

كلية مدينة العلم الجامعة

قسم هندسة الحاسوب

محاضرات المرحلة الاولى لمادة الهندسة الالكترونية

اعداد

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المحاضرة الثانية

Semiconductors اشباه الموصلات

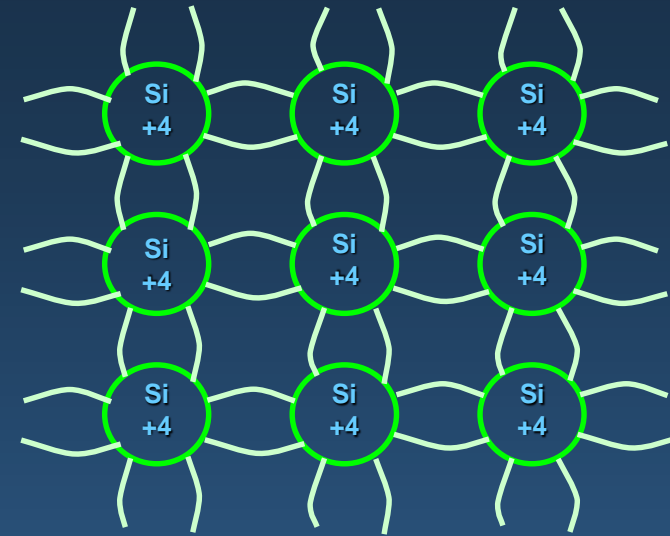
Electronic Devices and Circuit Theory

Eleventh Edition

Robert L. Boylestad and Louis Nashelsky

What Are Diodes Made Out Of?

- Silicon (Si) and Germanium (Ge) are the two most common single elements that are used to make Diodes. A compound that is commonly used is Gallium Arsenide (GaAs), especially in the case of LEDs because of its large bandgap.
- Silicon and Germanium are both group 4 elements, meaning they have 4 valence electrons. Their structure allows them to grow in a shape called the diamond lattice.
- Gallium is a group 3 element while Arsenide is a group 5 element. When put together as a compound, GaAs creates a zincblende lattice structure.
- In both the diamond lattice and zincblende lattice, each atom shares its valence electrons with its four closest neighbors. This sharing of electrons is what ultimately allows diodes to be built. When dopants from groups 3 or 5 (in most cases) are added to Si, Ge or GaAs it changes the properties of the material so we are able to make the P- and N-type materials that become the diode.

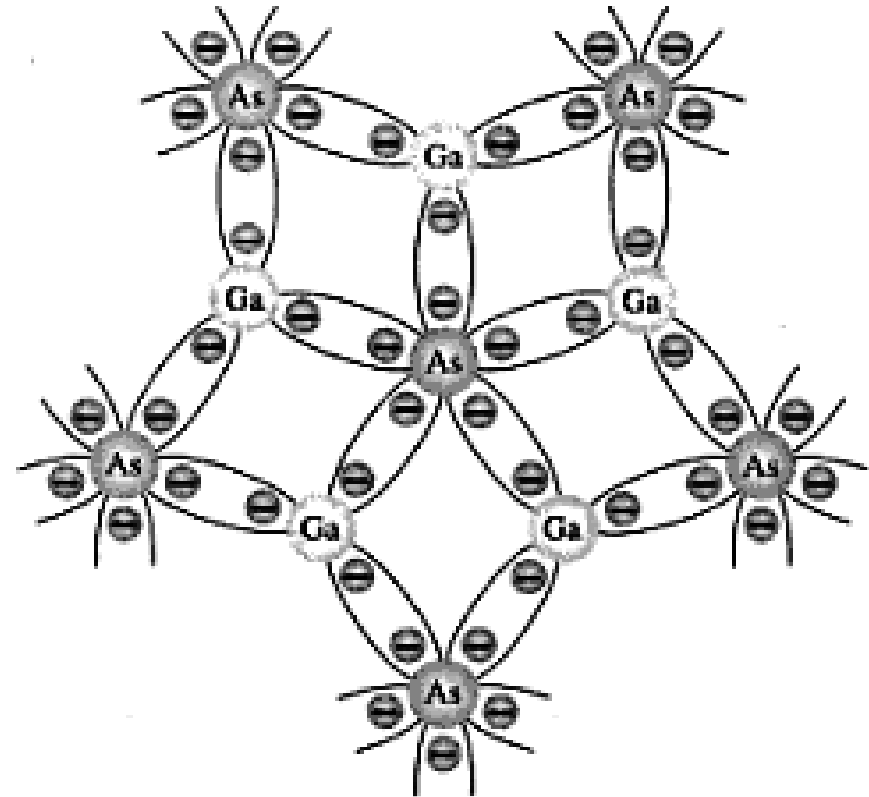


The diagram above shows the 2D structure of the Si crystal. The light green lines represent the electronic bonds made when the valence electrons are shared. Each Si atom shares one electron with each of its four closest neighbors so that its valence band will have a full 8 electrons.

Covalent Bonding Of The GaAs Crystal

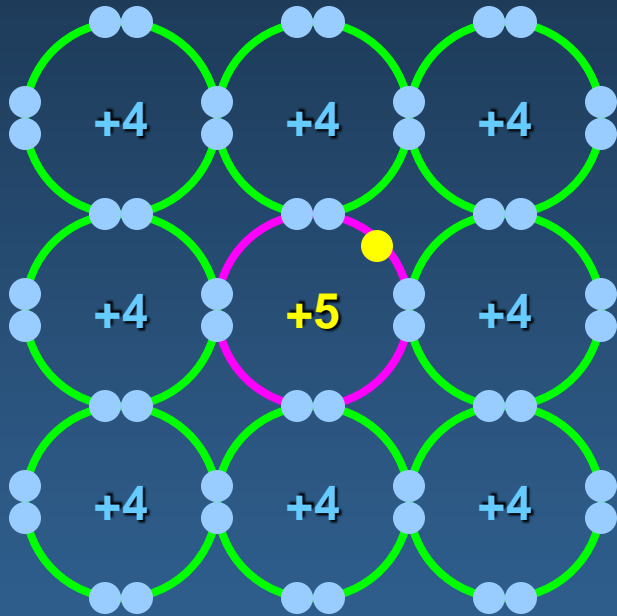
Gallium is a group 3 element while Arsenide is a group 5 element.

each atom shares its valence electrons with its four closest neighbors.



Covalent Bonding of the GaAs crystal

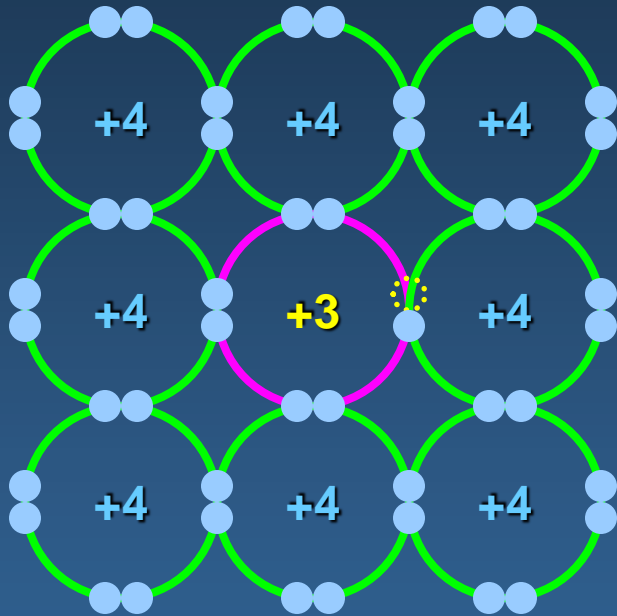
N-Type Material



When extra valence electrons are introduced into a material such as silicon an n-type material is produced. The extra valence electrons are introduced by putting impurities or dopants into the silicon. The dopants used to create an n-type material are Group V elements. The most commonly used dopants from Group V are arsenic, antimony and phosphorus.

The 2D diagram to the left shows the extra electron that will be present when a Group V dopant is introduced to a material such as silicon. This extra electron is very mobile.

P-Type Material

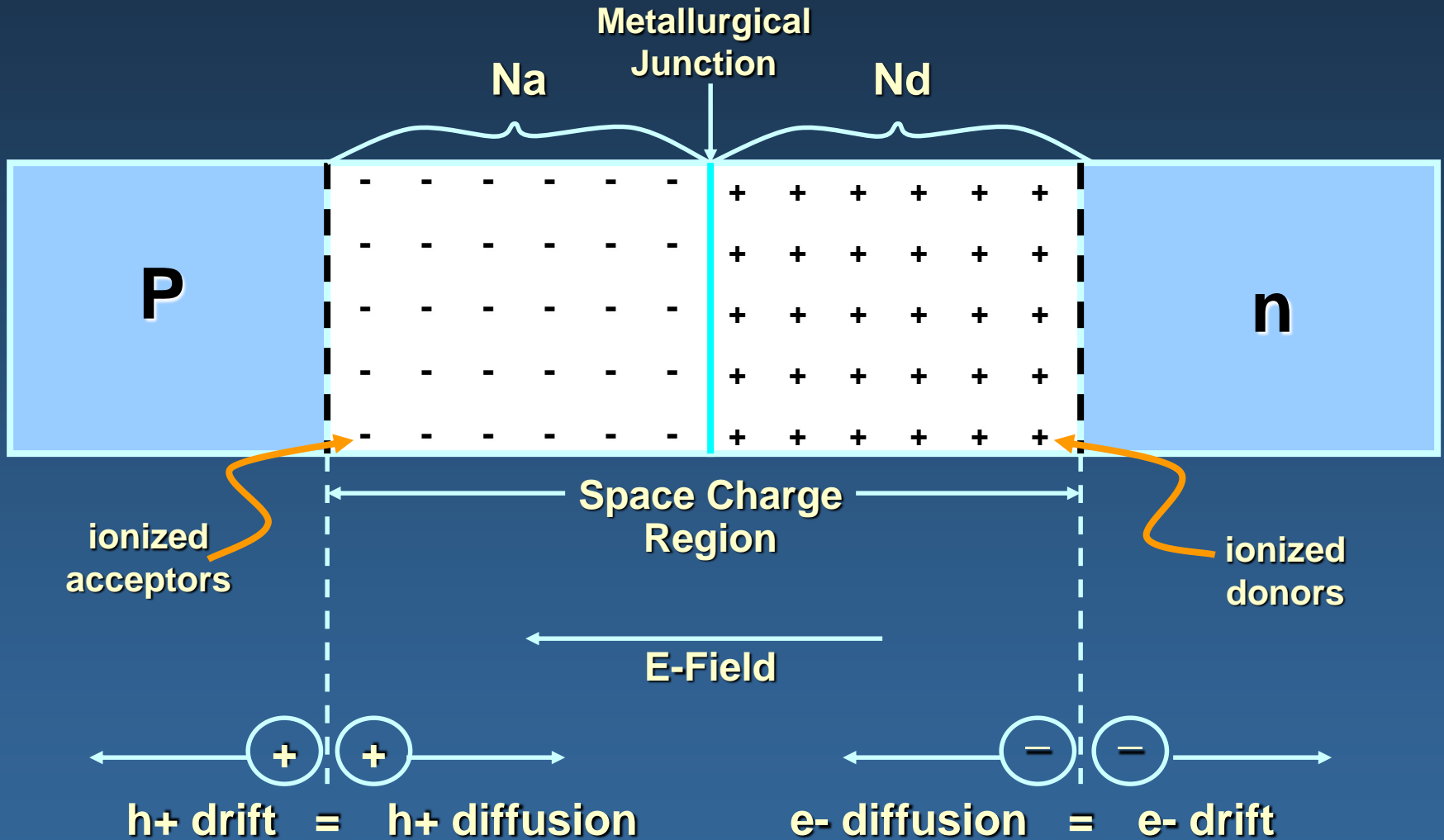


P-type material is produced when the dopant that is introduced is from Group III. Group III elements have only 3 valence electrons and therefore there is an electron missing. This creates a hole (h^+), or a positive charge that can move around in the material. Commonly used Group III dopants are aluminum, boron, and gallium.

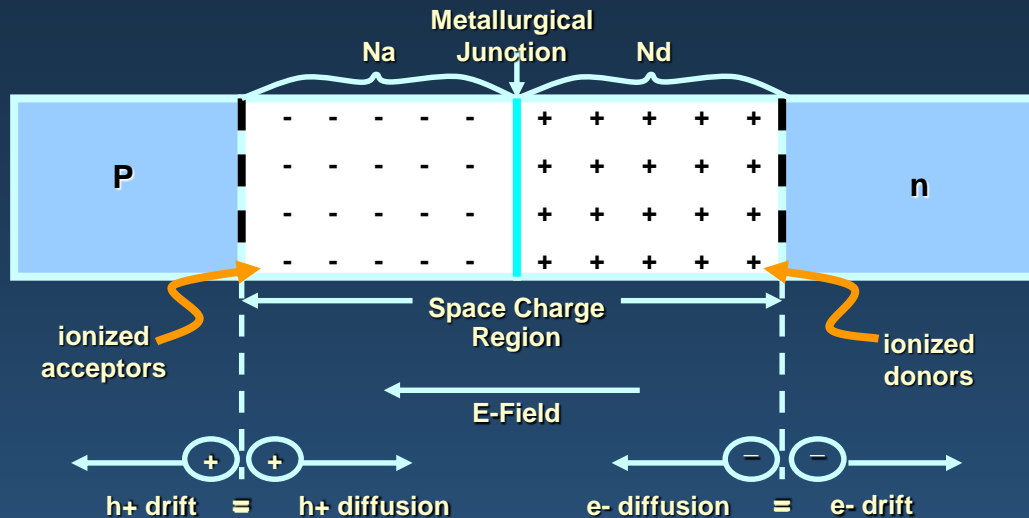
The 2D diagram to the left shows the hole that will be present when a Group III dopant is introduced to a material such as silicon. This hole is quite mobile in the same way the extra electron is mobile in a n-type material.

The PN Junction

Steady State¹



The PN Junction



Steady State

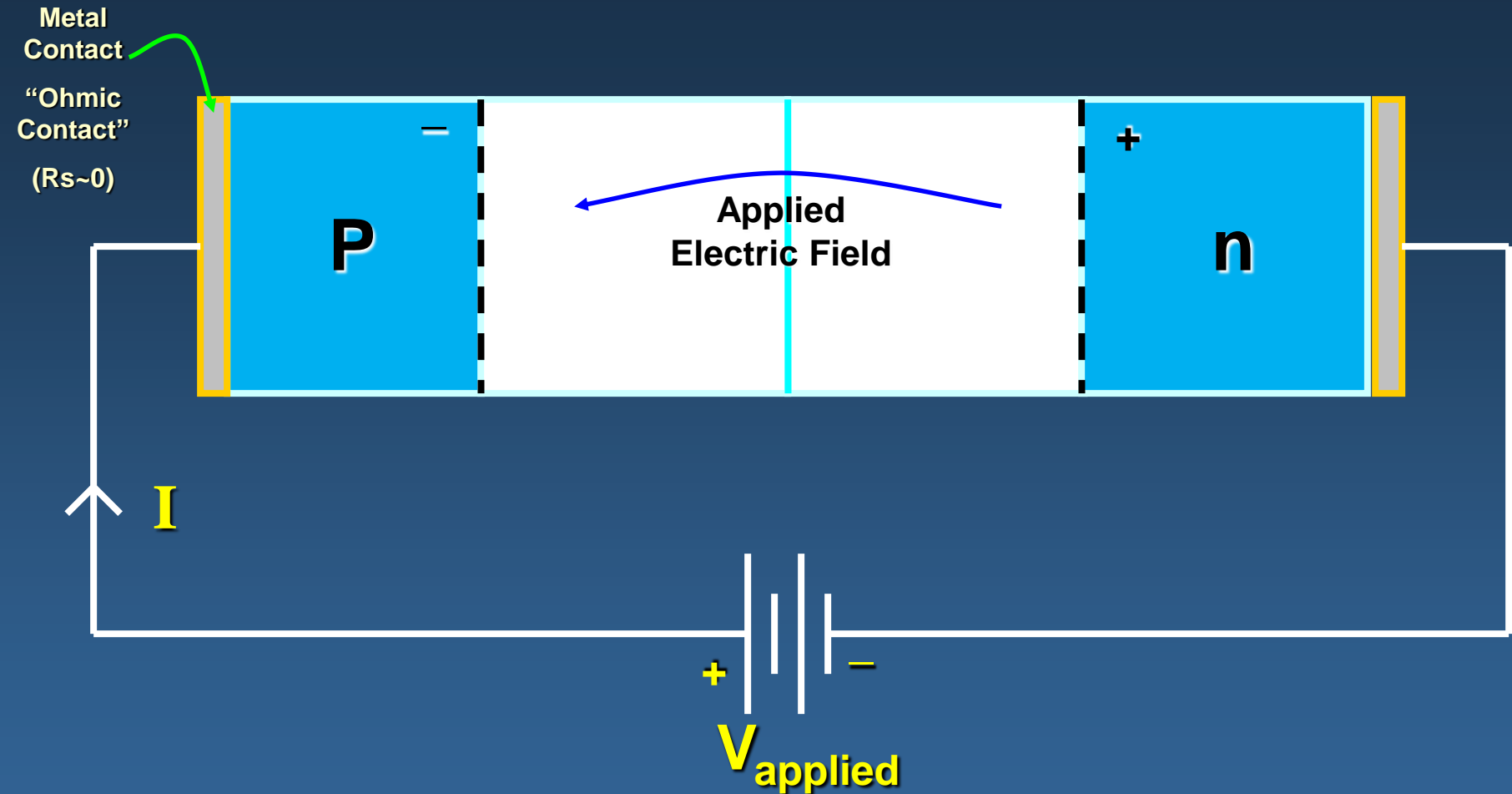
When no external source is connected to the pn junction, diffusion and drift balance each other out for both the holes and electrons

Space Charge Region: Also called the depletion region. This region includes the net positively and negatively charged regions. The space charge region does not have any free carriers. The width of the space charge region is denoted by W in pn junction formula's.

Metallurgical Junction: The interface where the p- and n-type materials meet.

Na & Nd: Represent the amount of negative and positive doping in number of carriers per centimeter cubed. Usually in the range of 10^{15} to 10^{20} .

The Biased PN Junction



The p-n junction is considered biased when an external voltage is applied. There are two types of biasing: Forward bias and Reverse bias. These are described on then next slide.



The Biased PN Junction

Forward Bias:

$$V_{\text{applied}} > 0$$

In forward bias the depletion region shrinks slightly in width. With this shrinking the energy required for charge carriers to cross the depletion region decreases exponentially. Therefore, as the applied voltage increases, current starts to flow across the junction. The barrier potential of the diode is the voltage at which appreciable current starts to flow through the diode. The barrier potential varies for different materials.

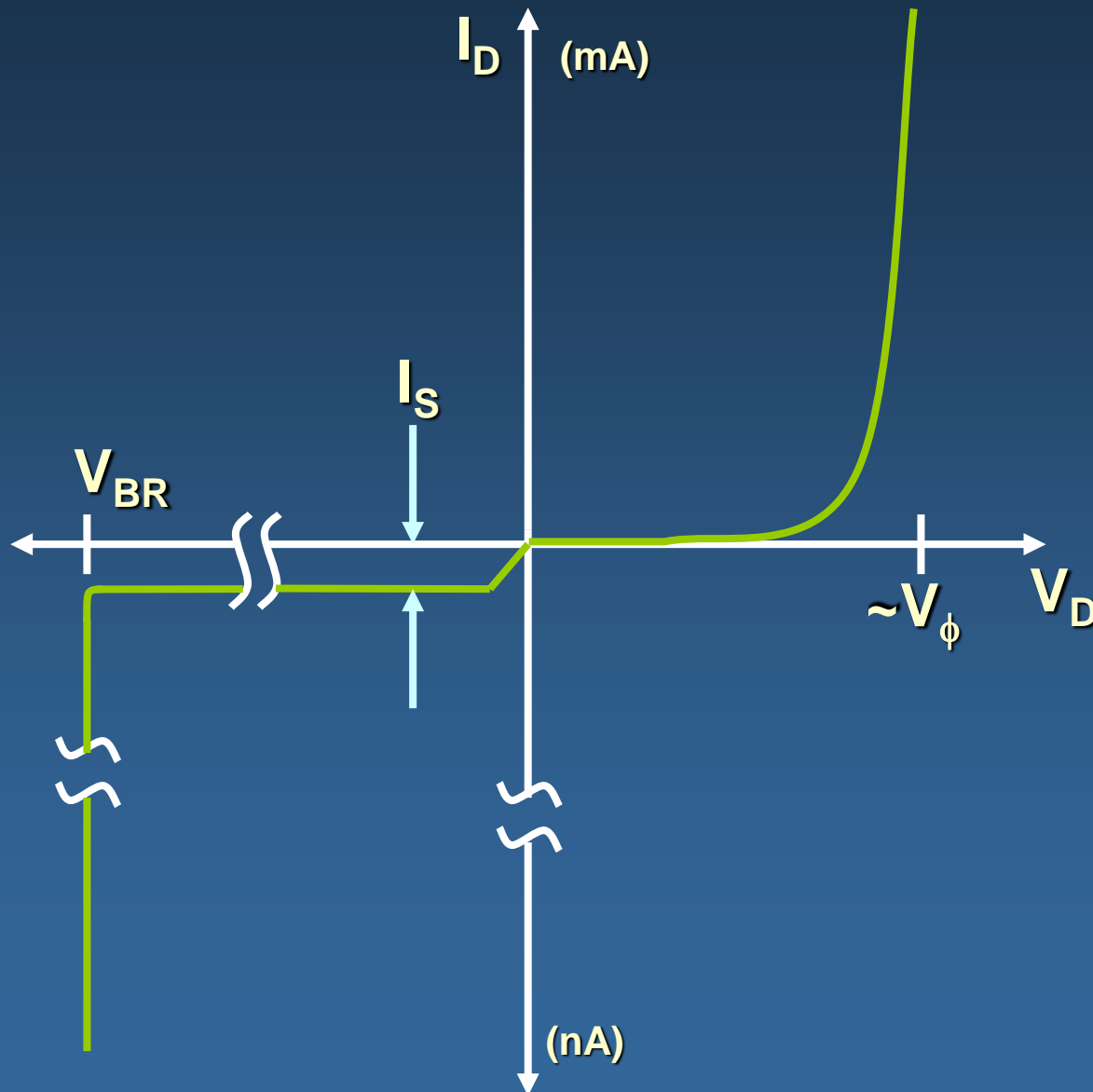
Reverse Bias:

$$V_{\text{applied}} < 0$$

Under reverse bias the depletion region widens. This causes the electric field produced by the ions to cancel out the applied reverse bias voltage. A small leakage current, I_s (saturation current) flows under reverse bias conditions. This saturation current is made up of electron-hole pairs being produced in the depletion region. Saturation current is sometimes referred to as scale current because of its relationship to junction temperature.

Properties of Diodes

Figure 1.10 – The Diode Transconductance Curve²



- V_D = Bias Voltage
- I_D = Current through Diode. I_D is Negative for Reverse Bias and Positive for Forward Bias
- I_S = Saturation Current
- V_{BR} = Breakdown Voltage
- V_ϕ = Barrier Potential Voltage

Properties of Diodes

The Shockley Equation

- The transconductance curve on the previous slide is characterized by the following equation:

$$I_D = I_S(e^{V_D/\eta V_T} - 1)$$

- As described in the last slide, I_D is the current through the diode, I_S is the saturation current and V_D is the applied biasing voltage.
- V_T is the thermal equivalent voltage and is approximately 26 mV at room temperature. The equation to find V_T at various temperatures is:

$$V_T = \frac{kT}{q}$$

$k = 1.38 \times 10^{-23}$ J/K

$T =$ temperature in Kelvin

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

- η is the emission coefficient for the diode. It is determined by the way the diode is constructed. It somewhat varies with diode current. For a silicon diode η is around 2 for low currents and goes down to about 1 at higher currents

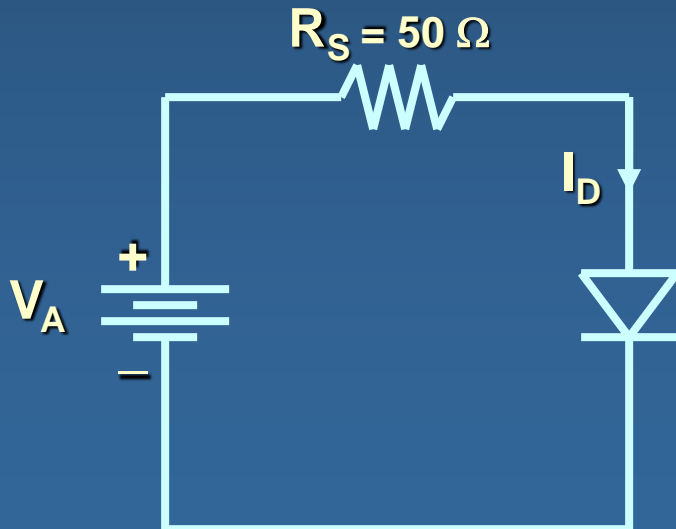
Diode Circuit Models

1-The Ideal Diode Model



The diode is designed to allow current to flow in only one direction. The perfect diode would be a perfect conductor in one direction (forward bias) and a perfect insulator in the other direction (reverse bias). In many situations, using the ideal diode approximation is acceptable.

Example: Assume the diode in the circuit below is ideal. Determine the value of I_D if a) $V_A = 5$ volts (forward bias) and b) $V_A = -5$ volts (reverse bias)



a) With $V_A > 0$ the diode is in forward bias and is acting like a perfect conductor so:

$$I_D = V_A / R_S = 5 \text{ V} / 50 \Omega = 100 \text{ mA}$$

b) With $V_A < 0$ the diode is in reverse bias and is acting like a perfect insulator, therefore no current can flow and $I_D = 0$.

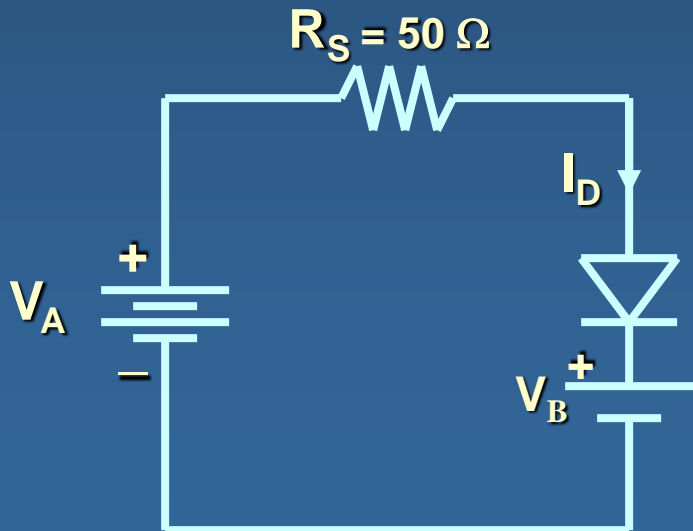
Diode Circuit Models

2-The Ideal Diode with Barrier Potential



This model is more accurate than the simple ideal diode model because it includes the approximate barrier potential voltage. Remember the barrier potential voltage is the voltage at which appreciable current starts to flow.

Example: To be more accurate than just using the ideal diode model include the barrier potential. Assume $V_B = 0.3$ volts (typical for a germanium diode) Determine the value of I_D if $V_A = 5$ volts (forward bias).



With $V_A > 0$ the diode is in forward bias and is acting like a perfect conductor so write a KVL equation to find I_D :

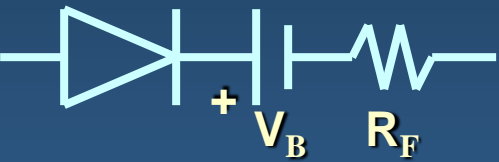
$$0 = V_A - I_D R_S - V_B$$

$$I_D = \frac{V_A - V_B}{R_S} = \frac{4.7 \text{ V}}{50 \Omega} = 94 \text{ mA}$$

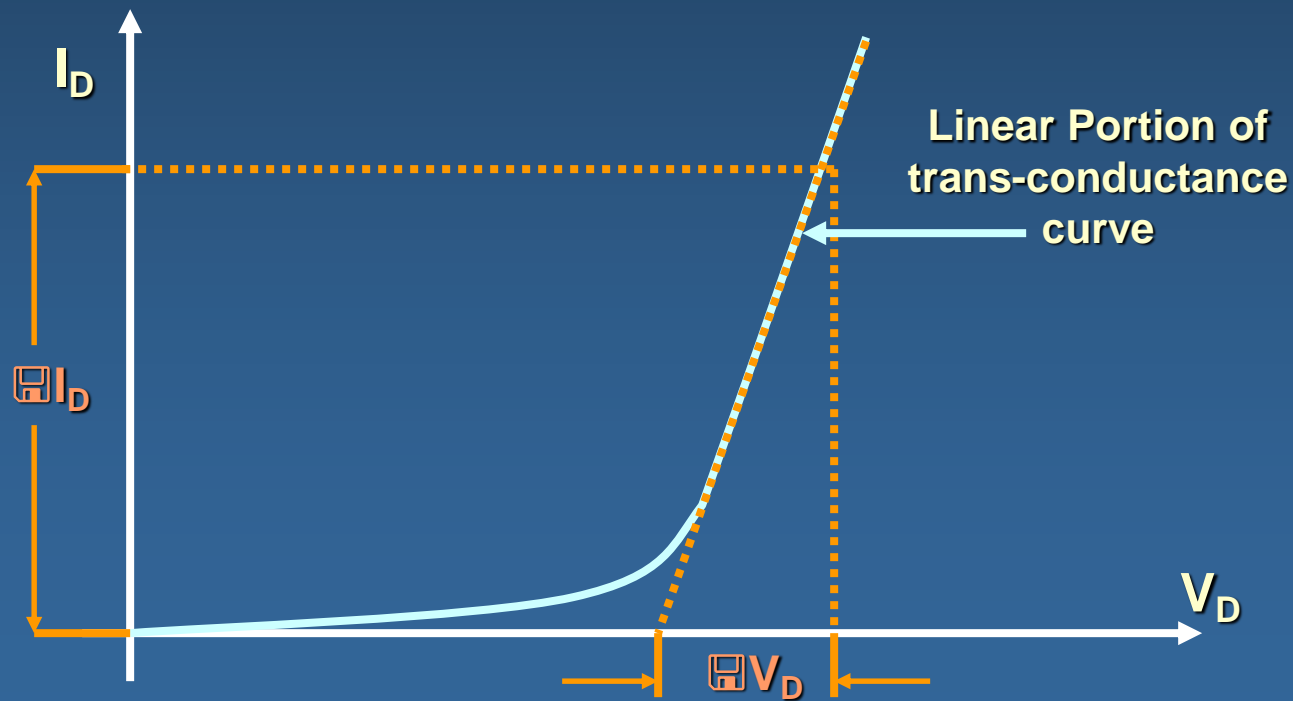
Diode Circuit Models

3-The Ideal Diode with Barrier Potential and Linear Forward Resistance

This model is the most accurate of the three. It includes a linear forward resistance that is calculated from the slope of the linear portion of the trans-conductance curve. However, this is usually not necessary since the R_F (forward resistance) value is pretty constant. For low-power germanium and silicon diodes the R_F value is usually in the 2 to 5 ohms range, while higher power diodes have a R_F value closer to 1 ohm.

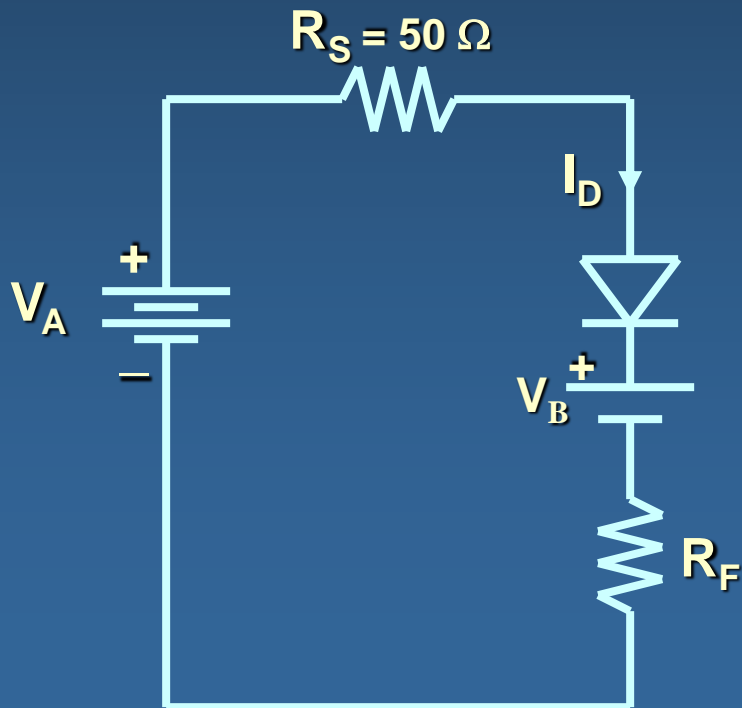


$$R_F = \frac{\Delta V_D}{\Delta I_D}$$



Diode Circuit Models

Example: Assume the diode is a low-power diode with a forward resistance value of 5 ohms. The barrier potential voltage is still: $V_B = 0.3$ volts (typical for a germanium diode) Determine the value of I_D if $V_A = 5$ volts.



Once again, write a KVL equation for the circuit:

$$0 = V_A - I_D R_S - V_B - I_D R_F$$

$$I_D = \frac{V_A - V_B}{R_S + R_F} = \frac{5 - 0.3}{50 + 5} = 85.5 \text{ mA}$$

Diode Circuit Models

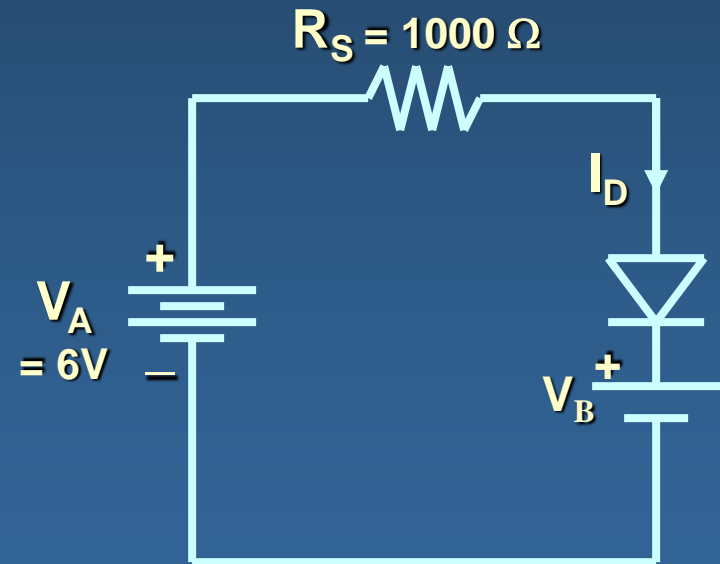
Values of I_D for the Three Different Diode Circuit Models

	Ideal Diode Model	Ideal Diode Model with Barrier Potential Voltage	Ideal Diode Model with Barrier Potential and Linear Forward Resistance
I_D	100 mA	94 mA	85.5 mA

These are the values found in the examples on previous slides where the applied voltage was 5 volts, the barrier potential was 0.3 volts and the linear forward resistance value was assumed to be 5 ohms.

The Q Point

The operating point or Q point of the diode is the quiescent or no-signal condition. The Q point is obtained graphically and is really only needed when the applied voltage is very close to the diode's barrier potential voltage. The example ³ below that is continued on the next slide, shows how the Q point is determined using the transconductance curve and the load line.



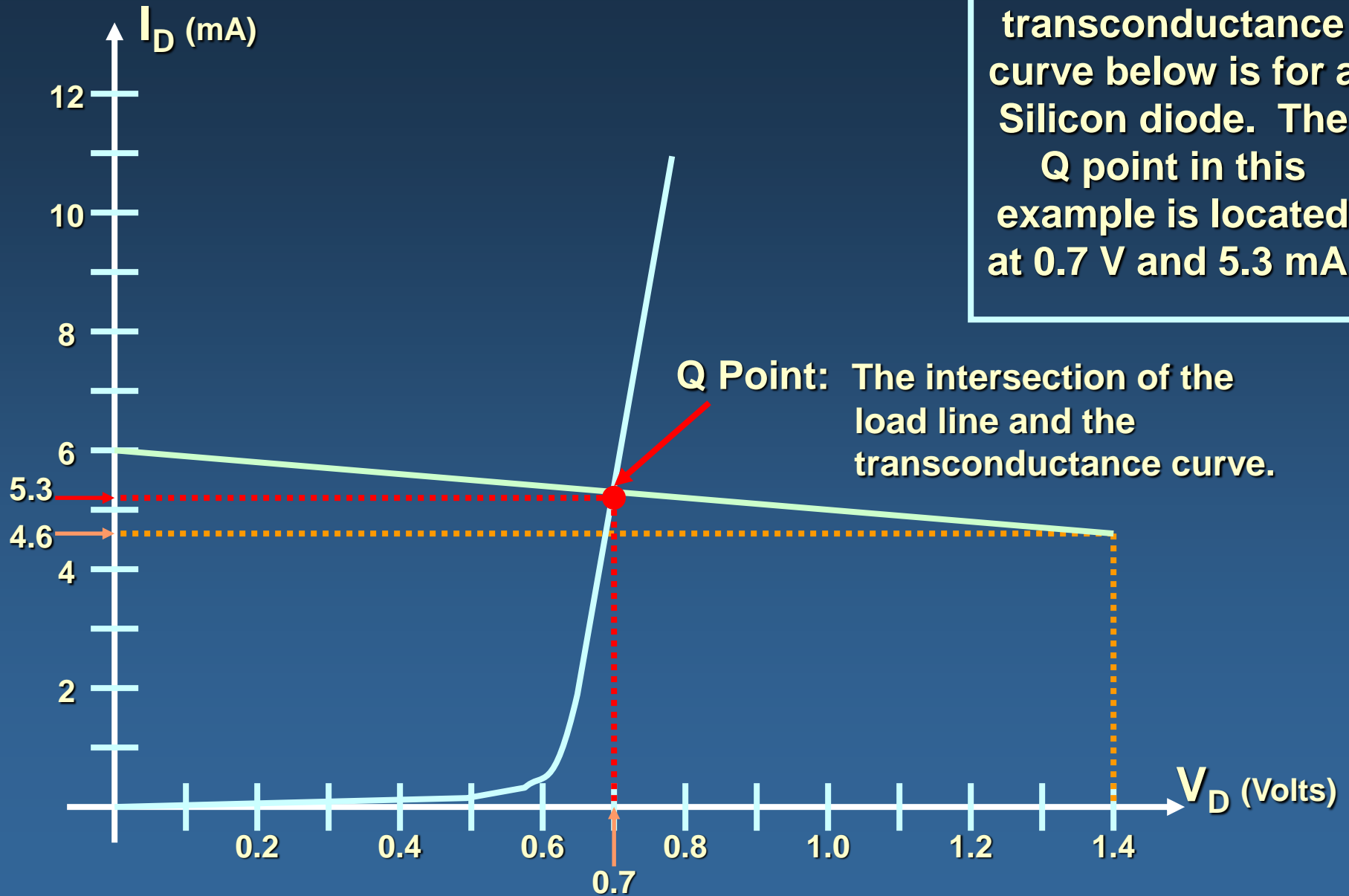
First the load line is found by substituting in different values of V_ϕ into the equation for I_D using the ideal diode with barrier potential model for the diode. With R_S at 1000 ohms the value of R_F wouldn't have much impact on the results.

$$I_D = \frac{V_A - V_B}{R_S}$$

Using V_ϕ values of 0 volts and 1.4 volts we obtain I_D values of 6 mA and 4.6 mA respectively. Next we will draw the line connecting these two points on the graph with the transconductance curve. This line is the load line.

The Q Point

The transconductance curve below is for a Silicon diode. The Q point in this example is located at 0.7 V and 5.3 mA.



Dynamic Resistance

The dynamic resistance of the diode is mathematically determined as the inverse of the slope of the transconductance curve.

Therefore, the equation for dynamic resistance is:

$$r_F = \frac{\eta V_T}{I_D}$$

The dynamic resistance is used in determining the voltage drop across the diode in the situation where a voltage source is supplying a sinusoidal signal with a dc offset.

The ac component of the diode voltage is found using the following equation:

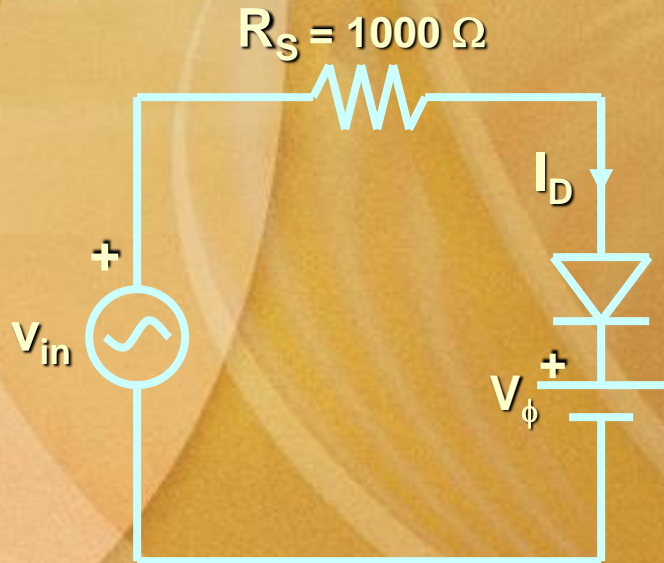
$$V_F = V_{ac} \frac{r_F}{r_F + R_S}$$

The voltage drop through the diode is a combination of the ac and dc components and is equal to:

$$V_D = V_B + V_F$$

Dynamic Resistance

Example: Use the same circuit used for the Q point example but change the voltage source so it is an ac source with a dc offset. The source voltage is now, $v_{in} = 6 + \sin(\omega t)$ Volts. It is a silicon diode so the barrier potential voltage is still 0.7 volts.



The DC component of the circuit is the same as the previous example and therefore $I_D = \frac{6V - 0.7V}{1000 \Omega} = 5.2 \text{ mA}$

$$r_F = \frac{\eta V_T}{I_D} = \frac{1 * 26 \text{ mV}}{5.3 \text{ mA}} = 4.9 \Omega$$

$\eta = 1$ is a good approximation if the dc current is greater than 1 mA as it is in this example.

$$V_F = v_{ac} \frac{r_F}{r_F + R_S} = \sin(\omega t) V \frac{4.9 \Omega}{4.9 \Omega + 1000 \Omega} = 4.88 \sin(\omega t) \text{ mV}$$

Therefore, $V_D = 700 + 4.9 \sin(\omega t) \text{ mV}$ (the voltage drop across the diode)

Equation of the Static Characteristic

The volt-ampere characteristics described above are called *static* characteristics because they describe the d.c. behavior of the diode. The forward and reverse characteristics have been combined into a single diagram of Fig. 52.4. These characteristics can be described by the analytical equation called *Boltzmann diode equation*

given below :

$$I = I_0 (e^{(eV/\eta kT)} - 1)$$

Where

I=current flowing in the diode

I_0 = diode reverse saturation current

V=voltage applied to the diode

V_T =volt-equivalent of temperature **$V_T = kT/e$**

η =1 (for Ge) and 2 (for Si)

V = voltage across junction – positive for forward bias and negative for reverse bias.

k = Boltzmann constant = 1.38×10^{-23} J/°K

T = crystal temperature in °K

Equation of the Static Characteristic

Let
$$V_T = \frac{k}{e} T = \frac{1}{11600} T$$

Now, at room temperature of $T = (273 + 20) = 293^\circ\text{K}$, $V_T = 293/11,600 = 0.025 \text{ V} = 25 \text{ mV}$. substituting in the above equation we have

$$I = I_0 (e^{V/\eta 0.025} - 1) = I_0 (e^{40V} - 1) \\ \cong I_0 e^{40V}$$

– for Ge $\eta=1$
– if $V > 1$ volt

$$I = I_0 (e^{V/\eta 0.025} - 1) = I_0 (e^{20V} - 1) \\ \cong I_0 e^{20V}$$

– for Si $\eta=2$
– if $V > 1$ volt