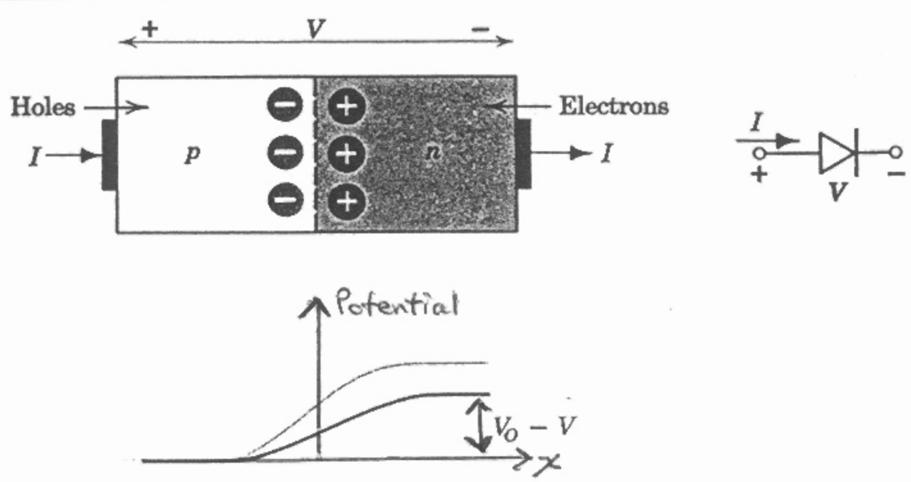
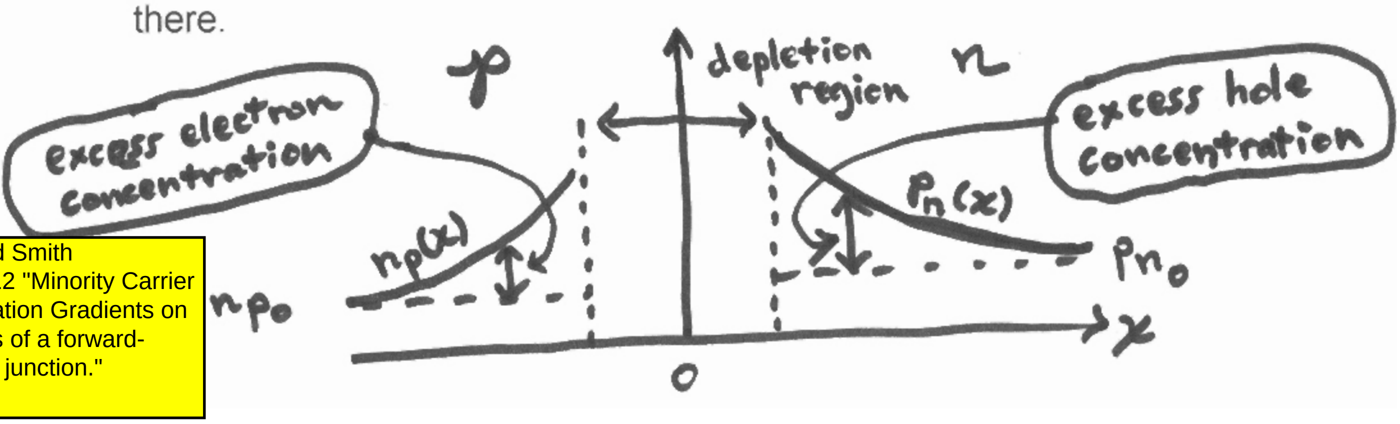
Now the probability of majority carriers possessing sufficient energy to overcome the potential barrier and diffuse across the junction is

$$e^{\frac{-q\cdot(Vo - V)}{k\cdot T}} \qquad (1 - 25)$$

**Fig. 1-11. Forward-biased pn junction diode**



Thus the probability of majority carriers possessing sufficient energy to surpass the potential barrier is *greatly increased*. Now diffusion current greatly outweighs the drift current. Holes from the p-type semiconductor diffuse toward the right through the depletion region and are "injected" into the n-type material, where they become minority carriers. Each of these minority carriers eventually recombines when it meets one of the many free electron majority carriers in the n-region. In similar fashion, electrons in the n-region diffuse toward the left across the depletion region into the p-region, where they become minority carriers, and they eventually recombine there.



Sedra and Smith Figure 3.12 "Minority Carrier Concentration Gradients on both sides of a forward-biased pn junction."

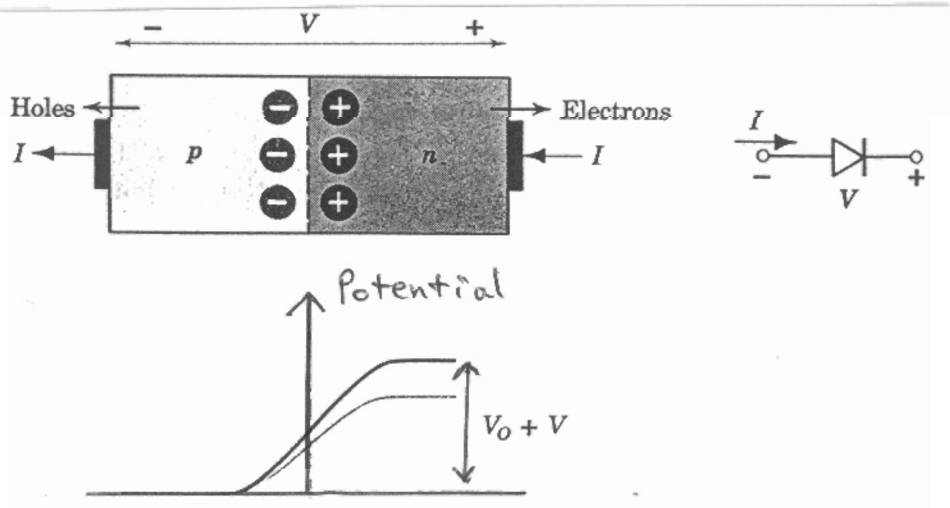
As an electron that is injected into the p region recombines, a negative electrical charge imbalance results in the crystal lattice that causes an electron to be pushed out onto the diode's p-region contact (anode), thereby supplying a new hole at this contact. Likewise, as a hole that is injected into the n region recombines, it creates a positive electrical charge imbalance in the crystal lattice that causes a new conduction electron to be attracted into the n-region contact (cathode). Thus a net current I flows through the diode.

Thus current flow is sustained in the forward-biased diode by the continuous generation of majority carriers (at the diode's anode and cathode contacts) and the recombination of the injected minority carriers (in the bulk p and n regions adjacent to either side of the depletion region.)

## 1.4.5 Reverse-biased pn Junction

If an external voltage source of V volts is connected in the opposite direction across the diode, making the n-region contact (cathode) the positive terminal, and the p-region contact (anode) the negative terminal, the junction potential barrier is raised to Vo+V volts, as shown in Fig. 1-12.

**Fig. 1-12. Reverse-biased pn junction diode**



The junction is said to be "***reverse-biased***", and now the probability of majority carriers possessing sufficient energy to surmount the potential barrier is greatly decreased from the case of the open-circuited junction. The net diffusion of majority carriers across the junction, and therefore the minority carrier injection current is essentially zero for a reverse bias of even a tenth of a volt.

However, a small reverse current does flow. This is due to the drifting of minority carriers that are thermally generated in and near the edges of the depletion region due to thermal generation of electron-hole pairs. All minority carriers appearing at the edge of the transition region are "swept across" this region by the electric field. Holes "roll down" the potential hill, free electrons "roll up".

This small reverse current, called the "***reverse saturation current***", ***Is***, depends only upon the rate of thermal generation and the junction dimensions, and is independent of the barrier height. The reverse current reaches its maximum value, or "***saturates***" at reverse-bias voltage levels of about a tenth of a volt, which is the level required to suppress the diffusion current to a negligible level.

At ordinary temperatures the reverse saturation current is very small, on the order of 1 nA = $10^{-9}$ A for silicon. This small value of Is makes the diode a nearly ideal rectifying device (one-way conductor), since such a device must pass current in only one direction. ***Is*** is directly proportional to the thermal electron-hole pair generation rate, $\boldsymbol{g = r (n_i)^2}$, which varies exponentially with temperature. As a rule of thumb, ***Is*** approximately ***doubles with each 10 degree Centigrade rise*** in temperature.

↕

5 (text)

## 1.5 Diode Equation

Diode current ***I*** consists of a reverse saturation component ***-Is*** that is independent of diode terminal voltage, and an injected component ***Ii***, which is proportional to the probability that the majority carriers have sufficient energy to cross the potential barrier of height ***(Vo-V)*** volts, which is proportional to

$\frac{kT}{q} = V_t$ = 26mV@ room Temp

$$e^{\frac{-q\cdot(Vo\,-\,V)}{k\cdot T}} = e^{\frac{-q\cdot Vo}{k\cdot T}}\cdot e^{\frac{q\cdot V}{k\cdot T}} = A_1\cdot e^{\frac{q\cdot V}{k\cdot T}} \qquad (1-26)$$

Where the constant $A_1$ is defined as $A_1 = e^{\frac{-q\cdot Vo}{k\cdot T}}$ since Vo, the open-circuit equilibrium potential barrier height, is a constant.

Therefore, at a given temperature, the injection current is given by

$$I_i = A_1\cdot A_2\cdot e^{\frac{q\cdot V}{k\cdot T}} = A\cdot e^{\frac{q\cdot V}{k\cdot T}} \qquad (1-27)$$

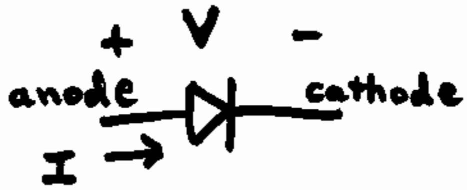
Where $A_2$ is the proportionality constant between the injection current and the probability that the majority carriers have sufficient energy to cross the junction's potential barrier.

The total diode current is therefore

$$I = I_i - I_s = A\cdot e^{\frac{q\cdot V}{k\cdot T}} - I_s \qquad (1-28)$$

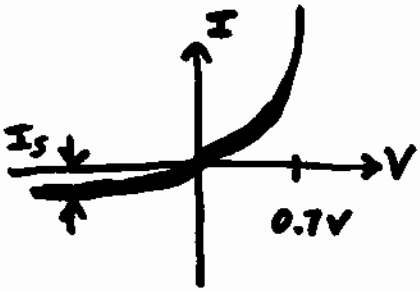
Under open-circuit conditions, the diode current I = 0 and the diode terminal voltage V = 0, therefore we may evaluate the constant A

$$I = 0 = A \cdot e^{0} - I_S \quad \Rightarrow \quad A = I_S$$



Thus the ***diode equation*** becomes:

$$I = I_S \cdot \left( e^{\frac{q \cdot V}{k \cdot T}} - 1 \right) \qquad (1-29)$$



Recall that q is the magnitude of charge on an electron

$$q = 1.6 \cdot 10^{-19} \ \text{C}$$

The Kelvin value of room temperature (25 degrees C)

$$T = 25 + 273 \quad \Rightarrow \quad T = 298 \ \text{K}$$

The value of Boltzmann's constant is $k = 1.381 \cdot 10^{-23}$ J/K

Therefore at room temp, $\frac{k \cdot T}{q} = 0.025721$ Volts (1 - 30)

Substituting (1-30) into (1-29) yields

$$I = I_S \cdot \left( e^{\frac{V}{0.0257}} - 1 \right) \qquad (1-31)$$

******************************************************************************

**Example 1-4**

For a Si diode at room temperature with a current of -1 nA at a diode voltage of -1V, find the diode current for diode voltages of -0.2V, 0.2V, and 0.5V. Plot the diode's I-V curve. Then repeat if the temperature is increased by 20 deg. C.

*Solution*: At V = -1 V, we can assume that the diode current is approximately ***-Is***, therefore we can assume that

$$I_S := 10^{-9} \quad A$$

$$I(V) := I_S \cdot \left( e^{\frac{V}{0.0257}} - 1 \right)$$

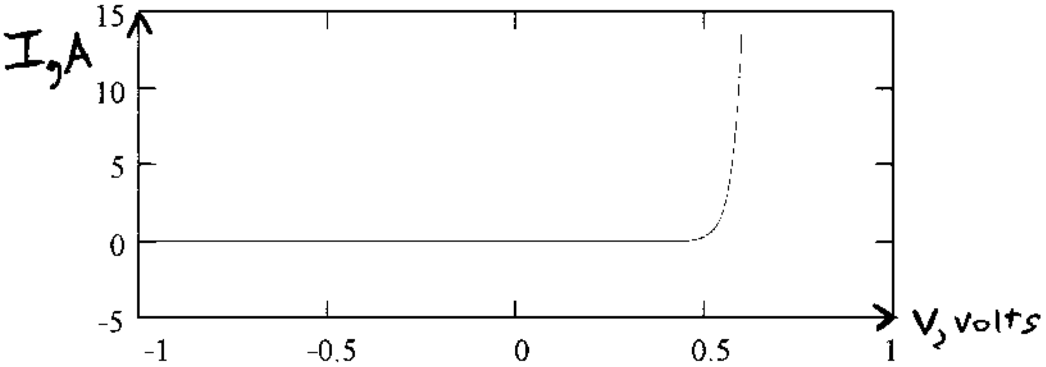
$$I(-0.2) = -9.995829 \cdot 10^{-10} \quad A$$ (Still very close to -Is)

$$I(0.2) = 2.396307 \cdot 10^{-6} \quad A$$

$$I(0.5) = 0.28139 \quad A$$

Fig. 1-13 shows the plot of the diodes I-V characteristic, as predicted by the above diode equation

**Fig. 1-13. Diode I-V curve plotted from the diode equation for room temp. (T = 298 K) and Is = 1 nA.**



Note that this result matches with the experimental diode I-V curve with the exception of the reverse breakdown region.

Since ***Is*** will double twice as the temperature rises through two 10 degree Centigrade increments, now $\swarrow k = 1.38\times10^{-23}\ J/K$

$$I_S = 4\cdot10^{-9} \quad \underline{\underline{\text{and}}} \quad \frac{kT}{q} = \frac{k(273+25+20)}{q} = 0.0274\ V$$

$$I(V) = I_S\cdot\left(e^{\left(\frac{V}{0.0274}\right)} - 1\right)$$

$I(-0.2) = -3.9972\cdot10^{-9}$ A (Still very close to -Is)

$I(0.2) = 5.839\times10^{-6}$ A

$I(0.5) = 0.326$ A (What a difference 20 degrees makes!)

****************************************************************************

Note from the (1-31) that for diode terminal voltages less than 0.1 V, the diode current is essentially -***Is***, since

$$e^{-\frac{0.1}{0.0257}} = 0.020424$$

which is much less than 1.

Likewise, for diode terminal voltages greater than 0.1 V, (1-31) shows that the diode current is approximately given by

$$I = I_S\cdot e^{\frac{V}{0.0257}}$$

Since

$$e^{\frac{0.1}{0.0257}} = 48.962299$$

(Which is much greater than 1)

Consideration of various second-order effects causes us to modify (1-29) slightly for the lower current levels typically encountered in electronic circuits by adding the correction factor η, *eta*:

$$I = I_S \cdot \left( e^{\frac{q \cdot V}{\eta \cdot k \cdot T}} - 1 \right) \qquad (1 - 32)$$

Where η = 2 for low currents (in the μA range)

η = 1 for higher currents (in the A range)

********************************************************************************

**Example 1-5**

A small signal diode's "forward junction voltage drop" is defined as the diode voltage when the diode is conducting 1% of its maximum rated current. Given a Si diode with ***Is*** = 1 nA, and ***Imax*** = 100 mA. Find its forward voltage drop.

***Solution***:

$$I_S := 10^{-9} \quad A$$

$$0.01 \cdot 100 \cdot 10^{-3} = I_S \cdot \left( e^{\frac{q \cdot V}{2 \cdot k \cdot T}} \right)$$

(use η = 2)

$$V := 2 \cdot \frac{\ln\left(1.0 \cdot \frac{10^{-3}}{I_S}\right)}{q} \cdot k \cdot T$$

$$V = 0.710701 \quad V$$

(So the forward junction drop of an Si diode will be taken to be 0.7 Volts.)

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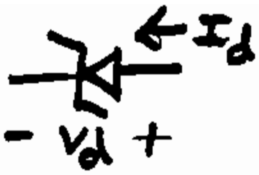
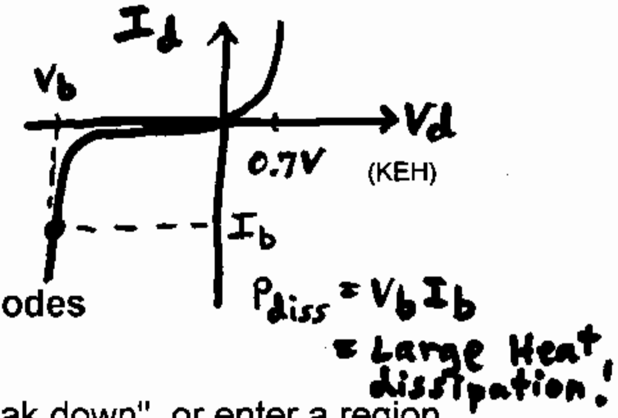




## 1.6 Special Diodes

### 1.6.1 Zener (Avalanche Breakdown) Diodes

All pn diode junctions eventually "break down", or enter a region of high conductance, which is not predicted by the above diode equation. Breakdown occurs when the reverse bias voltage is increased above a certain threshold value, Vb, which can range from a few volts to several hundred volts, depending on junction structure and doping levels. ***Zener breakdown*** occurs when the electric field in the depletion region gets so intense that electrons are literally torn out of their covalent bonds in neutral Si atoms.

The electron-hole pairs that result are accelerated in opposite directions by the intense electric field that exists in the depletion region, and this action acts to dramatically increase the reverse current. This results in a steep reverse breakdown slope in the diode I-V curve, or "***Zener knee***", as it is sometimes called. An additional effect occurs in diodes with higher breakdown voltages, the electron-hole pairs get accelerated to such a high speed that they collide with other neutral atoms with enough force to knock them loose, resulting in an "***avalanche***" of charge carriers, contributing to an even steeper slope of the I-V curve in the reverse breakdown region, and so the name ***avalanche breakdown***.

If the power dissipated (which can be large in the reverse breakdown region, since power is product of V times I) is within the capability of the diode, there is no damage, and if the reverse bias voltage is reduced below the breakdown threshold, Vb. then the current decreases back to the reverse saturation level.

Diodes manufactured with precisely specified Vb values are called ***Zener diodes.*** Such diodes are manufactured to dissipate larger amounts of heat than rectifying diodes, since even small diode currents can result in large P = Vb*I losses, since Vb is often large. Zener diodes are useful in making "regulated" dc power supply sources that provide nearly constant voltage under conditions of widely varying load currents.

### 1.6.2 Varactor (Variable Capacitance) Diodes

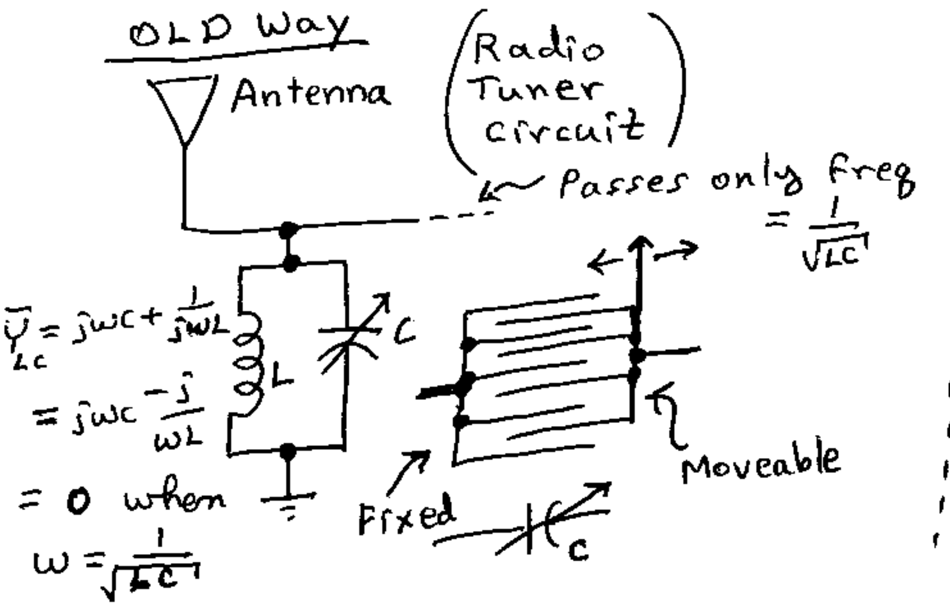
Sedra and Smith
Eqn 3.47

$C_j = C_{jo}/(1+V_r/V_o)^m$
Where m = 1/2 to 1/3, depending on junction grading profile.
Note: $V_r = -V_d$ = Cathode to anode voltage

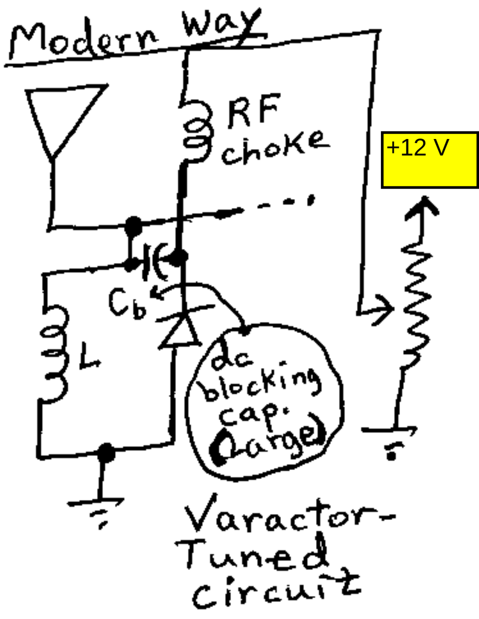
$$V_o = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

Along with change in junction potential due to forward and reverse biasing, there is a significant change in the width of the depletion region.

For a given junction potential, a certain number of bound lattice ion charges must be uncovered, therefore the width of the depletion layer depends on the doping density, and the width of the depletion region increases with increasing reverse bias voltage. Because the depletion region is essentially depleted of charge carriers, it acts like the dielectric of a capacitor, and the capacitance of the reverse-biased junction can be varied between perhaps 20 pF (at low reverse bias values) down to 5 pF at higher reverse-bias voltages, which are still below Vb. Varactors are diodes especially constructed (with large junction cross-sections) to exhibit a large range of reverse biased junction capacitances. Varactors are used as voltage-controlled variable capacitors in digitally-controlled RF tuner circuitry in modern radio and television receivers.



$$\bar{Y}_{LC} = j\omega C + \frac{1}{j\omega L} = j\omega C - \frac{j}{\omega L} = 0 \text{ when } \omega = \frac{1}{\sqrt{LC}}$$



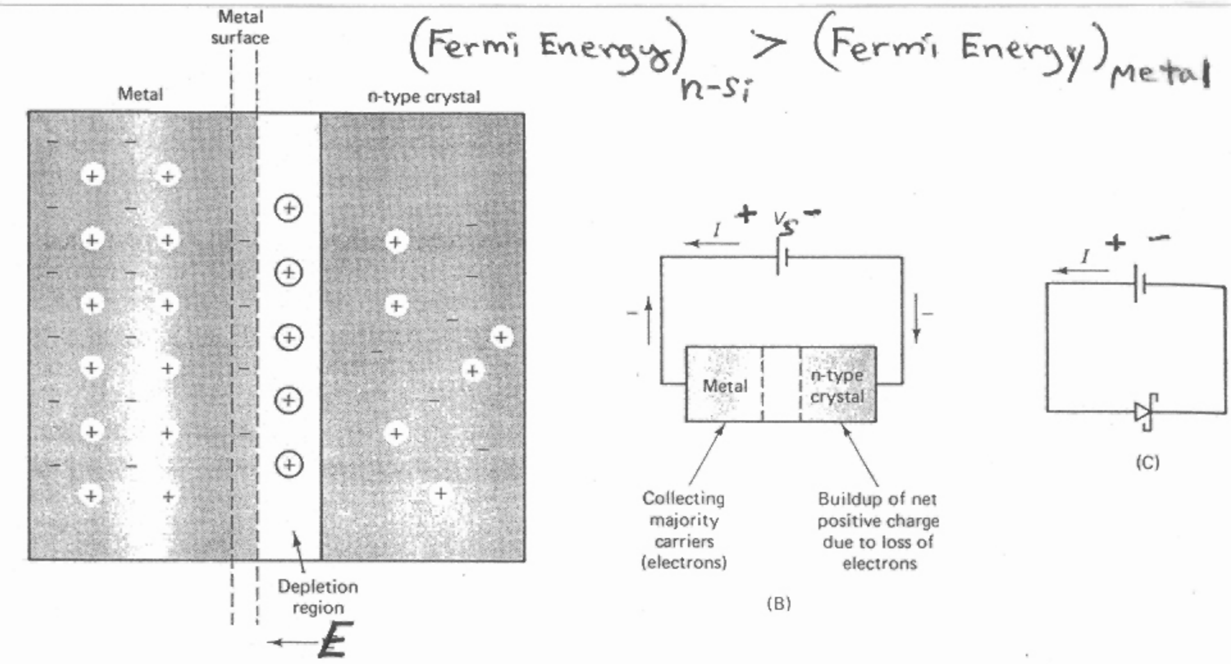
### 1.6.3 Schottky (Metal-Semiconductor) Junction Diodes

When aluminum comes in contact with n-type silicon, a rectifying Al-n junction diode is formed. This is because the average carrier energy (Fermi level) in lightly n-doped Si is greater than the average carrier energy in a metal like aluminum. When the bond is formed, the "hot" electrons in the n-type Si diffuse into the Al, leaving behind positive bound lattice ions. On the other side of the junction, a layer of electrons builds up on the metal surface. An internal electric field therefore develops that is directed from the positive bound ions to the electron layer. This internal field resists further electron diffusion from Al to n-silicon, and an equilibrium state is reached, that is similar, but not identical to that in the open-circuited pn junction. The potential barrier is lower than in n Si pn junction, so the forward voltage drop of a Schottky diode is only about half that of a Si diode

When the Schottky junction is forward-biased (Al made positive with respect to the n-type Si), the electric field is reduced, and the flow of electron majority carriers from the n-type Si will be greatly increased. In this way a large forward bias current can flow, as shown in Fig. 1-14

Note that when the electrons cross into the metal, they ARE NOT minority carriers, as in a pn junction. Instead, they are simply additional conduction electrons in the aluminum metal. When a pn junction diode is suddenly switched from forward bias to negative bias, the diode current does not immediately cease, since it takes time for the injected minority carriers to recombine. However, in a Schottky diode, because there are no injected minority carriers, the diode current will immediately cease when the diode voltage switches from forward to reverse bias. The speed with which Schottky diodes switch off makes them useful in high speed switching applications.

**Fig. 1-14. Al-n (Metal-Semiconductor) Schottky Diode (a) Junction barrier (b) forward bias (c) Schematic symbol**



(Fermi Energy)$_{n\text{-}Si}$ > (Fermi Energy)$_{Metal}$

## 1.6.4 Non-rectifying (Ohmic) metal-semiconductor contacts

In the previous section, we learned that metal-n type semiconductor junctions were rectifying. But how, then, are ordinary metal contacts applied to n-type silicon (say, in the fabrication of a pn junction diode, or in a bipolar junction or MOS transistor) in order to keep them from being rectifying contacts?

This is done by *heavily doping* the n-region (making it n$^+$ silicon) in the region just under the contact. Due to the very high acceptor ion concentration in the n$^+$ region where the depletion layer forms, the width of the depletion region ***W*** is very thin. This allows electrons to "***tunnel underneath***" the potential barrier (as predicted by quantum mechanical theory), rather than having to go over it. Because electrons on either side of the barrier may tunnel through to the other side, a symmetrical I-V curve for forward or reverse bias results. Thus the contact is non-rectifying, or "***ohmic***".

### 1.6.5 Photodiodes

A photodiode is a pn junction diode that is illuminated with light focused onto the depletion region, as shown in Fig. 1-14.

If the light is of frequency f, it consists of photons with energy

$$E_{photon} = h \cdot f \qquad (1 - 33)$$

$3 \times 10^{8}$ m/s (speed of light)

$$\lambda = \frac{c}{f} \Rightarrow \left( \frac{m/s}{1/s} = m \right)$$

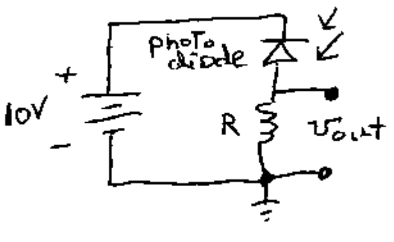
where ***h*** is ***Planck's constant***

$$h = 6.62 \cdot 10^{-34} \quad J \cdot s$$

or $$h = 4.14 \cdot 10^{-15} \quad eV \cdot s$$

If the photon energy $E_{photon}$ exceeds the energy gap between the conduction and valence bands, which for Si is 1.1 eV, the photons can succeed in creating electron-hole pairs in the depletion region by colliding with bound electrons in the crystal lattice. They give up their energy and vanish, knocking an electron free (raising its energy into the conduction band) while leaving behind a hole (whose energy remains in the valence band).

If the diode is reverse-biased (left side of the photodiode's I-V curve in Fig. 1-14), and no light shines on the junction, only the very small reverse saturation current (***Is***) is observed to flow, which is due to the relatively low rate of thermal electron-hole pair generation. This undesirable effect in a photodiode is called "***dark current***". However, when light shines through the photodiode onto the depletion region, the current dramatically increases. This is due to the greatly increased rate of optically stimulated electron-hole pair generation



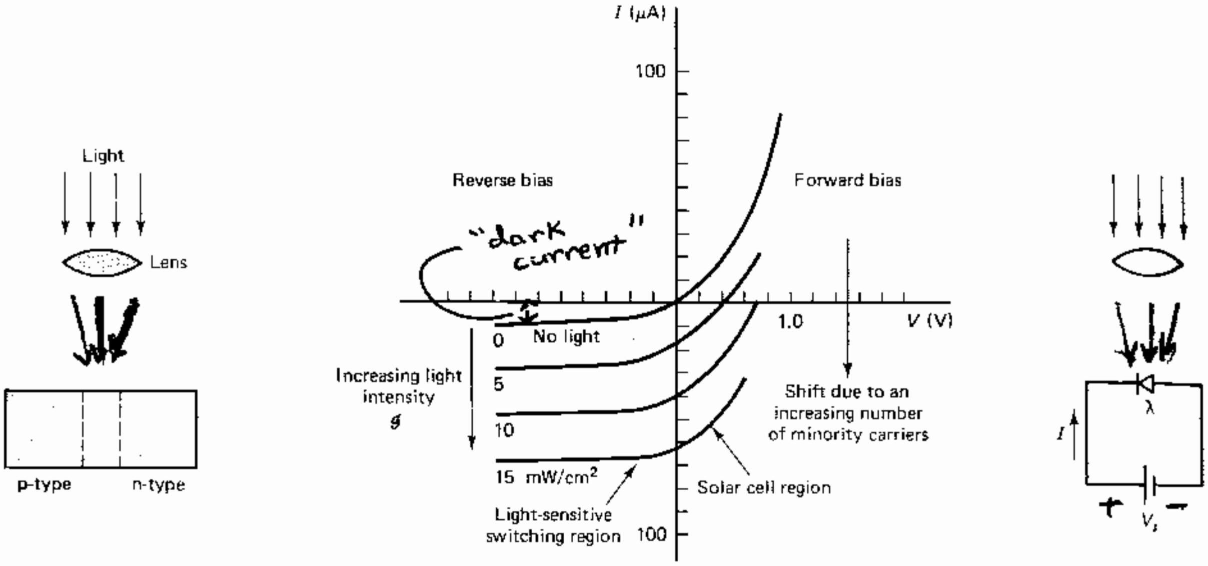
For Si diode, what is the longest wavelength that can be detected?

$$E_{photon} \geq E_g = hf = h\left(\frac{c}{\lambda}\right)$$

$$1.1\ eV = \underbrace{4.14 \times 10^{-15}}_{eV \cdot s} \cdot \underbrace{\left(\frac{3 \times 10^{8}}{\lambda}\right)}_{f = 1/s} \Rightarrow \lambda = 1.1 \times 10^{-6}\ m$$

$\Rightarrow$ (Infrared wavelength) (Red $\Rightarrow 0.7 \times 10^{-6}$m

## Fig. 1-14. Photodiode structure, I-V curve, and circuit



The photodiode can also be used as a power generating device called a ***photovoltaic cell***, or a ***solar cell***. This corresponds to the right half of the I-V curve in Fig. 1-14. The electron-hole pairs produced by the incident light serve to raise the internal pn junction potential beyond the usual amount that is exactly canceled out by the potentials developed across diode's metal-semiconductor contacts, thus a positive voltage that is proportional to incident light intensity will appear at the diode's anode terminal with respect to its cathode terminal. Unfortunately, the amount of voltage that can appear across this diode is limited by the usual forward voltage for a diode (between 0.5 to 1.0 V for silicon), so many of these diodes (or solar cells) must usually be connected to attain a meaningful level of power generation.

### 1.6.6 Light Emitting Diodes (LEDs)

LEDs are very popular sources of visible and infrared light. They are often used in conjunction with fiber-optic transmission cables to create optical communication links.

When a current flows through a diode, some of the electrons and holes recombine in the depletion region. The recombination releases energy that can either be in the form of thermal vibrations in the crystal lattice (heat) or as radiated light photons. The probability of producing photons is much higher in certain semiconductors that exhibit "***direct energy band transitions***", such as ***gallium arsenide***, GaAs. (Silicon is not a very efficient photon emitter, since several intermediate energy states are passed through as an electron and hole recombine.)

Light is emitted in all directions from the depletion region of a forward biased pn junction. The light photons correspond to a frequency that is related to the material's energy gap between the conduction and valence bands through (1-33).

Thus, the frequency of light that is emitted by a GaAs LED, with a direct band gap of 1.4 eV is

$$f = \frac{Eg}{h} = \frac{1.4}{4.14 \cdot 10^{-15}} \; \frac{eV}{eV \cdot s}$$

UV ..0.4µm - - - - - - - - 0.7µm..IR
↑ ↑ ↑ ↑ ↑
Violet blue green orange Red

$$f := 3.3816 \cdot 10^{14} \text{ Hz}$$

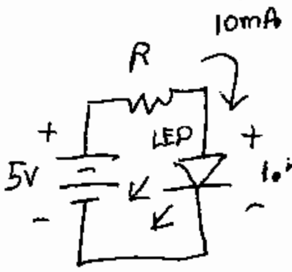
$$\lambda = \frac{v_{light}}{f} = \frac{3 \cdot 10^{8}}{3.3816 \cdot 10^{14}} = 0.887 \text{ microns}$$

The range of light visible to the human eye is from 0.4 microns (violet) to 0.7 microns (red). Therefore, the GaAs LED emits invisible infrared radiation. GaAsP diodes have a slightly higher band gap of 1.9 eV, and thus emit light at a wavelength of 0.653 micron, which is in the visible red band. Since some of the recombined holes and electrons emit heat instead of light, and because light is radiated equally in all directions within the depletion region, and some of this light gets absorbed rather than radiated, the radiation efficiency of LEDs is not very high. Perhaps only about 10% of the electric power dissipated by the LED gets converted into useful radiated light. Nevertheless, LEDs are very popular light sources because of their ease of use, low price, and their long lifetime (as compared to incandescent light sources).

LEDs that are used to launch light into optical fibers are often housed in a package that directly mates with the optical fiber. An example of such an LED package is shown in Fig. 1-15. Note that some light energy does not reach the lens and is lost in the coupling.

Small GaAs or GaAsP LEDs typically operate at a forward voltage drop of 1.4 V (about twice that of Si diodes) and a forward current of 10 mA, while larger (super-bright) LEDs might require up to 100 mA at about the same forward voltage drop. It is important to realize that an LED cannot be placed directly across a dc power supply -- instead a current limiting resistor must be placed in series with it. For example, for a small LED with a 1.4 V junction drop and a 10 mA forward current must be placed in series with a 5 V power supply and a current limiting resistor R, such that

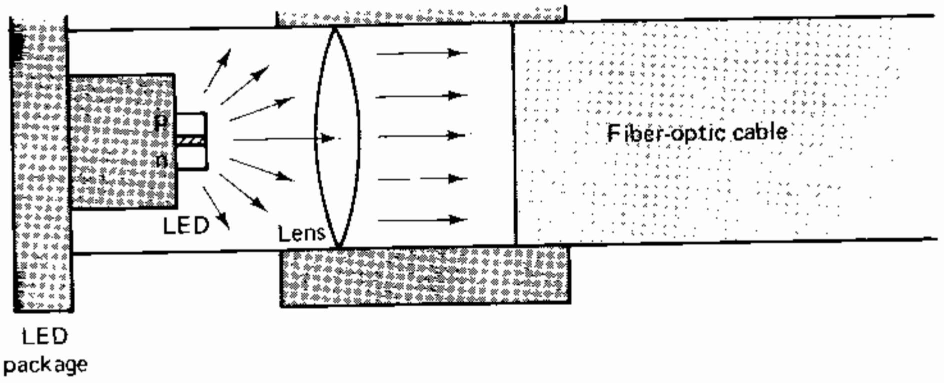
current for max brilliance



$$R = \frac{5 - 1.4}{10 \cdot 10^{-3}} \quad R = 360 \text{ ohms}$$

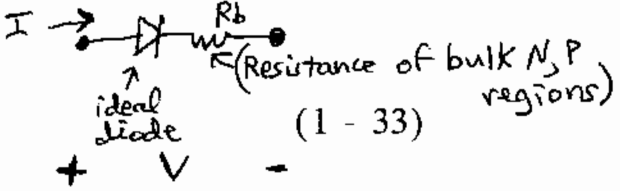
*A 330Ω resistor is the closest standard value.*

**Fig. 1-15 LED source coupled to a fiber**



## 1.7 Diode Modeling

When we include the voltage drop across the resistance of the bulk conducting regions of a pn junction diode, Rb, the junction resistance is equal to V - I*Rb, where V is the diode terminal voltage and I is the diode terminal current, thus the diode equation (1-32) becomes

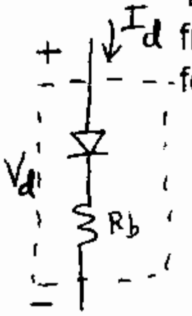


$$I = I_S \cdot \left[ e^{\frac{(V - I \cdot Rb) \cdot q}{\eta \cdot k \cdot T}} - 1 \right] \qquad (1 - 33)$$

This diode equation (except for ignoring reverse breakdown behavior) is an excellent diode model that is used in computer models and graphical load line analyses. But because of its complexity, it is of limited use in "back-of-the envelope" analyses that are so important to one's intuitive understanding of how a diode circuit actually works. Therefore, several approximate "***diode models***", of increasing complexity and correspondingly increasing accuracy, are used when analyzing diode circuits.

## AC Model of Forward-Biased Diode

First of all, in many applications (such as analog signal switching using diodes) the total voltage across forward-biased diode, ***$V_d(t)$***, can be viewed as a large dc (***quiescent operating point***) voltage component, ***Vdc***, with a small time-varying (ac) signal riding on top of it, ***$v_d(t)$***. Therefore we may write the total diode voltage as ***$V_d(t) = Vdc + v_d(t)$***. In such a situation, we may use the principle of ***Linear Superposition*** to perform a "***small-signal, or ac, analysis***", where the dc component of the diode voltage is set to 0, and only the small ac portion of the signal is traced through the circuit. In this case, the ***ac equivalent model*** of the diode may be approximated by the "***ac resistance***" ***r*** $= \Delta V_d / \Delta I_d$ whose value equals the inverse slope of the I-V curve in the vicinity of the dc bias point (Vdc, Idc). This concept is explained in Fig. 1-16.



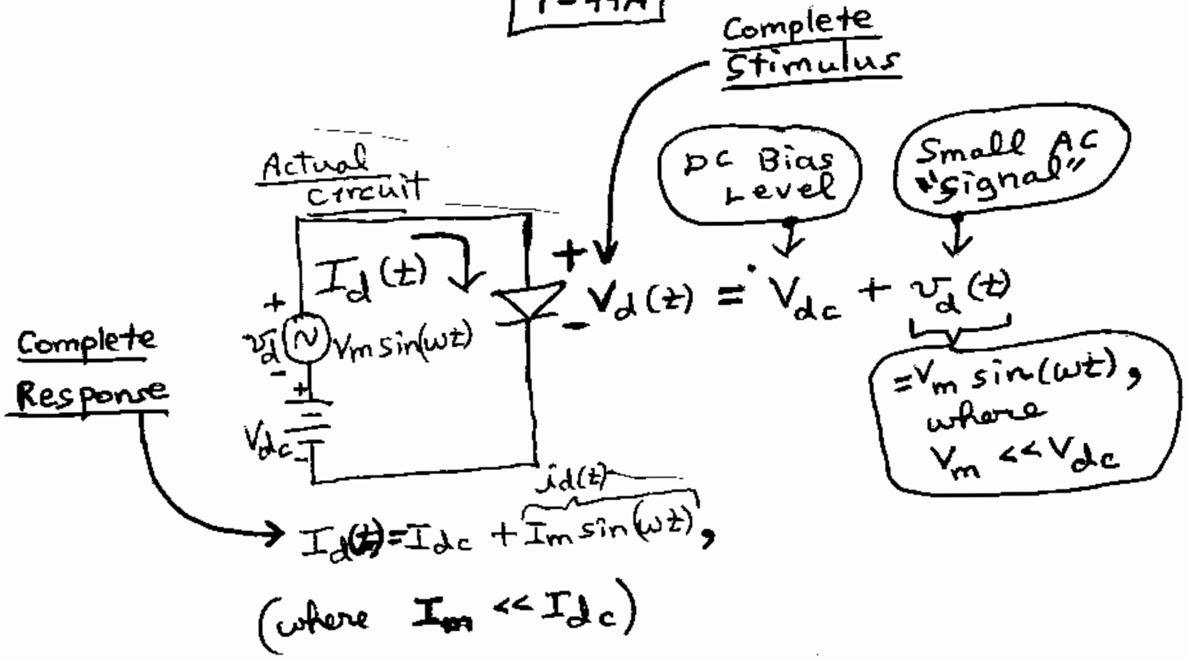
The value of this ac resistance is found by removing the factor of 1 from (1-33), which is a valid approximation since the diode is forward-biased, solving for V, then differentiating with respect to I:

$$I_d = I_s\left(e^{(V_d - I_d R_b)/\eta V_T} \overset{\to 0}{\cancel{-1}}\right) \text{ (fwd bias approx)}$$

$$\Rightarrow V_d = \eta V_T \ln(I_d/I_s) + I_d R_b$$

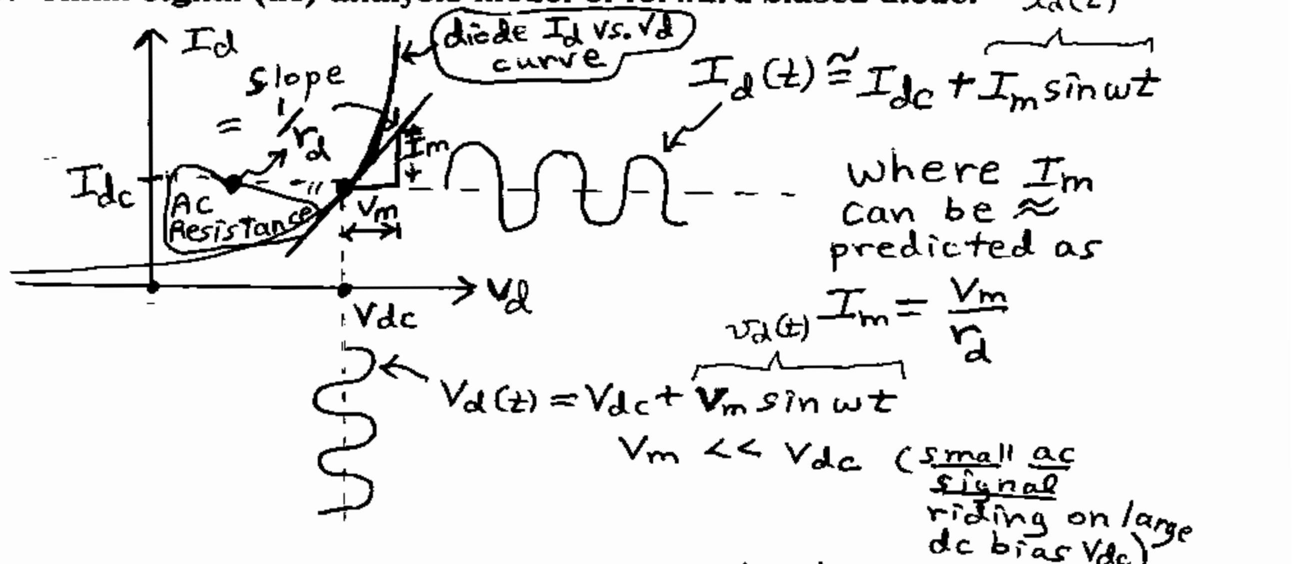
$$r_d = \left(\frac{dV_d}{dI_d}\right)_{I_d = I_{dc}} = \left[\frac{d}{dI_d}\left[\underbrace{\left(\ln\left(\frac{I_d}{I_s}\right)\right)}_{= \ln(I_d) - \underbrace{\ln(I_s)}_{\text{const. wrt } I_d}} \cdot \eta \underbrace{\left(k\frac{T}{q}\right)}_{= V_T} + I_d Rb\right]\right]_{I_d = I_{dc}}$$

$$r_d = \frac{\eta}{I_{dc}} \cdot \underbrace{\frac{k \cdot T}{q}}_{\substack{(V_T = 26\text{mV} \\ @\text{room temp})}} + Rb = \frac{\eta(0.026)}{I_{dc}} + Rb \text{ (At room temperature)} \quad (1-34)$$



Finding the complete response $I_d(t)$ from $V_d(t)$ graphically, we can fit a straight line to the $I_d$ vs. $V_d$ curve at the $I_d = I_{dc}$ "bias point", if $V_m << V_{dc}$. Then we may "reflect" $V_d(t)$ off of this line to get $I_d(t)$.

**Fig. 1-16. Small-Signal (ac) analysis model of forward-biased diode.**



Note from Fig. 1-16 that $\left. \text{slope} \right|_{I_d = I_{dc}} = \left. \frac{dI_d}{dV_d} \right|_{I_d = I_{dc}} = \frac{I_m}{V_m}$

peak value of ac current component

peak value of ac voltage component

**Note:** $I_m = \frac{V_m}{\left( \frac{1}{\left. \text{slope} \right|_{I_d = I_{dc}}} \right)} = \boxed{\frac{V_m}{r_d}}$, where $r_d \triangleq \frac{1}{\left. \text{slope} \right|_{I_d = I_{dc}}}$

"small-signal (ac)" resistance of diode

$$r_d = \frac{1}{\left. \text{slope} \right|_{I_d = I_{dc}}} = \frac{1}{\left. \frac{dI_d}{dV_d} \right|_{I_d = I_{dc}}} = \left. \frac{dV_d}{dI_d} \right|_{I_d = I_{dc}} \overset{\text{See Eqn (1-34)}}{\cong} \boxed{\frac{\eta \overset{RT/q}{V_T}}{I_{dc}} + R_b}$$

In summary, the "small-signal" diode resistance $r_d$ is given by

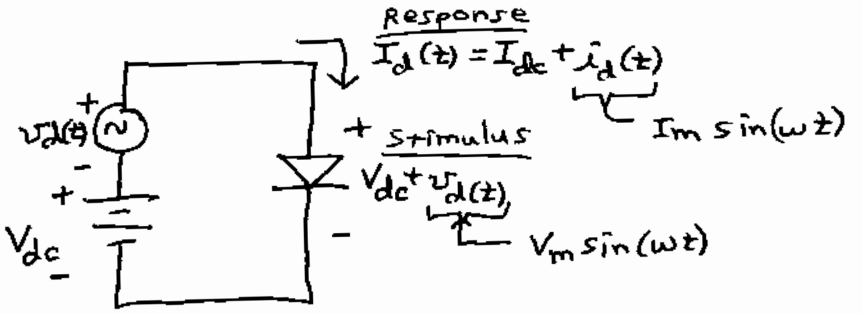
$$\boxed{r_d = \frac{V_m}{I_m} = \frac{V_m \sin(\omega t)}{I_m \sin(\omega t)} = \frac{v_d(t)}{i_d(t)} = \frac{2V_T}{I_{dc}} + R_b}$$

∴ "$r_d$" effectively translates the ac signal voltage $v_d(t)=V_m \sin(\omega t)$ into the ac signal response current $i_d(t) = I_m \sin(\omega t)$, since

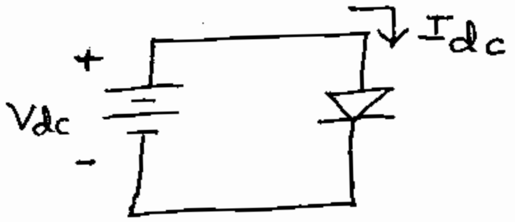
But note $I_{dc}$ (the dc "bias point") must be known first in order to find $r_d$.

Thus we shall use the concept of "Linear Superposition" to break the complete problem (DC bias + AC signal) down into 2 parts.

Referring to the actual circuit:

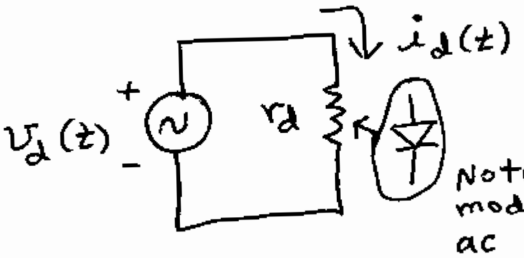


We find the portion of the response $I_d(t)$ due to $V_{dc}$ acting alone. This is called the "dc model" of the circuit.



(Note that the dc analysis must be done BEFORE the ac analysis, since the ac model "$r_d$" depends upon $I_{dc}$!)

Next we find the portion of the response due to $v_d(t) = V_m \sin(\omega t)$ acting alone. This is called the "ac model" of the circuit.

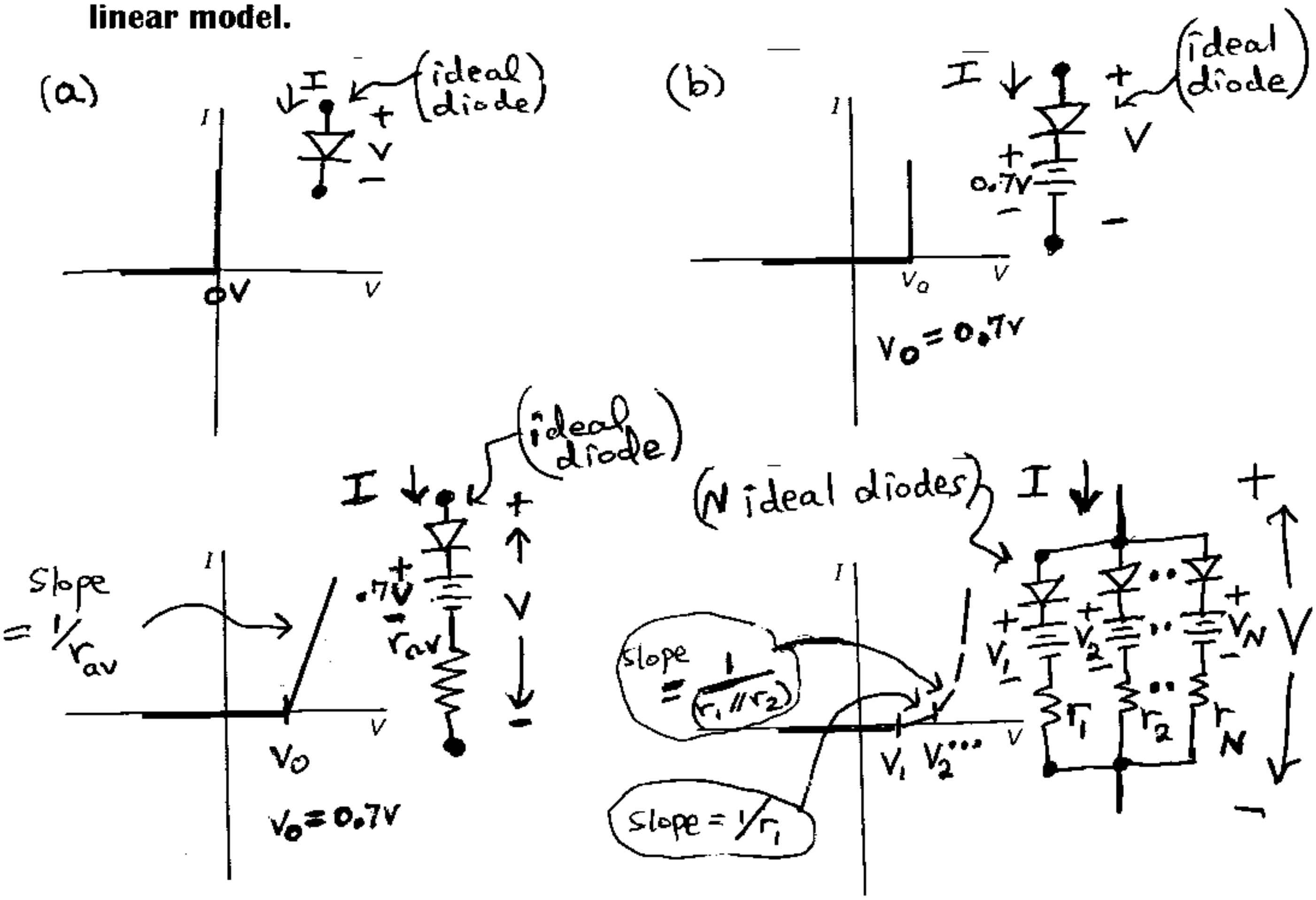


Note: diode may be modelled by "$r_d$" in ac small-signal case, since $r_d = v_d(t)/i_d(t)$

Actual circuit respons
Is sum of dc model
and ac model
responses:
$I_d(t) = I_{dc} + i_d($

For "***large-signal analysis***" cases, where the entire voltage waveform must be considered (as in digital logic circuits), the various models shown in Fig. 1-17 are used.

**Fig. 1-17. Junction diode models. (a) Ideal Rectifying Diode. (b) Model with constant Vo-volt battery added to establish voltage threshold. (c) Model with forward resistance added. (d) Piecewise linear model.**



The model of Fig. 1-17(a) is the ideal diode model. If the diode is forward-biased (we try to pass current through it in the forward direction), it has zero resistance, acting like a ***closed switch***, but if it is reverse-biased (we try to pass current through it in its reverse direction), it has infinite resistance, acting like an ***open switch***.

The model of Fig. 1-17(b) is slightly closer to the real diode behavior. It consists of an ideal diode in series with an internal 0.7 V source. Now the switch does not close until the applied voltage rises to the 0.7 V threshold.

The model of Fig. 1-17(c) is even closer to reality. It consists of an ideal diode in series with the internal 0.7 V source and a resistor equal to the average ac resistance of the diode over the range of forward operating voltages of interest.

The "***piecewise-linear***" model of Fig. 1-17(d) is the closest to the diode equation. It consists of several ***piecewise linear*** steps. Over a small range of forward voltages, the diode is assumed to have a constant resistance, $r_{av}$, equal to the average value of the ac resistance in this range. The value of $r_{av}$ changes when different sections of the model are used.

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## Example 1-6

A silicon diode at room temperature with ***Is*** = 10 nA, $\eta$=2, and Rb = 0 is used in the ***analog diode switching circuit*** of Fig. 1-18. Assume that the amplitude of vi(t) is small compared to Vc, which can be either +5.0 V (analog path ON) or -5.0 V (analog path OFF). Assume that the impedance of C is much smaller than 10 kΩ for lowest frequency of interest in vi(t). Find the ac resistance of the diode when the control voltage Vc = 5.0 V, and hence the analog signal path is turned on. Find the signal voltage gain for the analog signal path, vo(t)/vi(t).