Schottky Diodes

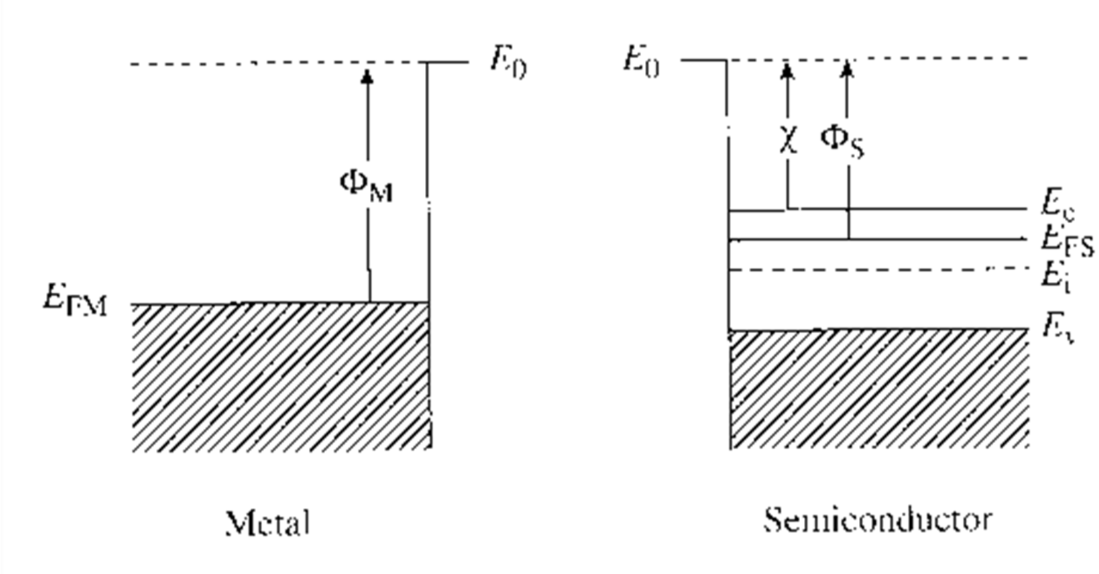
Heterojunctions and NDR Diodes

- Why a Schottky?
    - 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 (motors, etc…)
    - Cheaper
- Disadvantages:
    - Generally higher leakage currents
    - Generally lower breakdown voltages

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)

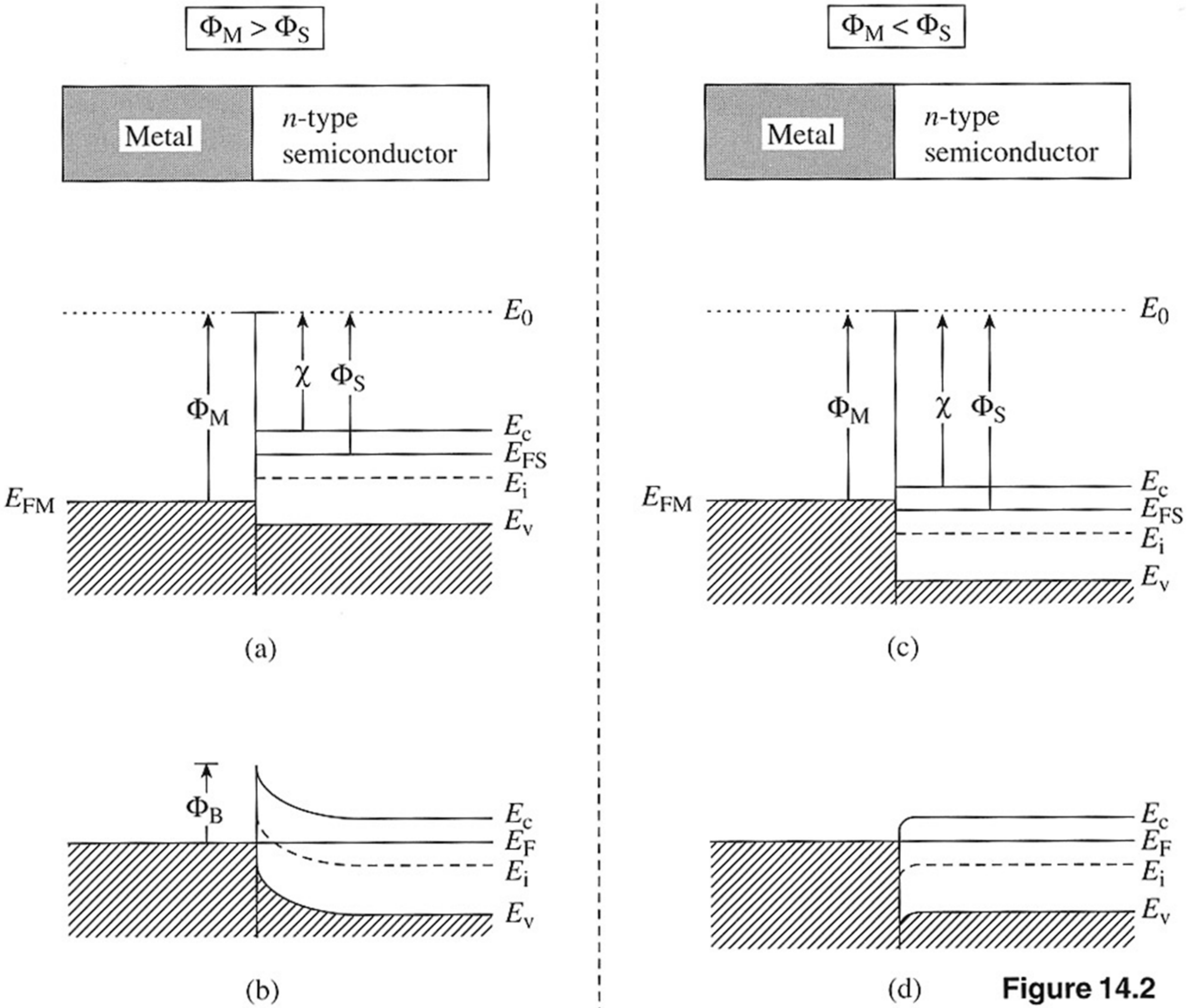
Definitions

- **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



An instant after contact formation

Under equilibrium conditions

Schottky

$\Phi_M > \Phi_S$

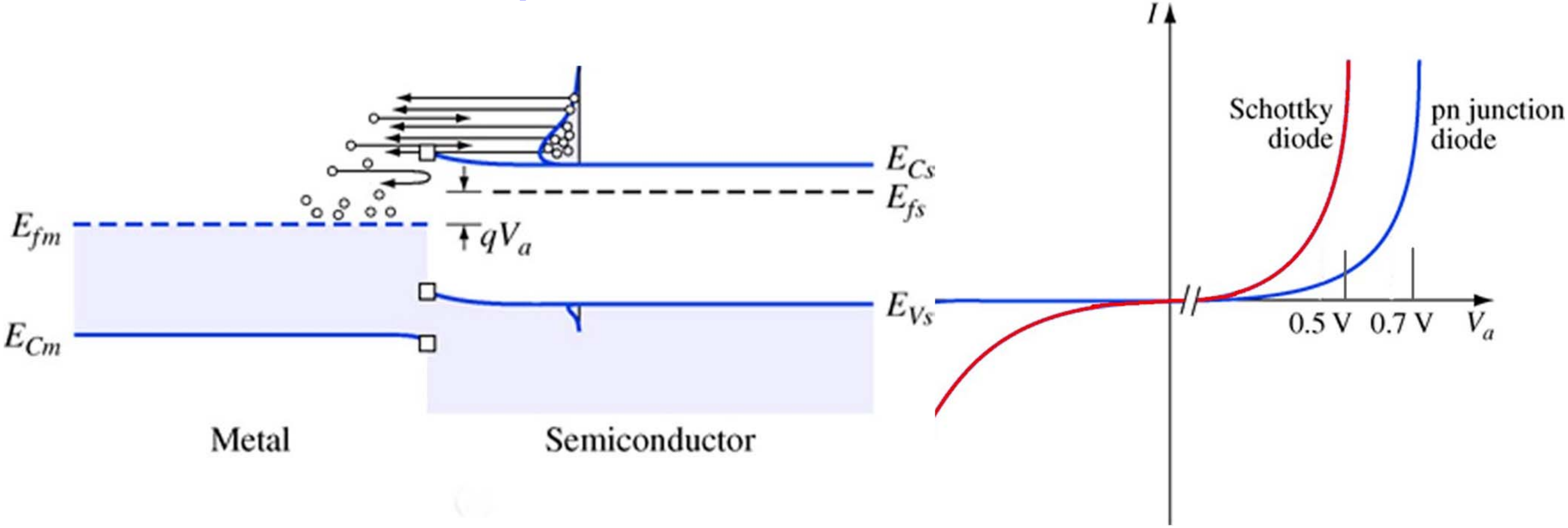
Ohmic

$\Phi_M < \Phi_S$

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

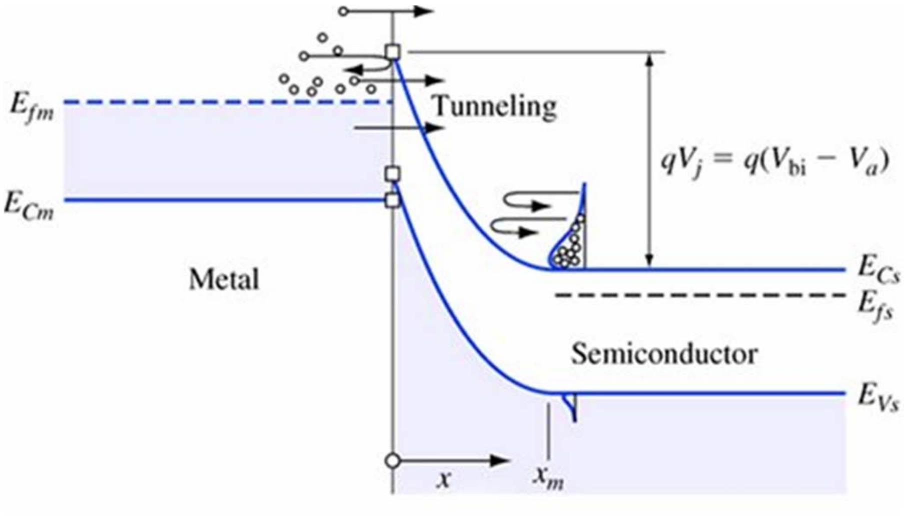


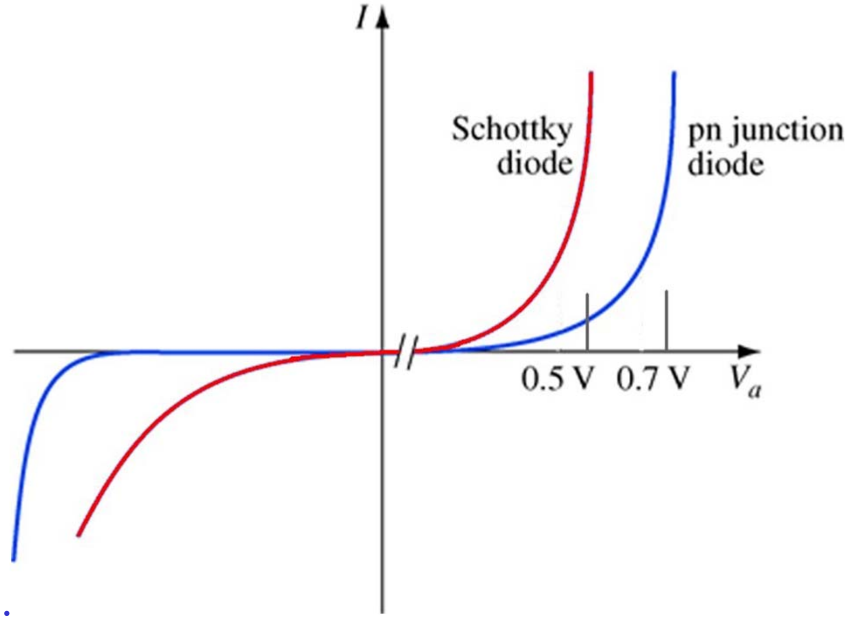
Since MS Schottky diode is a majority carrier device (i.e only majority carriers are injected from semiconductor to the metal) and thus has no minority carrier storage, the frequency response of the device is much higher than that of equivalent p^+ n diode.

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 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.

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 or very high electric fields).

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.

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.

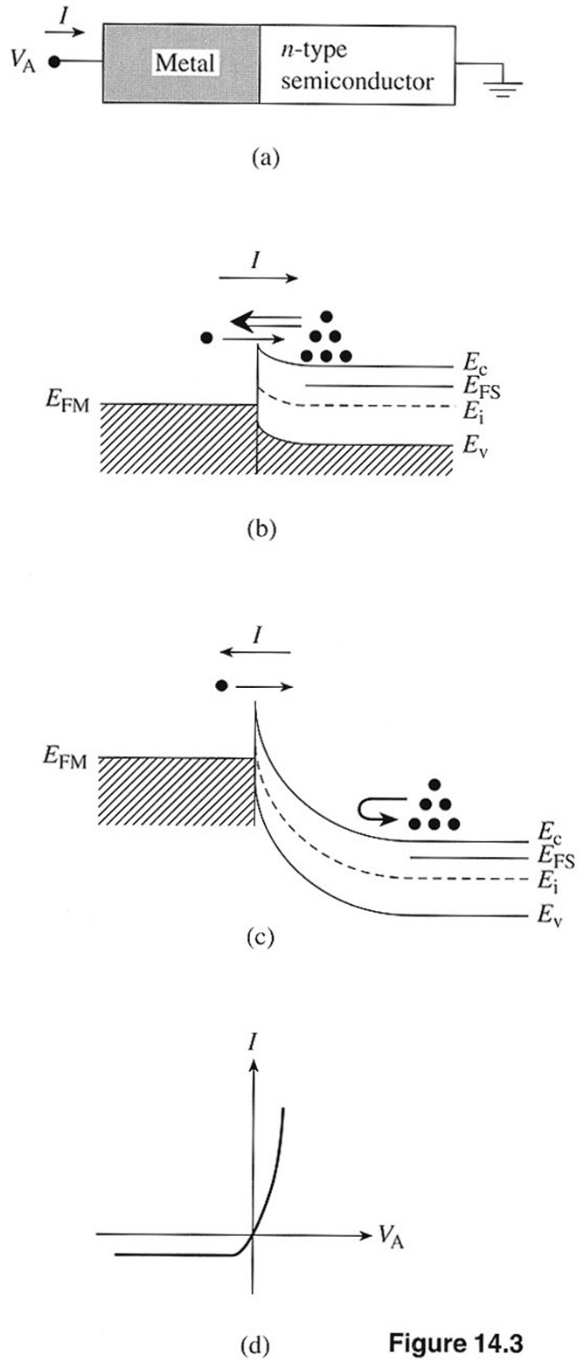
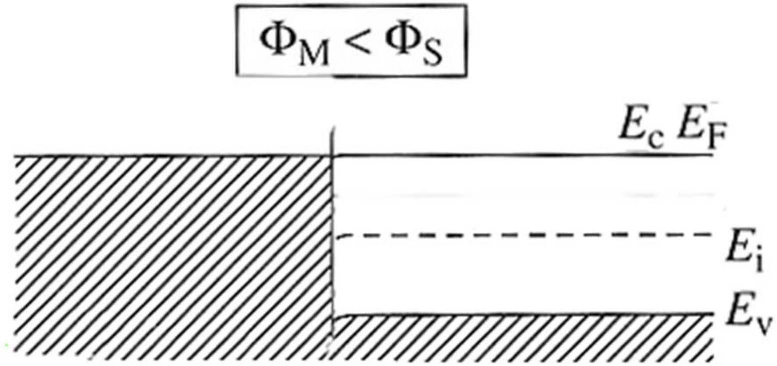
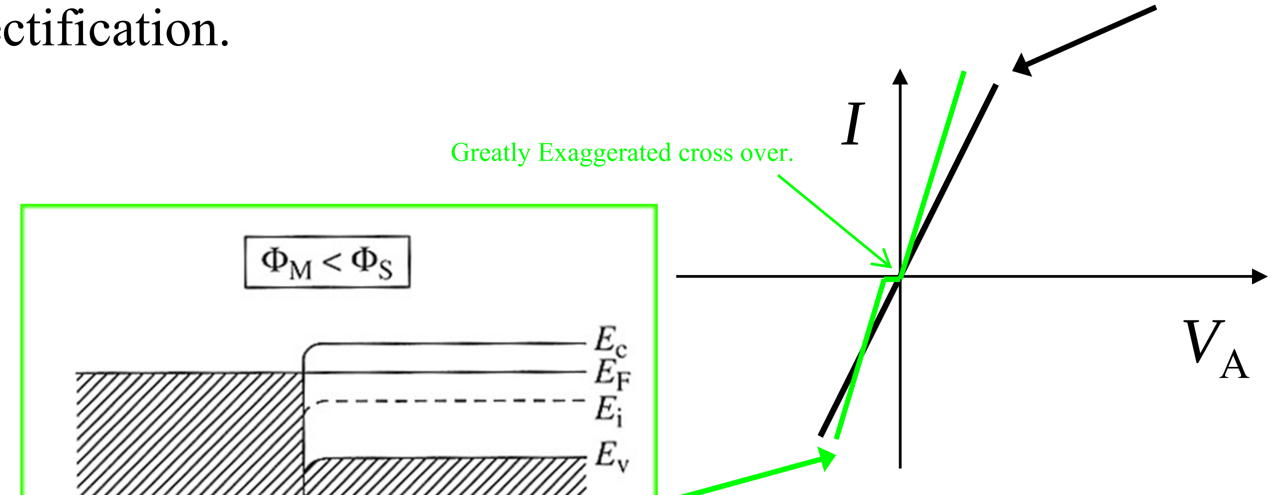


Figure 14.3

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 $V_A > 0$ results in large current.
- The small barrier that exists for electron flow from metal to the semiconductor, 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.
- Lack of depletion (accumulation occurs) means (essentially) no rectification.



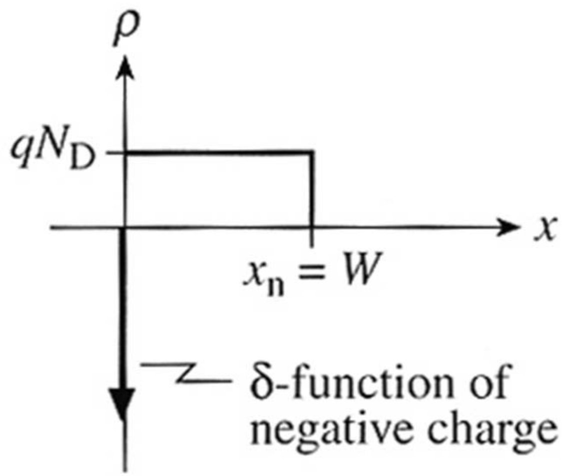


Generalization of Metal Semiconductor Contact Energy Relationships

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

Schottky Diode Electrostatics

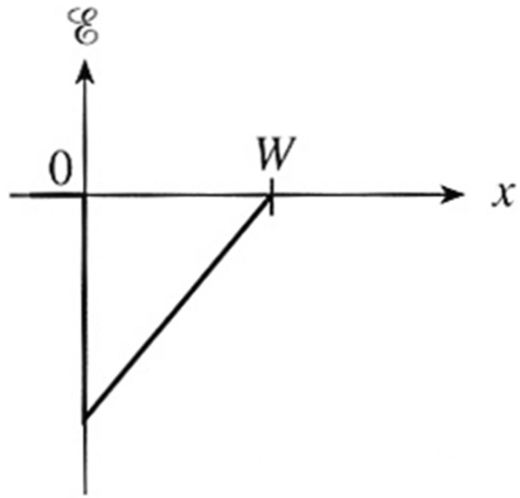
$$V_{bi} = \frac{1}{q}\left[\Phi_B - (E_C - E_F)_{FB}\right]$$



$$\rho \approx qN_D \quad \text{for } 0 \le x \le W$$
$$\approx 0 \quad \text{for } x > W$$

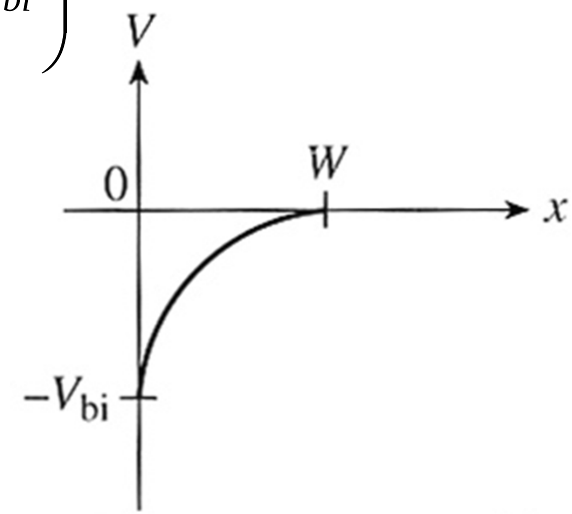
Schottky Diode Electrostatics

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon_{Si}} = \frac{qN_D}{\varepsilon_{Si}} \quad \text{for} \quad 0 \le x \le W$$



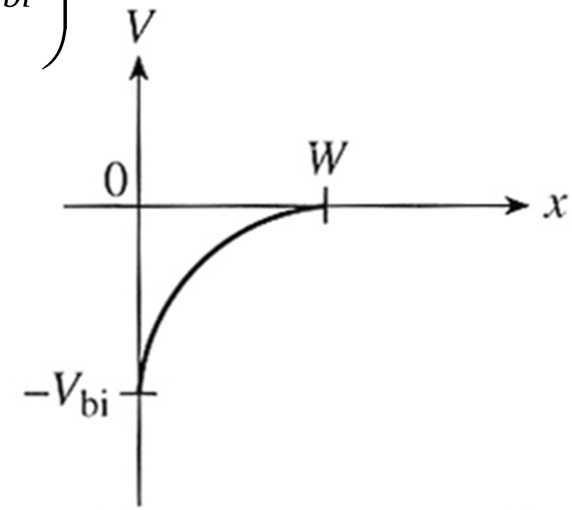
$$\mathbf{E} = \frac{qN_D}{\varepsilon_{Si}}(x - W) \quad \text{for} \quad 0 \le x \le W$$

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

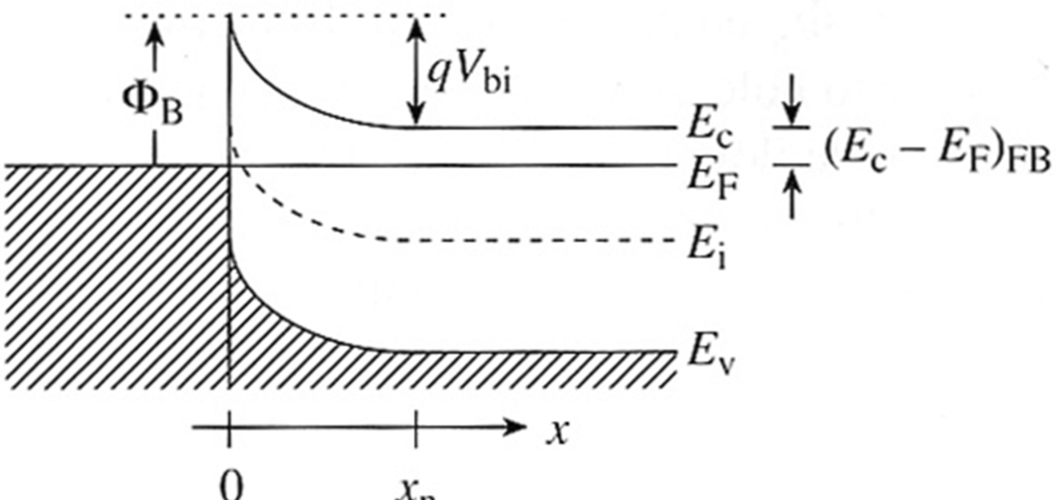


Schottky Diode Electrostatics

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



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



Example

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

Solution:

Find $E_F - E_i$ $\quad E_F - E_i = 0.357\text{eV}$

Find $E_C - E_F$ $\quad E_C - E_F = 0.193\text{eV}$

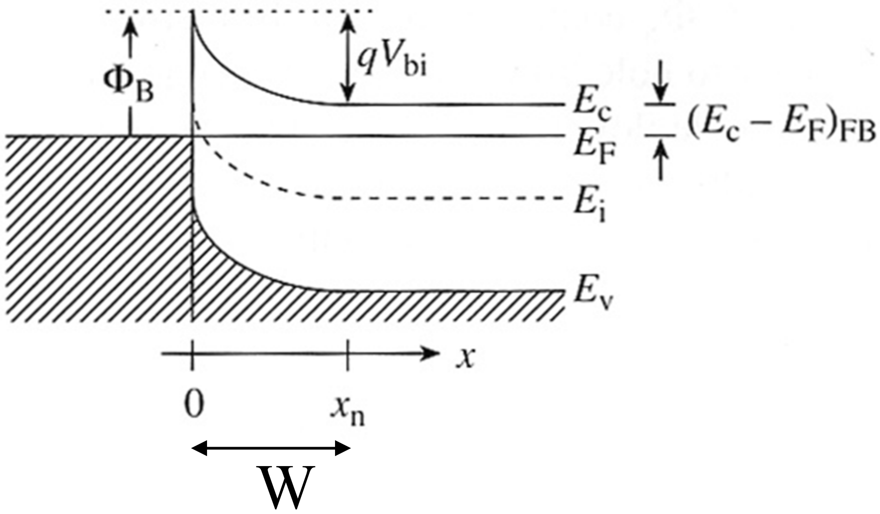
$$\Phi_B = \Phi_M - \chi = 0.54\text{eV}$$

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

$V_{bi} = 0.347$ V

$W = 0.21\ \mu\text{m}$

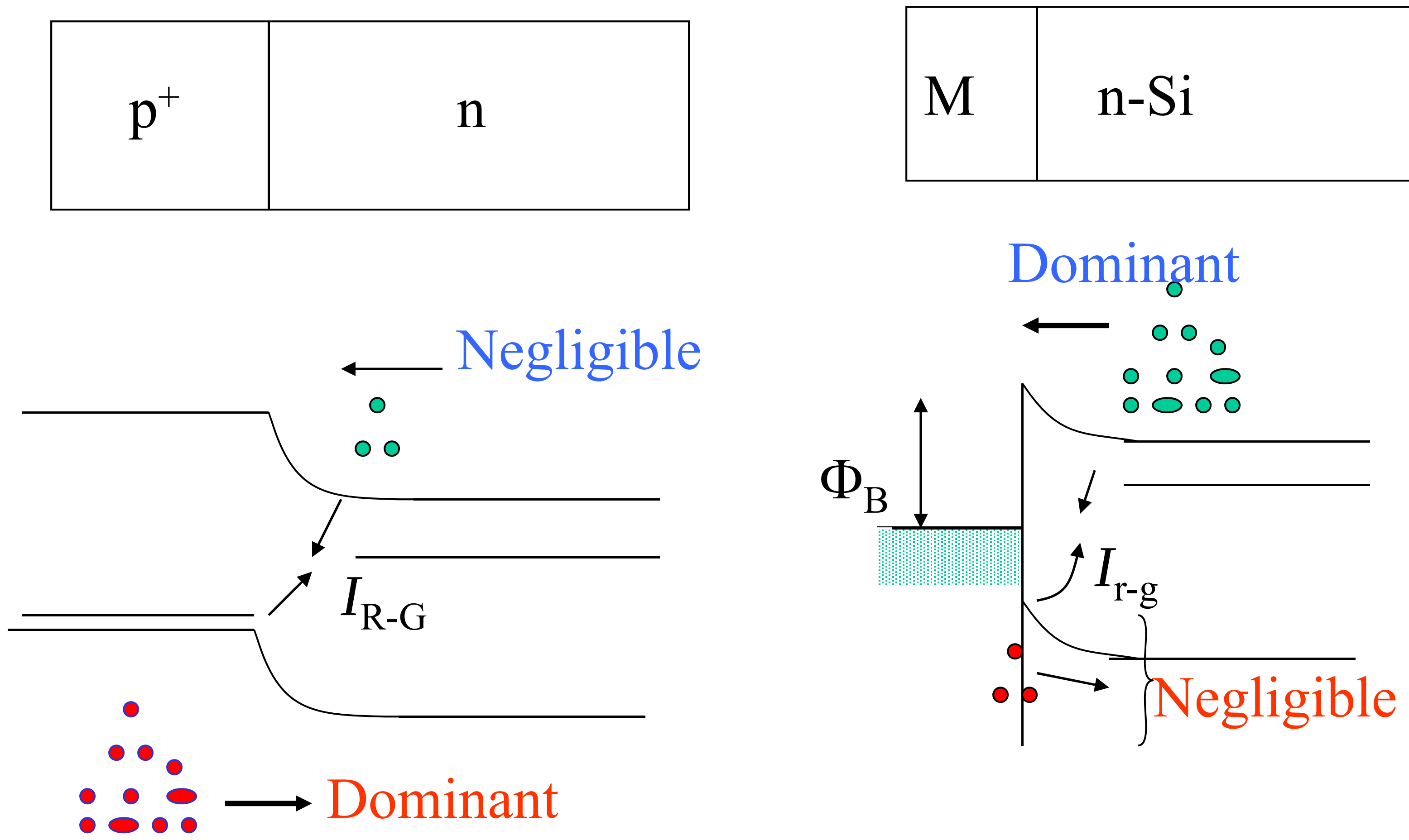
$\mathcal{E}(x = 0) = \mathcal{E}_{max} = 3.4 \times 10^4$ V/cm



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.

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

Note: $\mathcal{A}^*$ is Richardson's constant but often times, there is an extra prefactor λ which accounts for quantum mechanical reflection of the electrons approaching the potential barrier and to a lesser degree varies with the band structure of the emitting material.

I-V Characteristics

$$I = \left(A\mathbf{A}^{*}T^{2}\, e^{-\frac{\Phi_B}{kT}} \right) e^{\frac{qV_A}{kT}} - \left(A\mathbf{A}^{*}T^{2}\, e^{-\frac{\Phi_B}{kT}} \right)$$

Results from the emission of electrons from the semiconductor to the metal over the barrier, qV_{BI}. This must balance the leakage current at zero bias and increases exponentially due to diffusion current as the barrier is lowered in forward bias.

Results from the emission of electrons from the metal to the semiconductor over the barrier, Φ_B

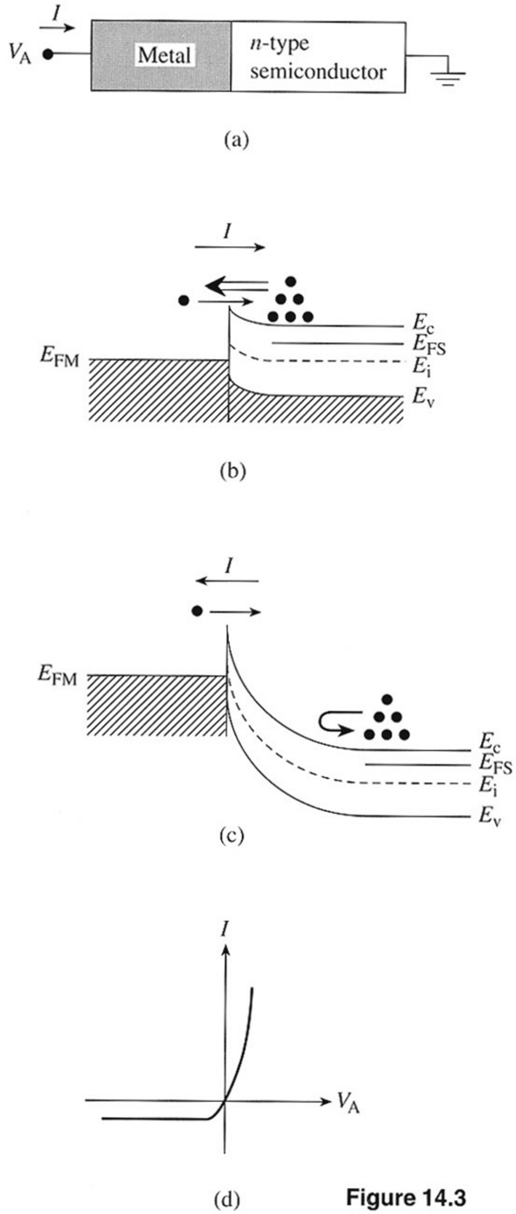
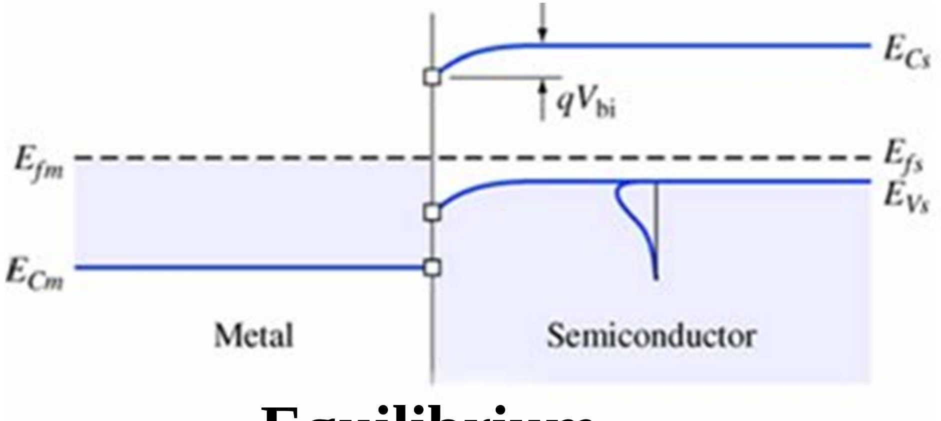
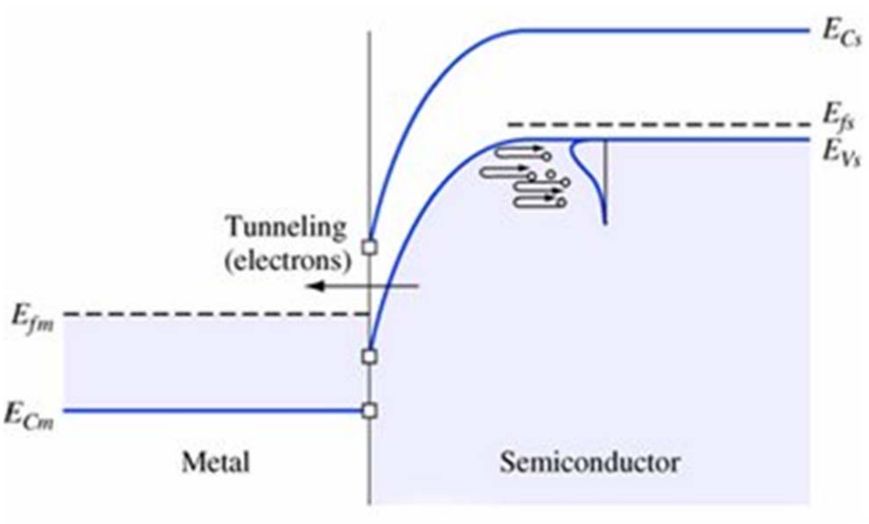


Figure 14.3

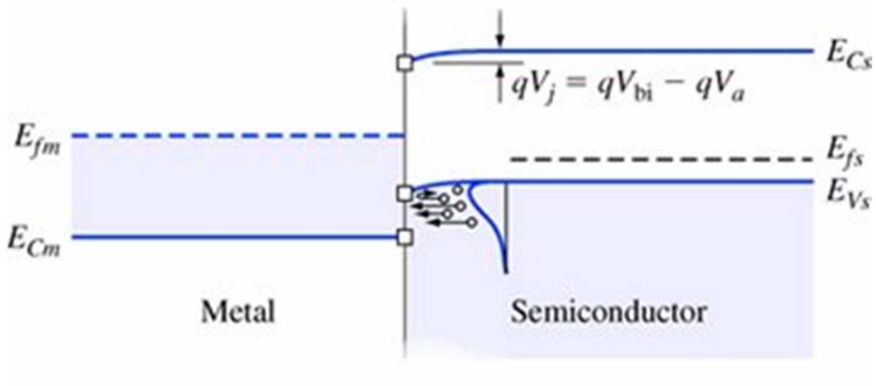
P-type Schottky Diodes



Equilibrium

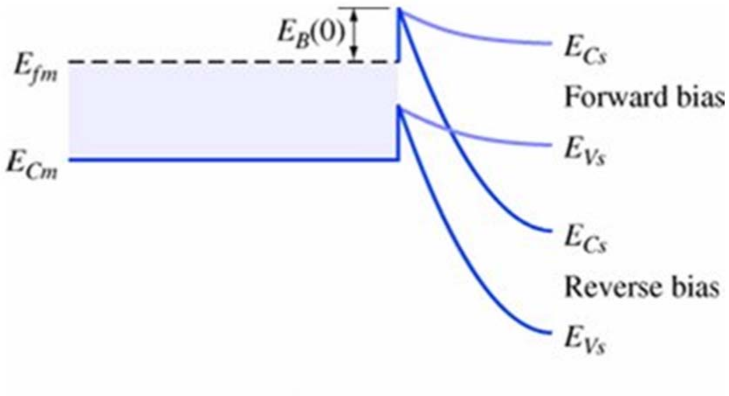


Reverse Bias

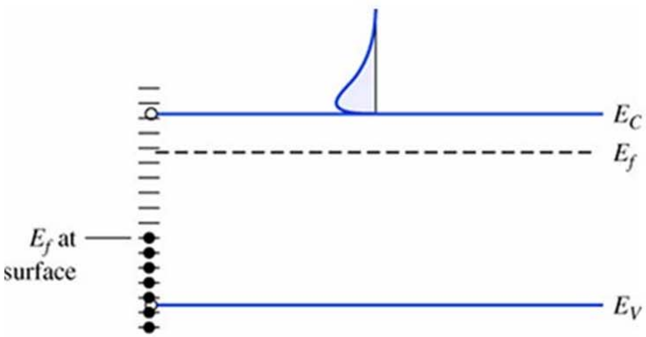


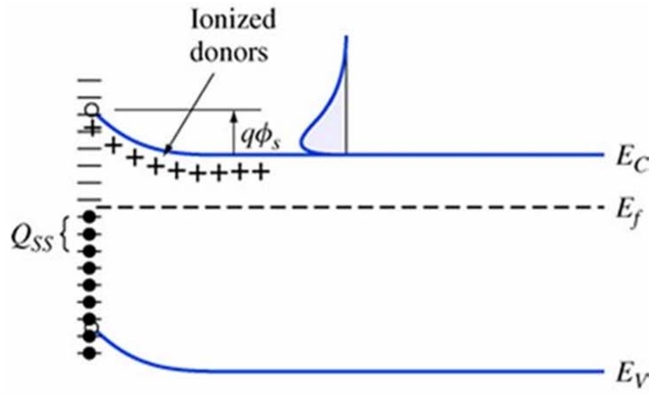
Forward Bias

Details of Schottky Behavior



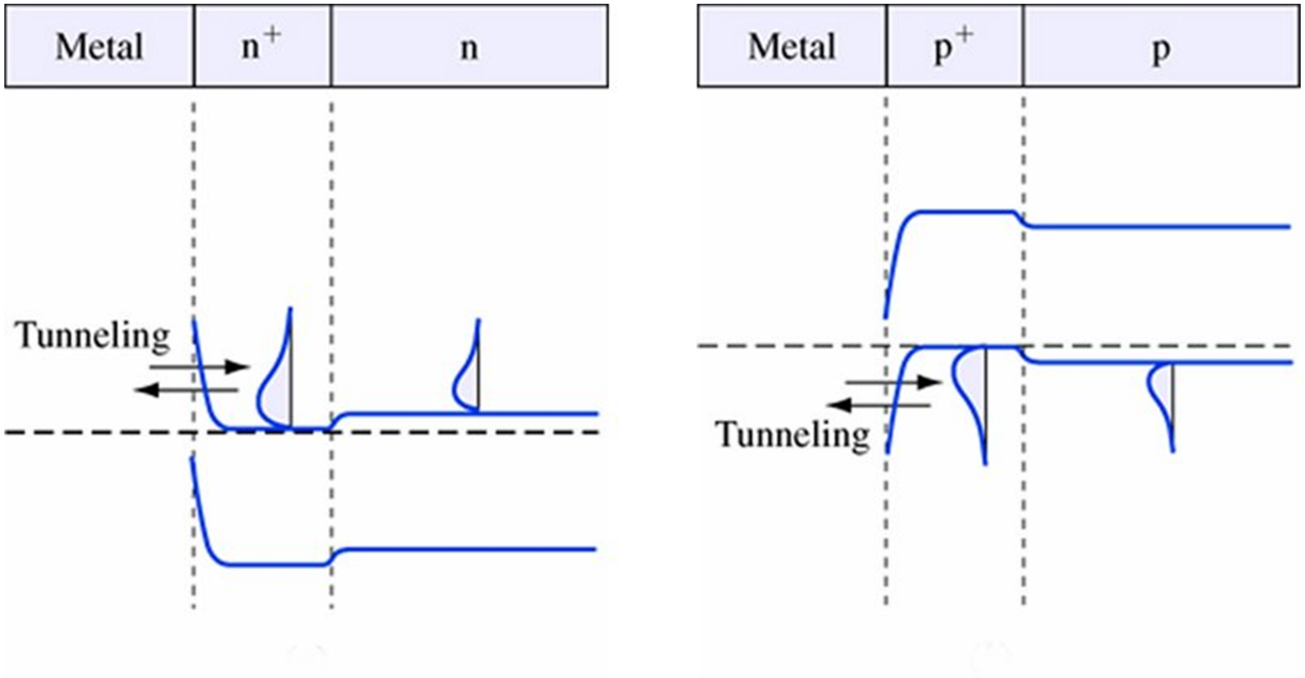
Note that the barrier height is (mostly) independent of bias.





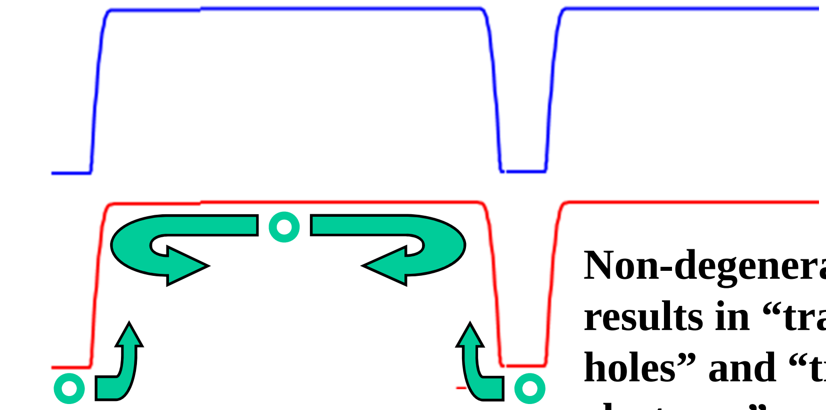
Surface charges resulting from broken bonds, surface contamination or even surface oxidation can dominate band alignment making the EAM invalid. One common case is the "fermi-level pinning" often found in III-As and III-P materials. In these materials, the large numbers of surface states force the surface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

Ohmic Contact Using Highly Doped Semiconductors

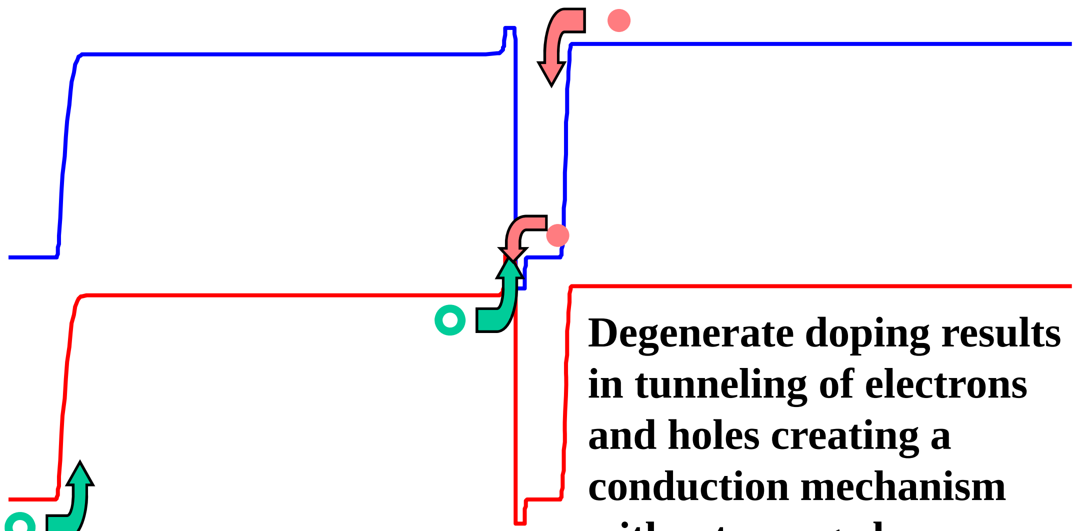


Highly doped contacts result in very small depletion widths and thus small tunneling barriers. These contacts are always ohmic regardless of metal chosen. This is a common method of making contact to a semiconductor device.

Semiconductor to Semiconductor Ohmic Contacts



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



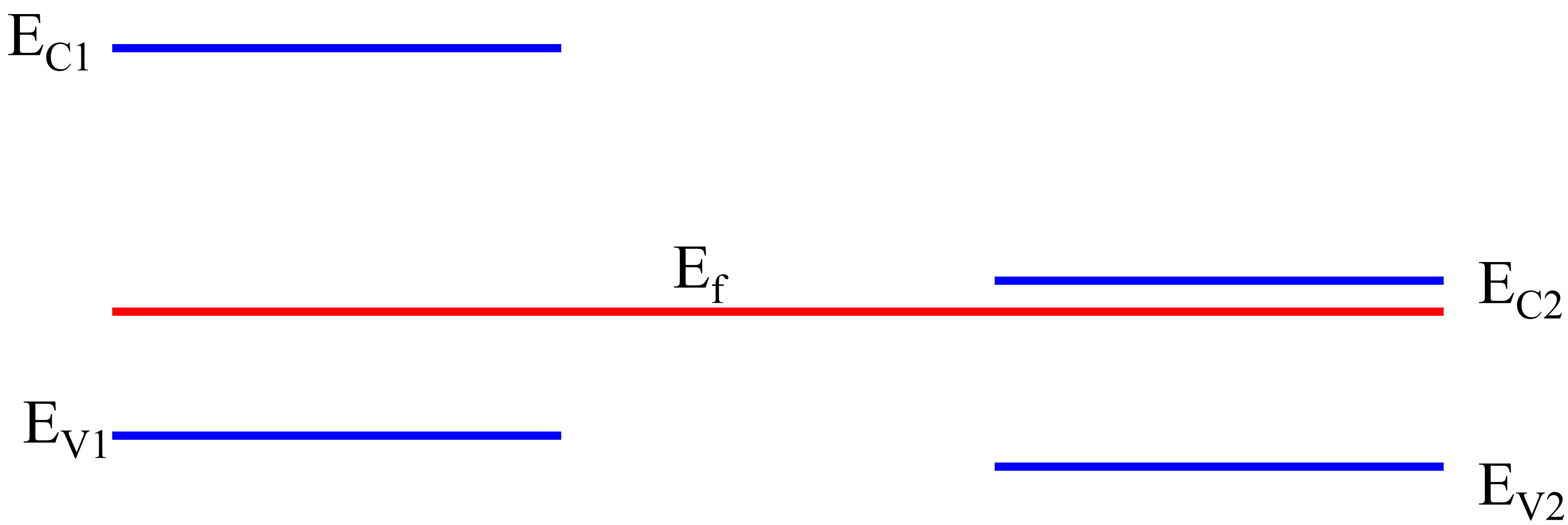
Degenerate doping results in tunneling of electrons and holes creating a conduction mechanism without energy loss – an ohmic contact

- 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.

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

Heterojunctions

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

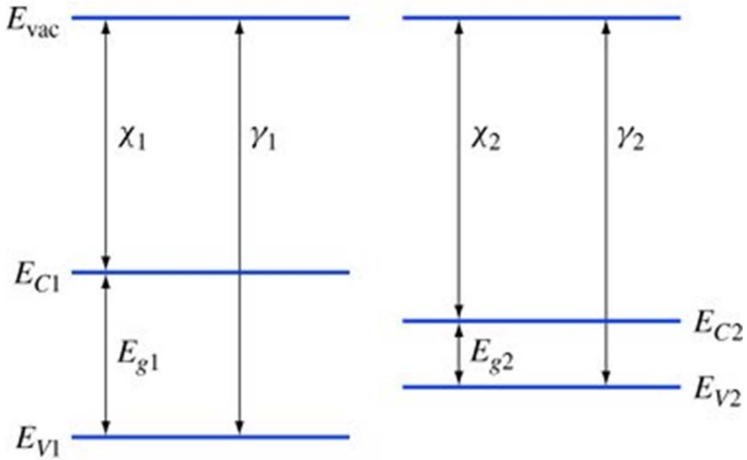


Classifications of Heterojunctions

Definitions:

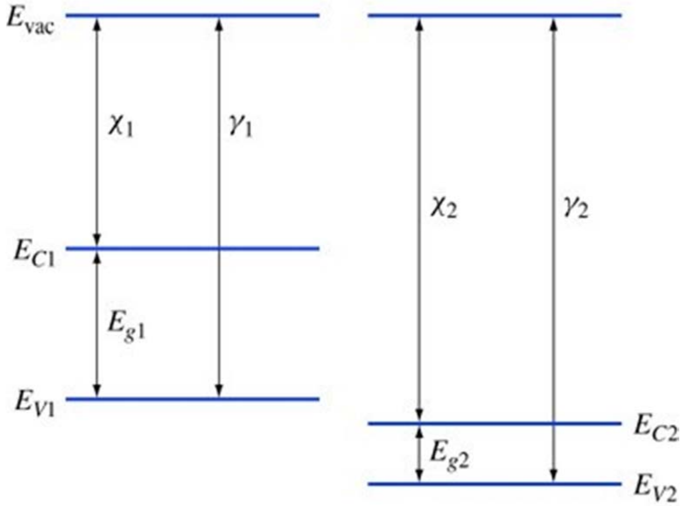
$\chi \equiv$ Electron Affinity – energy needed to free a conduction electron into the vacuum level

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



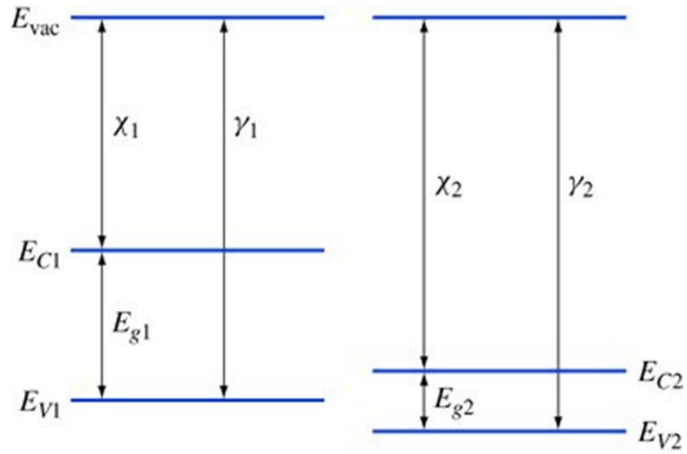
Type I

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



Type II

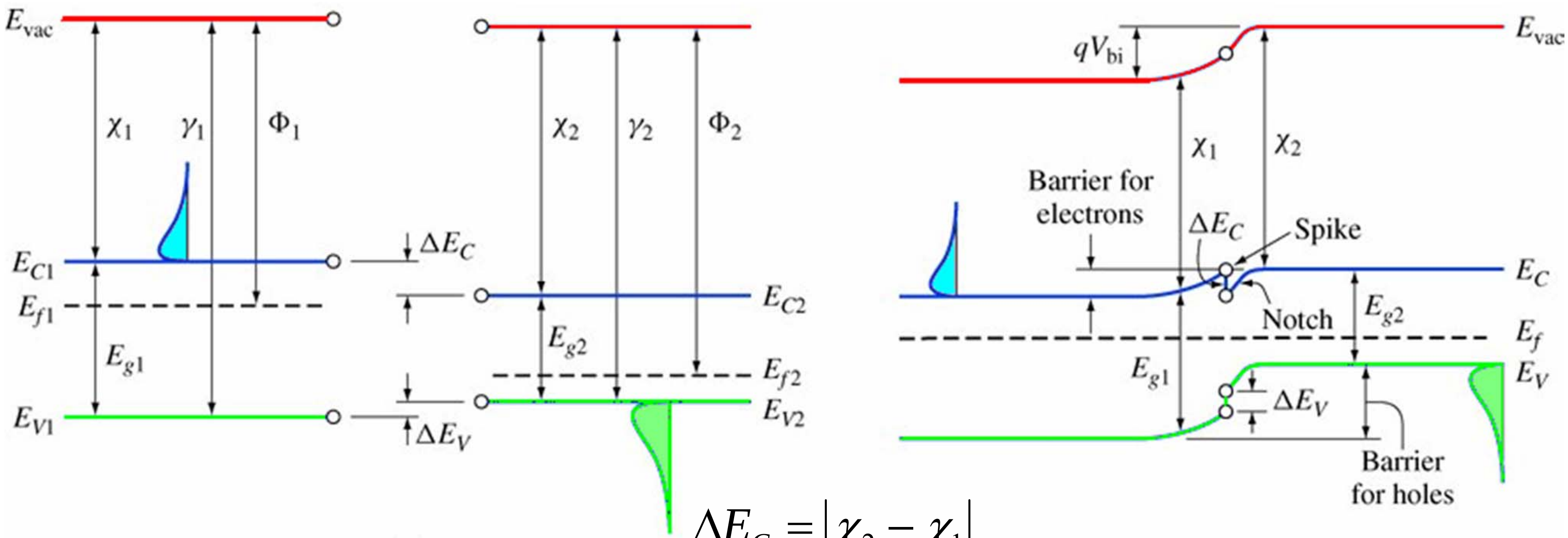
Type II: Staggered (small Eg material is outside of large Eg band edges – either above or below)



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)



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

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

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.

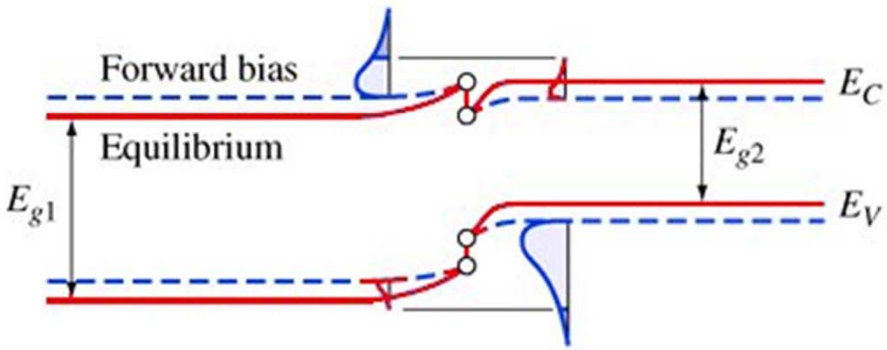
Other things to note:

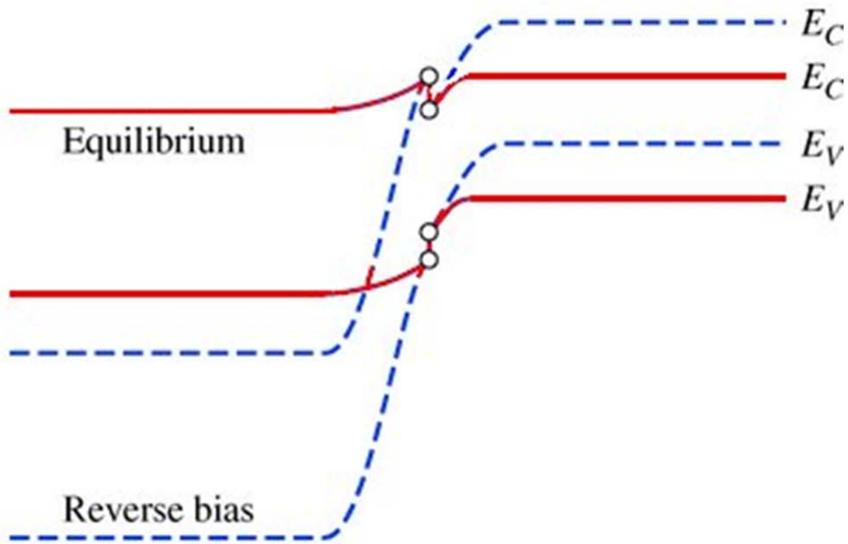
•Drift and Diffusion currents balance in equilibrium just like a homojunction.

•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

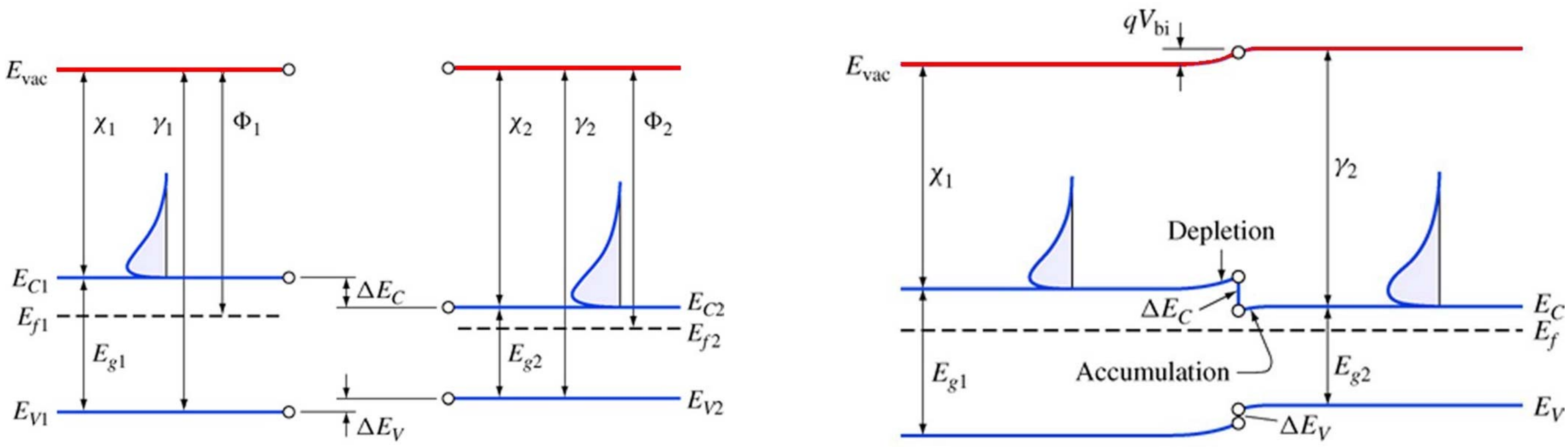




•Electrons may be easier to inject (lower barrier as in this case) than Holes or vise versa making these junctions inherently asymmetric (useful in both transistors and optical devices).

•Heterojunction Emitter-Base junctions in Heterojunction Bipolar Transistors result in increased emitter injection efficiency using this effect

Band Alignment of Heterojunctions (Nn)



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

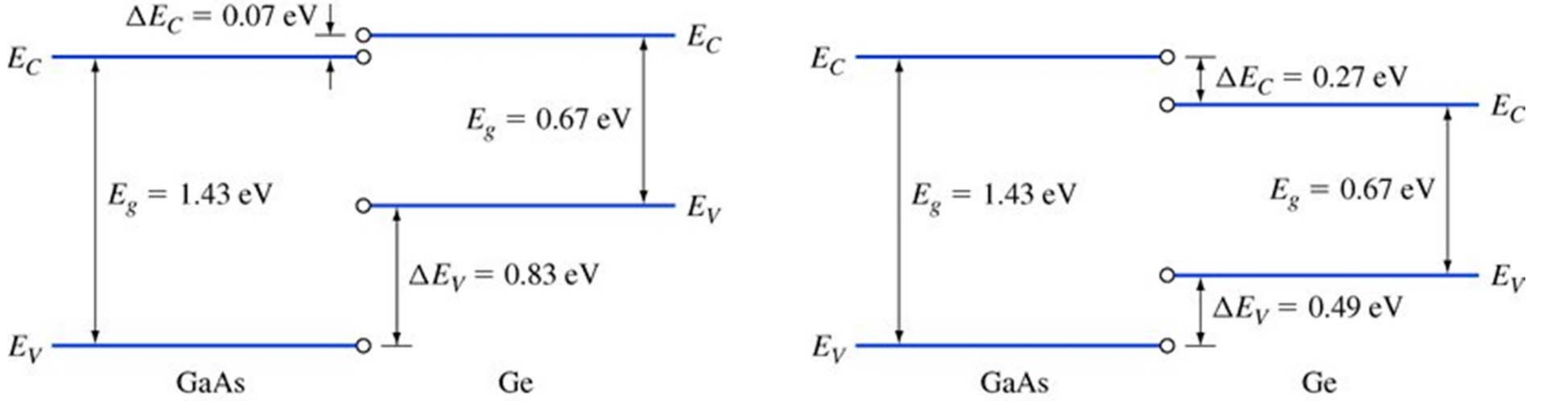
$$\Delta E_V = |\gamma_2 - \gamma_1|$$

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.

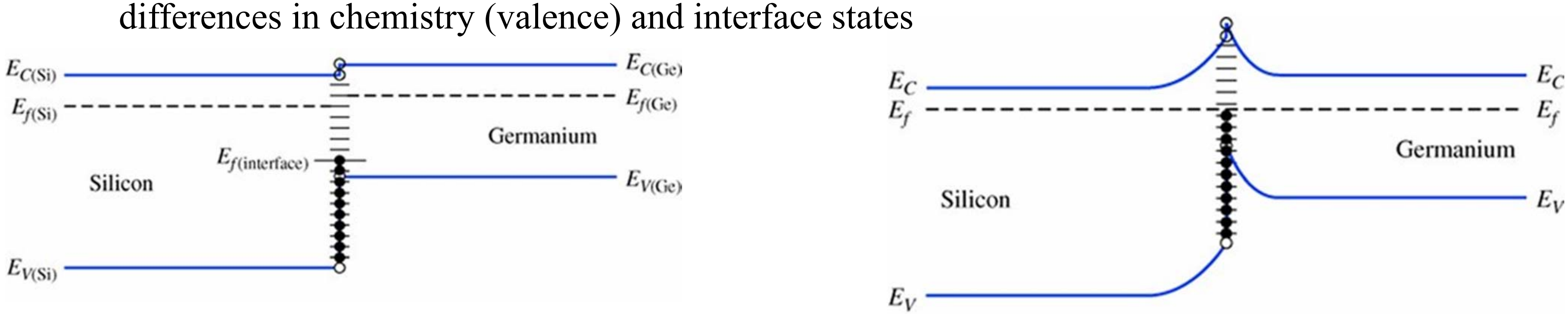
Validity of EAM for Real Heterojunctions

•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

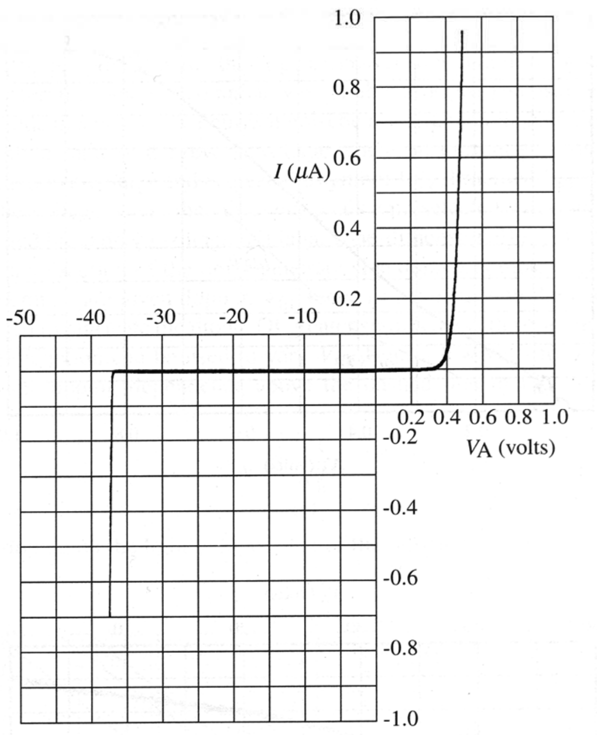


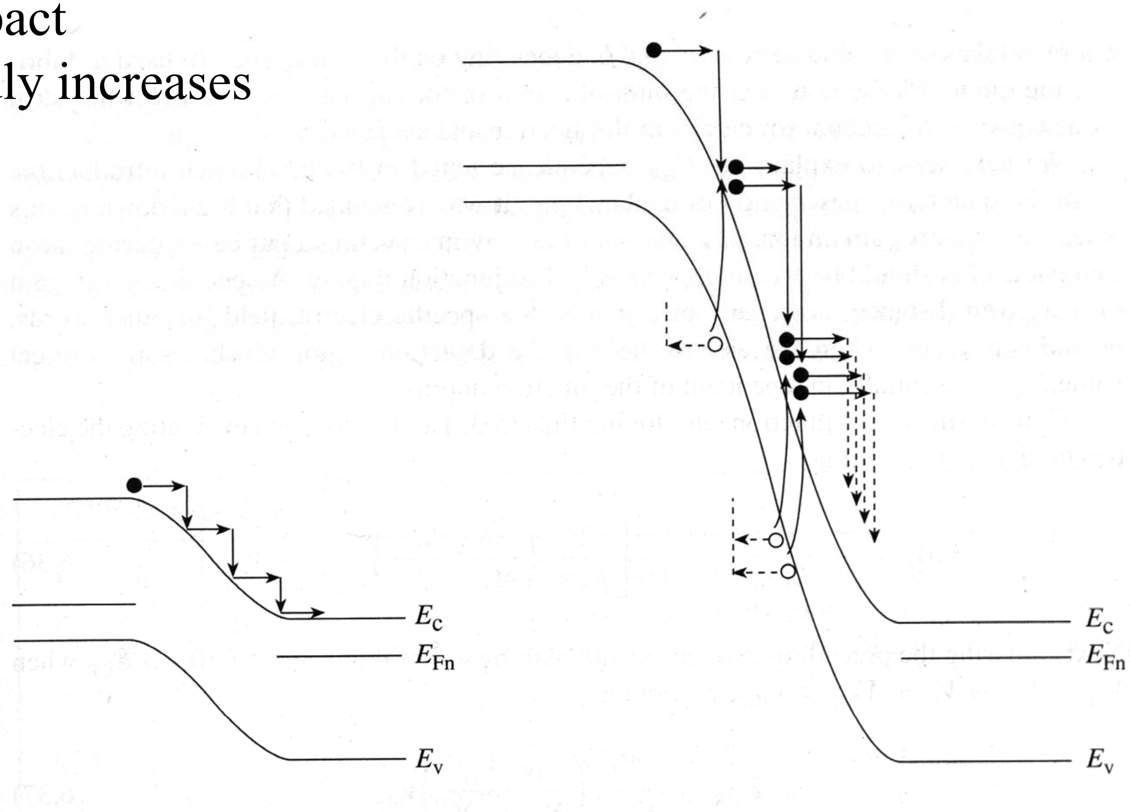
Even in covalent heterojunctions interface states can greatly disrupt EAM expected results leading to unexpected band bending and carrier wells (valence band well shown here).

Breakdown Mechanisms

Avalanche Breakdown:

Excess current flows due to electron-hole pair multiplication due to impact ionization. This current rapidly increases with increasing reverse bias.





(a) Small reverse bias (b) $|V_A| \rightarrow V_{BR}$

Breakdown Mechanisms

Zener Breakdown:

Excess current flows due to bonding electrons "tunneling" into empty conduction band states. The "tunneling barrier" must be sufficiently thin. This current rapidly increases with increasing reverse bias.

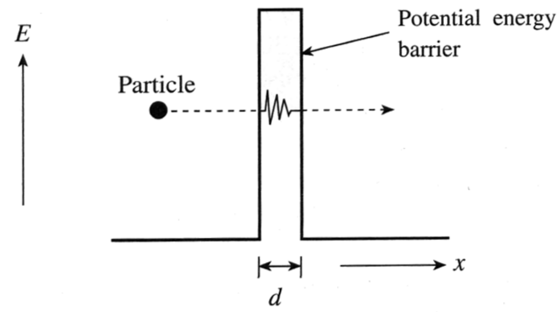
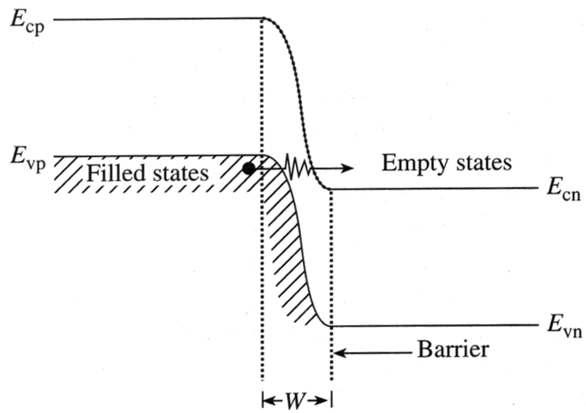


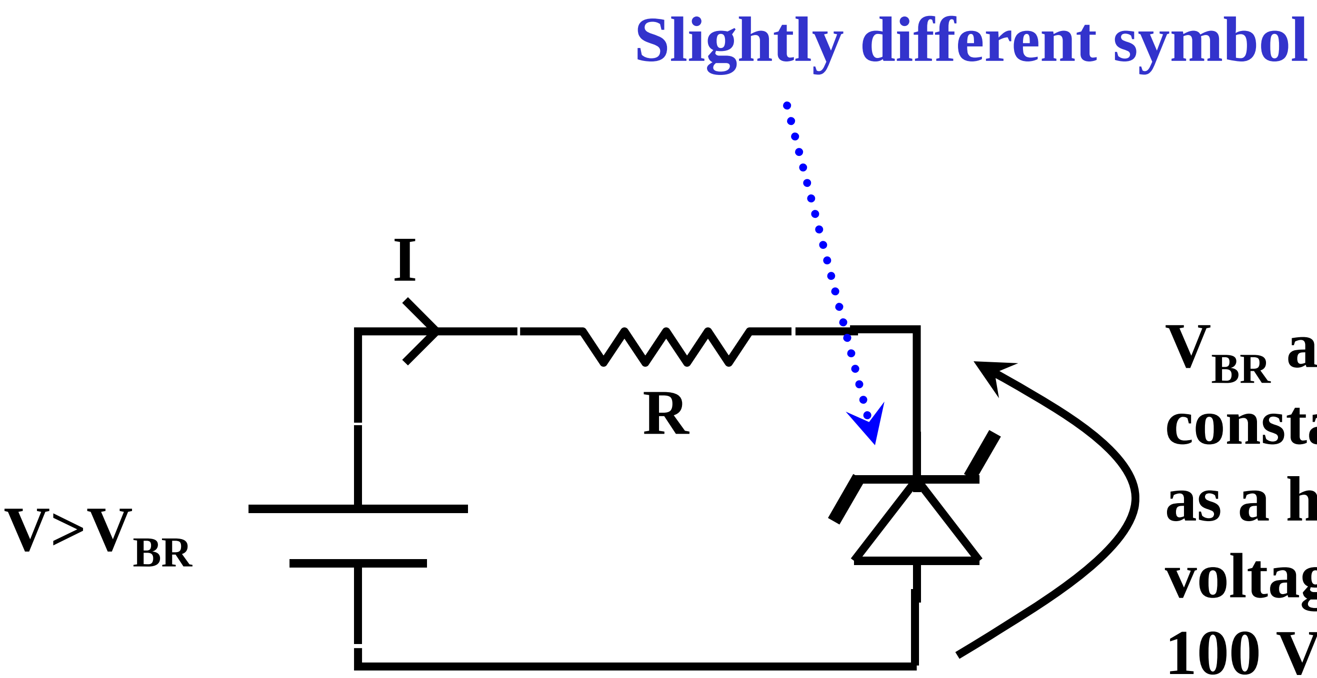
Figure 6.13 General visualization of tunneling.



"Zener" Diodes

Zener diodes may actually operate based on either avalanche or zener breakdown mechanisms.

Rule of thumb: $|V_{BR}|>6E_G/q$ is typically Avalanche Breakdown

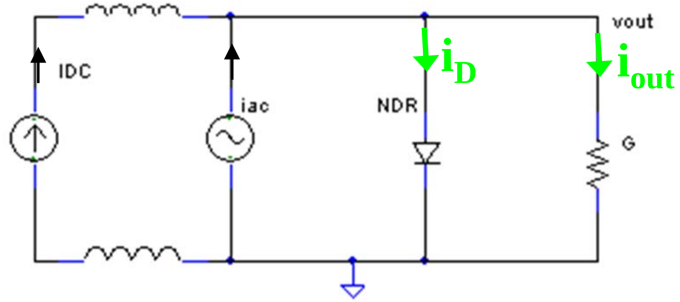


V_{BR} almost constant can act as a high voltage (~1V - 100 V) DC reference

Negative Differential Resistance Diodes

•Negative Differential Resistance (NDR) Diodes can be used for high frequency oscillators and even ac amplifiers (two terminal instead of 3-terminal transistors)

•Consider the following Circuit, IV curve and load line.



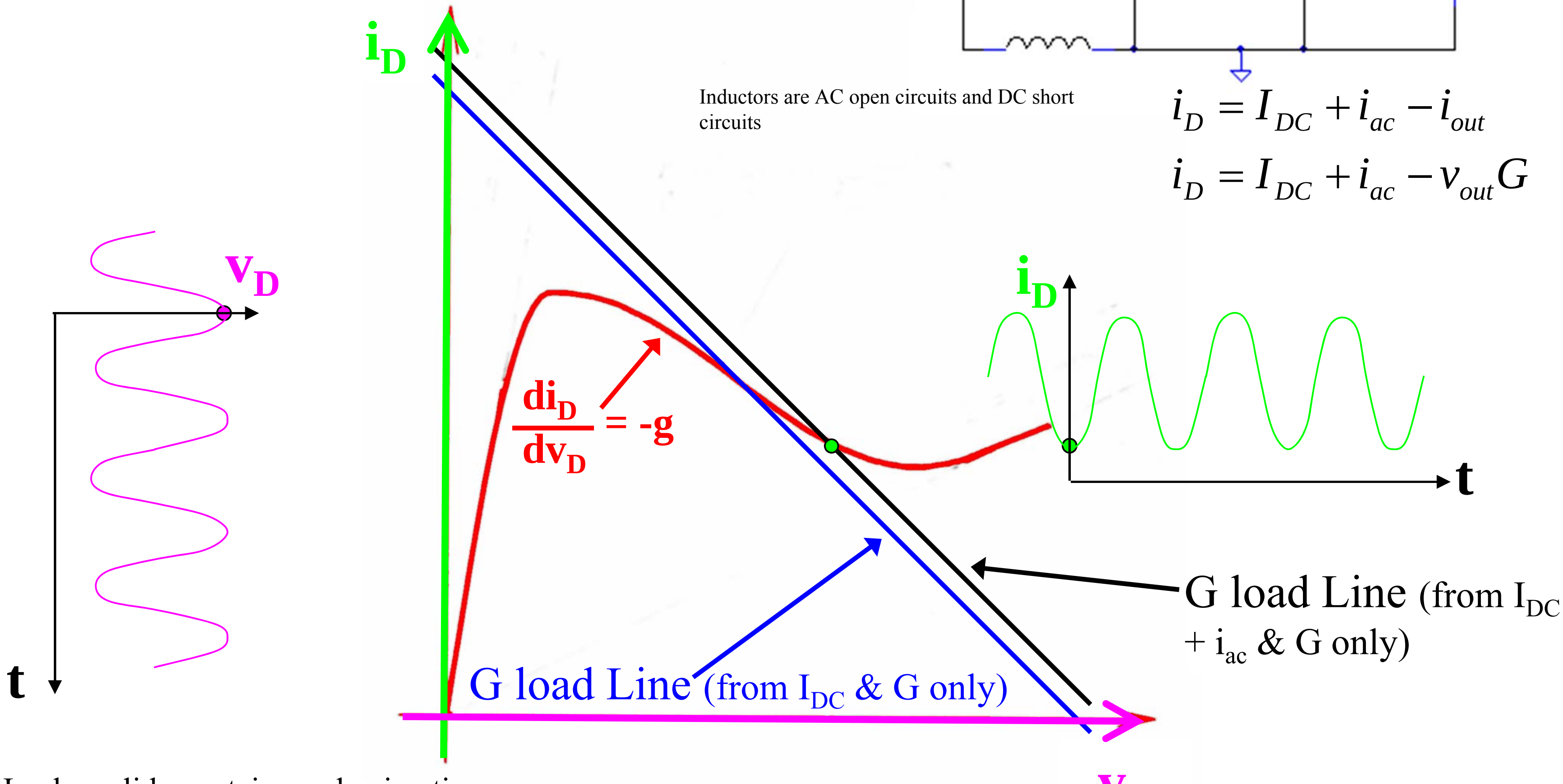
•Unlike a regular diode,

i_D is 180 degrees out of phase with v_D

Inductors are AC open circuits and DC short circuits

$$i_D = I_{DC} + i_{ac} - i_{out}$$

$$i_D = I_{DC} + i_{ac} - v_{out} G$$



Note: In class slide contains and animation

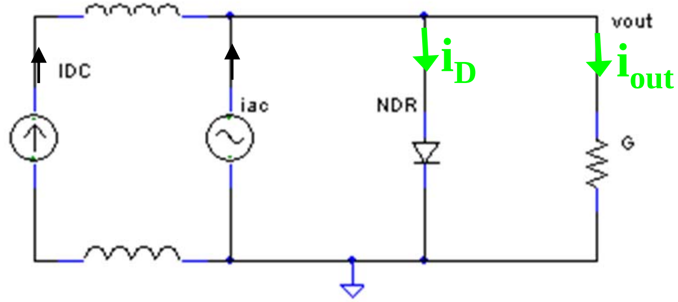
Negative Differential Resistance Diodes

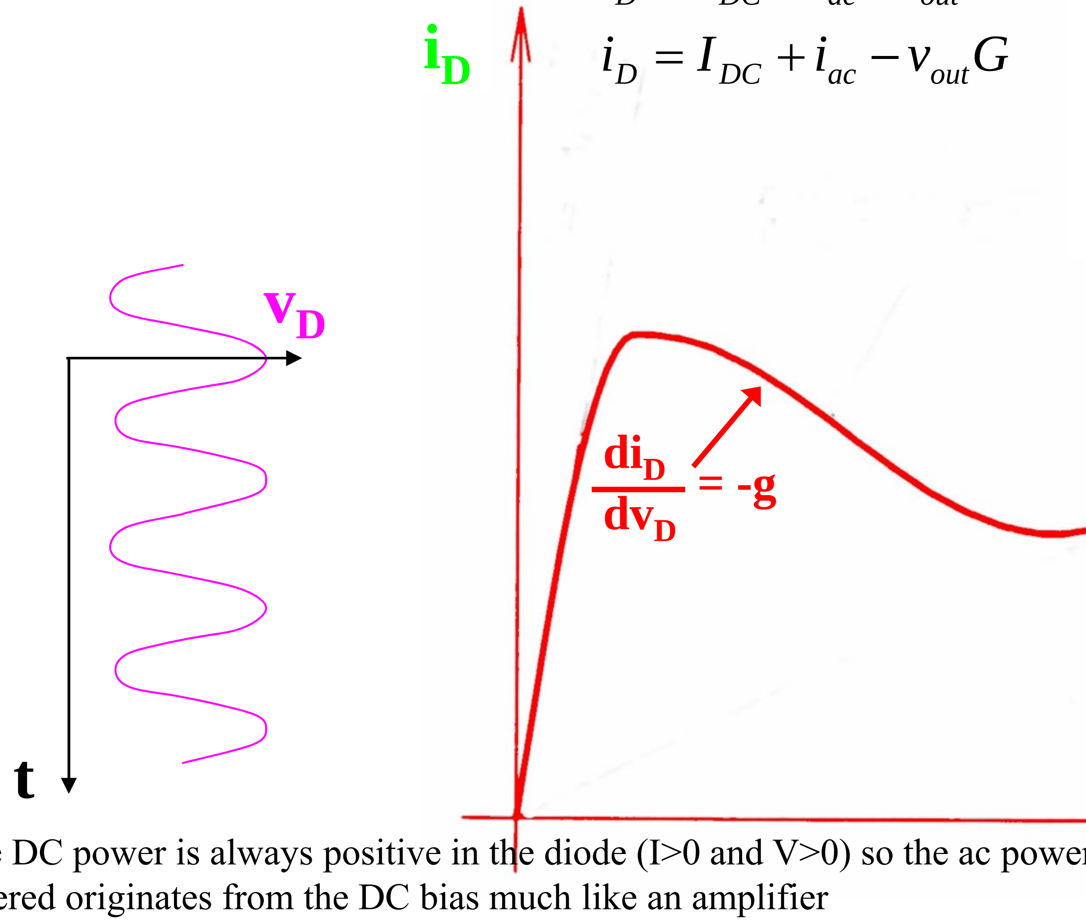
•Unlike a regular diode, i_D is 180 degrees out of phase with v_D

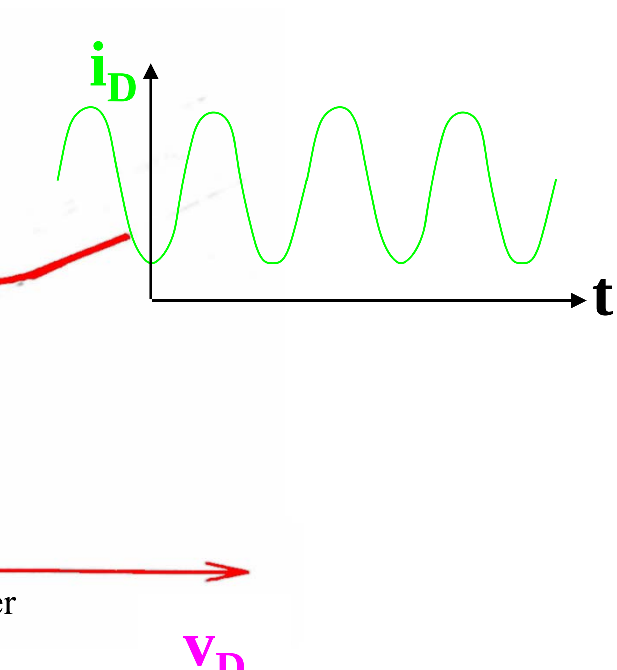
•AC power in the diode is negative ($p_d = v_d i_d < 0$) but AC power in the load G is positive $p_{out} = v_{out} i_{out}$. This means the diode is delivering power (sourcing power)*

$$i_D = I_{DC} + i_{ac} - i_{out}$$

$$i_D = I_{DC} + i_{ac} - v_{out} G$$







* The DC power is always positive in the diode (I>0 and V>0) so the ac power delivered originates from the DC bias much like an amplifier

Negative Differential Resistance Diodes

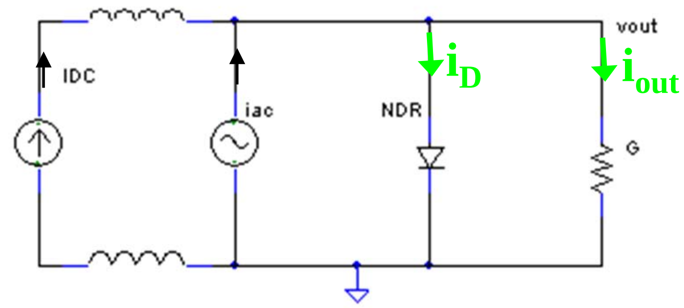
•If we define the ac current gain as $A_i = i_{out}/i_{ac}$

$$i_{ac} = \frac{i_{out}}{A_i} = i_d + i_{out}$$ and since there is only one ac voltage in this circuit, v_{out}

$$\frac{Gv_{out}}{A_i} = gv_{out} + Gv_{out},$$ where g is negative

Solving for A_i,

$$A_i = \frac{G}{G+g} \text{ or } \frac{G}{G-|g|}$$



•If the load conductance G>|g| (NDR conductance) then A_i is positive and A_i>1 → we get current amplification

•If G=|g| then A_i is infinite → the circuit is not stable and thus we CAN get oscillation. Even for no intentional input, i_{ac}, a finite ac output, $i_{out}=A_i i_{ac}$, is still possible – oscillation frequency can be very high speed!!!!! Noise currents can and will initiate oscillation.

Advanced Devices: Tunnel Diodes (Esaki and RTDs)

- Tunnel diodes are typically used in low power high frequency circuits.
- They have in many cases been superseded by higher power Gunn and IMPATT diodes

Advanced Devices: Tunnel (Esaki) Diodes

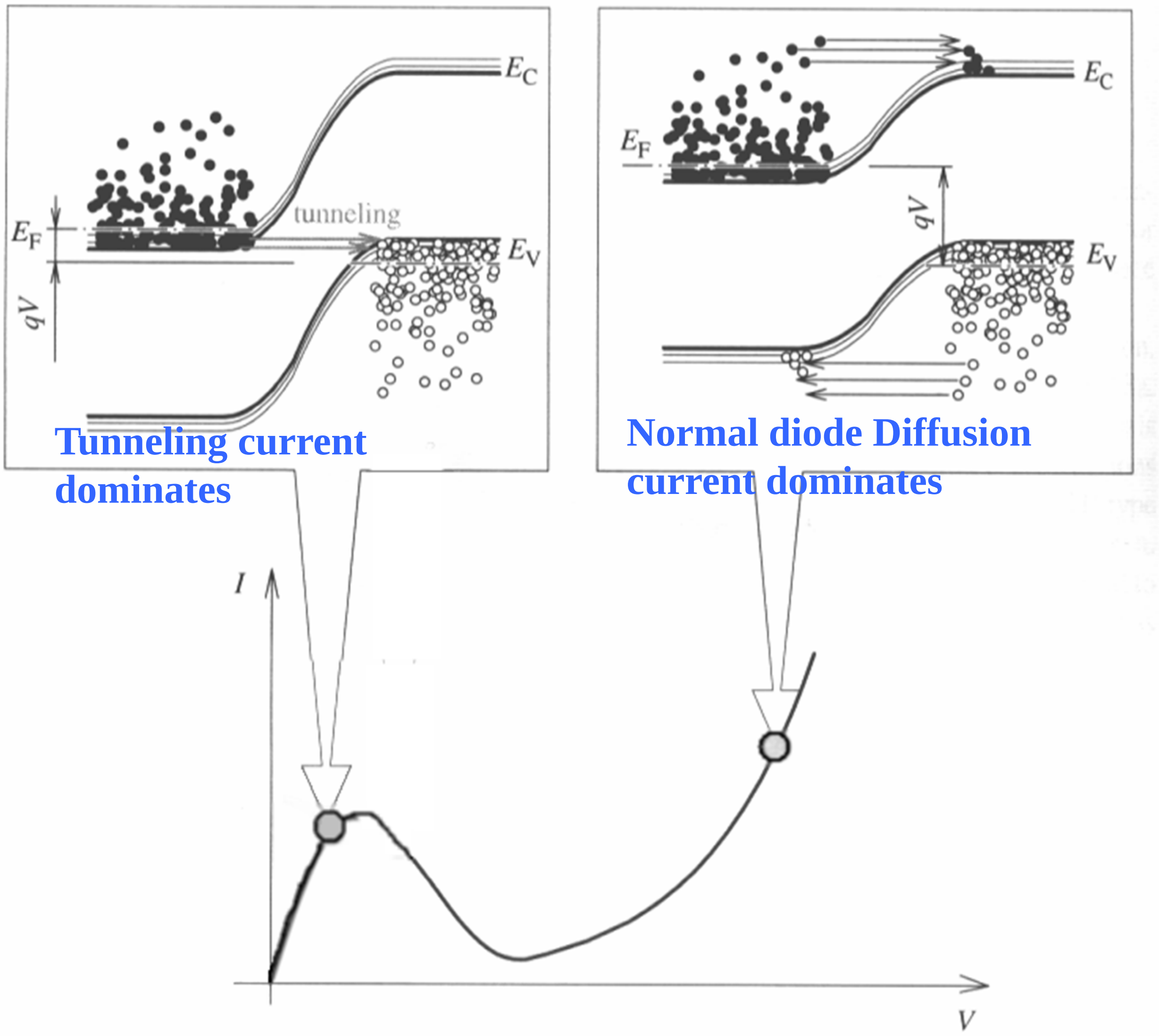
•Start with degenerately doped p+ - n+ diodes so that the fermi energy is in the conduction and valence bands as shown

•At small voltages, the degenerate doping results in a tunneling current that reduces the normal diffusion current creating a “negative differential resistance” (negative slope in IV curve).

•As the forward bias increases, the tunnel barrier increases as the bands flatten, lowering the current flow.

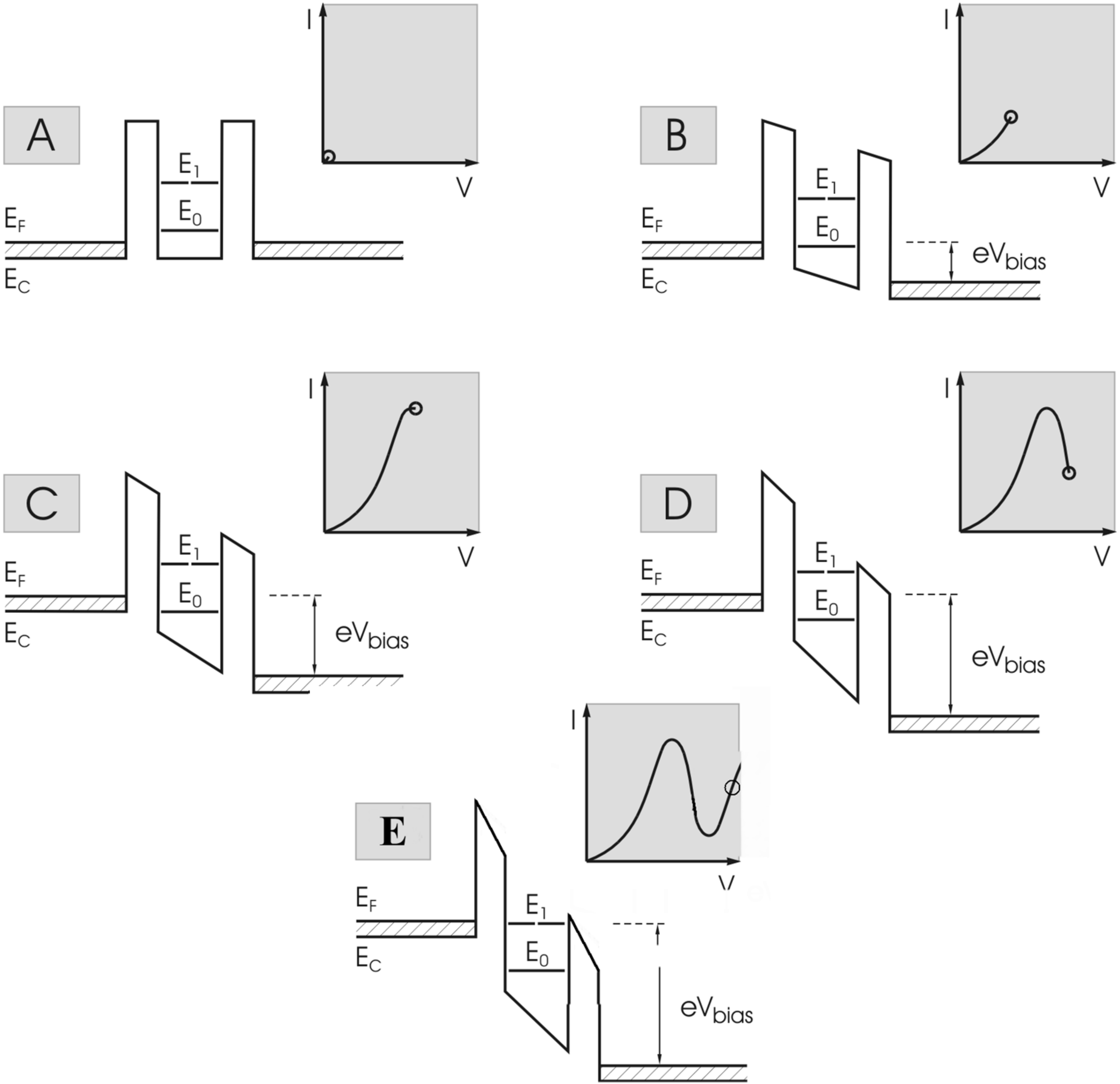
•At larger forward voltages, tunneling current is not allowed since bands are not aligned resulting in normal diffusion current creating a “positive differential resistance” (positive slope in IV curve).

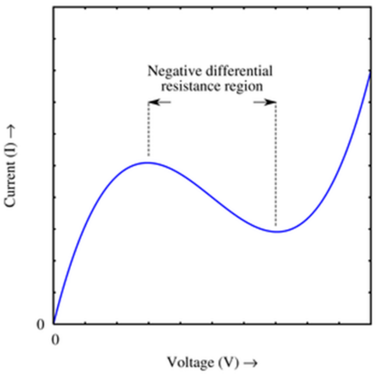
•Such an IV curve can result in natural oscillation at high frequencies.



Advanced Devices: Resonant Tunneling Diode (RTD)

- Conduction proceeds through quantum states in quantum wells
- As bias changes, the states align and misalign governing current flow
- The abruptness of the quantum confined states generally results in larger NDR conductance's and sharper transitions than compared to p+/n+ diodes.





Advanced Devices: Transferred Electron Devices
Gunn Diodes

We will study two types of Transferred Electron devices:

1) A Gunn Diode is a moderately high power (up to ~ 1 watt) diode used in high-frequency electronics and microwave devices.

Multiple modes of operation are possible. We will only consider the transit time mode (also know as the Gunn Oscillation mode or the accumulation layer mode).

Compared to the IMPATT diode (see later) Gunn diodes are used more often in circuitry where phase noise (low jitter) is required (radar, PLLs etc…) .

Typically used for 1-100 GHz but can be higher.

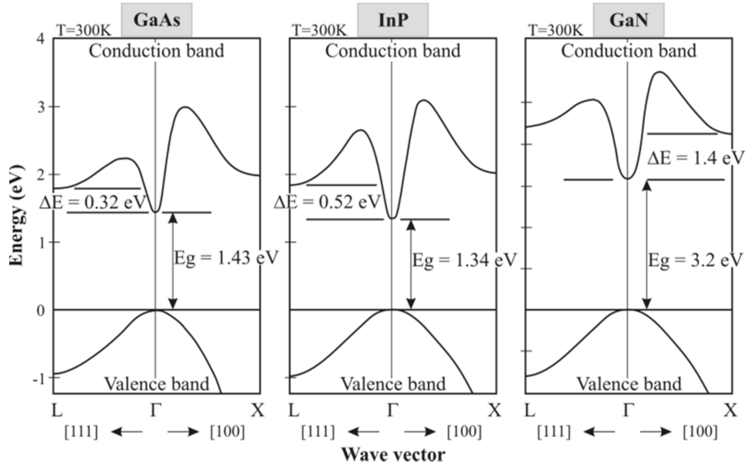
Advanced Devices: Transferred Electron Devices
Gunn Diodes

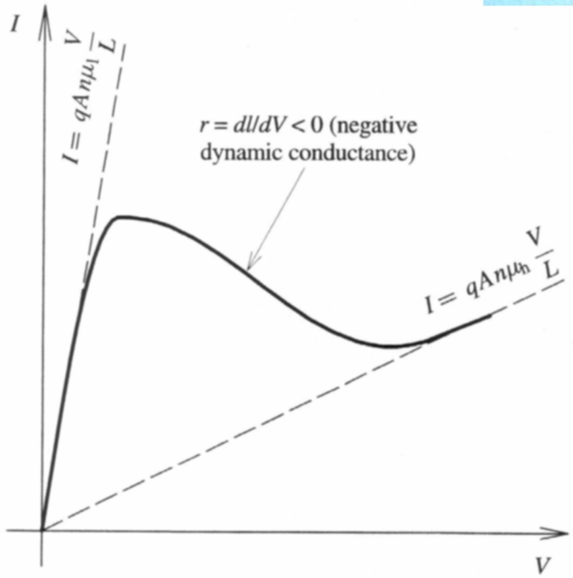
•Many semiconductors have multiple valleys in the conduction band, each having a different curvature and thus different effective mass

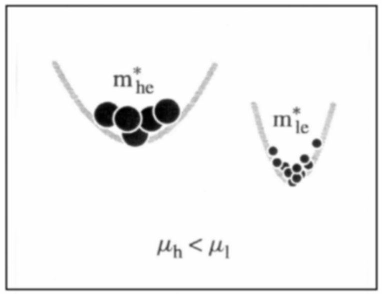
•If a large enough electric field is applied, electrons in the lowest valley can be accelerated and collide with atoms or other electrons and scatter into different directions (most often [111]) where they appear heavier and thus the electron velocity (v_{Drift}=Eμ) slows down

•Since current is I=(Area q n v_{Drift}), the current reduces for the same number of electrons.

•Note: Only a piece of n-type semiconductor is needed (i.e. no p-n junction or heterojunction is needed)







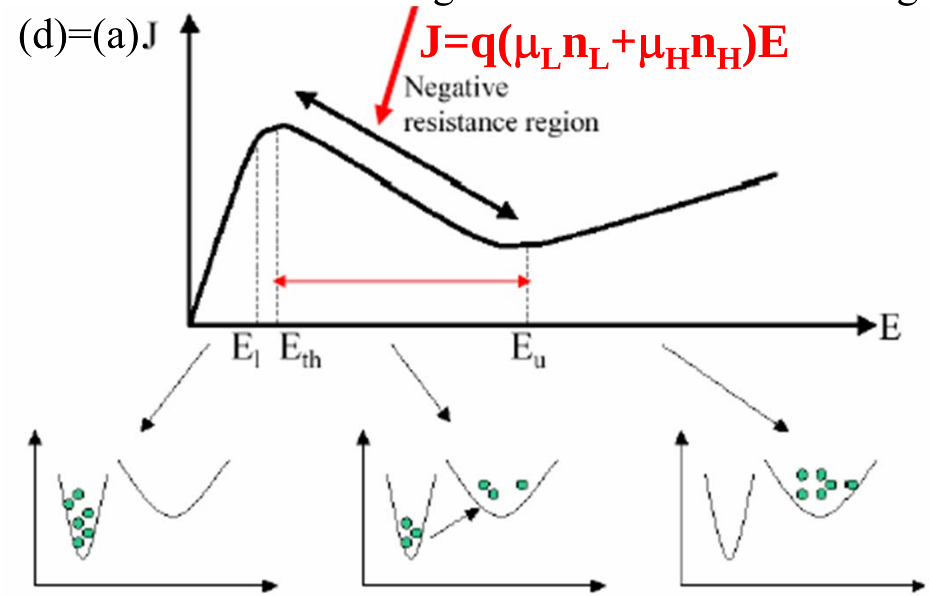
Advanced Devices: Transferred Electron Devices

Gunn Diodes

•Initially electrons flow (a) but as the electrons travel through the n-type layer, some gain enough energy to be scattered into slower k-space valleys (b).

•This pile up of electrons (b) occurs creating a traffic jam of electrons and a resulting electric field profile change and current reduction. Note the majority of the electric field is dropped across the more resistive region.

•As the slower "packet" of electrons finally reaches the anode, the current increases again (c) until the electrons are cleared from the device returning the device back to it's original state (d)=(a).



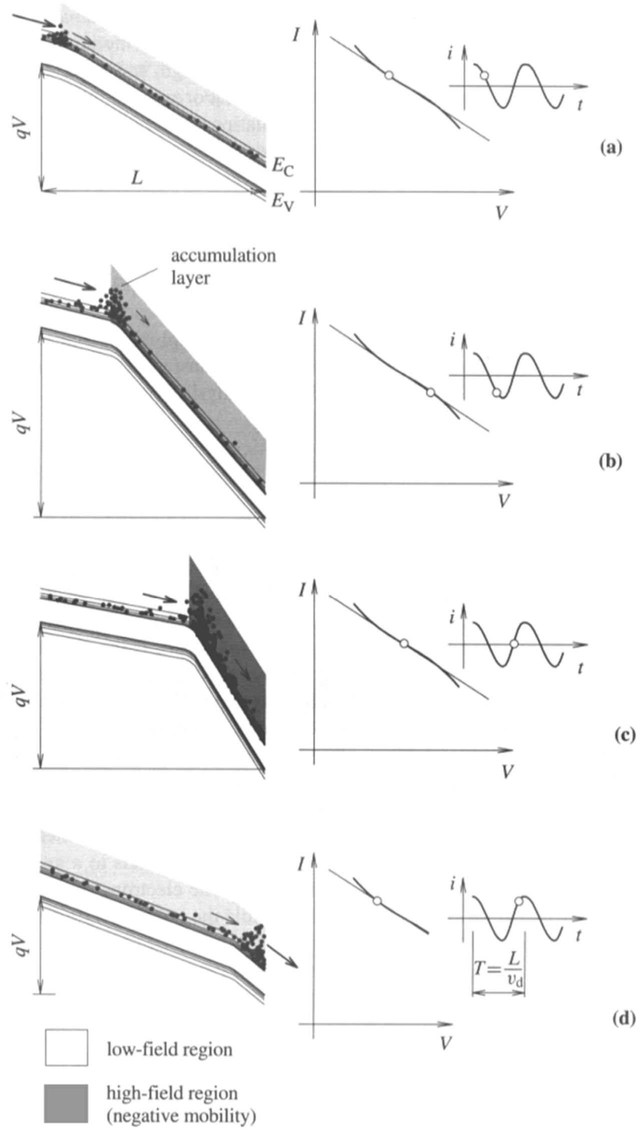


Figure 9.17 Illustration of a Gunn-effect oscillator.

See http://www.st-andrews.ac.uk/~www_pa/Scots_Guide/RadCom/part5/page1.html for details on how to use in an oscillator circuit

Advanced Devices: Transferred Electron Devices
IMPATT Diodes

•**2) IMPATT diode** (**IMP**act ionization **A**valanche **T**ransit-**T**ime) is a high power diode used in high-frequency electronics and microwave devices.

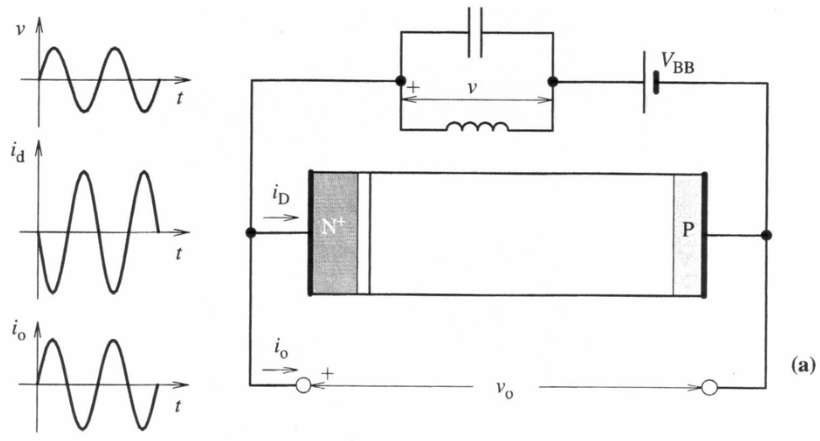
•Main advantage is their VERY high power capability.

•Due to the avalanche operational principle, they have very large phase noise (bad jitter) which is a drawback in many timing critical circuitry (radar, PLLs etc…) .

•Capable of watts of CW power from ~ 3-200 Ghz and many ten's of watts pulsed power.

•IMPATT diodes require an external (or sometimes internal packaging induced) resonant circuit for proper operation.

•Again, the "trick" to creating an oscillator is to create a current that is
out of phase with the ac voltage.



Advanced Devices: Transferred Electron Devices
IMPATT Diodes

•A heavily one sided diode such as a (n+ - i – p) diode is typically used

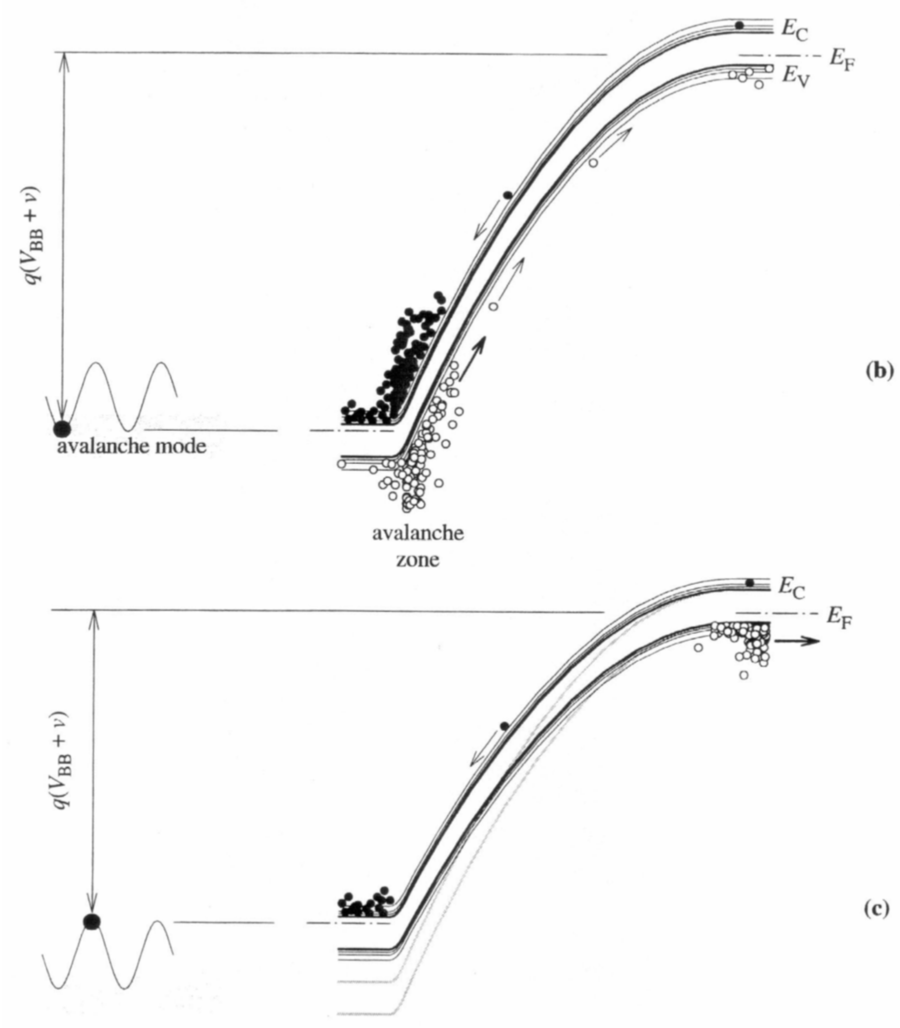
•The diode is biased on the verge of avalanche

•The n+ doping insures the highest electric field is near the cathode (n+ region)

•When a small ac voltage is superimposed on the high DC bias, the device goes into (and later out of) avalanche breakdown

•The electron avalanche packet is quickly collected but the hole packet must drift through the lower field (slightly below avalanche) i-layer. This time delay before reaching the cathode results in a phase shift in the current.

•If the transit time of the hole packet is designed correctly the current pulse at the cathode (p-side) can be out of phase with the perturbing ac voltage resulting in oscillations which are sustained by the external resonant circuit. This requires precise selection of internal electric fields and thicknesses of the i-layer as well as proper selection of the resonant L and C.



Advanced Devices: Final Comments

•While simple Tunnel diodes and Avalanche diodes can be easily made in silicon technologies, the speed requirements and precision of the thicknesses and energy band alignments most often result in these devices being made via compound semiconductor epitaxy.

•The abruptness of the NDR region effects the ease of design (easier to design circuitry for a large NDR conductance, g.

•Noise is always present in any real device. Noise can serve as the ac current source to induce oscillations which are then sustained if the ac current is out of phase with the ac voltage by 180 degrees.

•Avalanche based processes are noisy so in general, one should use a tunneling or Gunn effect device unless power or voltage limits require an avalanche device.