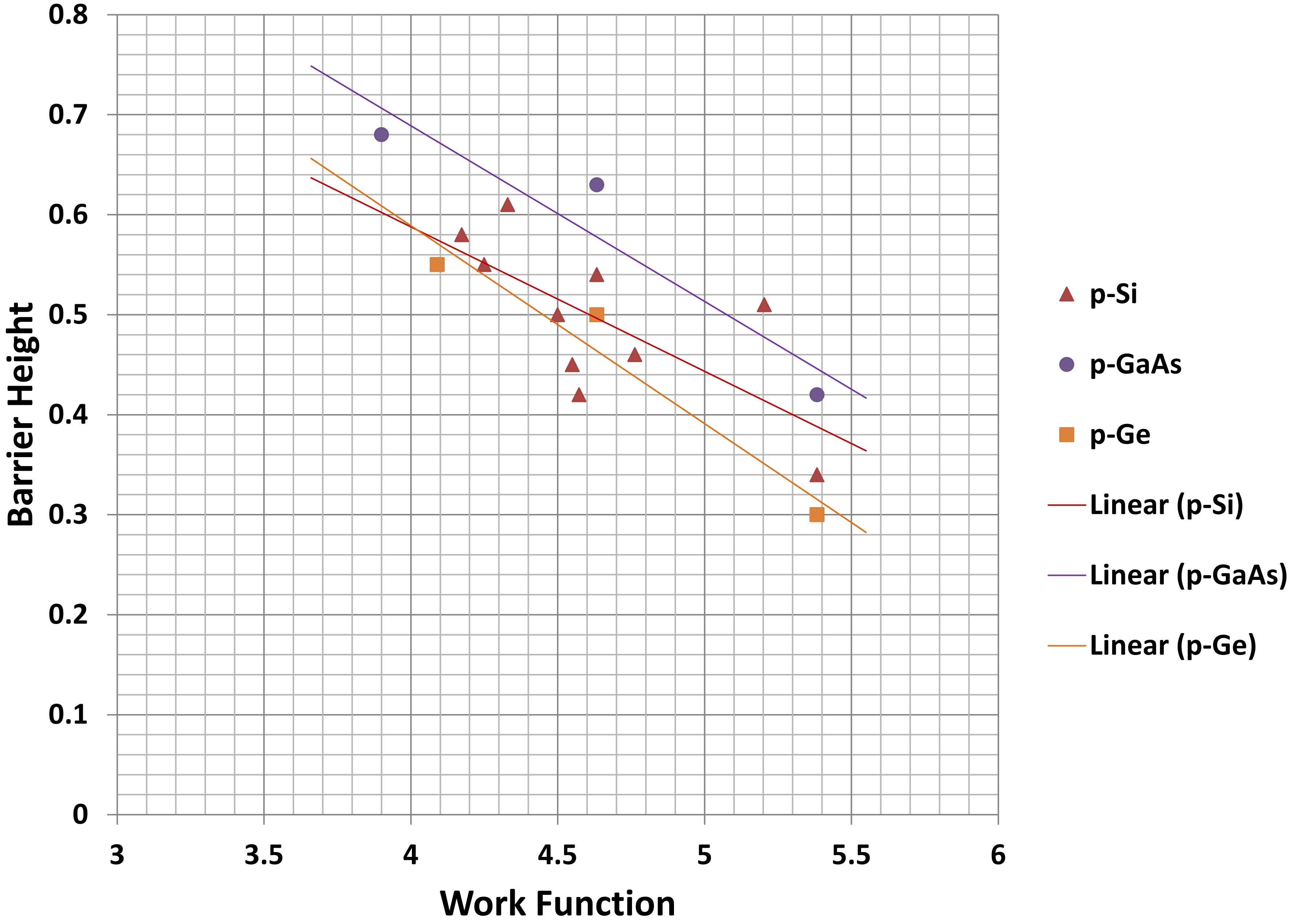
Note that the barrier height is (mostly) independent of bias.





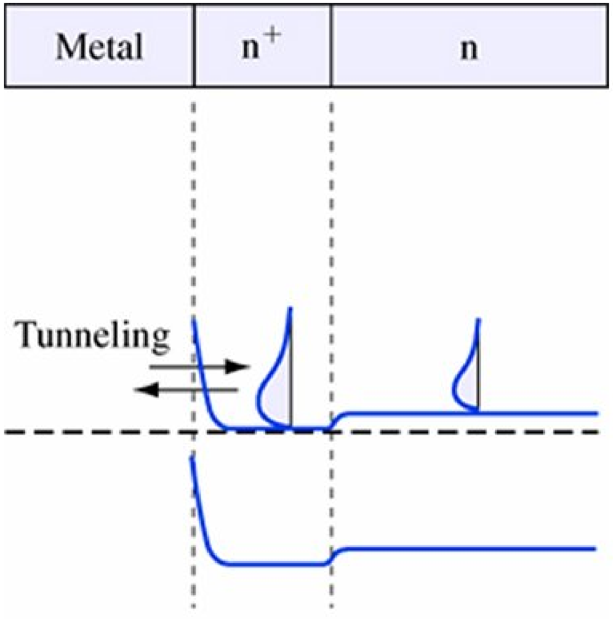
Surface charges resulting from broken bonds, surface contamination or even surface oxidation can dominate band alignment making the EAM invalid. One common case is the “fermi-level pinning” often found in III-As and III-P materials. In these materials, the large numbers of surface states force the surface fermi level to become fixed (pinned) at one energy position regardless of the metal used to contact the surface.

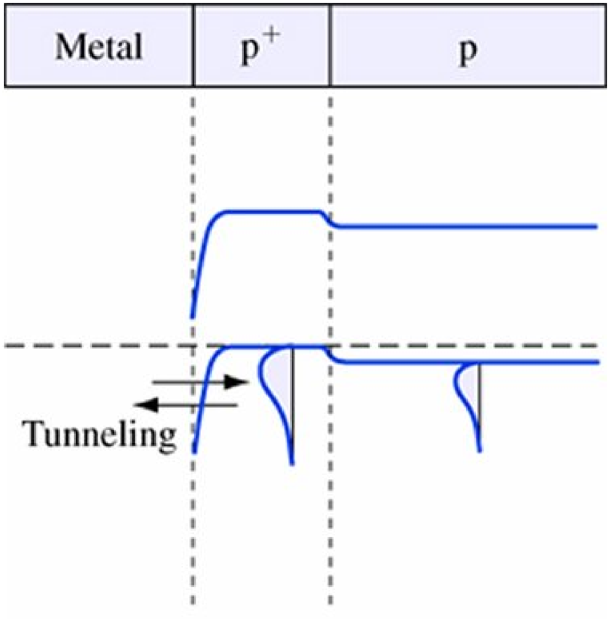

Barrier Height
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
3.5
4
4.5
5
5.5
6
Work Function
▲ n-Si
● n-GaAs
■ n-Ge
Linear (n-Si)
Linear (n-GaAs)
Linear (n-Ge)



Barrier Height
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
3.5
4
4.5
5
5.5
6
Work Function
▲ p-Si
● p-GaAs
■ p-Ge
Linear (p-Si)
Linear (p-GaAs)
Linear (p-Ge)

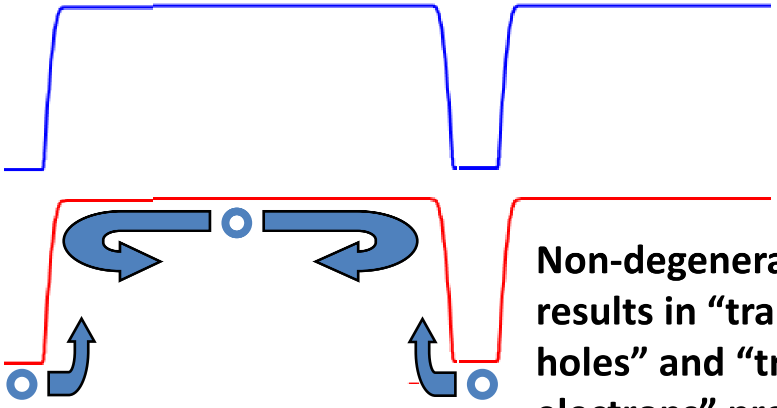
Ohmic Contact Using Highly Doped Semiconductors





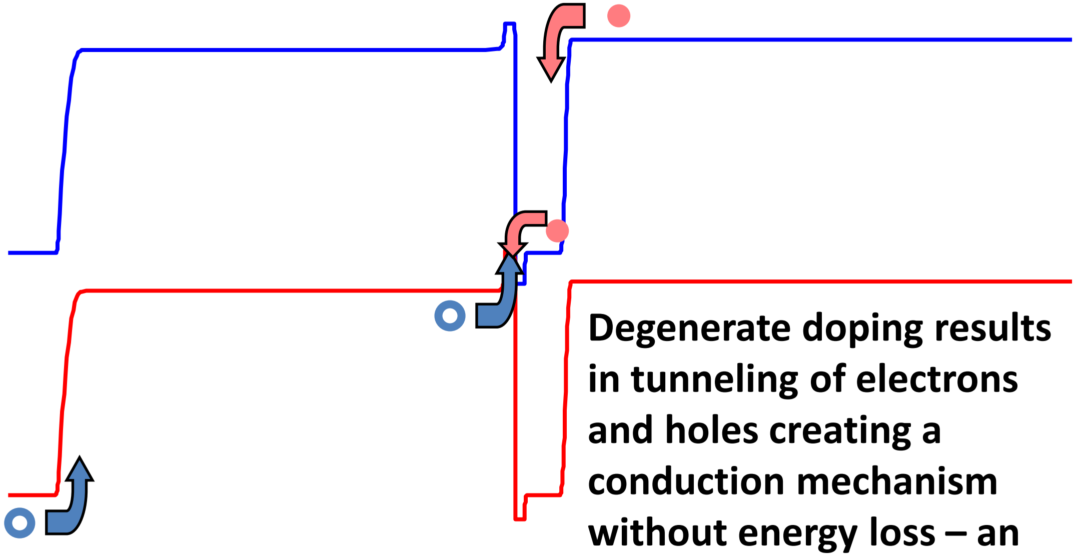
Highly doped contacts result in very small depletion widths and thus small tunneling barriers. These contacts are always ohmic regardless of metal chosen. This is a common method of making contact to a semiconductor device.

Semiconductor to Semiconductor Ohmic Contacts



Non-degenerate doping results in "trapping of holes" and "trapping of electrons" preventing conduction.

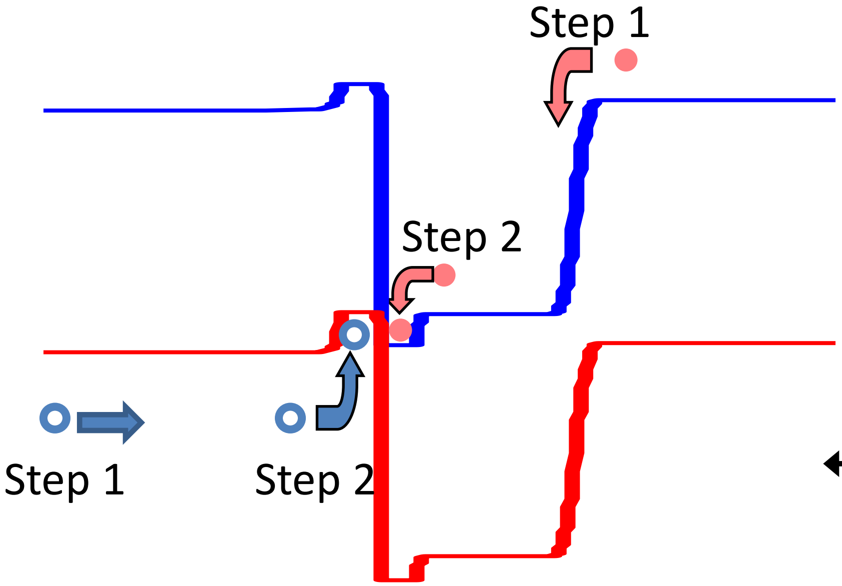
- Normally a p-n junction would create a rectifying junction. In some devices (Tandem solar cells for example), a semiconductor to semiconductor ohmic contact is needed to "series connect" devices.

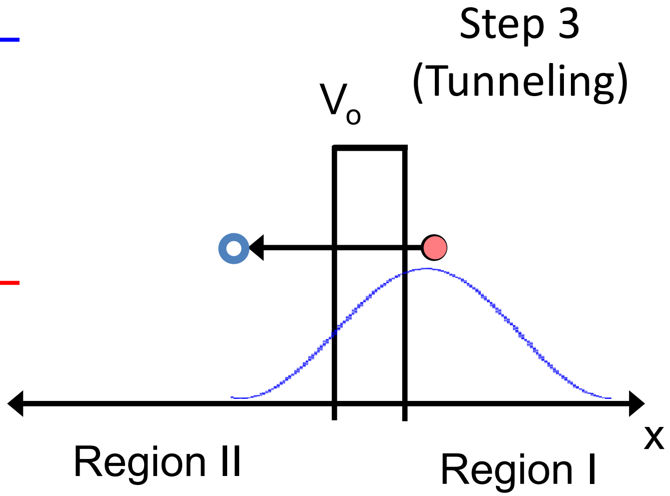


Degenerate doping results in tunneling of electrons and holes creating a conduction mechanism without energy loss – an ohmic contact.

- Using two degenerately doped semiconductors, an ohmic contact can be made between two semiconductors. The mechanism is valence band to conduction band tunneling.

Semiconductor to Semiconductor Ohmic Contacts





Step 1: Collection of the minority carriers by the electric field (p/n junction for example)
Step 2: movement of now majority carriers into the degenerately doped regions.
Step 3: Tunneling of electron into the hole.
Step 4: Neither the electron nor the hole exist anymore (removed from the ends of the device as would be the case for a n ohmic contact metal)

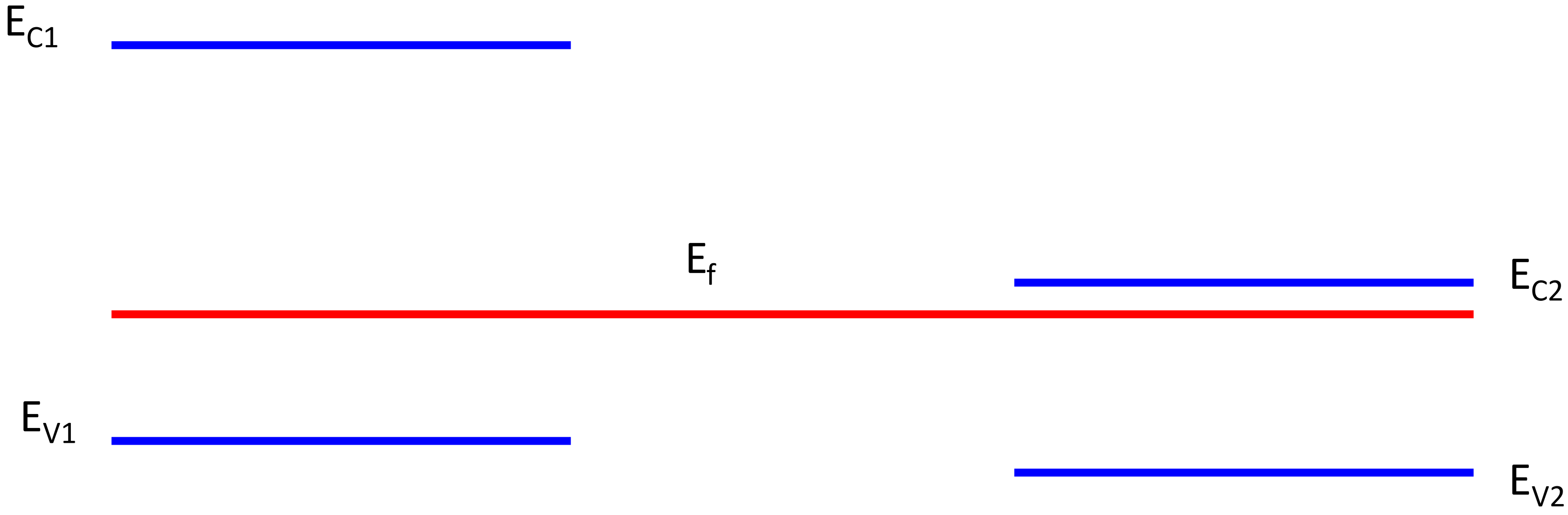
Tunneling Details: Since the electron exists simultaneously at many positions (described by the probability envelope for finding the electron at a given position), the electron has a finite probability to "tunnel" through the potential energy barrier (conduction band barrier) into an empty valance band state (hole) and will do so if the barrier is thin enough. Once through, the electron and hole have been lost effectively emulating an ohmic contact (removal of majority carriers from the semiconductor).

Other types of Collecting Junctions

Heterojunctions

Heterojunctions

Heterojunctions are formed in the same way as homo-junctions, metal-semiconductor and metal-metal junctions.

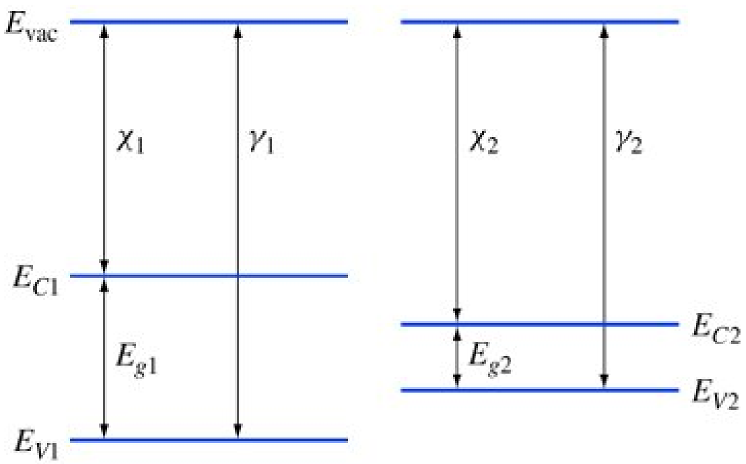


Classifications of Heterojunctions

Definitions:

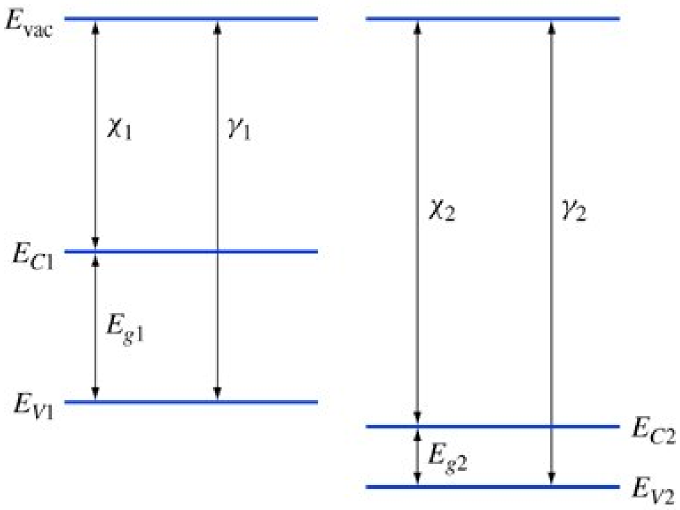
$\chi \equiv$ Electron Affinity – energy needed to free a conduction electron into the vacuum level

$\gamma \equiv$ Ionization Potential – energy needed to free a valence electron into the vacuum level



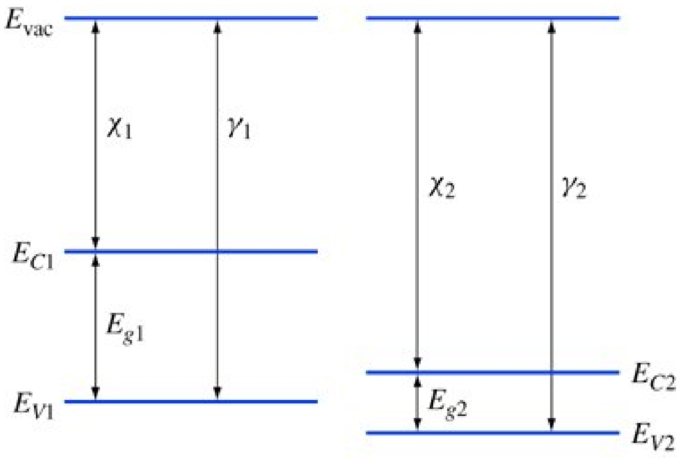
Type I

Type I: Straddling (small Eg material is within large Eg band edges)



Type II

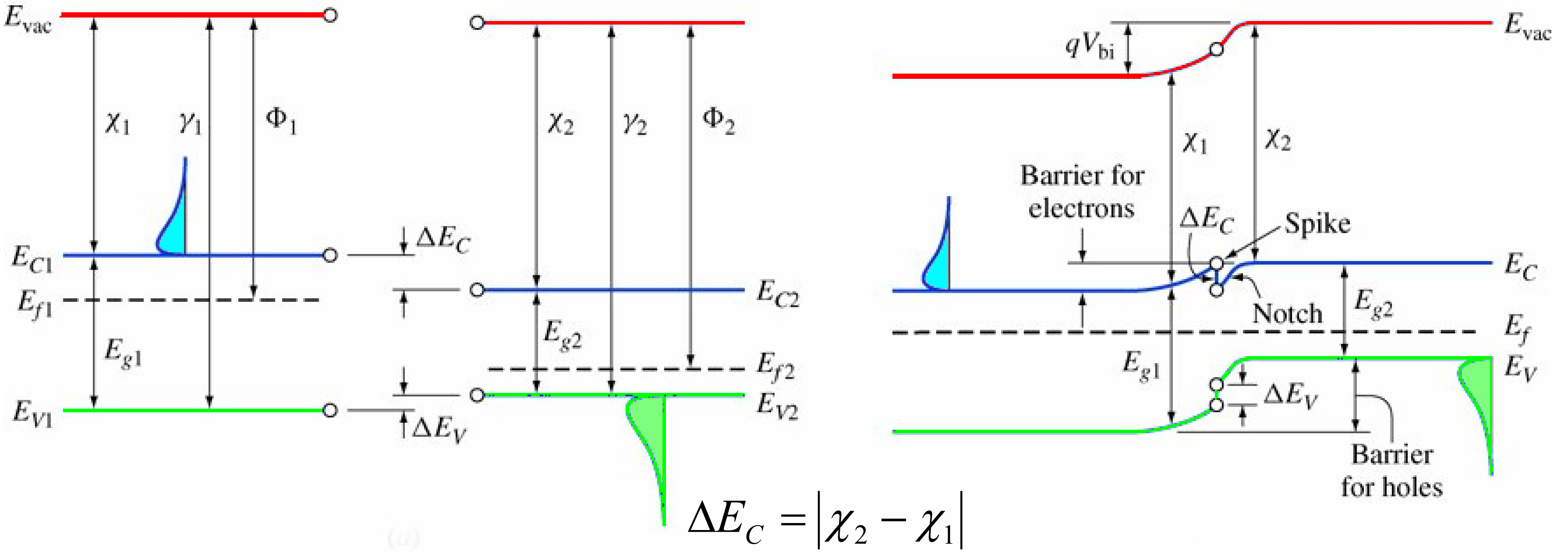
Type II: Staggered (small Eg material is outside of large Eg band edges – either above or below)



Type III

Type III: Broken Gap (One band edge of small Eg is within large Eg band edges – either above or below)

Band Alignment of Heterojunctions (Np)



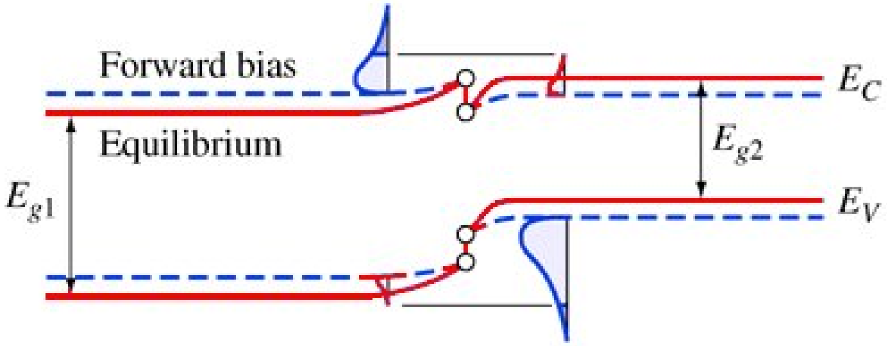
$$\Delta E_C = \left|\chi_2 - \chi_1\right|$$

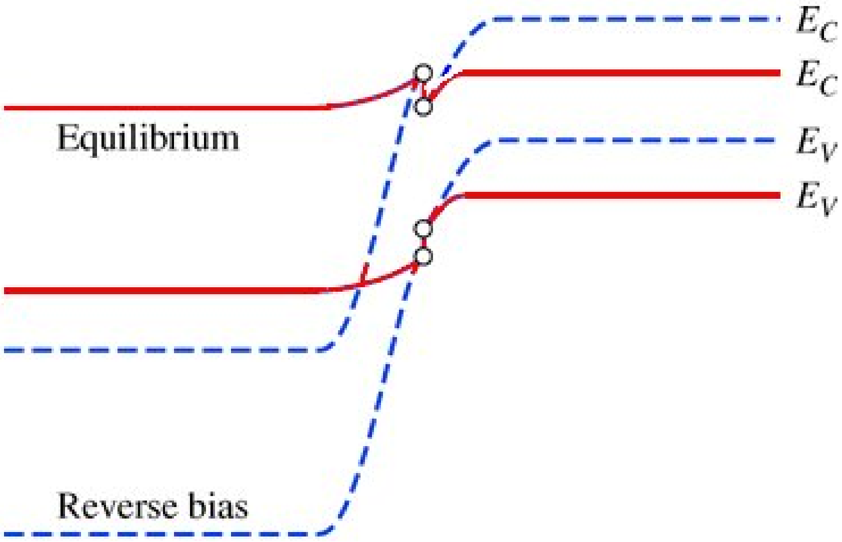
$$\Delta E_V = \left|\gamma_2 - \gamma_1\right| \text{ where } \gamma_i = \chi_i + E_{Gi}$$

Some observations to aid drawing energy band diagrams:

- In equilibrium, E_f is flat (constant – no energy transfer / no current).
- The vacuum level is continuous even though E_C and E_V may not be.
- Drift and Diffusion currents balance in equilibrium just like a homojunction.
- Electrons may be easier to inject (lower barrier) than Holes or vise versa making these junctions inherently asymmetric (useful in both transistors and optical devices).
- The "Triangular Well" can be used to trap carriers and can be exploited in both transistors (can create a high density electron channel) and in optical devices (localizing carriers to enhance radiative recombination).

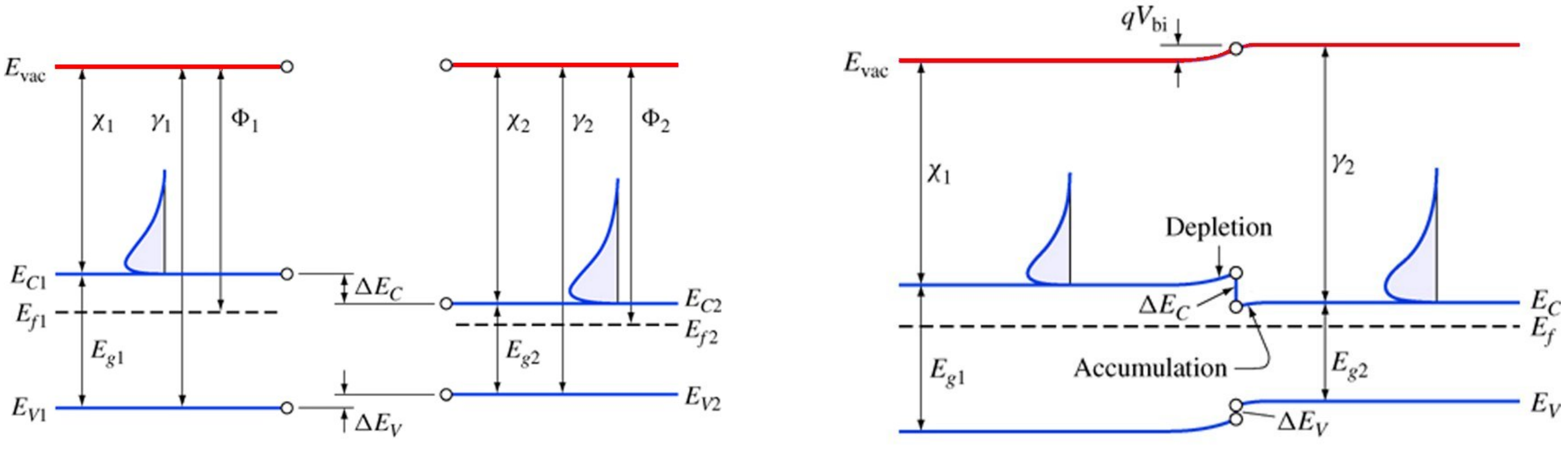
Band Alignment of Heterojunctions (Np) under Bias





- Electrons may be easier to inject (lower barrier as in this case) than Holes or vise versa making these junctions inherently asymmetric (useful in both transistors and optical devices).
  - Heterojunction Emitter-Base junctions in Heterojunction Bipolar Transistors result in increased emitter injection efficiency using this effect

Band Alignment of Heterojunctions (Nn)



$$\Delta E_C = \left|\chi_2 - \chi_1\right|$$

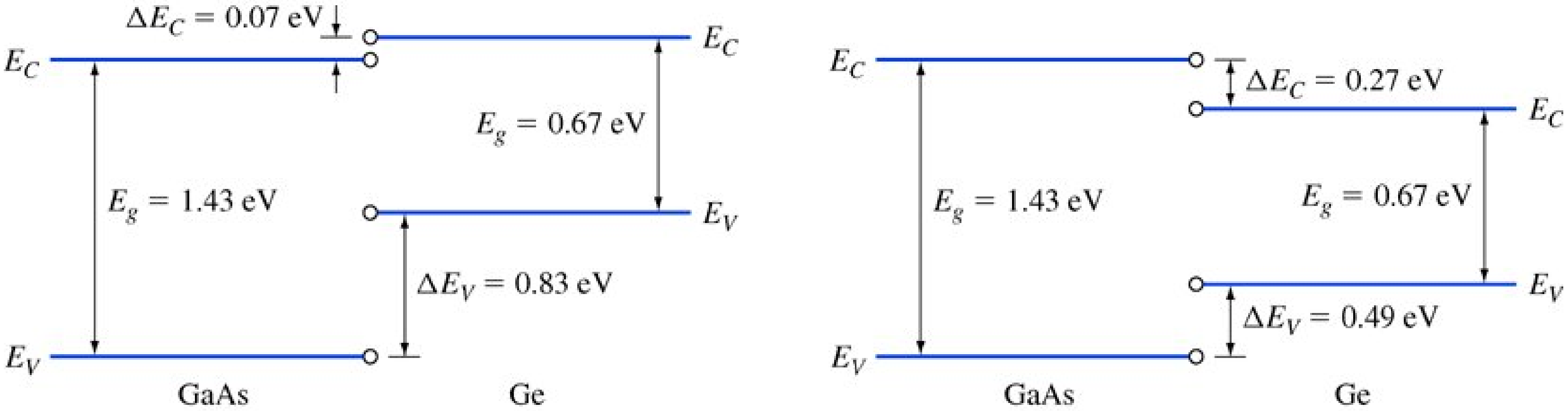
$$\Delta E_V = \left|\gamma_2 - \gamma_1\right|$$

Injection of electrons in a Nn device can result in “ballistic electron flow”. Ballistic electrons are electrons that when injected into the low bandgap material from the large bandgap material instantly gain kinetic energy equal to ΔE_C thus instantly accelerating. While this is a short range effect, it can be utilized to achieve very fast devices.

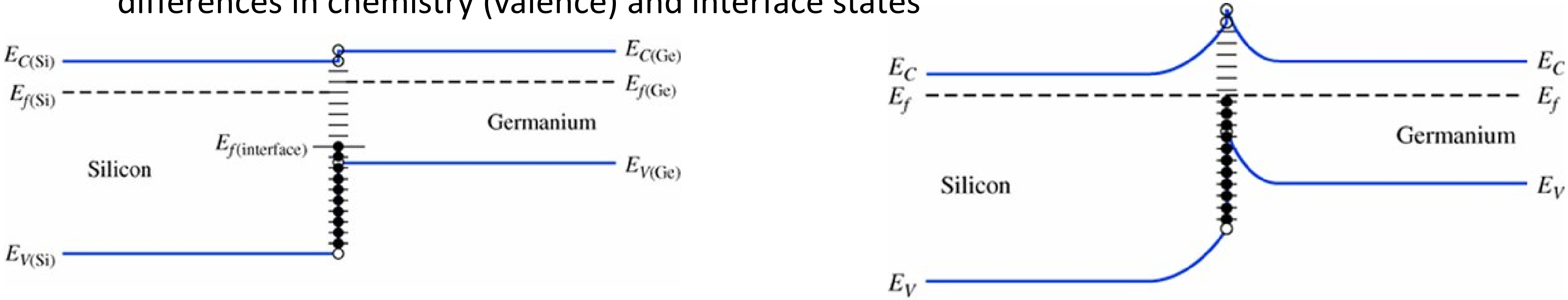
Validity of EAM for Real Heterojunctions

- EAM model is best followed when maintaining similar chemical and crystal structures (i.e. GaAs/AlGaAs/InGaAs or InP/GaP/AlP etc…)

- Dissimilar valance and/or interfacial states can lead to deviations from the ideal EAM model.



Predicted band alignment (left) does not match with experiment (right) due to significant differences in chemistry (valence) and interface states



Even in covalent heterojunctions interface states can greatly disrupt EAM expected results leading to unexpected band bending and carrier wells (valence band well shown here).

Validity of EAM for Real Heterojunctions

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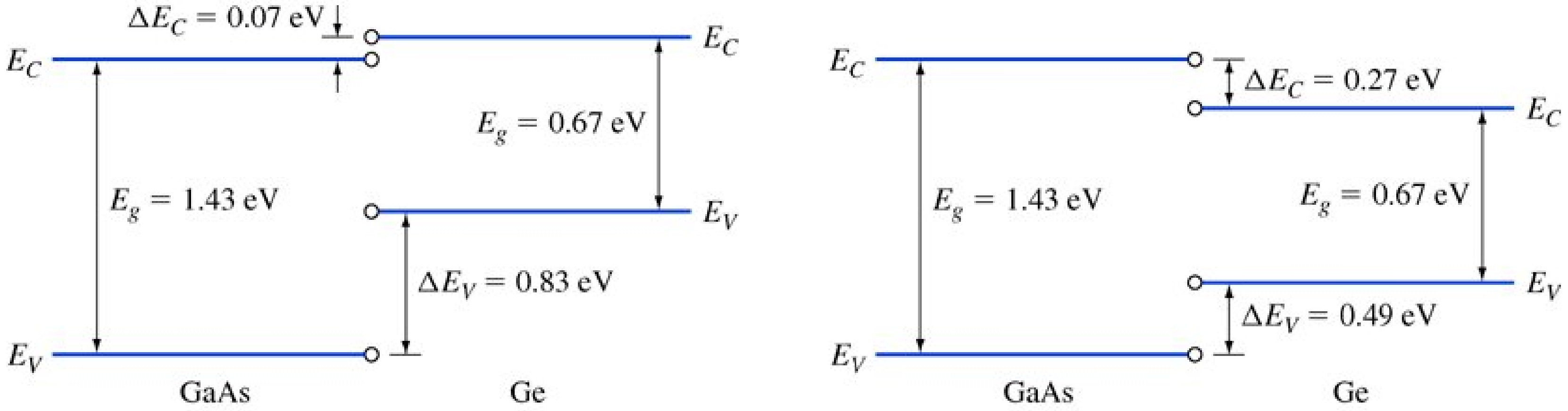
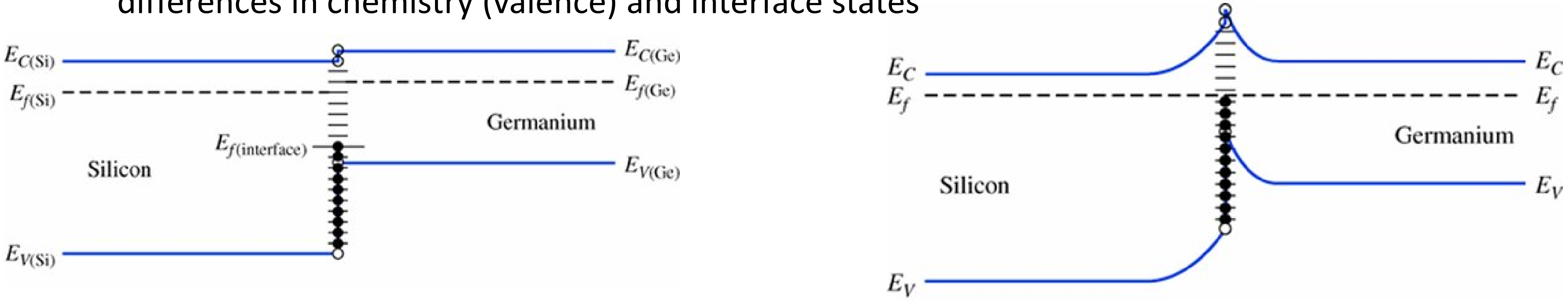
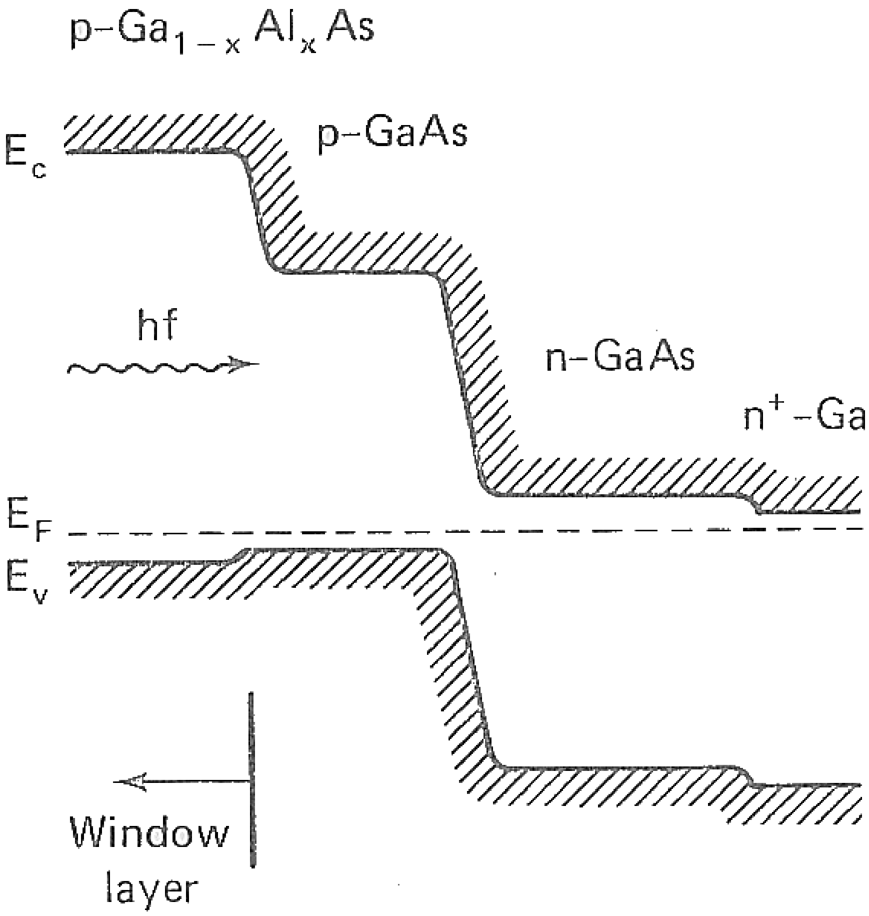


Predicted band alignment (left) does not match with experiment (right) due to significant differences in chemistry (valence) and interface states



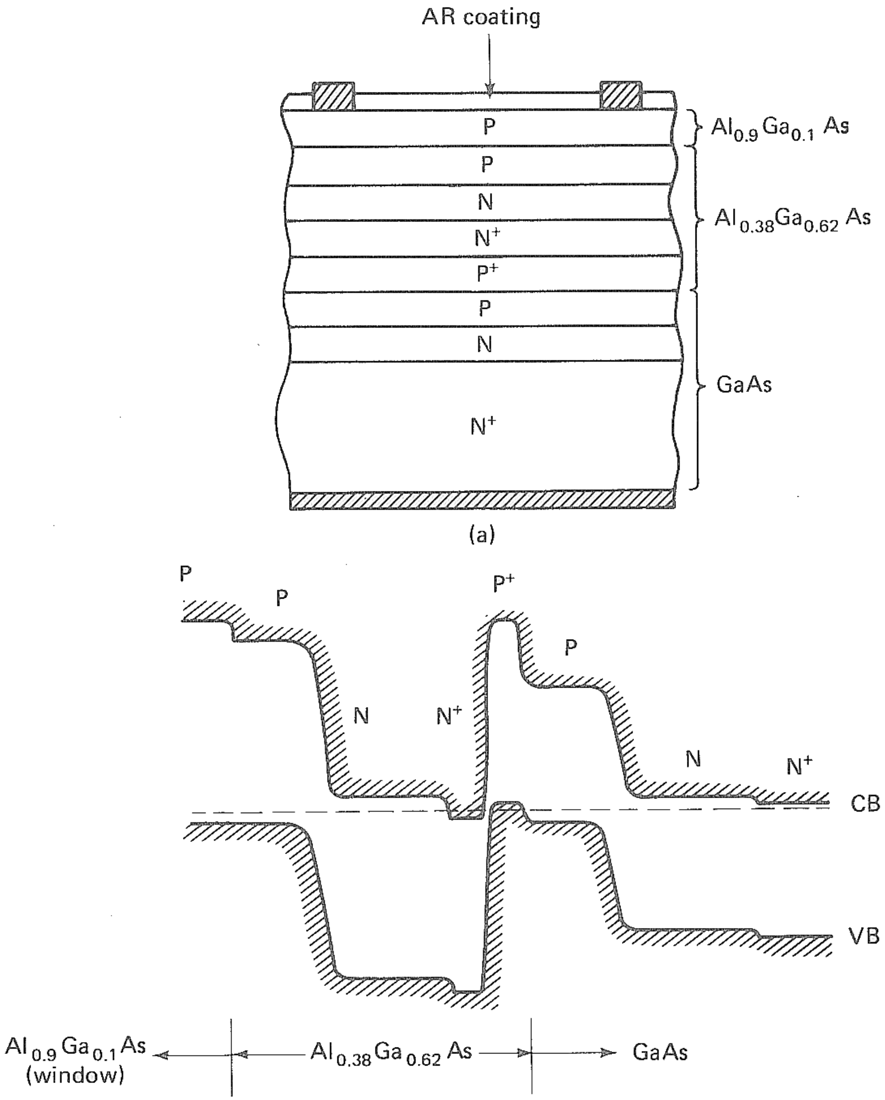
Even in covalent heterojunctions interface states can greatly disrupt EAM expected results leading to unexpected band bending and carrier wells (valence band well shown here).

Examples of uses of Heterojunctions in Solar Cells



Window layer minimizes surface recombination

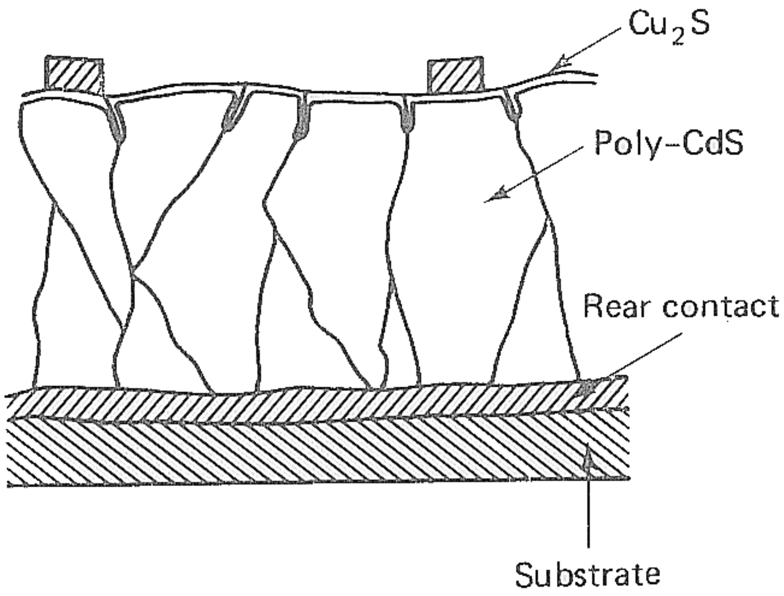
Examples of uses of Heterojunctions in Solar Cells

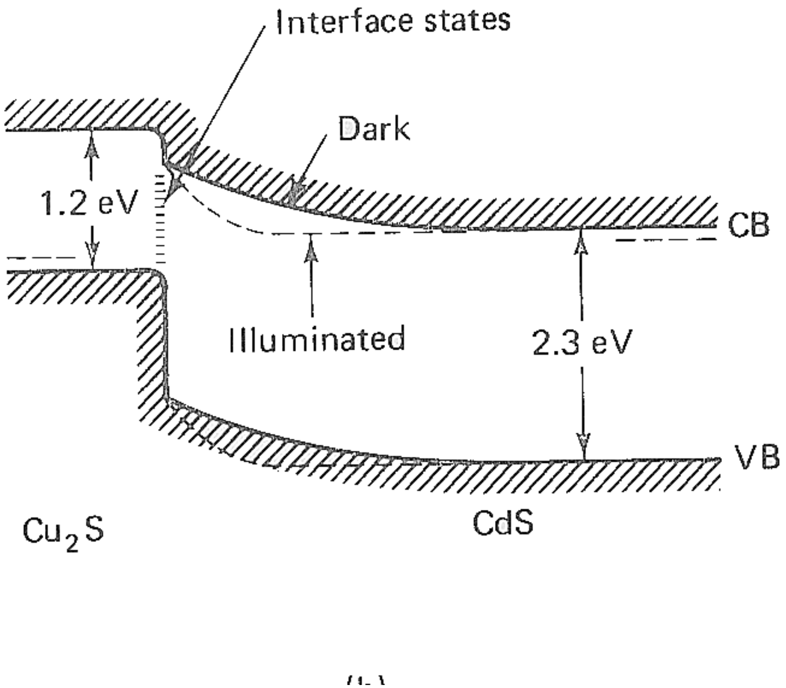


(b)

Tunnel junction makes a semiconductor-semiconductor ohmic contact between sub-cells in tandem devices.

Examples of uses of Heterojunctions in Solar Cells



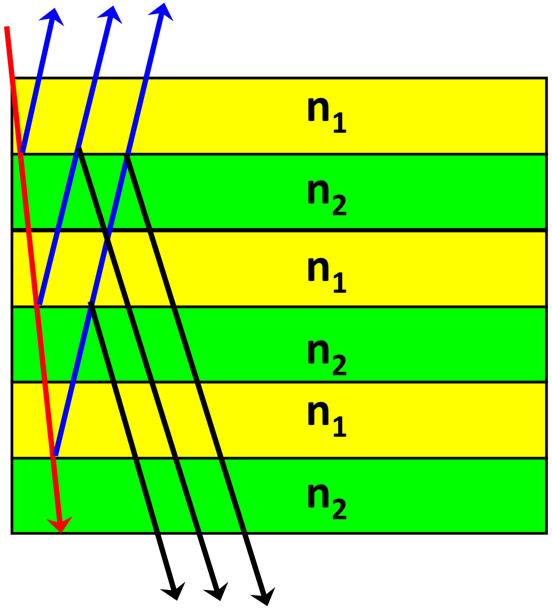


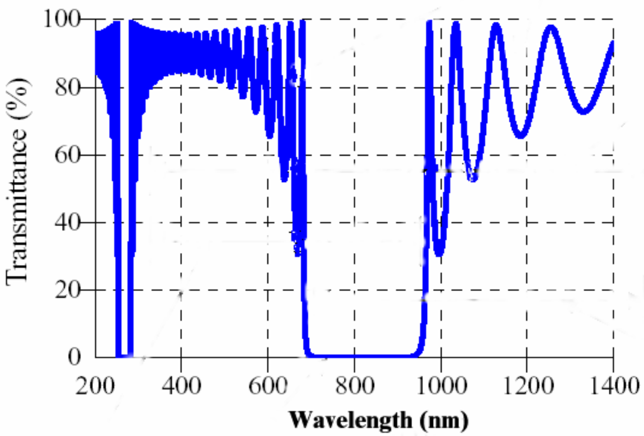
Heterojunctions can also be the collecting junction

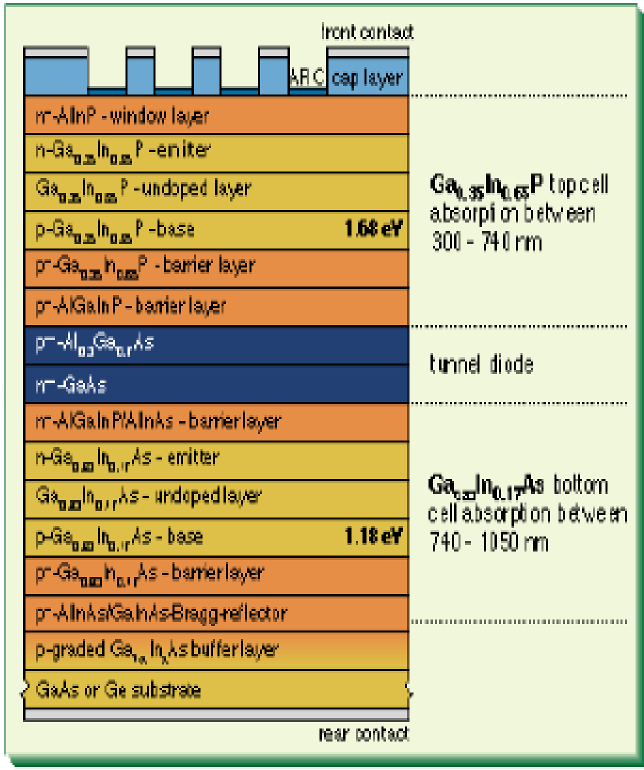
Examples of uses of Heterojunctions in Solar Cells

Optical Benefits of Heterojunctions

Can you make a buried mirror and still maintain the crystalline structure to grow the solar cell on? – Yes – Bragg Mirrors use slight changes in optical index of refraction but 10-80 alternating layers to create crystalline mirrors

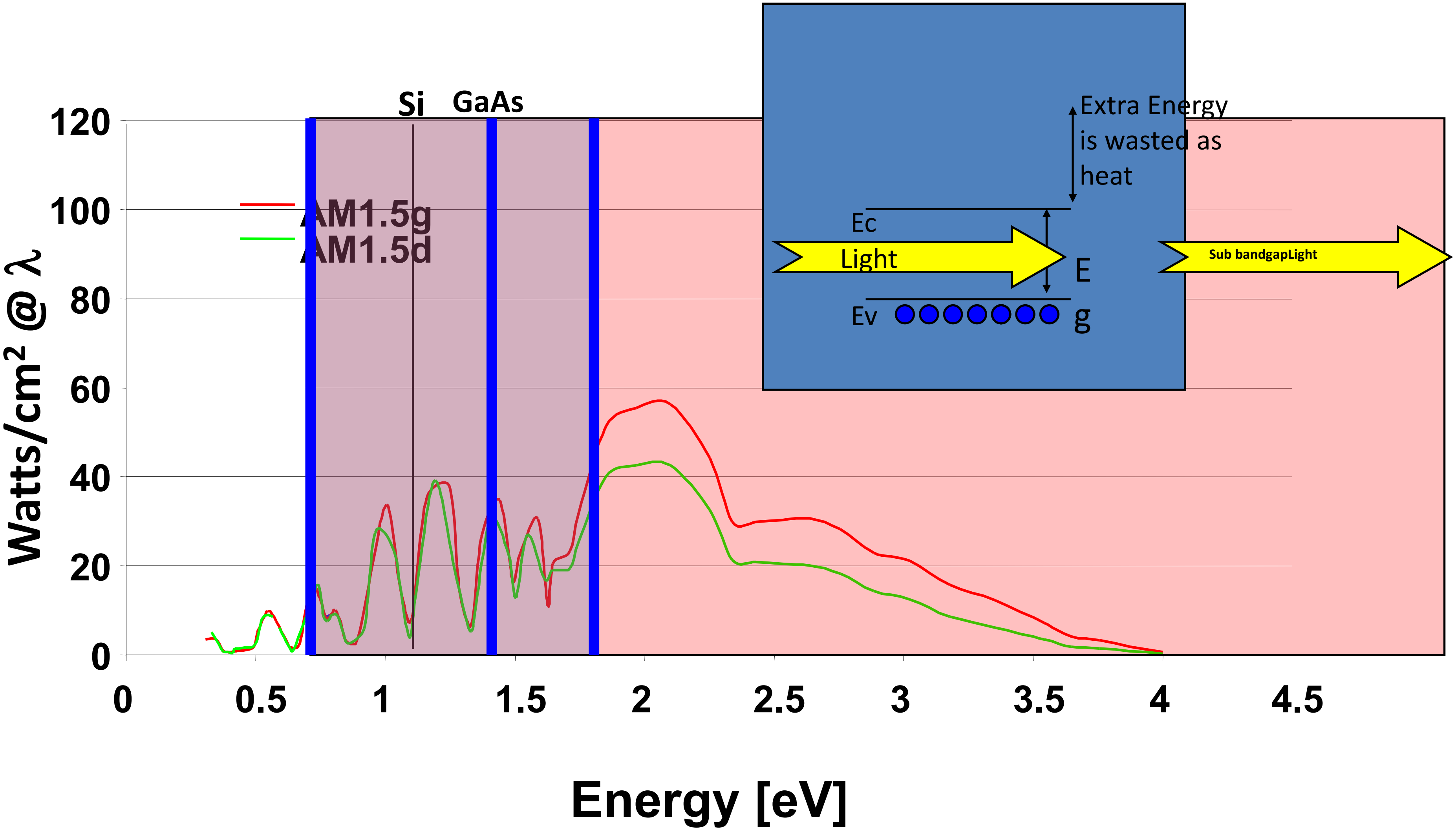




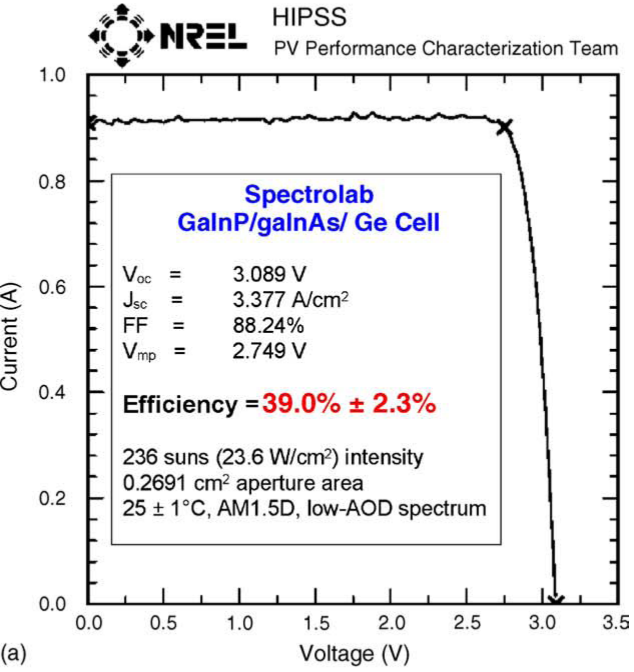


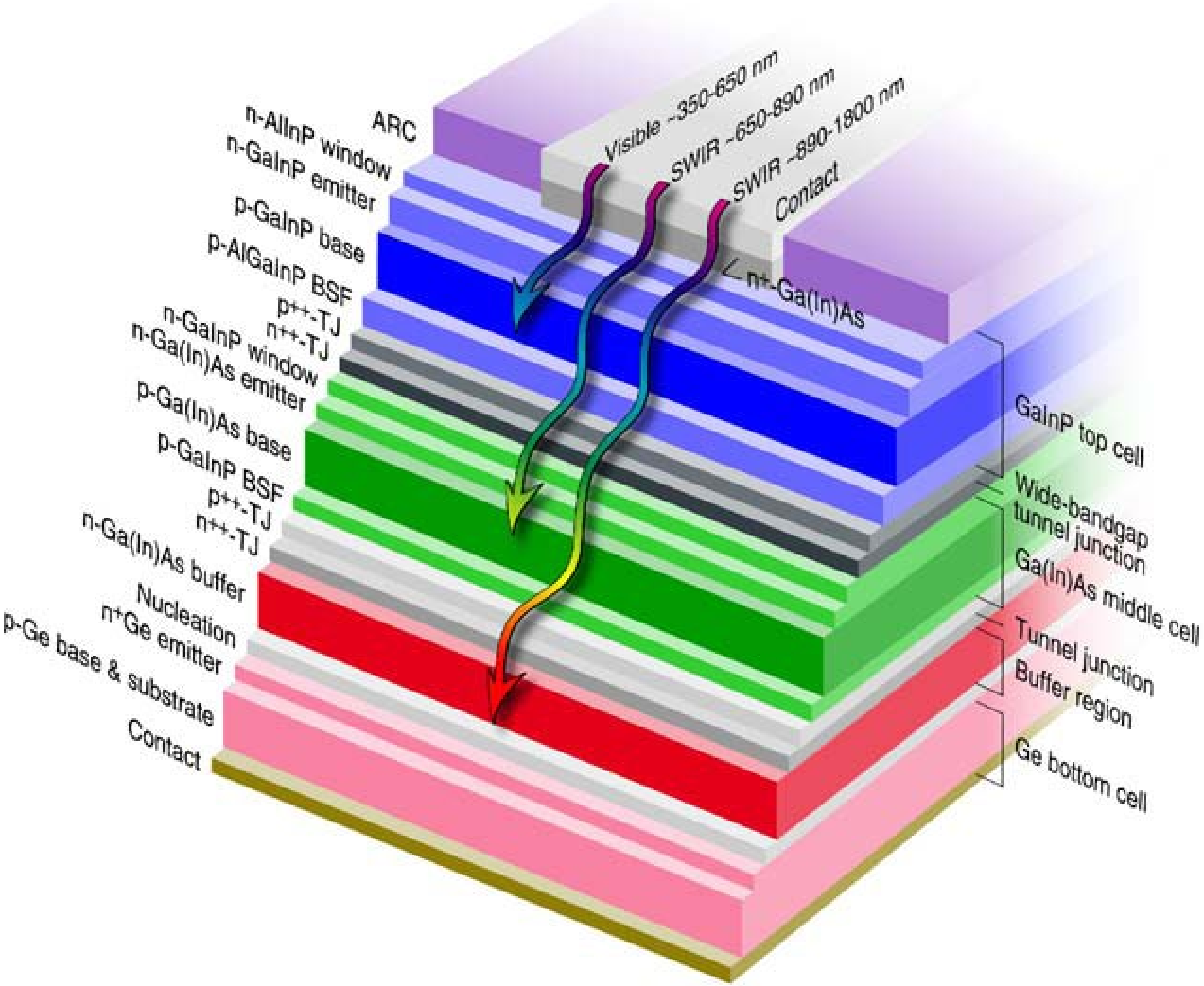
Two junction tandem solar cells use this technique to achieve a double chance for optical absorption.

Why InGaN?


Si
GaAs
120
100
80
60
40
20
0
Watts/cm^2 @ λ
AM1.5g
AM1.5d
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Energy [eV]
Extra Energy is wasted as heat
Ec
Light
E
g
Ev
Sub bandgapLight

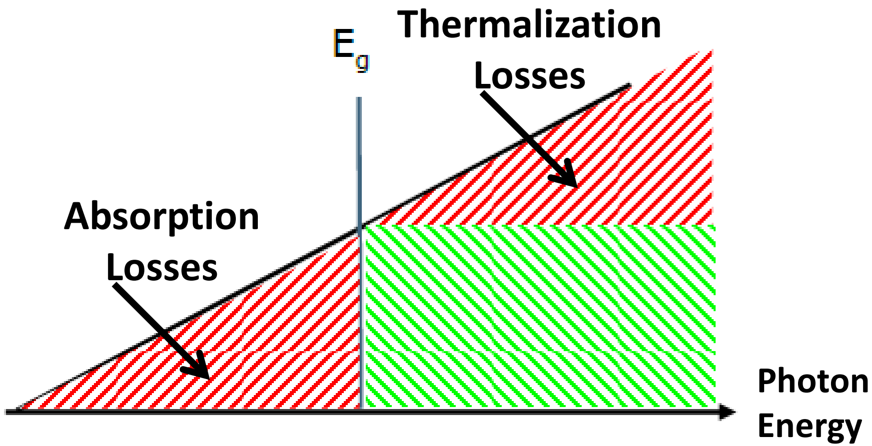
Ultra-high Performance III-V Solar Cells

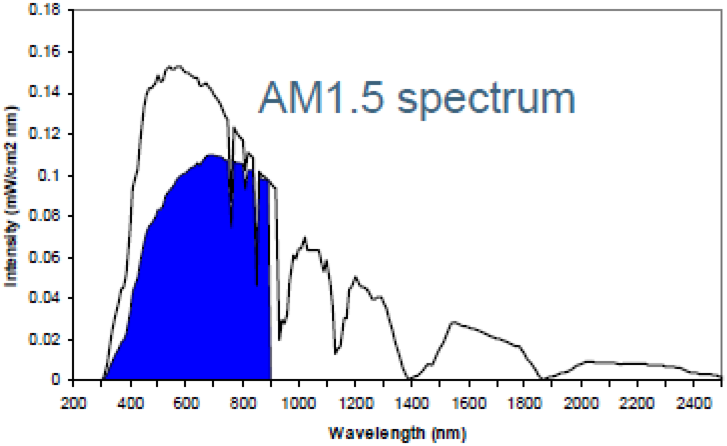




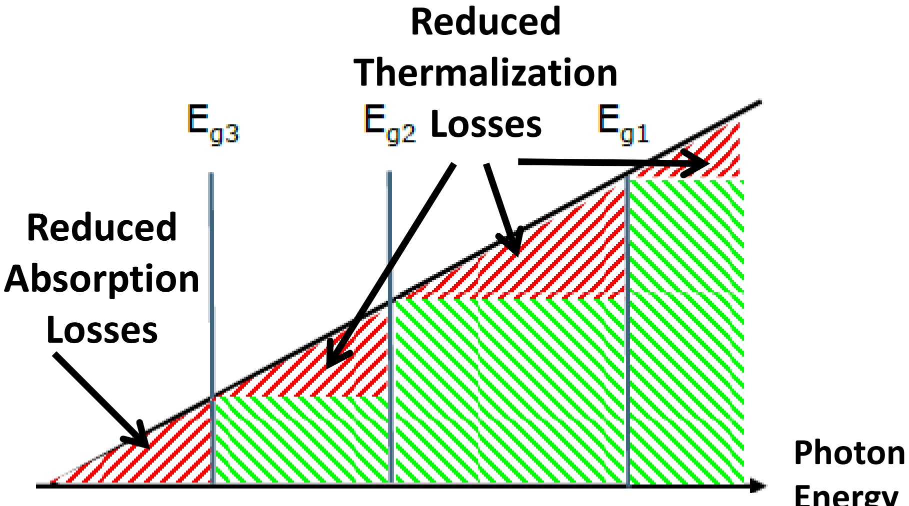
Why Use a Tandem Solar Cell?

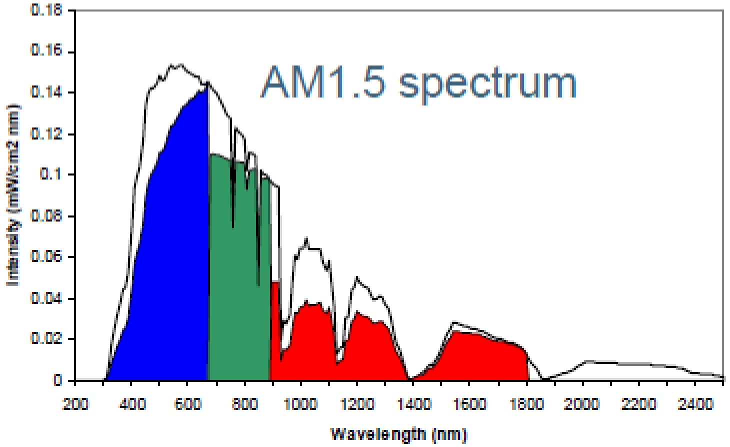
Single Junction

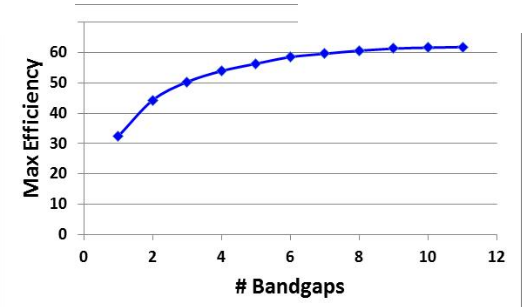




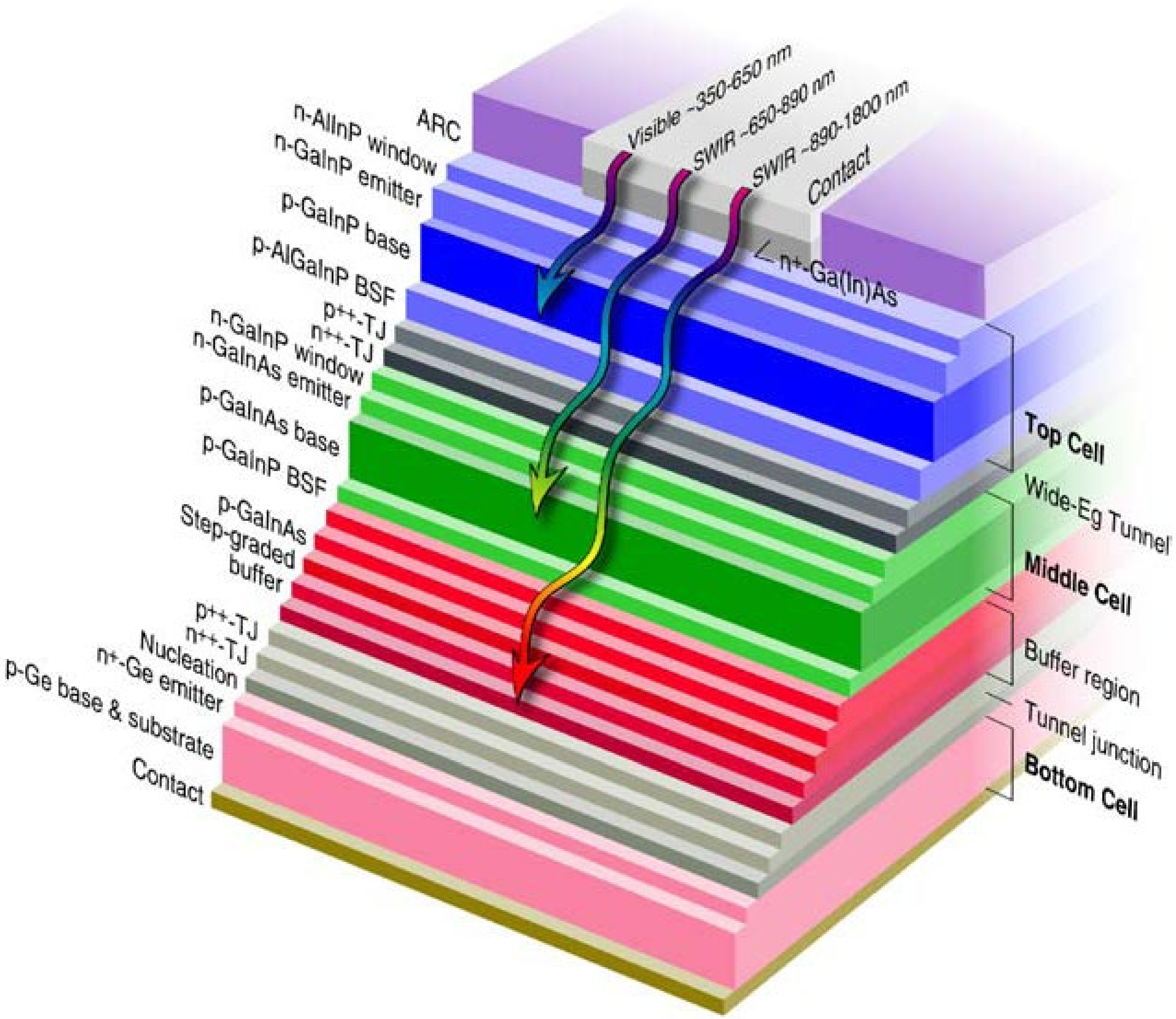
Multiple Junctions







Ultra-high Performance III-V Solar Cells



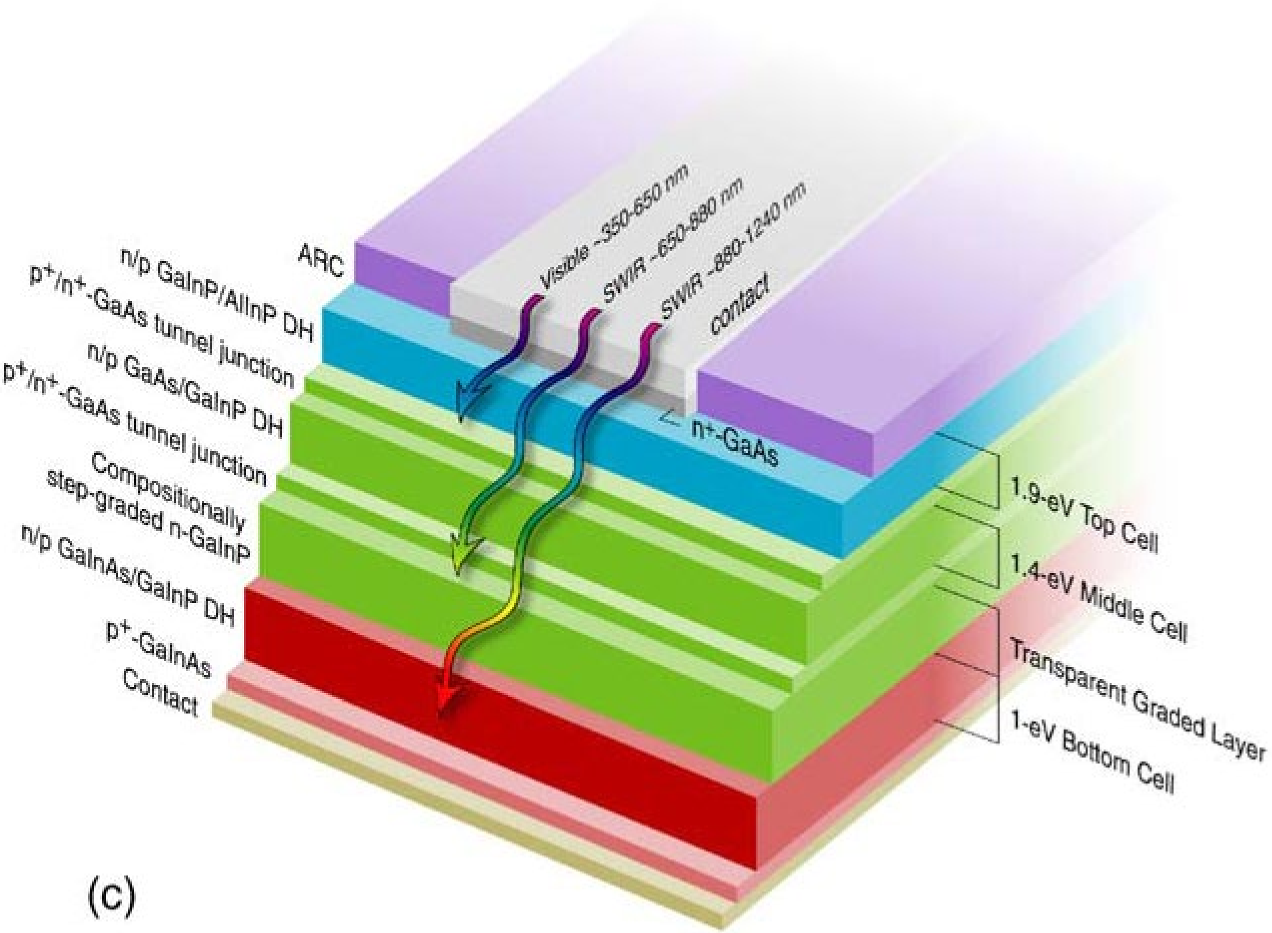
Optimal Energy Bandgaps

Efficiency and band gap for tandem solar cells at 1000X

# of band gaps	Eff. 1000X AM1.5	Approximate Energy Band gaps (eV)
2	44.3%	1.0, 1.8
3	50.3%	1.0, 1.6, 2.2 **0.66, 1.42, 1.88 for Ge/GaAs/$Ga_{0.51}In_{0.49}P$**
4	53.9%	0.8, 1.4, 1.8, 2.2
5	56.3%	0.6, 1.0, 1.4, 1.8, 2.2
6	58.5%	0.6, 1.0, 1.4, 1.8, 2.0, 2.2
7	59.6%	0.6, 1.0, 1.4, 1.8, 2.0, 2.2, 2.6

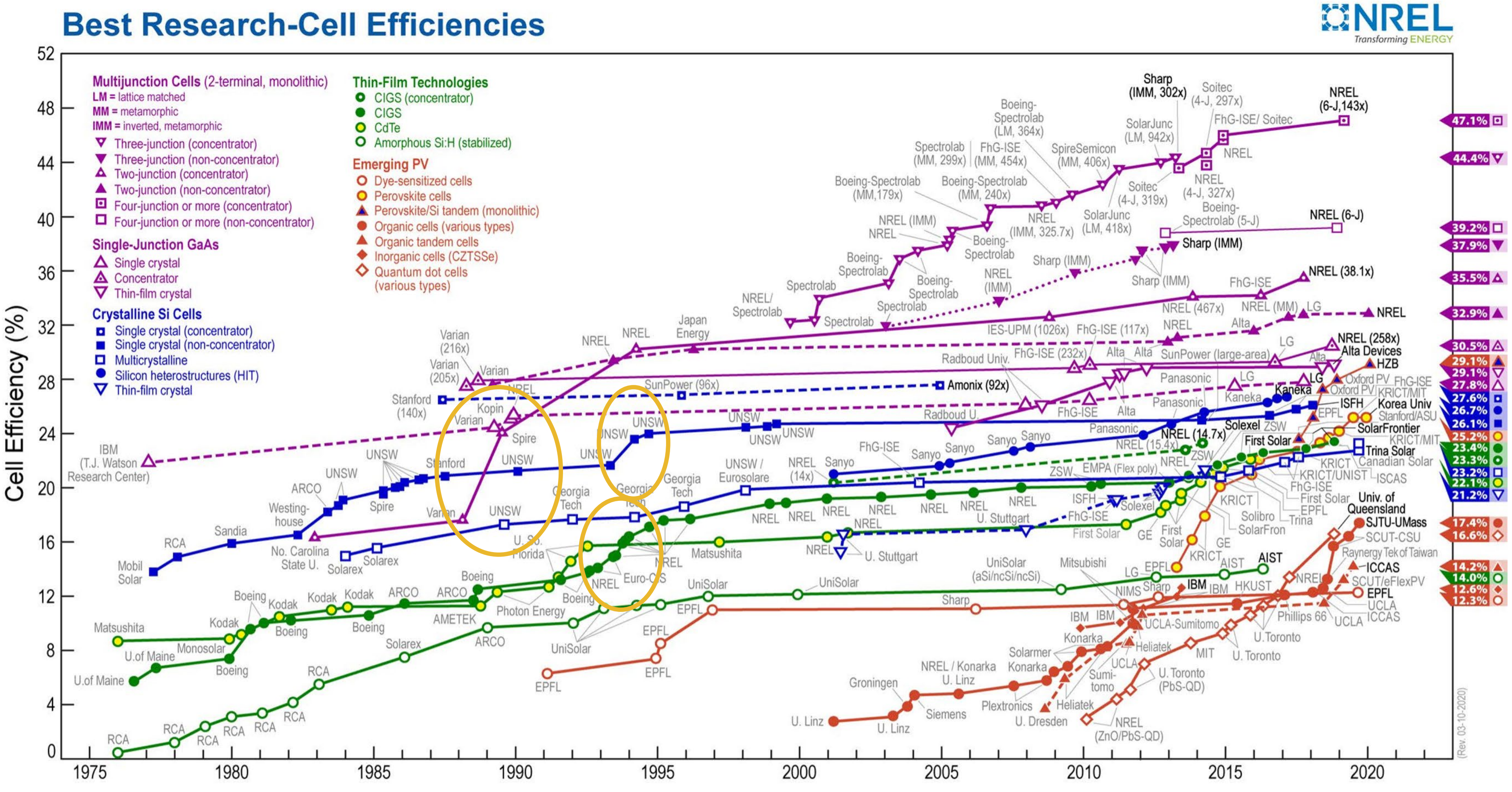
A. Bennett and L. C. Olsen, “Analysis of Multiple-Cell Concentrator/Photovoltaic Systems”, Proceedings of the 13th Photovoltaic Specialists Conference, 868 – 873, (1978).

Ultra-high Performance III-V Solar Cells



Opportunities for III-Nitride Solar

Why do we need another solar material?



Ga Tech ECE 4833

Dr. Alan Doolittle

Effect of Polarity on Heterojunction: Electrostatic Boundary Condition

Some semiconductors have net charges across their unit cells creating static or strain induced polarization.

Gauss's Law Normal to an interface:

$$\nabla \bullet D = \rho \quad \text{or} \quad \nabla \bullet (\varepsilon E + P) = \rho$$

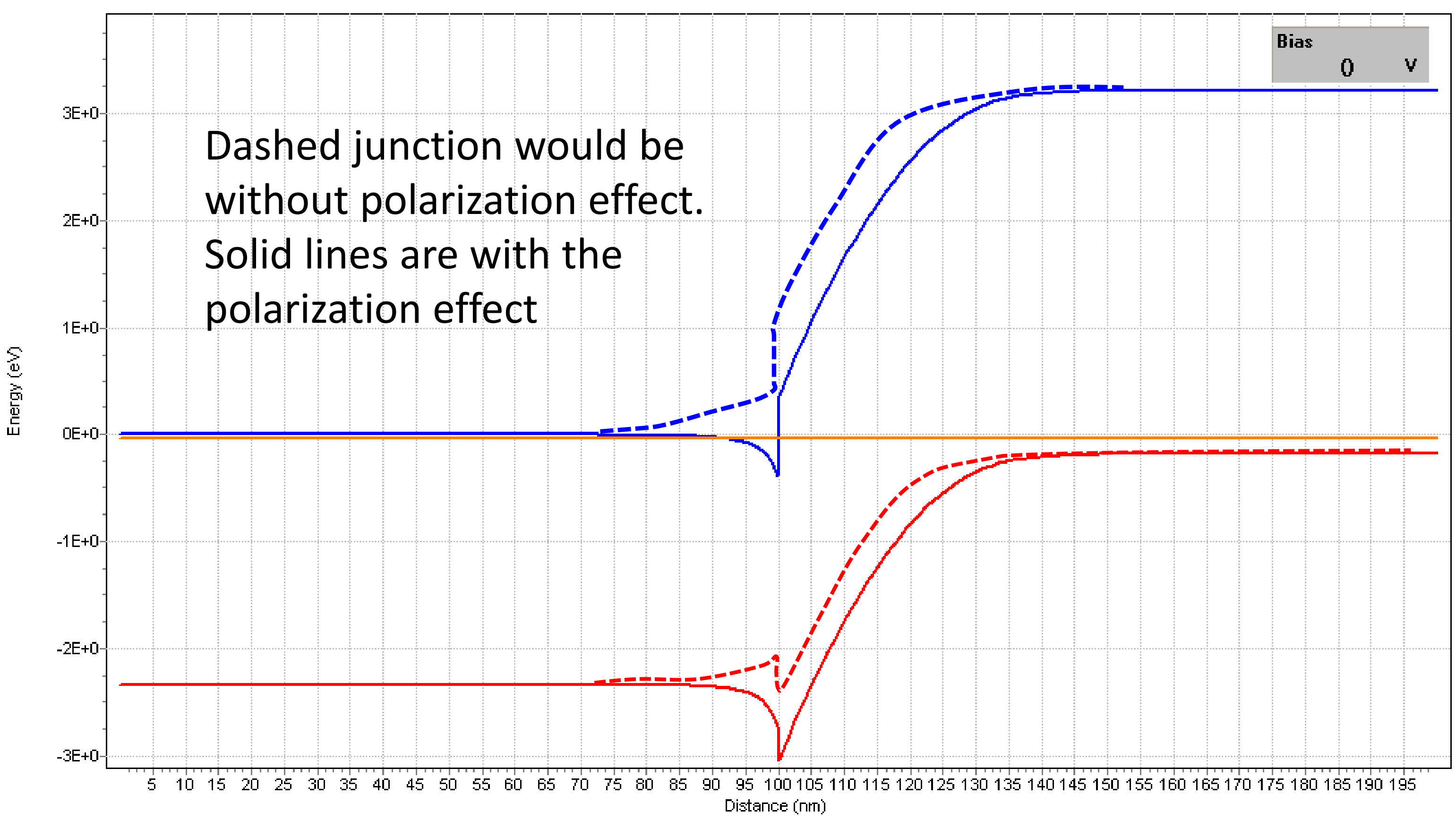
1D: $(\varepsilon_{semi} E_{semi} + P_{semi}) - (\varepsilon_{substrate} E_{substrate} + P_{substrate}) = \rho_{sheet}$

1D: $(P_{semi} - P_{substrate}) + (\varepsilon_{semi} E_{semi} - \varepsilon_{substrate} E_{substrate}) = \rho_{sheet}$

Polarization discontinuities can result in either “free charge at the interface” (ρ) or differences in electric displacement fluxes (and thus energy band bending) or both. Small polarization discontinuities are initially compensated by the energy bands bending but larger discontinuities require free charge to be created at the interface.

Examples of uses of Heterojunctions in Solar Cells

Polar Semiconductors Heterojunctions can be beneficial / detrimental to carrier collection.
Example: InGaN/GaN



Dashed junction would be without polarization effect. Solid lines are with the polarization effect

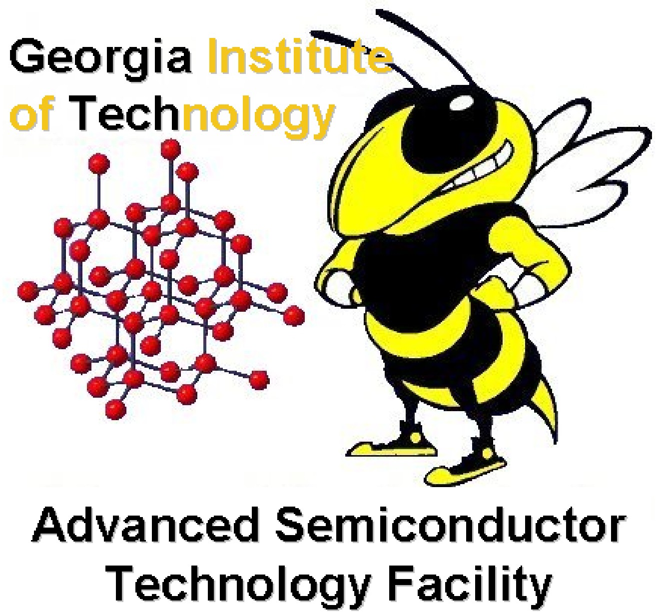
Outline

- **Why InGaN?**
- **Comments on InN Bandgap Controversy**
- **Opportunities and Challenges for InGaN in Photovoltaics**
  - **Advantages and Disadvantages of the InGaN System**
  - **Performance Limitations for InGaN-GaN Heterojunction Solar Cells**
  - **Bringing some reality to the myth of a graded solar cell**
- **Comments on Epitaxy Issues**

- **Conclusions**
  - **InGaN is a promising Photovoltaic material**
  - **A totally different approach is required for InGaN PV**
  - **Major improvement in P-type GaN and/or InGaN is the key to solar cell success**
  - **InN is not currently a viable option for photovoltaics but *InGaN* is**

Examples of complications of epitaxy and strain/defects can have on Heterojunction Solar Cells

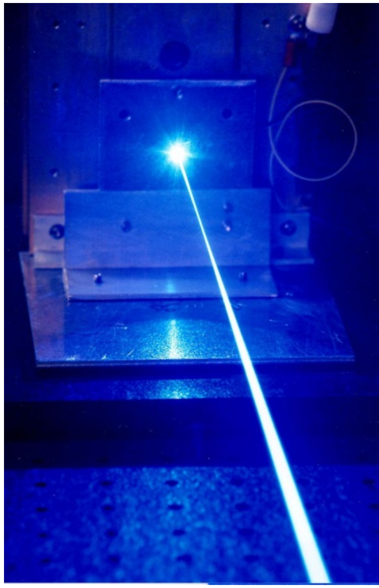
Extremely Immature PV technology - InGaN: A Material with Photovoltaic Promise and Challenges



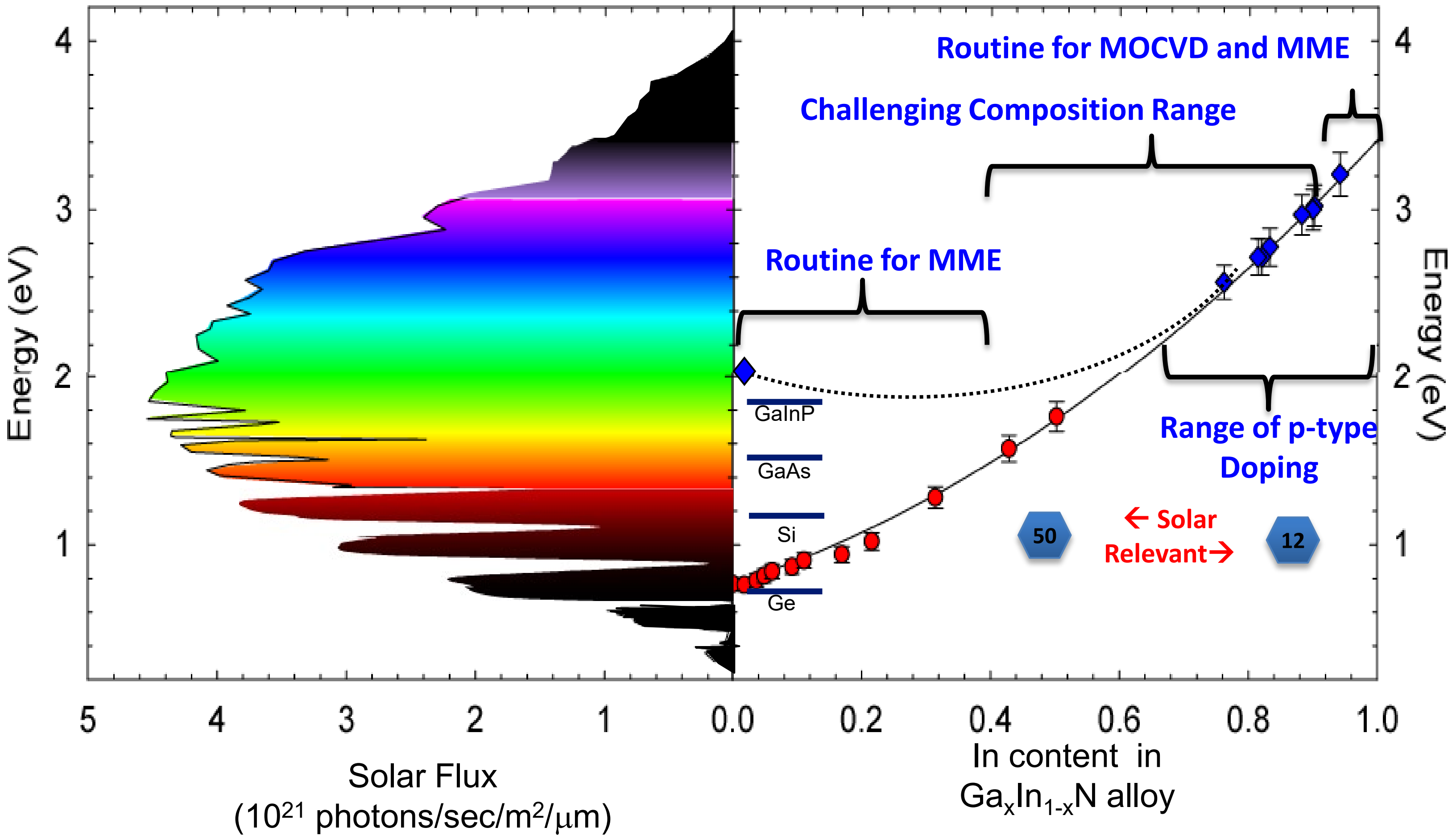
Opportunities for III-Nitride Solar

Why do we need another solar material?

- Economic/Market Reasons:
    - Supporting Markets already exist
        - Second only to Si, III-Nitrides are the highest volume semiconductor market
            - Blue and UV LEDs
            - Blue and UV Lasers
            - White Lighting
            - Power Switching (higher efficiency)
            - RF Electronics
    - Existing infrastructure
        - Falling Price Structure
    - III-Nitrides are substantially cheaper and safer to produce than traditional III-V’s



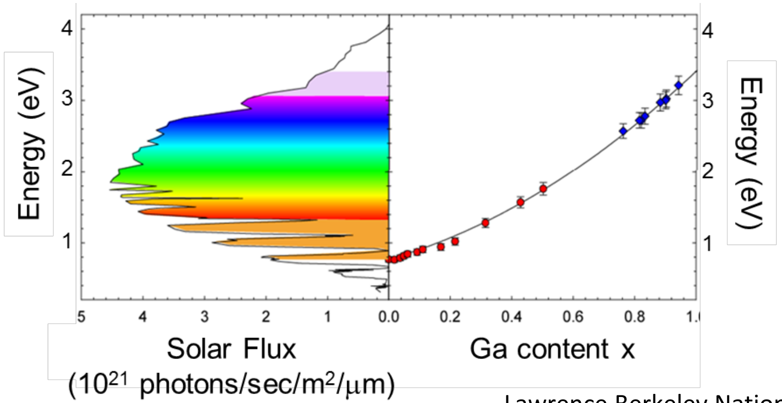
Summary of InGaN Challenges for Photovoltaics



Advantages and Challenges of InGaN for PV

Advantages

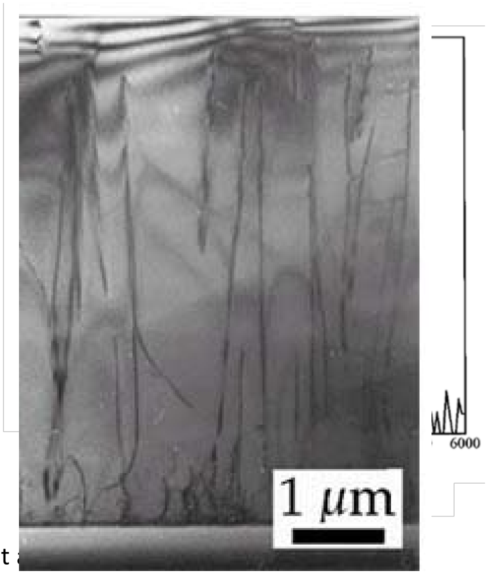
- Tunable bandgap
- High absorption coefficients
- Strong piezoelectric & polarization effects
- Can be an "add on" to other cells
- Existing $6 Billion+ dollar industry with existing Infrastructure



Lawrence Berkeley National Lab

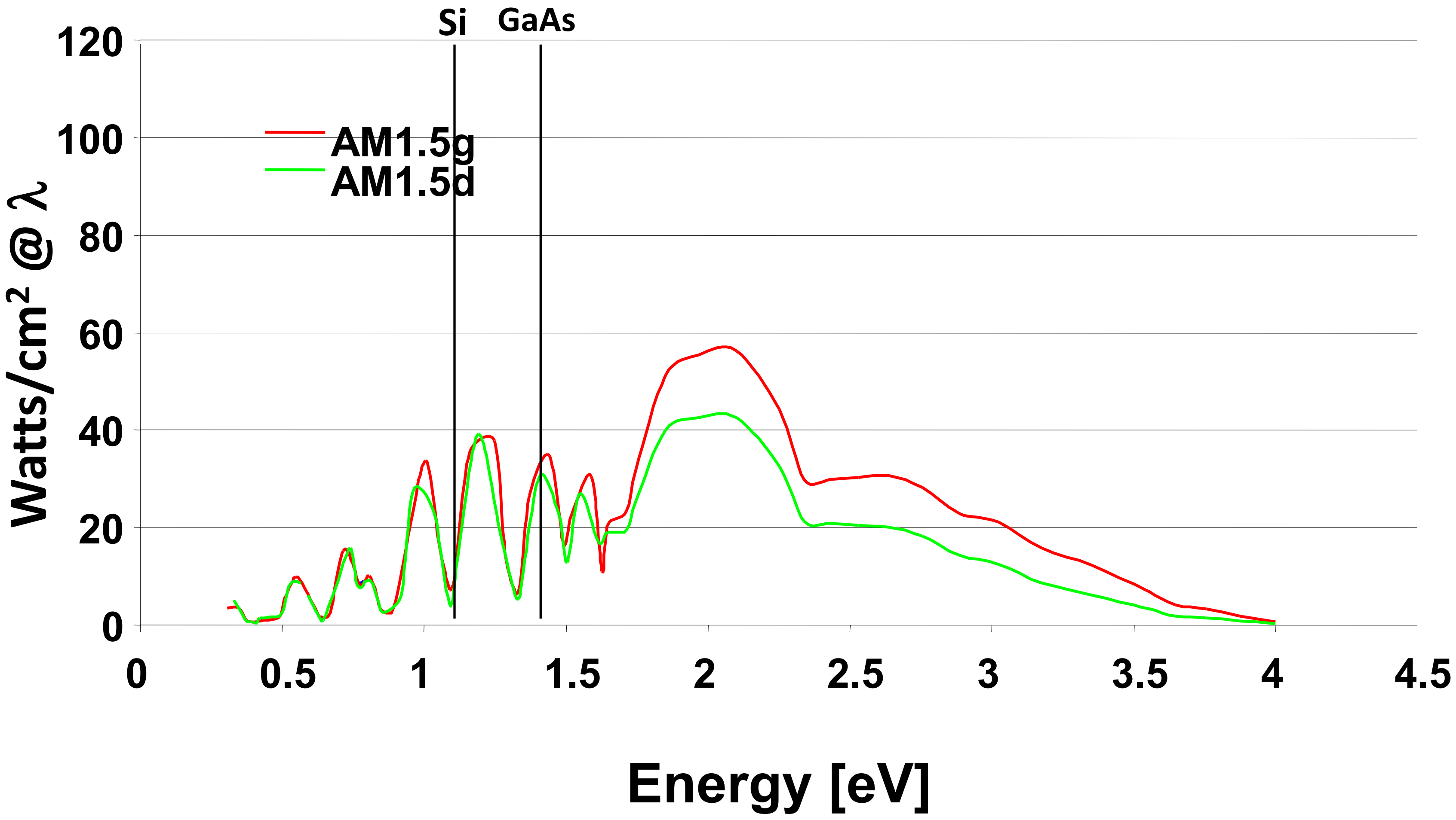
Challenges

- ~~**Phase separation** in high indium InGaN~~
  Localization of electron-hole pairs
- ~~No Demonstrated Tunnel Junctions~~
  - Need Degenerate p-type material
- ~~High defect densities & **threading dislocations**~~
  - Partially Shorted Junctions



R. Singh, et

Why InGaN?

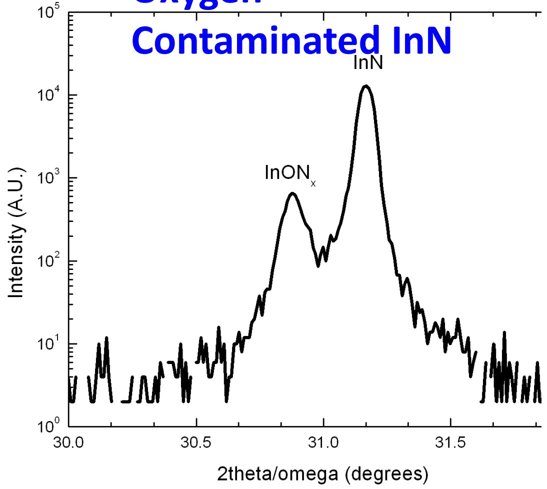

Si
GaAs
AM1.5g
AM1.5d
Watts/cm² @ λ
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Energy [eV]

Comments on InN Bandgap Controversy

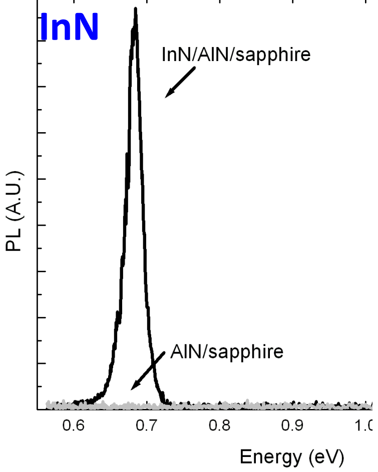
History of InN Bandgap

- First Report on the InN bandgap was given by University of Marques in Sydney Australia as 1.9 eV
  - 1.9 eV = 650 nm the same as the 2nd harmonic of the 325 nm wavelength used for the PL measurements – Student Mistake
- Later reports indicated a bandgap of 1.7-1.8 eV
  - Turns out to be the Cr: defect in sapphire
- All these initial “sputtered” materials contained an enormous amount of oxygen and were in fact $InON_x$
- Davadov clearly showed that the PL peak and absorption edge increased in energy for InN when annealed in various partial pressures of oxygen

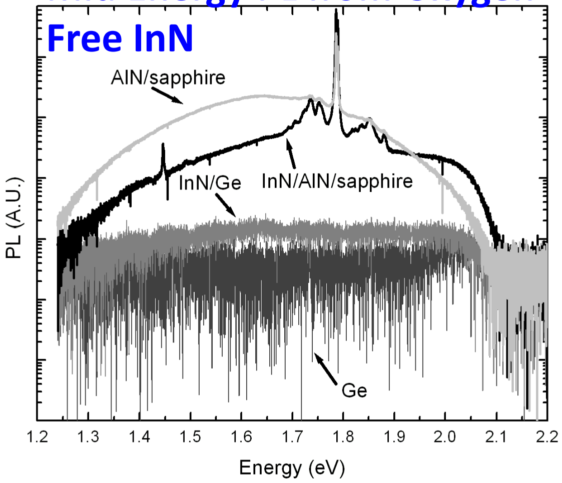
Oxygen Contaminated InN



PL from Oxygen Free InN



Mid Energy PL from Oxygen Free InN



Opportunities and Challenges for InN in Photovoltaics

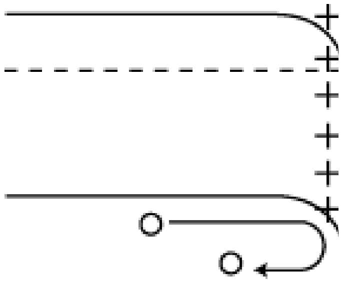
Point-Counter Point

Advantages

- Massive span in PV energies for high efficiencies in one material system

- Nitrides (AlGaN) generally offer recombination insensitivity to dislocations – still not proved for low energy alloys

- Strong band bending is perfect for low surface recombination velocity



- MBE can span the entire alloy range of InGaN but MOCVD has gaps in composition ranges.

Disadvantages

- Massive span in PV energies is not in a lattice matched system

- High dislocation density

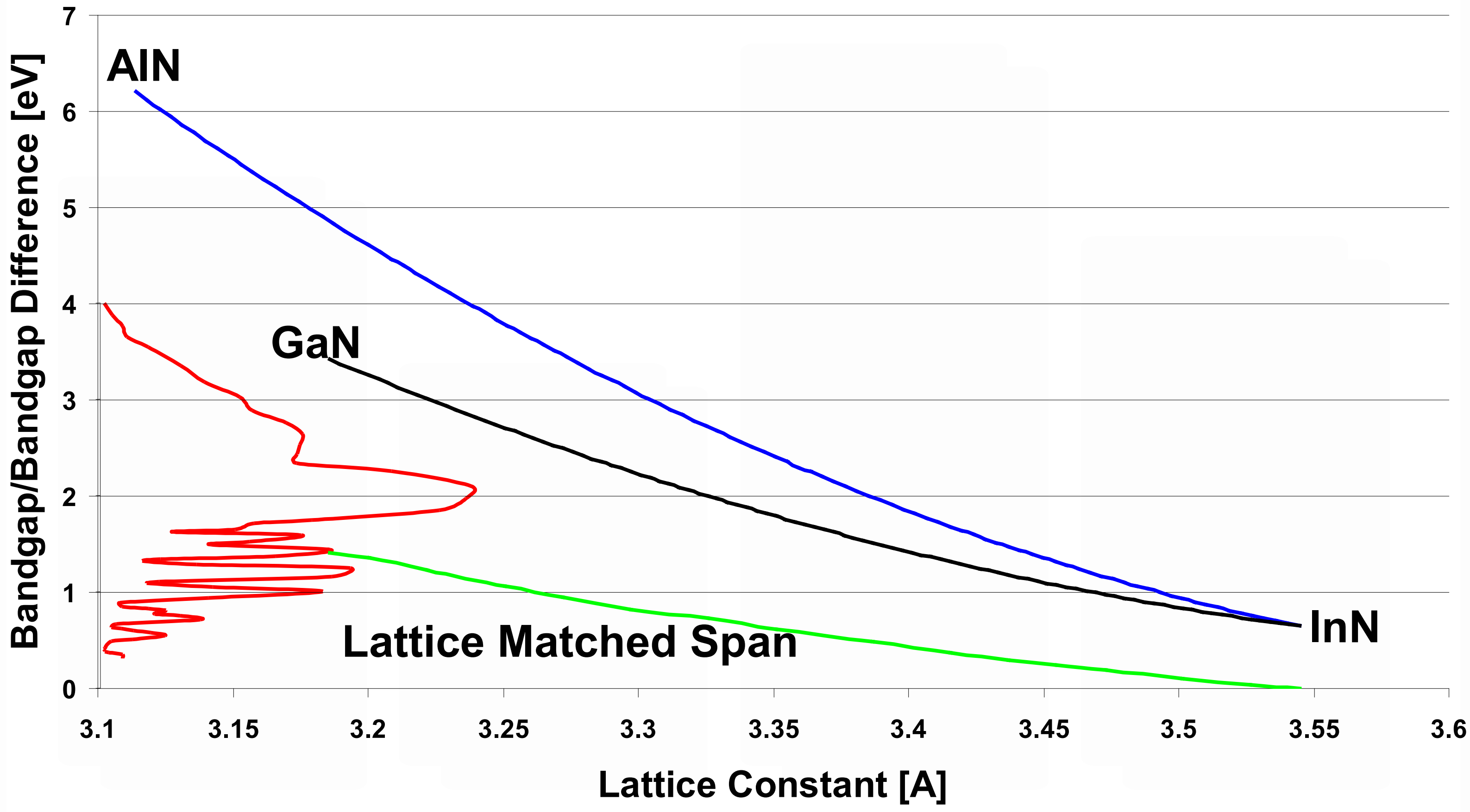
- Strong band bending has resulted in inability to form a solid state junction

- P-type doping undemonstrated for In>30%
  - Tunnel junctions ~~probably not~~ possible
  - P-type base is usually preferred due to higher mobility of minority electrons
  - ~~Even in an n-InGaN / p-GaN heterojunction device, the p-doping is insufficient~~

- Tendency to phase separate at high Indium

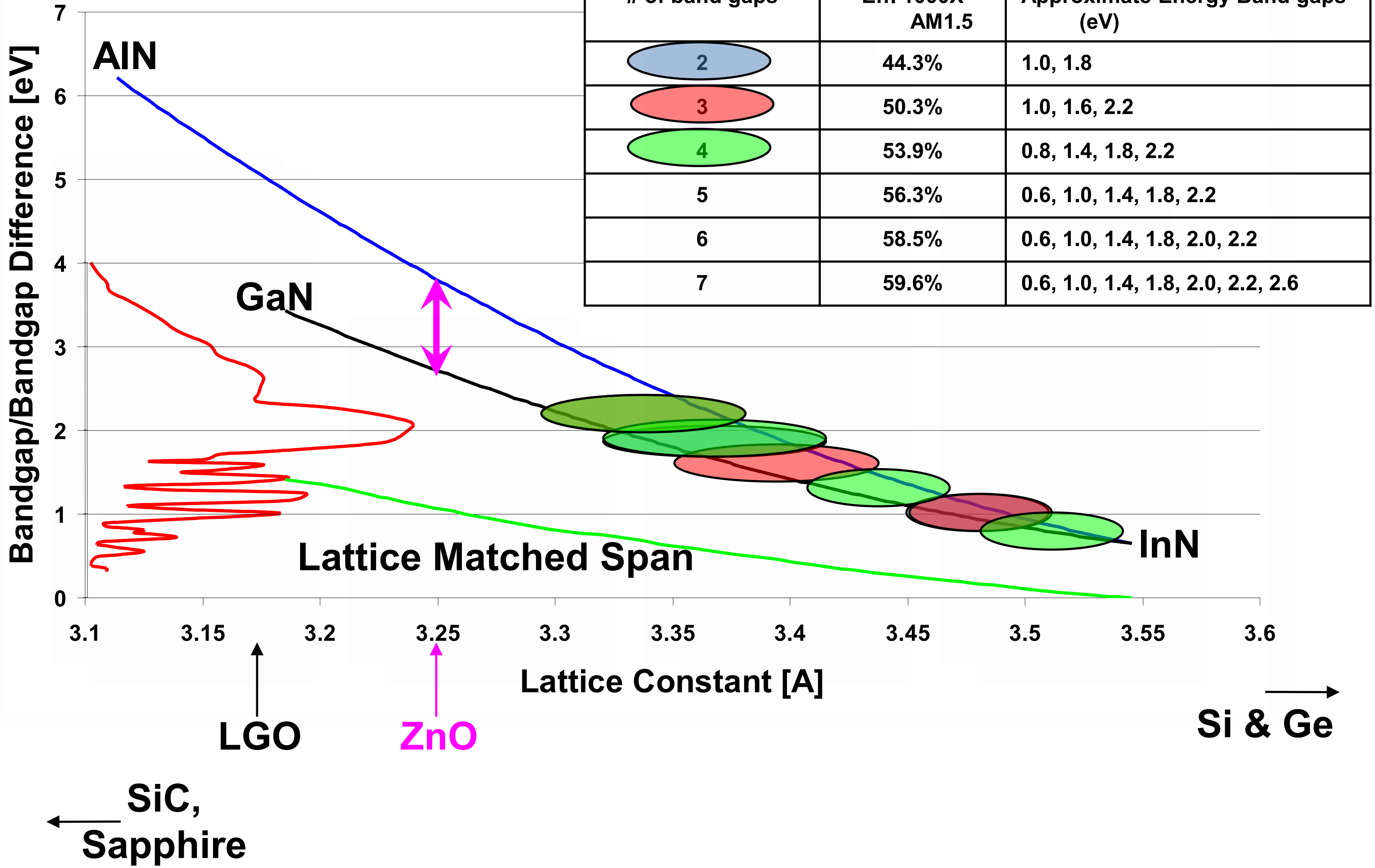
- 3-junction high concentration solar cells are already in excess of 34% efficient (GaInP/GaAs/Ge Spectrolabs –King et al)

Comparison of Available Bandgaps and Solar Spectrum



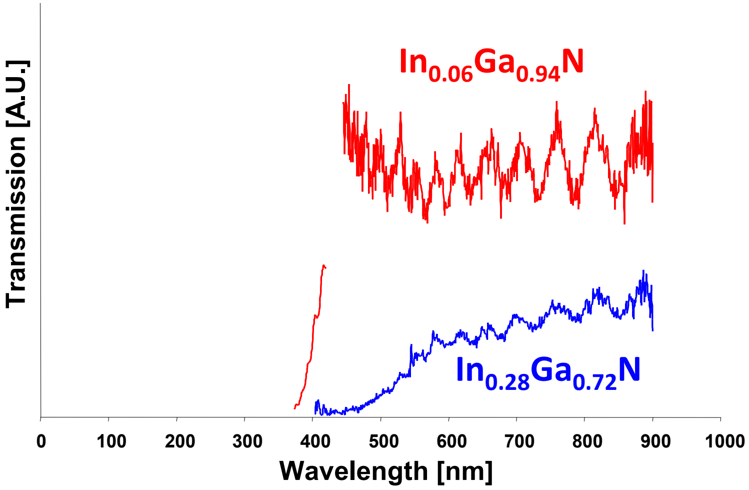
Comparison of Available Bandgaps and Solar Spectrum

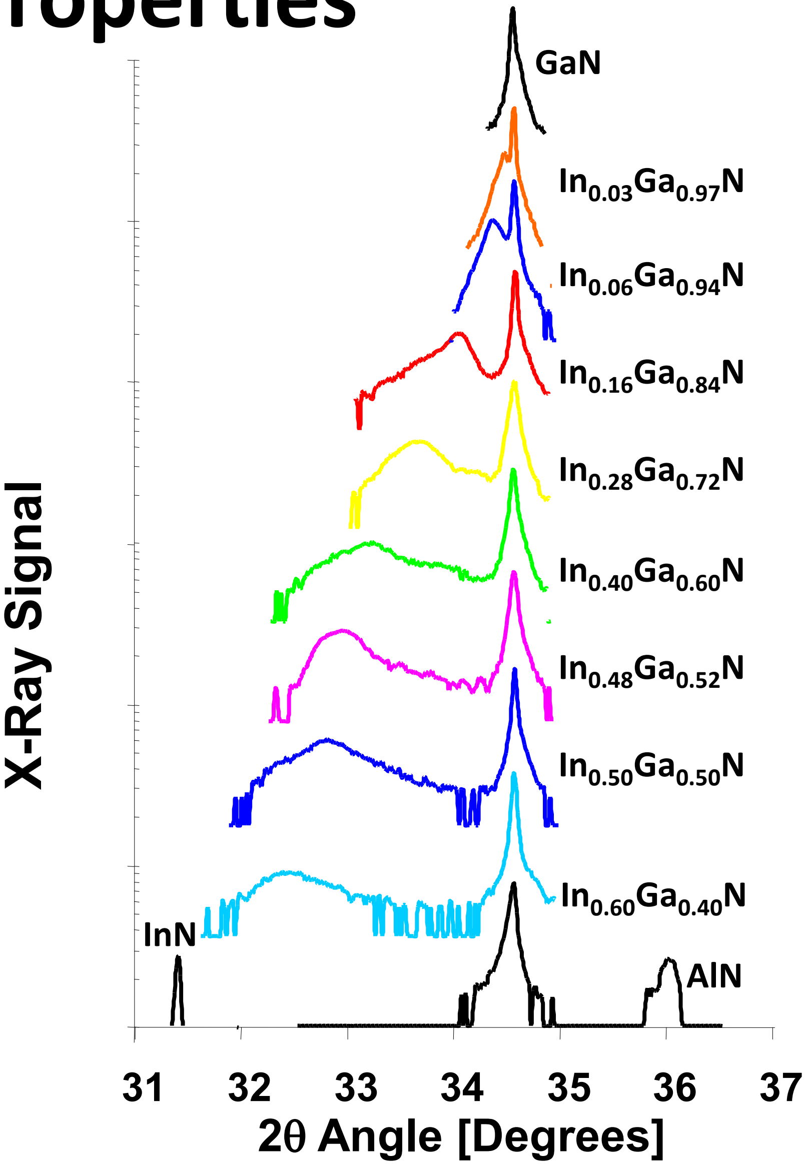
# of band gaps	Eff. 1000X AM1.5	Approximate Energy Band gaps (eV)
2	44.3%	1.0, 1.8
3	50.3%	1.0, 1.6, 2.2
4	53.9%	0.8, 1.4, 1.8, 2.2
5	56.3%	0.6, 1.0, 1.4, 1.8, 2.2
6	58.5%	0.6, 1.0, 1.4, 1.8, 2.0, 2.2
7	59.6%	0.6, 1.0, 1.4, 1.8, 2.0, 2.2, 2.6



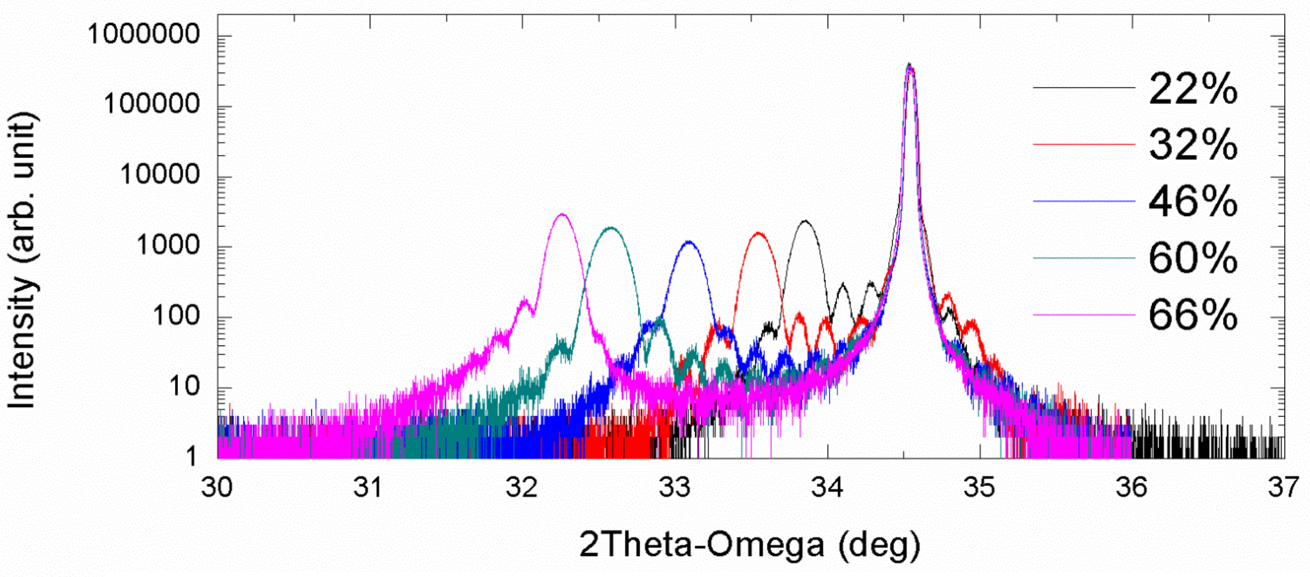
In Phase Separation Effect on Optical Properties

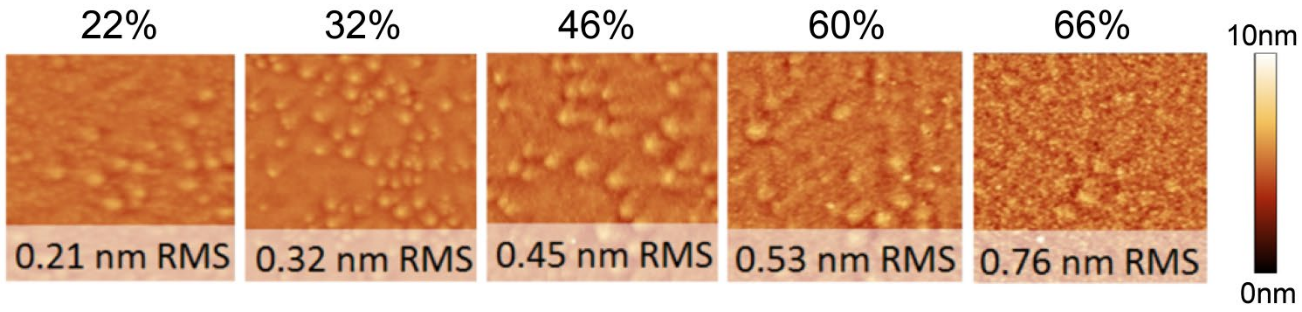
- MBE can span the entire range from GaN to InN
- Phase separation increases for 85%>In>15%





Ga Tech - grown InGaN solves this problem – Many more left





- **Single-phase** InGaN throughout the miscibility gap
- Very smooth surface

M. Moseley *et al.*, Appl. Phys. Lett. **97**, 191902 (2010).
M. Moseley *et al.*, J. Appl. Phys. **112**, 014909 (2012).