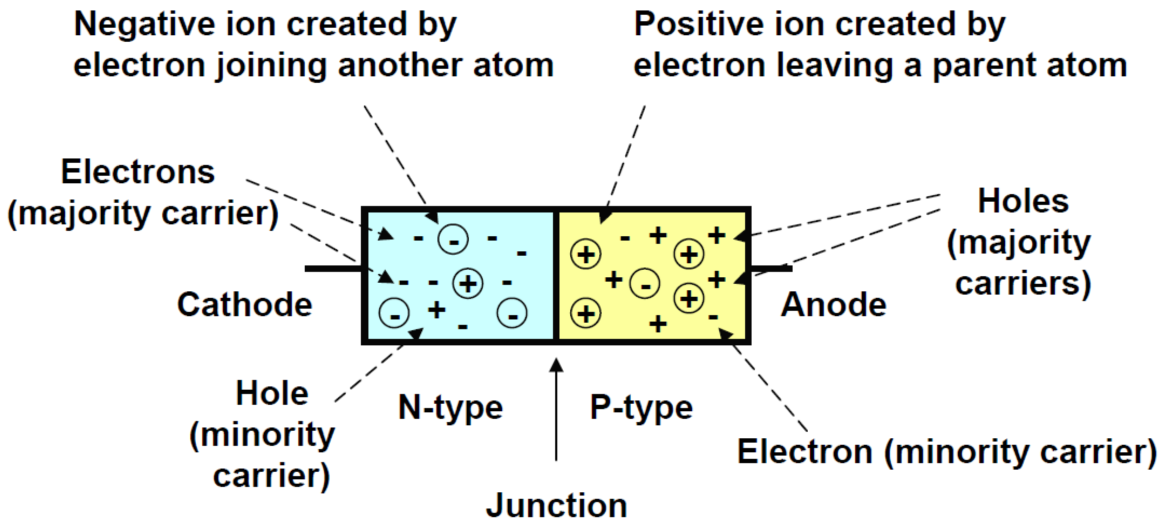
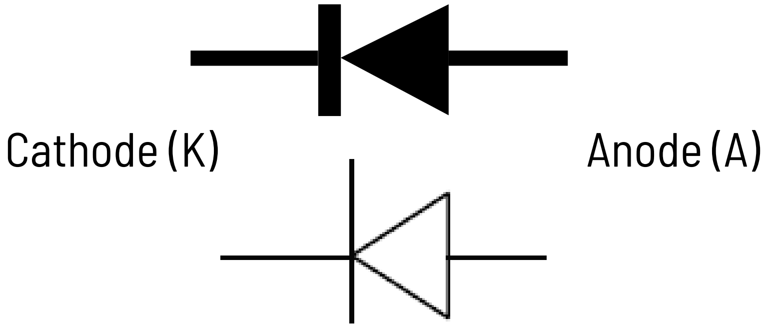
Semiconductor Diode

Semiconductor Diode

- A semiconductor **diode** is an electronic component created by "joining" an **n-type material with a p-type material.**
- In reality, one part of an intrinsic semiconductor is **doped with pentavalent** impurities and the other part is **doped with trivalent** impurities.



Construction of a Semiconductor Diode



Schematic Symbol

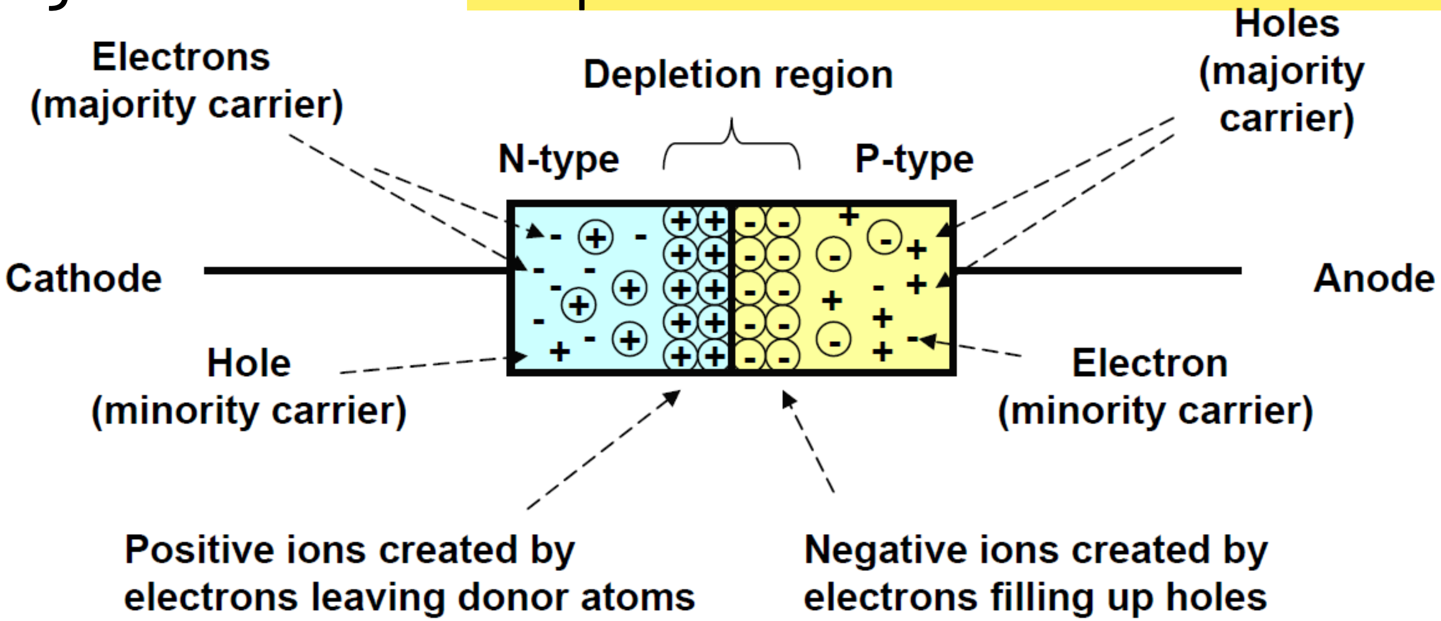
PN Junction

- At the p-n junction, the negatively charged atoms of the n-type side are attracted to the positively charged atoms of the p-type side.
- The electrons in the n-type material migrate across the junction to the p-type material (electron flow).
- Similarly, the 'holes' in the p-type material migrate across the junction to the n-type material (conventional current flow).
- The result is the formation of a **depletion region** around the junction.

reduction in the number or quantity of something:

Depletion Region

- This region of uncovered positive and negative ions is called the depletion region due to the "depletion" of free carriers in the region.

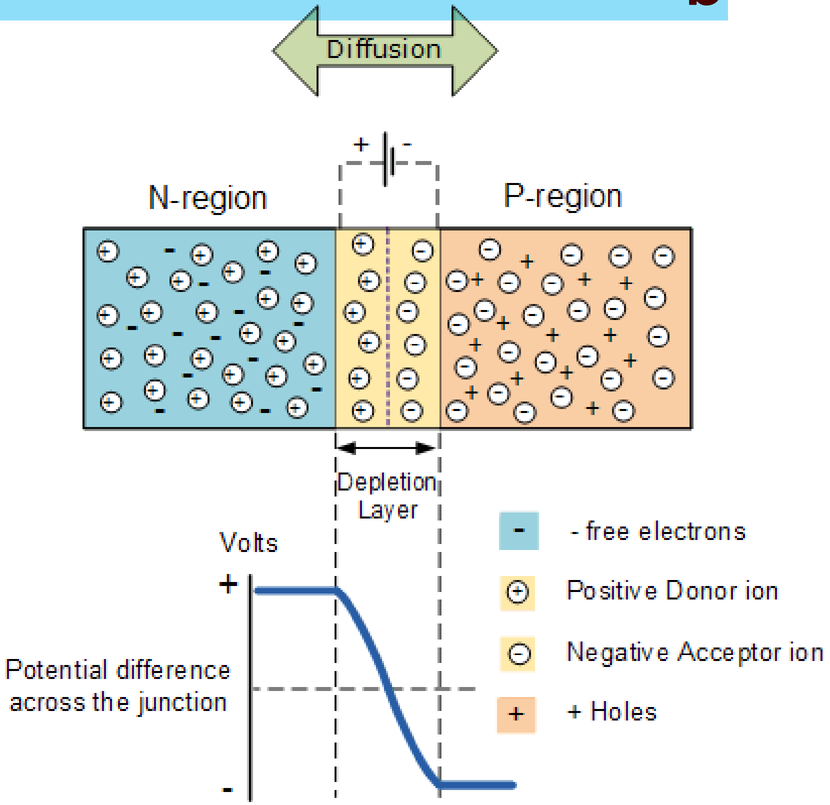


Depletion Region

Internal Barrier Potential, V_b

- Once the PN junction is joined, free electrons from the n-type material migrate across the newly formed junction to the p-type material.
- Similarly, the holes from the p-type material migrate to the n-type material where a large number of free electrons exist.
- Since electrons have moved from the n-type junction, they leave behind holes (positively charged) and holes from the p-type junction are filled with electrons (negatively charged).
- This is known as **diffusion** and it continues until the number of electrons that have moved from one junction to another have a **large enough electrical charge** to repel or prevent any more charge carriers from crossing over the junction.
- A state of equilibrium then follows which produces the internal barrier potential V_b.

Internal Barrier Potential, V_b



- V_b is an internal contact that cannot be measured directly, its effects can be overcome by applying an external voltage of 0.3 V for Ge or 0.7 V for Si, in the correct polarity. The V_b is higher for silicon (in the covalent bonds) junction because its lower atomic number allows more stability in the covalent bonds.

Effect of Temperature

- The values 0.3V for Ge and 0.7V for Si are at normal room temperature of 25 °C.
- However, V_b decreases at higher temperature. The reason is that more minority charge carriers are produced by increased thermal energy.
- The decrease in V_b is the reason why avoiding high temperature is important precaution in operations of circuits with NPN or PNP junction transistors.

Conclusions and Concepts

- A **semiconductor** is a material that has a conductivity level somewhere **between** that of a good **conductor** and that of an **insulator**.
- A **bonding of atoms**, strengthened by the **sharing** of **electrons** between neighboring atoms, is called **covalent bonding**.
- **Increasing temperatures** can cause a significant **increase** in the number of **free electrons** in a semiconductor material.
- Most semiconductor materials used in the electronics industry have **negative temperature coefficients** ; that is, the **resistance drops** with an **increase in temperature**.
- **Intrinsic materials** are those semiconductors that have a **very low level of impurities**, whereas **extrinsic materials** are semiconductors that have been exposed to a **doping process** .
- An **n-type material** is formed by adding **donor atoms** that have **five valence electrons** to establish a high level of relatively free electrons. In an n-type material, the **electron** is the **majority carrier** and the **hole** is the **minority carrier**.
- A **p-type material** is formed by adding **acceptor atoms** with **three valence electrons** to establish a high level of holes in the material. In a a p-type material, the **hole** is the **majority carrier** and the **electron** is the **minority carrier**.

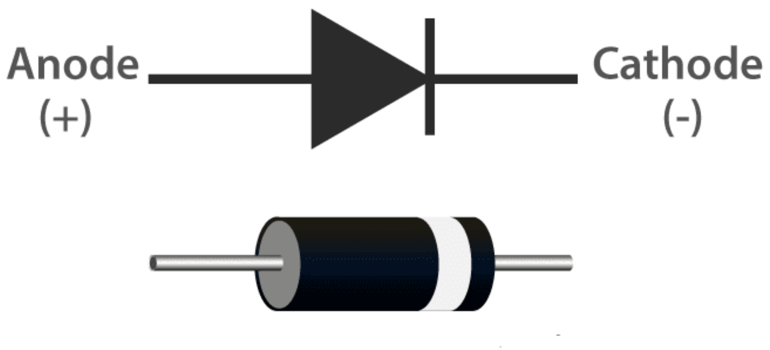
DIODES

Topic Outcomes

- Develop a clear understanding of the basic operation and characteristics of a diode in the **no-bias**, **forward-bias**, and **reverse-bias** regions.
- Be able to calculate the **dc**, **ac**, and **average ac resistance** of a diode from the characteristics.
- Understand the **impact** of an **equivalent circuit** whether it is **ideal** or **practical**.

Diode

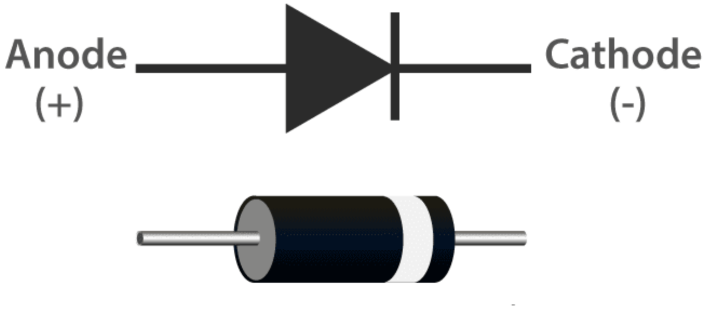
- A semiconductor device with a single *pn* junction that conducts current in only one direction.
- A modern diode is a two-terminal semiconductor device formed by two doped regions of silicon separated by a *pn* junction.



Diode Schematic Symbol and Structure

Diode

- made from a small piece of semiconductor material, usually Si, in which half is doped as a p region and half is doped as an n region with a PN junction and depletion region in between.
- The **p region** is called the **anode** and is connected to a conductive terminal.
- The **n region** is called the **cathode** and is connected to a second conductive terminal



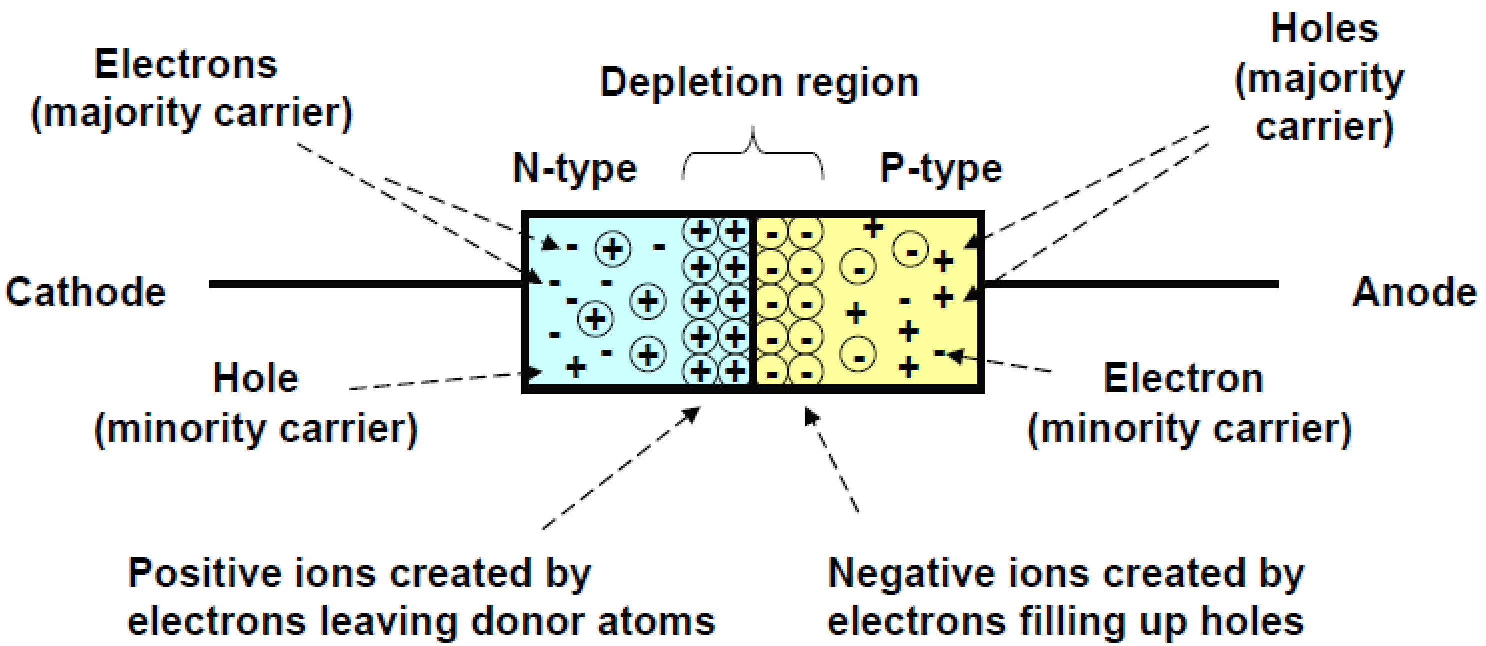
Diode Schematic Symbol and Structure

Diode Operating Conditions

Diode Operating Conditions

- A diode has three operating conditions:
  1. **No bias** – no applied voltage across the diode
  2. **Forward bias** - established by applying the positive potential to the p-type material and the negative potential to the n-type material.
  3. **Reverse bias** – established by applying external potential of **V** volts across the p-n junction such that the positive terminal is connected to the n-type material and the negative terminal is connected to the p-type material.

No Bias

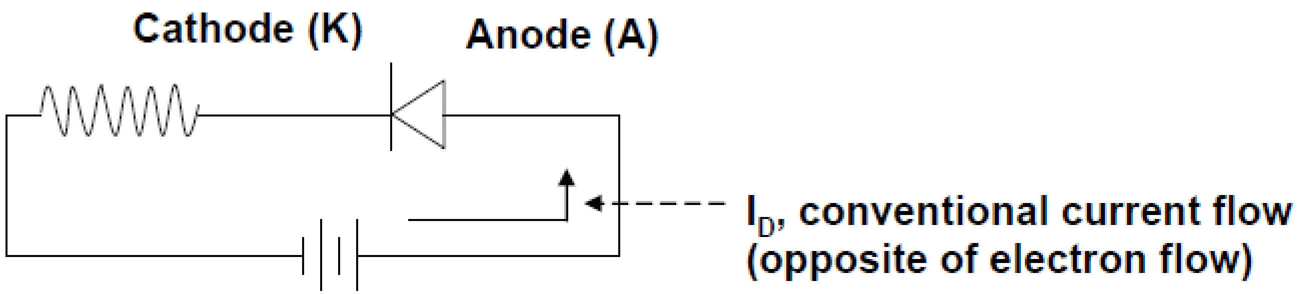


No Bias Condition

No Bias

Forward Bias

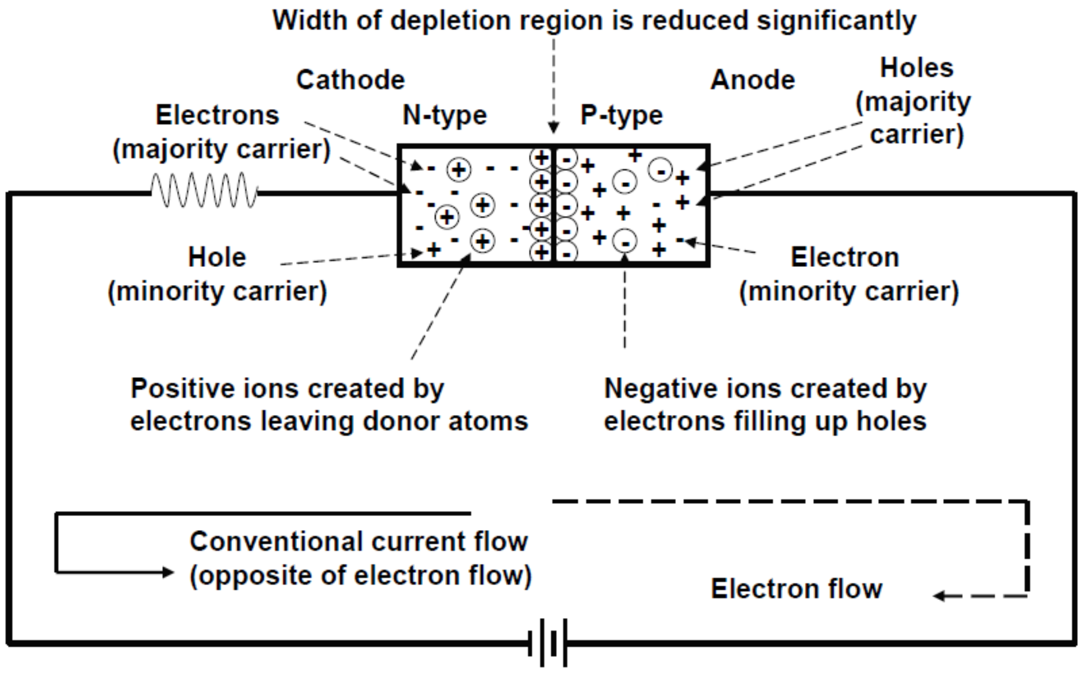
- When a diode is forward biased, the **resistance** of the diode is low and there could be **significant current flow** across the diode depending on the applied voltage across the terminals of the diode.



Forward Biased Semiconductor Diode

Forward Bias

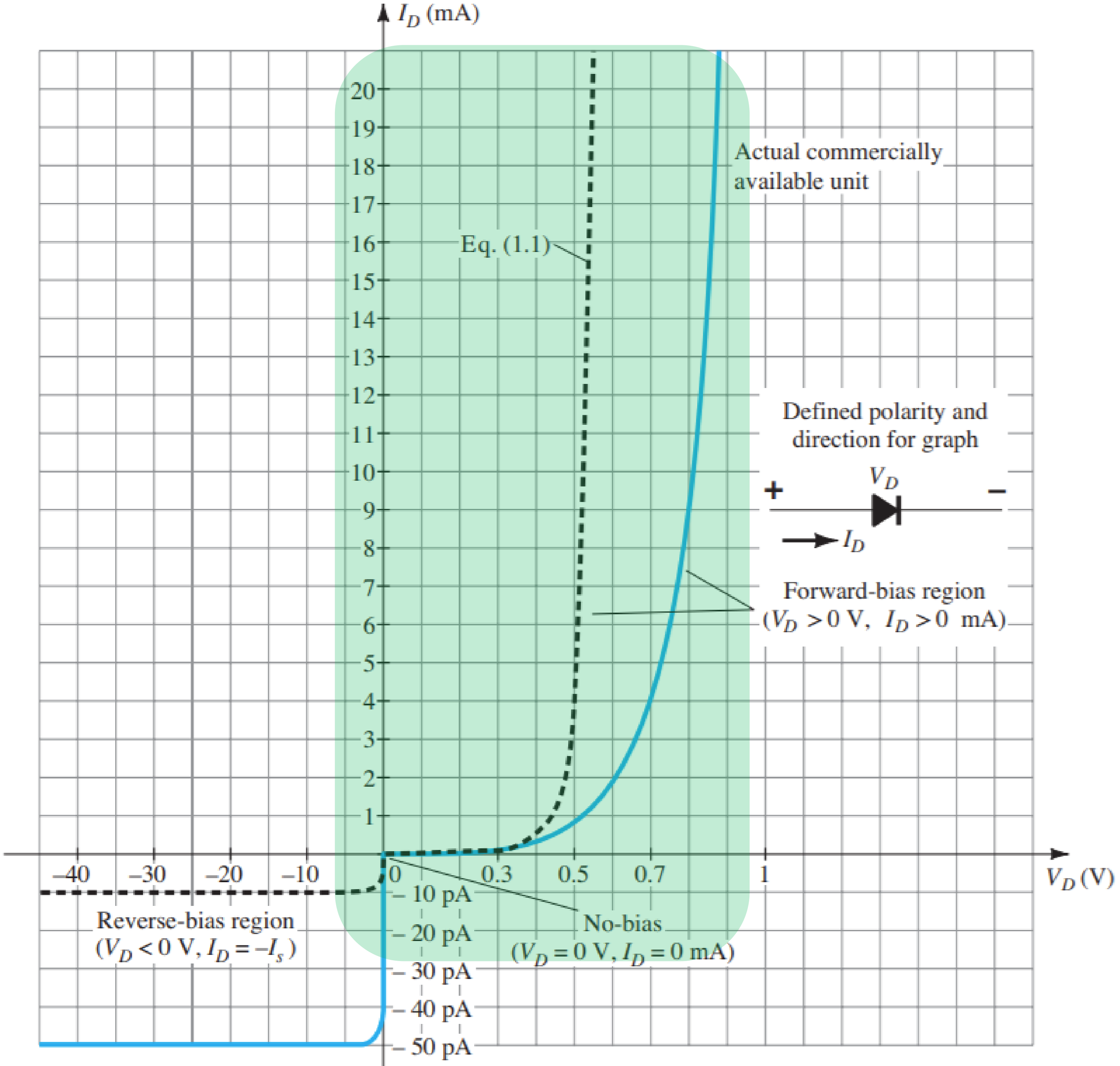
- As more electrons flow into the depletion region, the number of positive ions is reduced.
- As more holes effectively flow into the depletion region on the other side of the pn junction, the number of negative ions is reduced. This reduction in positive and negative ions during forward bias causes the depletion region to narrow
- Note that minority carrier flow has not changed in magnitude, but the reduction in the width of the depletion region has resulted in heavy majority flow across the junction.
- The magnitude of the majority carrier flow will increase exponentially with increasing forward bias.



Forward Biased Semiconductor Diode

Forward Bias

- There is a ***minimum forward bias voltage (knee voltage)*** needed to establish a significant current flow across the diode .
    - For ***Germanium***, the ***knee voltage*** is ***0.3 volt.***
    - For ***Silicon,*** the ***knee voltage*** is ***0.7 volt***.
    - For ***Gallium Arsenide***, the ***knee voltage*** is ***1.2 volt***
- ***Typically***, the voltage across a forward biased diode is ***no greater than 1 volt***.



Si Diode Characteristics

Forward Bias

with the help of external bias voltage - the free electrons can now overcome the barrier potential, can pass in the depletion region.

immediately combine with the holes - the valence bond become valence electrons

these valence electrons continue to move to the left because they were attracted to the positive side of the external biased voltage

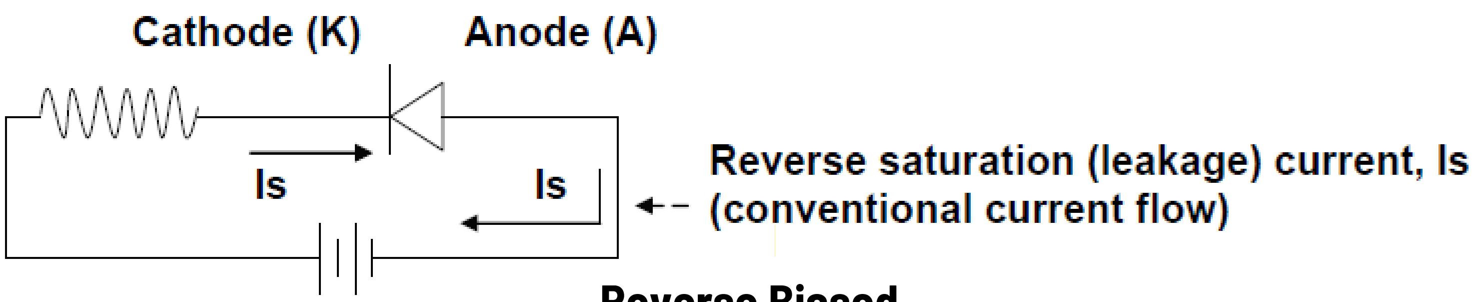
the holes become the pathway of the electrons
hole movement - HOLE CURRENT

as the valence electron leave the p region and flow to the external region, they leave holes behind in the p region, so there's a continuous

voltage drop around pn junction - due to barrier potential

Reverse Bias

- When the ***anode*** of the diode is made ***negative with respect to the cathode***, the diode is said to be ***reverse biased***.
- The ***resistance*** of a reverse biased diode is ***very high (no reading in the Mohm range).***

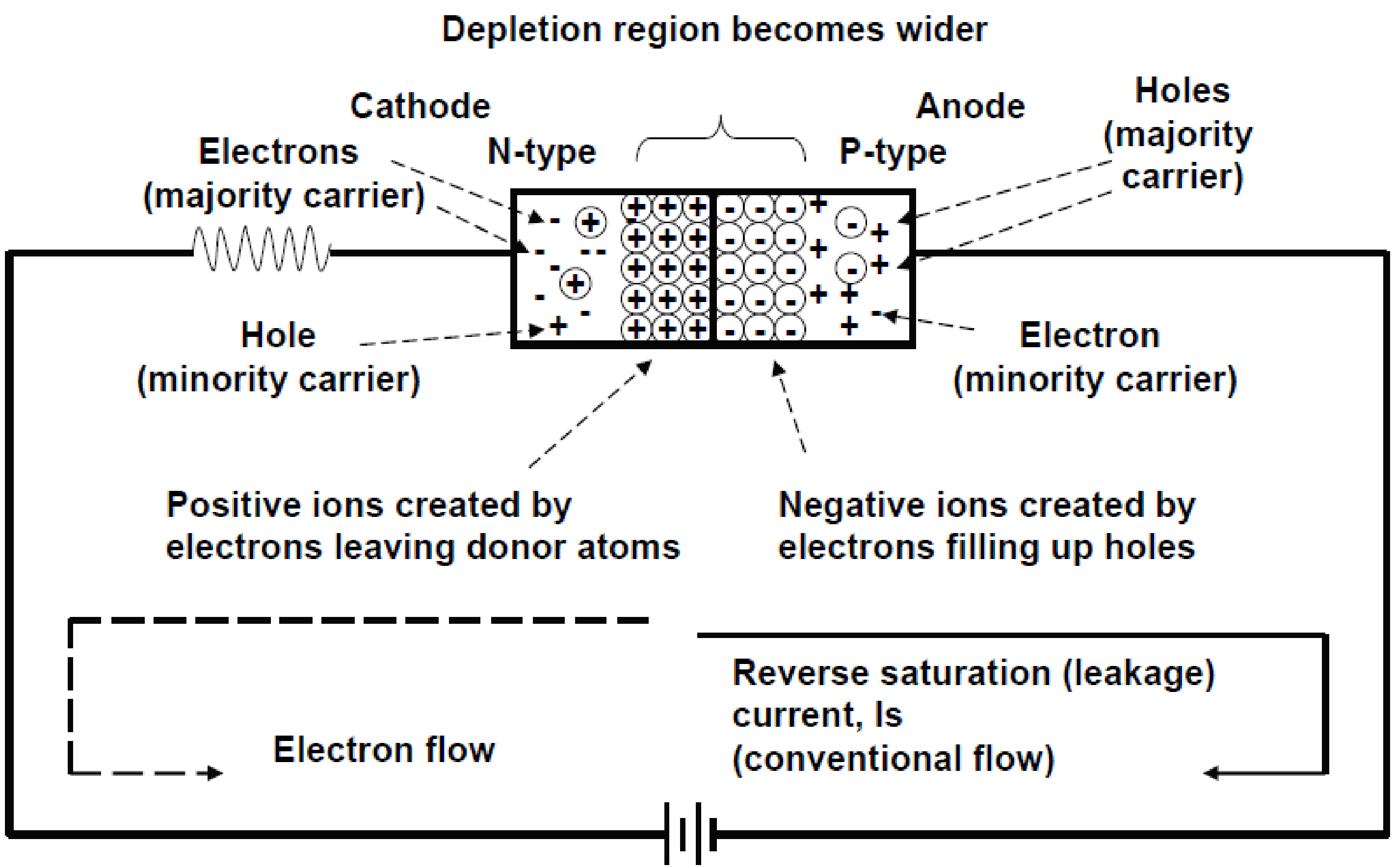


Reverse Biased Semiconductor Diode

- The number of **uncovered positive ions** in the depletion region of the n-type material **will increase** due to **large number of "free" electrons** drawn to the positive potential of the applied voltage.
- For similar reasons, the **number of uncovered negative ions** will increase in the **p-type material**. The net effect, therefore, is the widening of the depletion region.

Reverse Bias

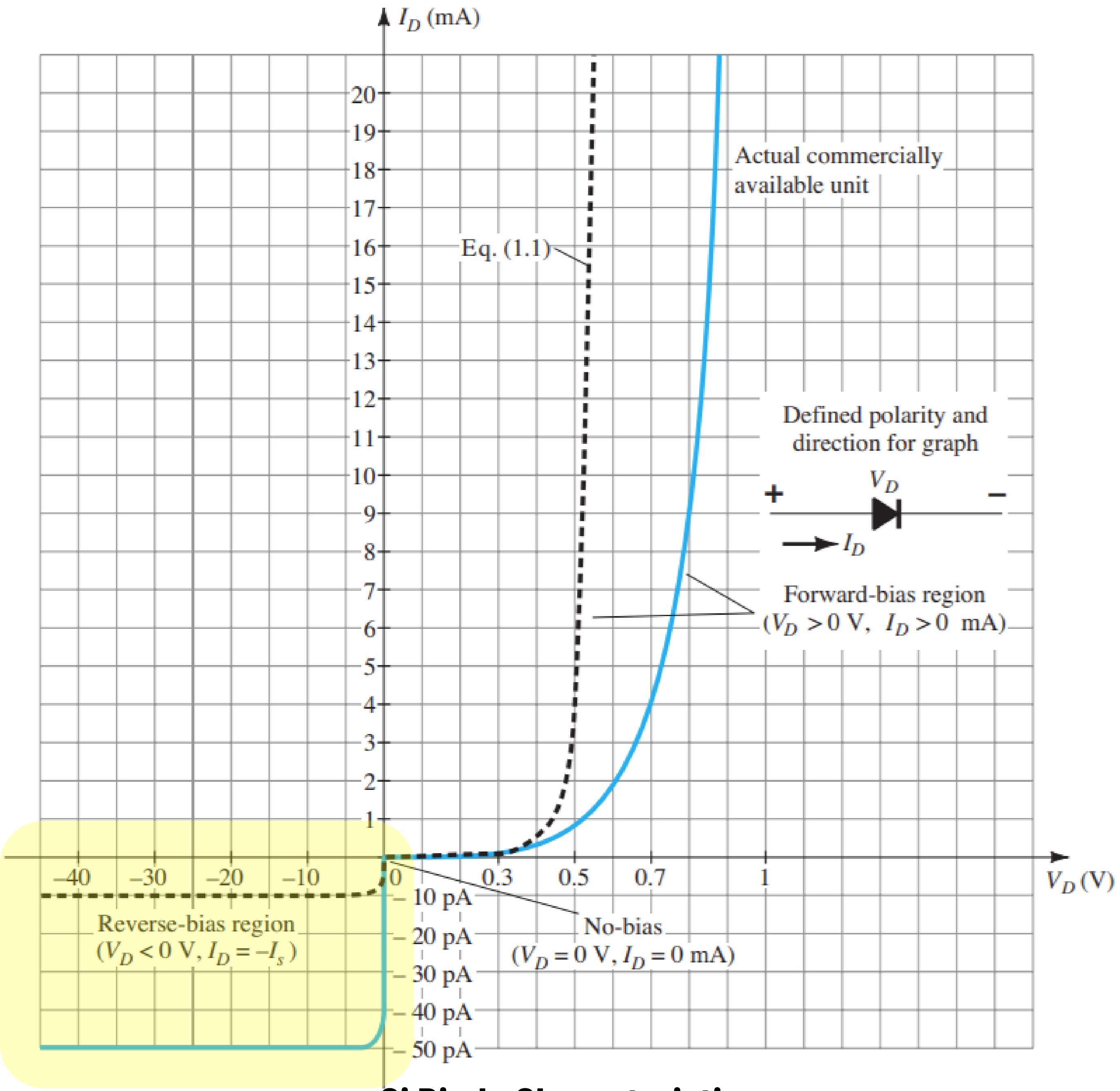
- The **widening of the depletion region** will establish for a great barrier for the majority carriers to overcome, effectively **reducing the majority carrier flow to zero**.
- The **number of minority carriers**, however that find themselves entering the depletion region **will not change** resulting in minority carrier flow vectors with the same magnitude with no applied voltage.
- The current that exist under this condition is called the **Reverse Saturation Current (I_s)**.
- It is **seldom more than a few microamperes** in magnitude **except for high-power devices**.
- The term "**saturation**" comes from the fact that it **reaches the maximum value quickly** and does not change significantly with increase in the reverse bias potential.



Reverse Biased Semiconductor Diode

Reverse Bias

- Values of reverse voltage can be much higher, in the order of 10 to 20 V or higher, since there is no forward current.



Si Diode Characteristics

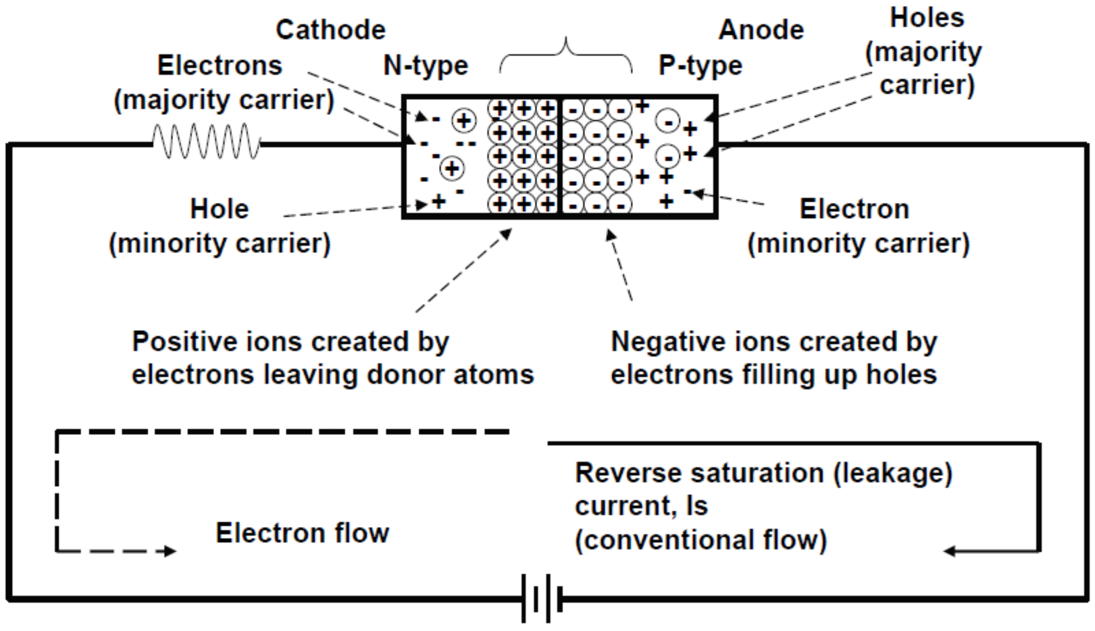
Reverse Bias

there are thermally generated electron hole pairs, the negative side of the external biased voltage pushes the carriers in the p region, which are free electrons, towards the pn junction.

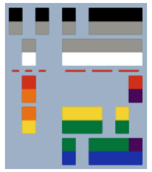
the minority electrons can easily pass the pn junction since there is no energy required

Reverse Breakdown

- Also called **Avalanche Breakdown** and **Zener Breakdown**
- Normally, the reverse current is so small that it can be neglected. However, if the external reverse-bias voltage is increased to a value called the **breakdown voltage**, the **reverse current will drastically increase**.
- The **high reverse-bias voltage** imparts energy to the **free minority electrons** so that as they **speed through the p region**, they collide with atoms with **enough energy to knock valence electrons** out of orbit and into the **conduction band**.
- The **newly created conduction electrons** are also high in energy and **repeat the process**. If one electron knocks only two others out of their valence orbit during its travel through the p region, the **numbers quickly multiply**.
- As these **high-energy electrons** go through the **depletion region**, they have **enough energy** to **go through the n region** as conduction electrons, rather than combining with holes.

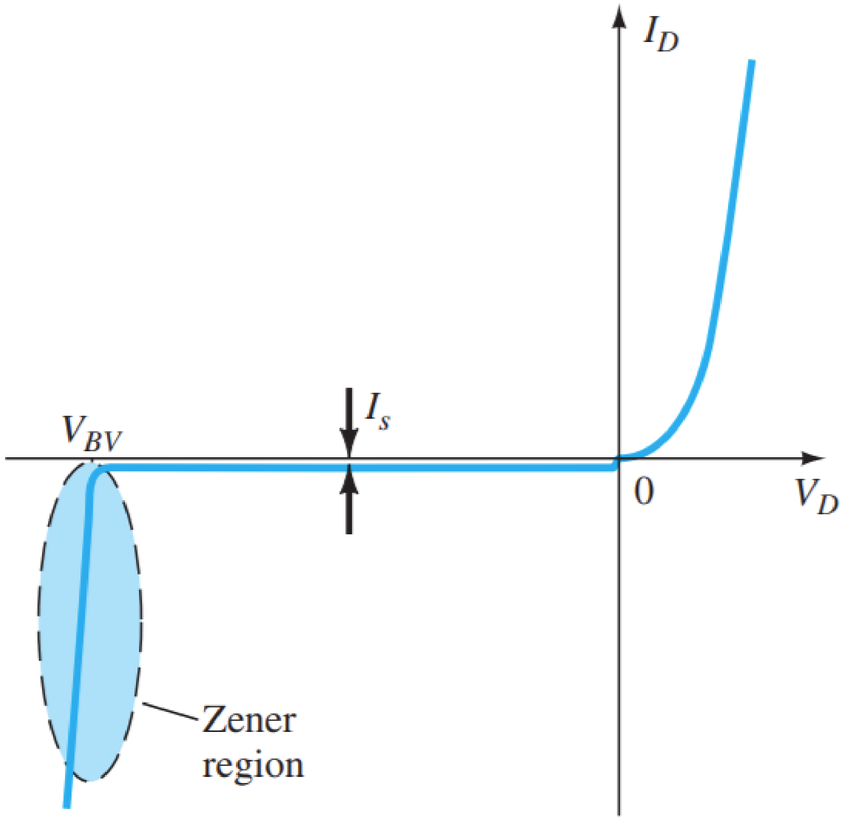


Reverse Biased Semiconductor Diode



Reverse Breakdown

- The multiplication of conduction electrons just discussed is known as the **avalanche effect**, and reverse current can **increase dramatically** if steps are not taken to limit the current.
- When the **reverse current is not limited**, the **resulting heating** will **permanently damage the diode**.
- **Most diodes** are not operated in reverse breakdown, but if the current is limited (by adding a series-limiting resistor for example), there is no permanent damage to the diode.



Diode Characteristics

Diode Characteristic Curve

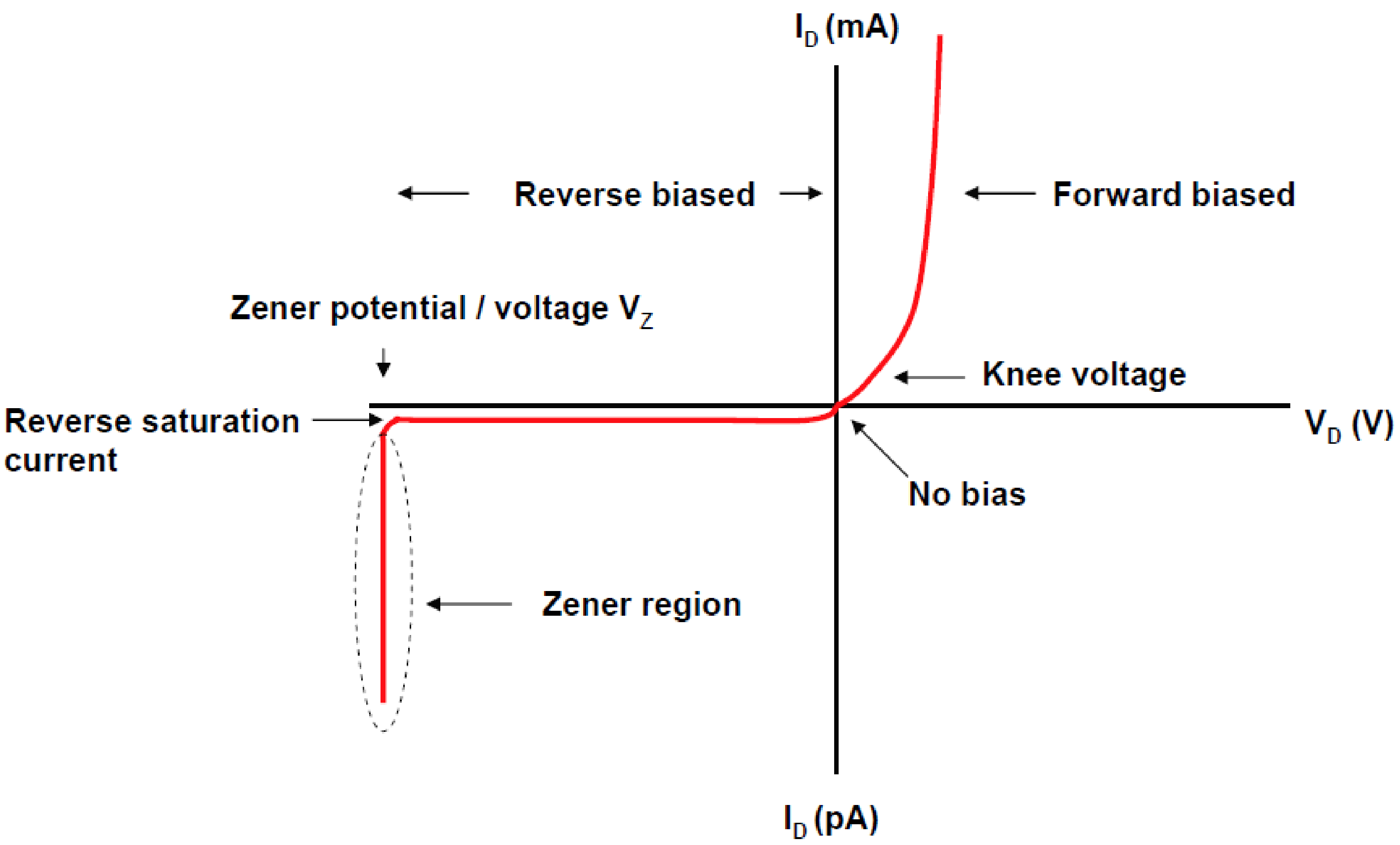
- The **general characteristic curve** of a semiconductor diode can be defined by:

$$I_D = I_s\left(e^{\frac{V_D}{nV_T}} - 1\right) = I_s(e^{\frac{qV_D}{nkT}} - 1)$$

Where:
I_D = current flowing through the diode
I_s = reverse saturation current
e = Euler's constant, $\approx$2.71828
V_D = applied forward bias voltage across the diode
n = ideality factor
n=1 for indirect semiconductors (Si, Ge, etc.)
n=2 for direct semiconductors
V_T = thermal voltage = $\frac{kT}{q}$
k = Boltzmann's constant, $1.38064852 \times 10^{-23}\, J/K$
T = absolute temperature in kelvin = 273 + temp in $°C$
q = electric charge, 1.602×10^{-19} C (Coulomb)

Diode Characteristic Curve

- The diode equation applies when the diode is **forward or reverse biased except** when the diode enters the **Zener region** (diode current rises abruptly).



Diode Characteristic Curve

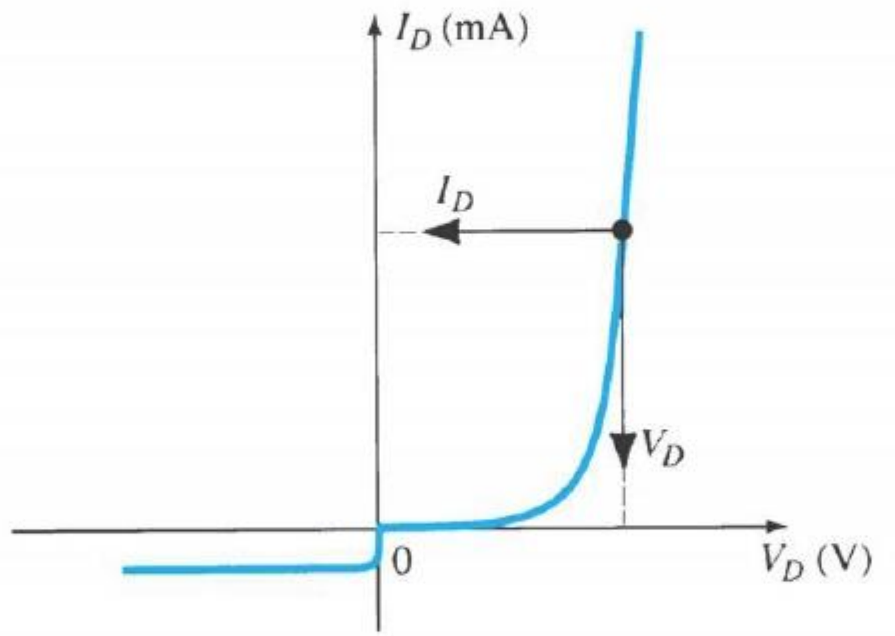
Resistance Levels

As the operating point of a diode moves from one region to another the resistance of the diode will also change due to the nonlinear shape of the characteristic curve.

DC or Static Resistance

- The application of a **DC voltage** to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that **will not change with time**.
- The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D as shown:

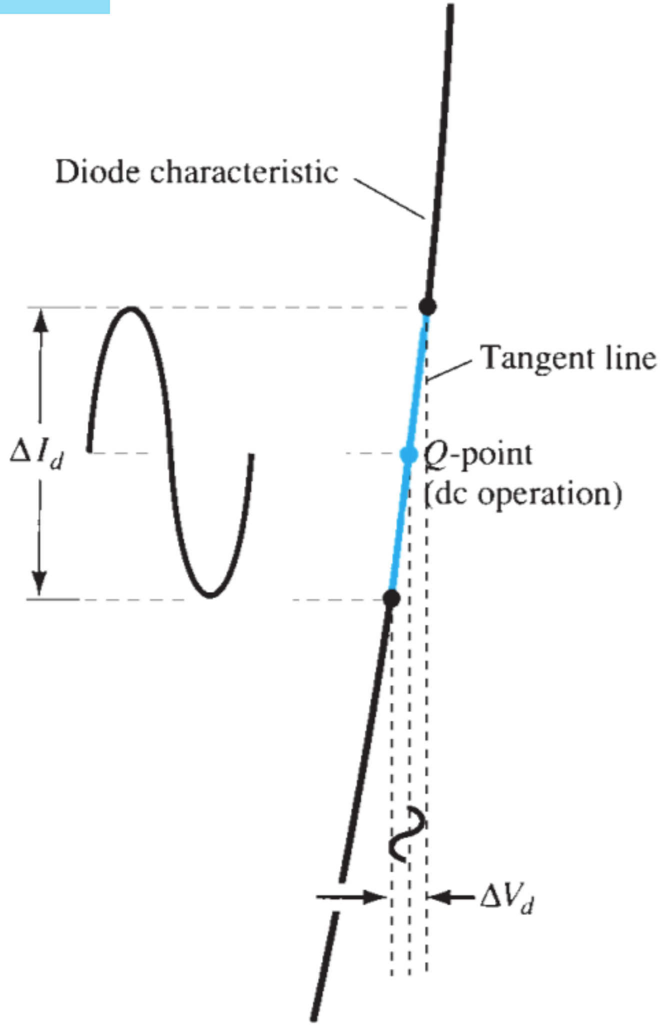
$$R_D = \frac{V_D}{I_D}$$



Determining the DC resistance

AC or Dynamic Resistance

- If a **sinusoidal** rather than a dc input is applied, the situation will change completely.
- The **varying input** will **move the instantaneous operating point up and down** a region of the characteristics and thus defines a specific change in current and voltage as shown below.
- With no applied varying signal, the point of operation would be the Q -point (Quiescent point) appearing on the figure, determined by the applied dc levels. The designation Q-point is derived from the word quiescent, which means "still or unvarying."



Determining the AC resistance

AC or Dynamic Resistance

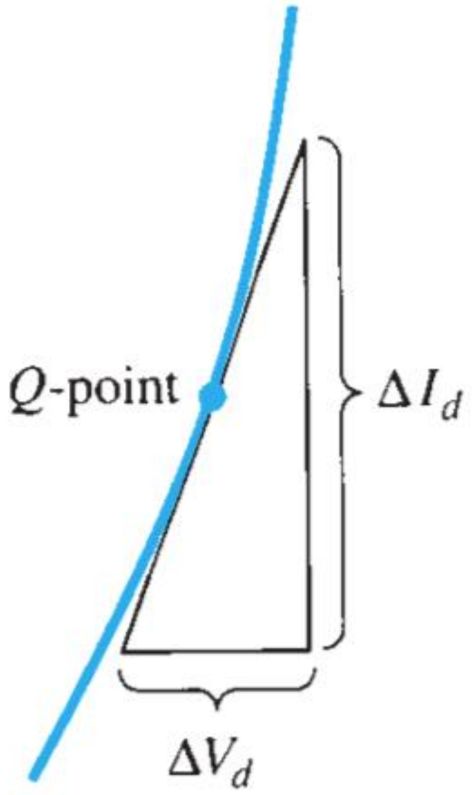
- A **straight line drawn tangent** to the curve through the Q -point as shown in the figure will define a particular change in voltage and current that can be used to determine the ac or dynamic resistance for this region of the diode characteristics.
- An effort should be made to keep the change in voltage and current as small as possible and equidistant to either side of the Q -point. In equation form,

$$r_d = \frac{\Delta V_d}{\Delta I_d}$$

- Using the diode equation, assuming n=1, T = 27 $°C = 300\ \mathrm{K}$

$$r_d = \frac{26mV}{I_D}$$

Where I_D is the **DC (quiescent) current** passing through the diode.

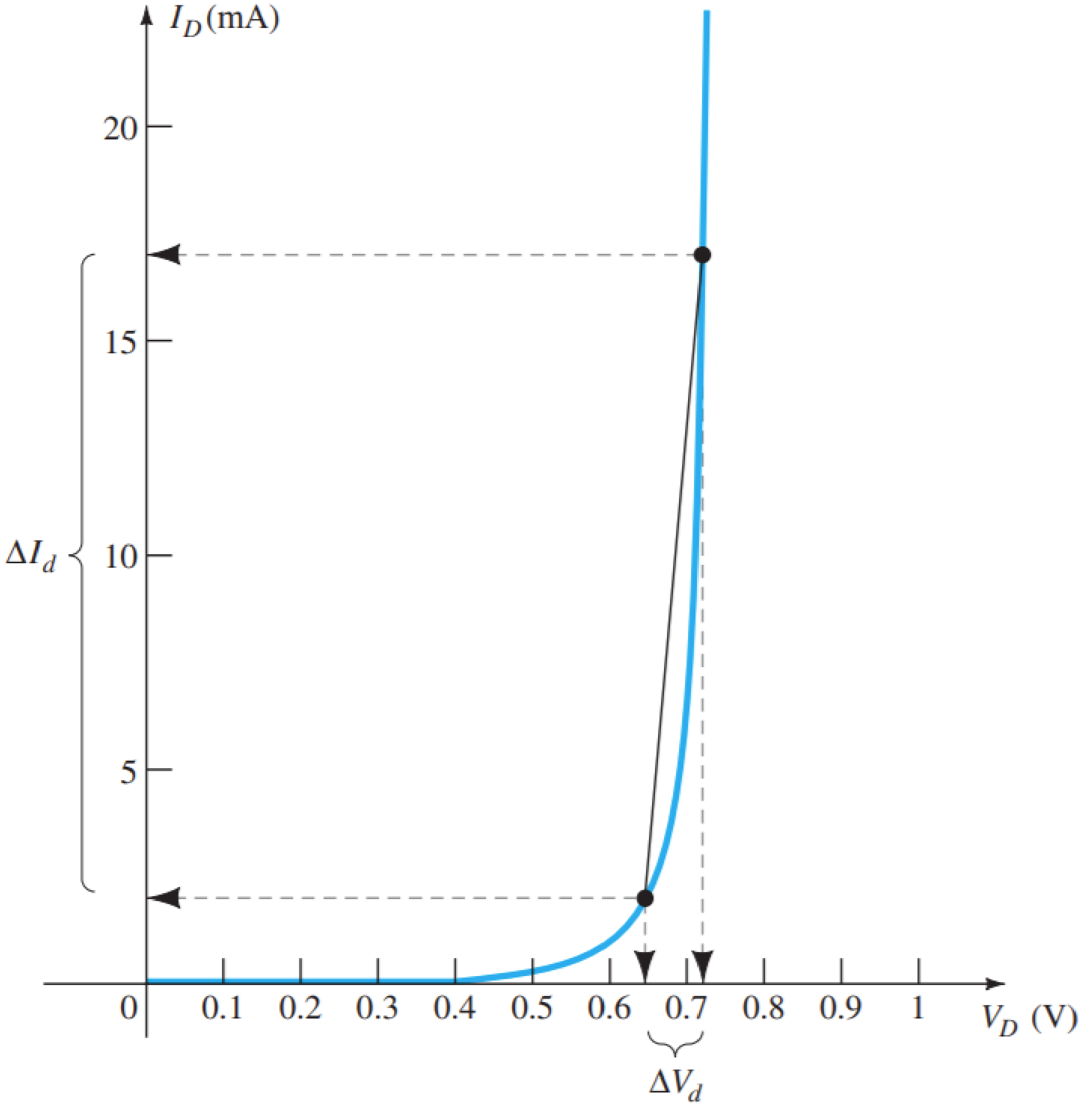


Determining the AC resistance

Average AC Resistance

- If the input signal is sufficiently large to produce a broad swing such as indicated in the figure, the resistance associated with the device for this region is called the **average AC resistance**.
- The average AC resistance is, by definition, the resistance determined by a straight line drawn between the two intersections established by the maximum and minimum values of input voltage.

$$r_{av} = \frac{\Delta V_d}{\Delta I_d}\bigg|_{pt.\,to\,pt.}$$

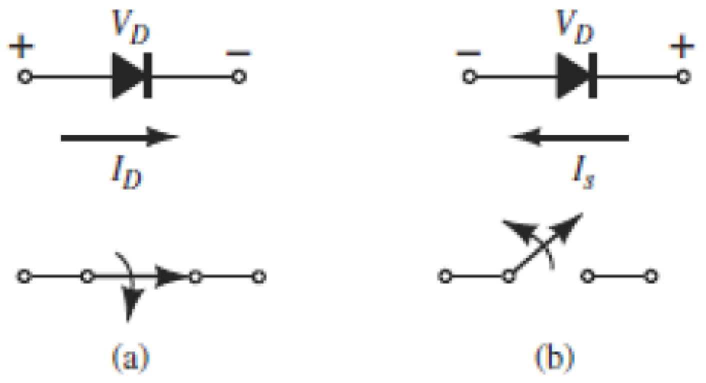


Determining the average AC resistance

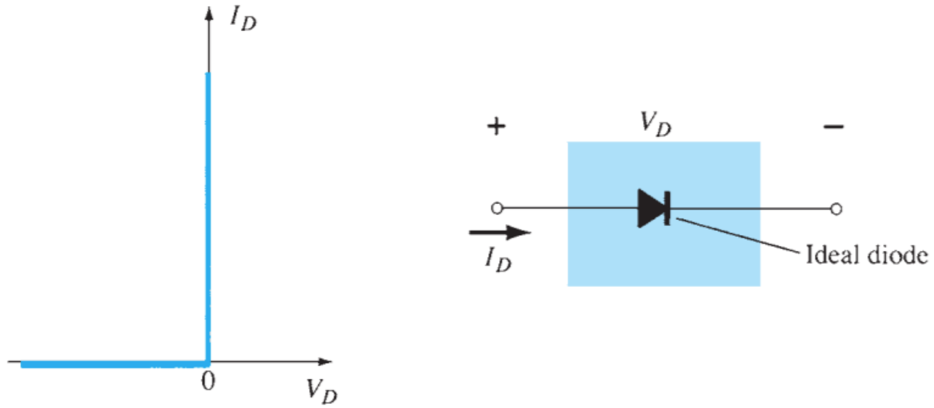
Diode Models

Ideal Diode Model

- Is a perfect two-state device that **exhibits zero impedance** when **forward biased** and **infinite impedance** when **reversed biased**.
- The semiconductor diode behaves in a **manner similar** to a **mechanical switch** in that it can control whether current will flow between its two terminals.
- Ideally, if the semiconductor diode is to behave like a closed switch in the forward-bias region, the resistance of the diode should be **0 Ω**. In the reverse-bias region its resistance should be **∞ Ω** to represent the open-circuit equivalent.



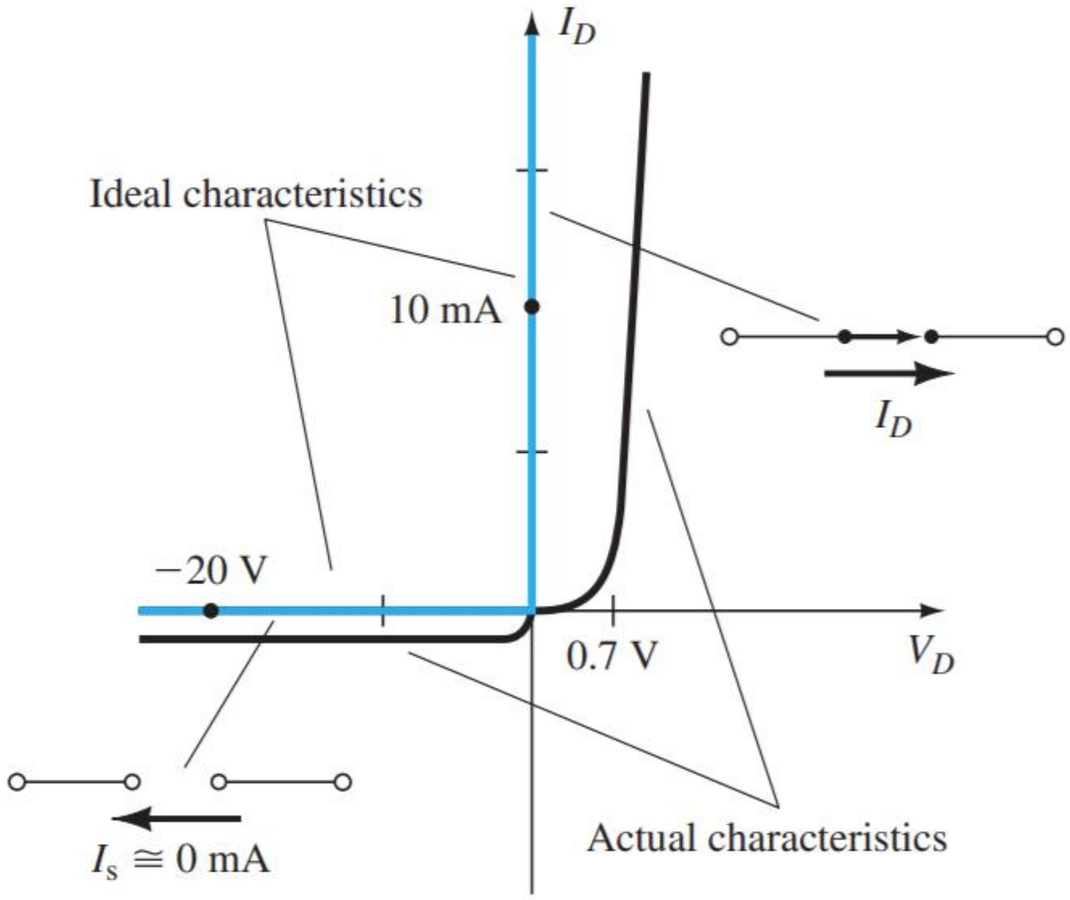
Ideal Diode – Forward (a) and reverse (b) bias



Ideal Diode Characteristics

Ideal Diode Model

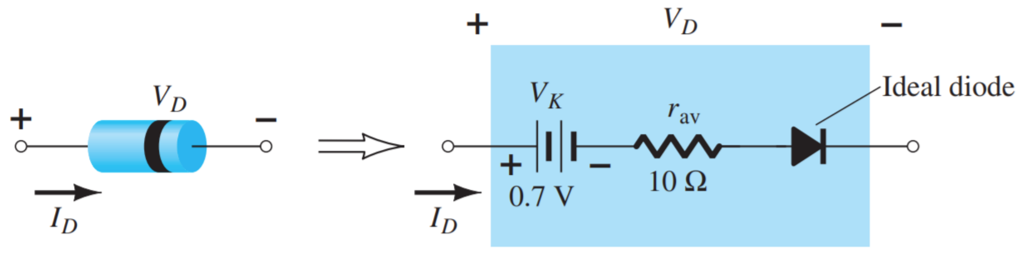
- The figure shows the ideal Si diode to a real-world Si diode.
- The only major difference is that the real-world diode rises at **0.7 V** rather than 0V.
- When a switch is closed, the resistance between the contacts is assumed to be 0 Ω.
- In an ideal diode, the voltage across the diode is 0V at any current level which means the resistance is 0 Ω.
- On the horizontal line, the resistance is considered infinite ohms (open circuit) at any point on the axis since current is 0 mA.



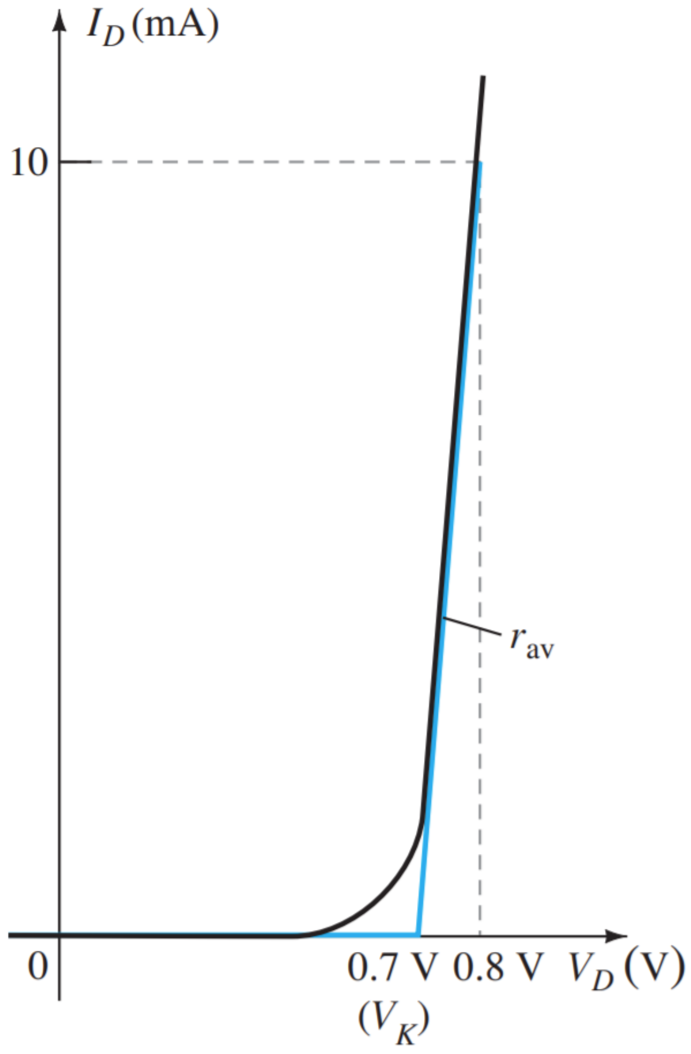
Ideal vs Real world Si Diode

Practical or Actual Diode (Piecewise Linear Model)

- One technique for obtaining an equivalent circuit for a diode is to approximate the characteristics of the device by straight-line segments.
- The resulting equivalent circuit is called a **piecewise-linear equivalent** circuit



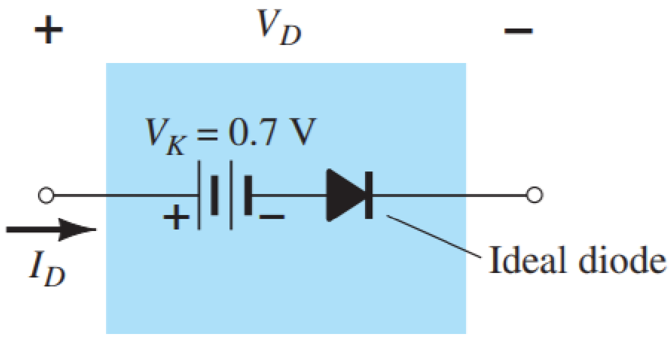
Components of the piecewise-linear equivalent circuit



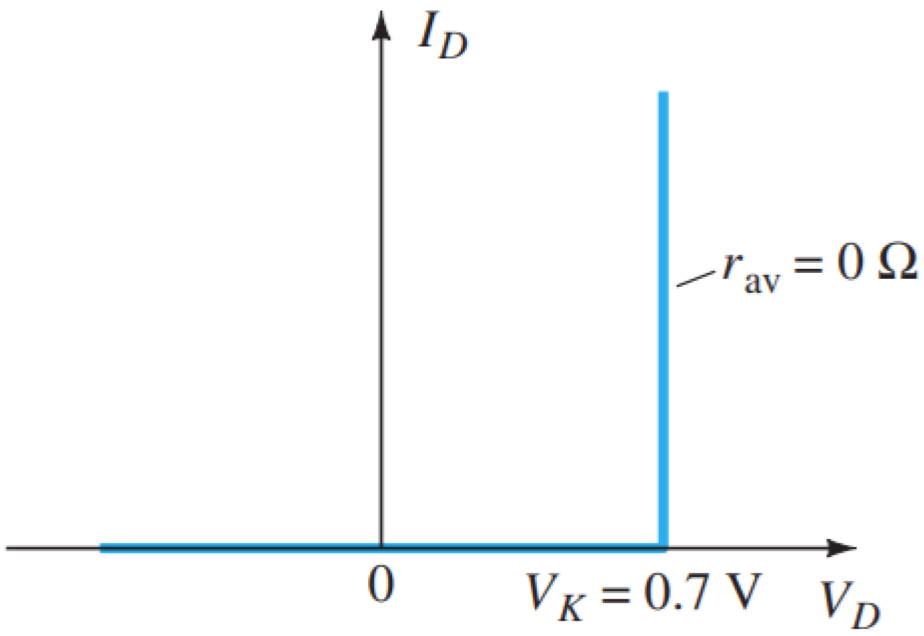
Piecewise –Linear Segments

Simplified Equivalent Model

- For most applications, the resistance r_{av} is **sufficiently small** to be ignored in comparison to the other elements of the network.
- Removing r_{av} from the equivalent circuit is the same as implying that the characteristics of the diode appear as:

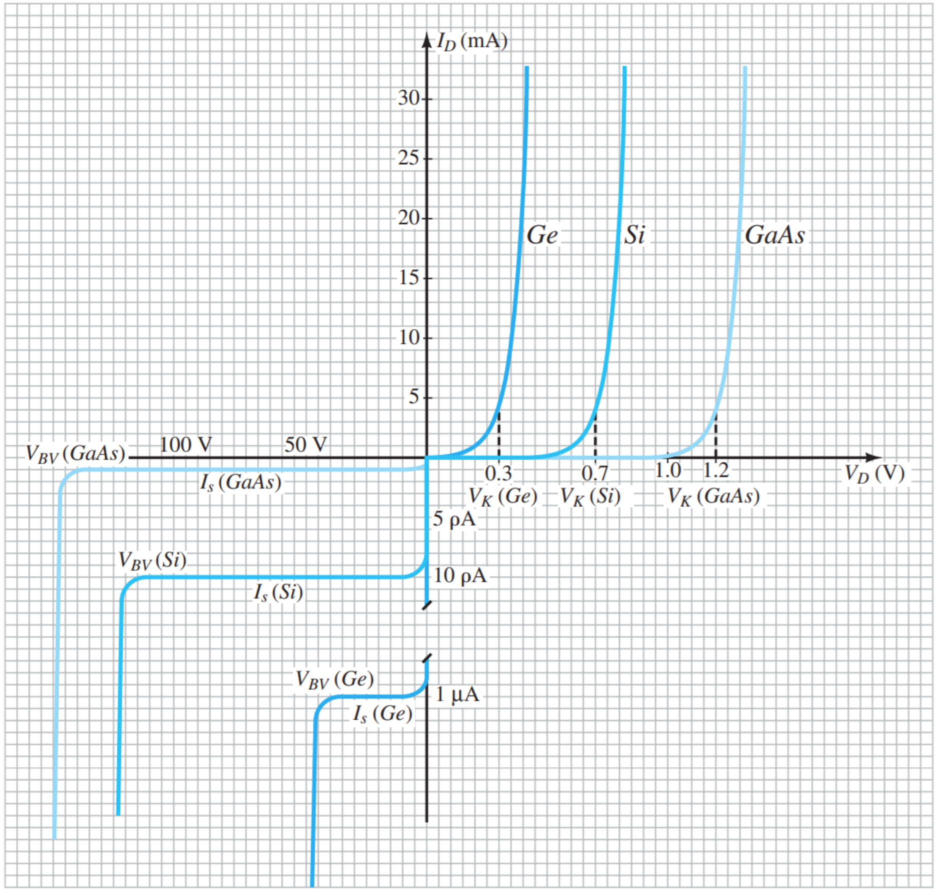


Simplified equivalent circuit



Simplified equivalent model characteristic plot

Comparison of Diodes



Comparison of Ge, Si and GaAs Diodes

Diode Specification Sheets

Diode Specification Sheets

- Data on specific semiconductor devices are normally provided by the manufacturer in one of two forms.
- Most frequently, they give a very brief description limited to perhaps one page.
- At other times, they give a thorough examination of the characteristics using graphs, artwork, tables, and so on.
- In either case, there are specific pieces of data that must be included for proper use of the device. They include:
  1. Forward voltage[1] V_F
  2. Maximum forward current [2] I_F
  3. Reverse saturation current [3] I_R
  4. Reverse voltage rating [2] (PIV or PVR or $V_{(BR)}$, where BR is breakdown)
  5. Maximum Power dissipation [2], $P_D = V_F I_F$
  6. Capacitance levels
  7. Reverse recovery time
  8. Operating temperature range

[1] ***at a specified current and temperature***
[2] ***at a specified temperature***
[3] ***at a specified voltage and temperature***

Diode Specification Sheet

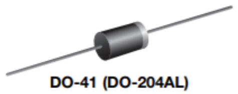
VISHAY.

1N4001, 1N4002, 1N4003, 1N4004, 1N4005, 1N4006, 1N4007

www.vishay.com

Vishay General Semiconductor

General Purpose Plastic Rectifier



DO-41 (DO-204AL)

FEATURES

- Low forward voltage drop
- Low leakage current
- High forward surge capability
- Solder dip 275 °C max. 10 s, per JESD 22-B106
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT

e3

I_F

PIV

V_F

PRIMARY CHARACTERISTICS	
$I_{F(AV)}$	1.0 A
V_{RRM}	50 V, 100 V, 200 V, 400 V, 600 V, 800 V, 1000 V
I_{FSM} (8.3 ms sine-wave)	30 A
I_{FSM} (square wave t_p = 1 ms)	45 A
V_F	1.1 V
I_R	5.0 µA
T_J max.	150 °C
Package	DO-41 (DO-204AL)
Circuit configuration	Single

TYPICAL APPLICATIONS

For use in general purpose rectification of power supplies, inverters, converters, and freewheeling diodes application.

MECHANICAL DATA

Case: DO-41 (DO-204AL), molded epoxy body
Molding compound meets UL 94 V-0 flammability rating
Base P/N-E3 - RoHS-compliant, commercial grade

Terminals: matte tin plated leads, solderable per J-STD-002 and JESD 22-B102
E3 suffix meets JESD 201 class 1A whisker test

Polarity: color band denotes cathode end

MAXIMUM RATINGS (T_A = 25 °C unless otherwise noted)

PARAMETER		SYMBOL	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	UNIT
Maximum repetitive peak reverse voltage		V_{RRM}	50	100	200	400	600	800	1000	V
Maximum RMS voltage		V_{RMS}	35	70	140	280	420	560	700	V
Maximum DC blocking voltage		V_{DC}	50	100	200	400	600	800	1000	V
Maximum average forward rectified current 0.375" (9.5 mm) lead length at T_A = 75 °C		$I_{F(AV)}$	1.0							A
Peak forward surge current 8.3 ms single half sine-wave superimposed on rated load		I_{FSM}	30							A
Non-repetitive peak forward surge current square waveform T_A = 25 °C (fig. 3)	t_p = 1 ms	I_{FSM}	45							A
	t_p = 2 ms		35							
	t_p = 5 ms		30							
Maximum full load reverse current, full cycle average 0.375" (9.5 mm) lead length T_L = 75 °C		$I_{R(AV)}$	30							µA
Rating for fusing (t < 8.3 ms)		I^2t [1]	3.7							A^2s
Operating junction and storage temperature range		T_J, T_{STG}	-50 to +150							°C

Note

[1] For device using on bridge rectifier application

I_R

Operating temperature

ECE 421

Diode Specification Sheet

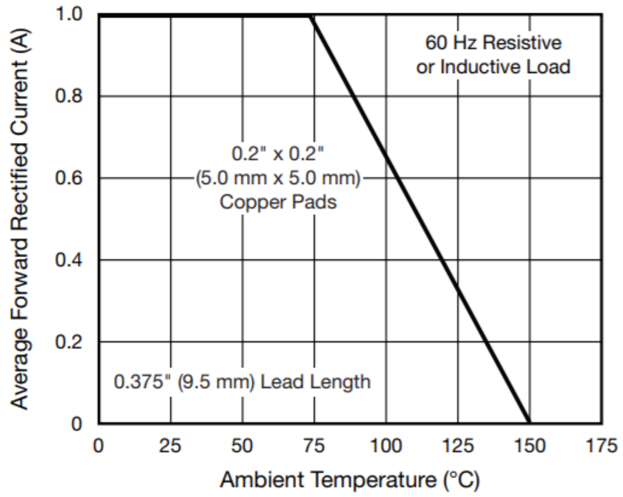


Fig. 1 - Forward Current Derating Curve

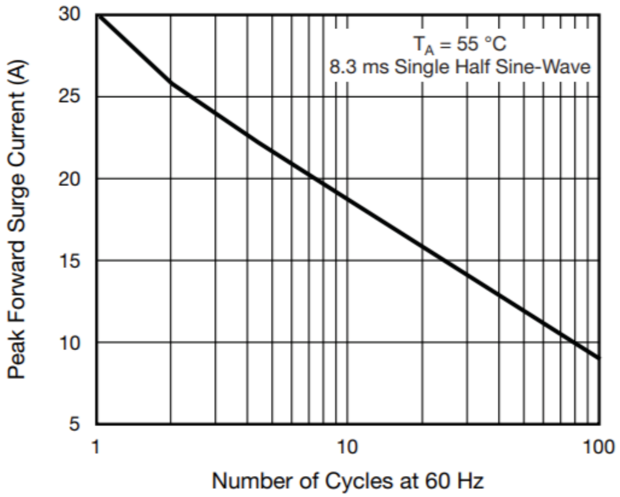


Fig. 2 - Maximum Non-repetitive Peak Forward Surge Current

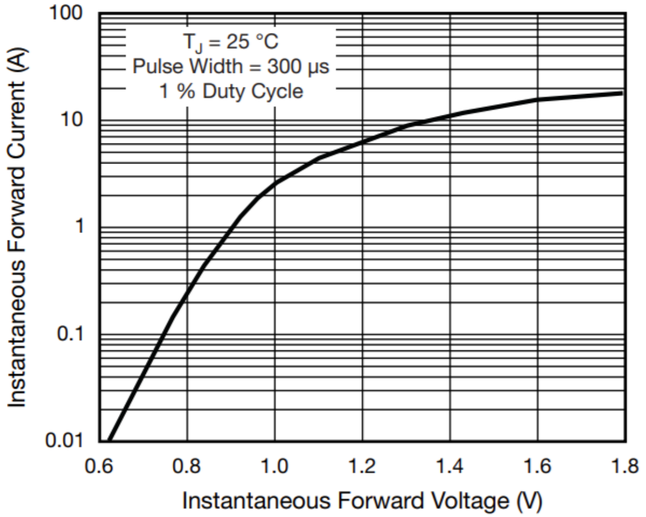
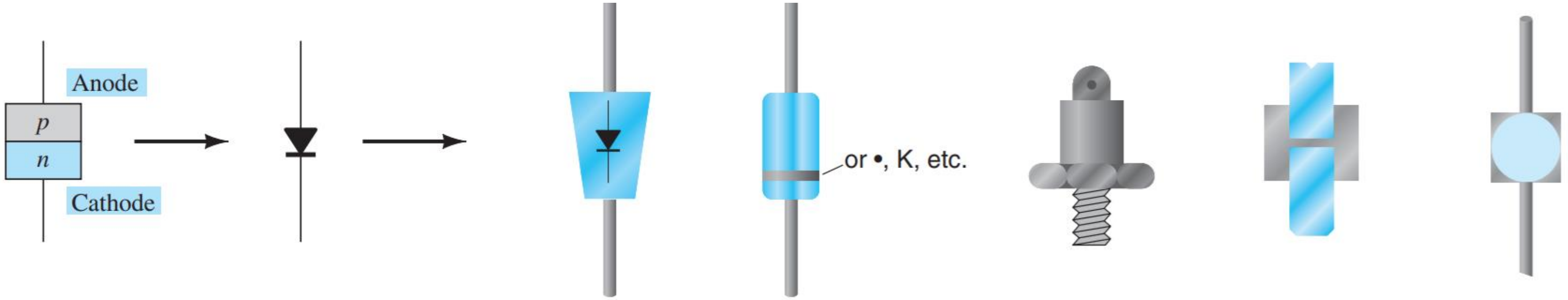
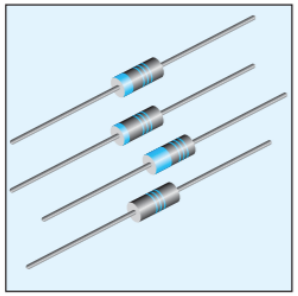
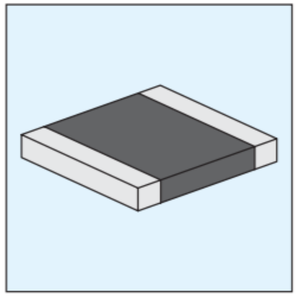


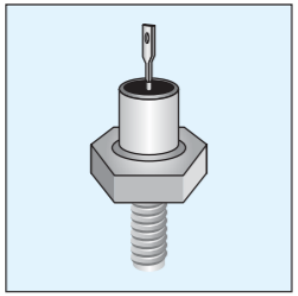
Fig. 4 - Typical Instantaneous Forward Characteristics

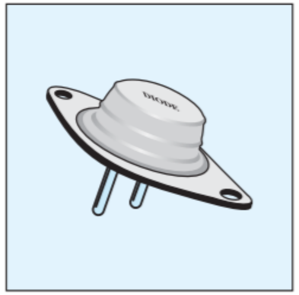
Typical Diode Packages

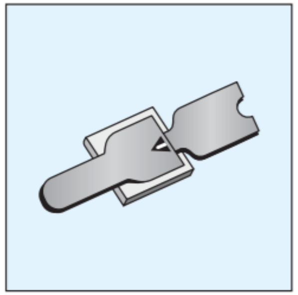


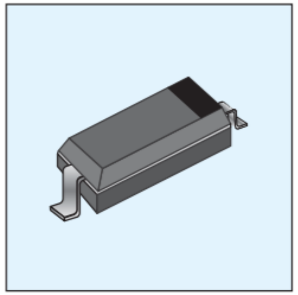

General purpose diode

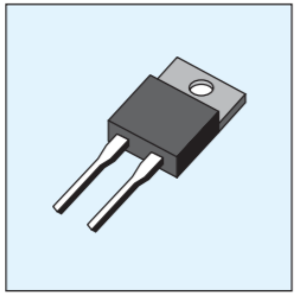

Surface mount high-power PIN diode

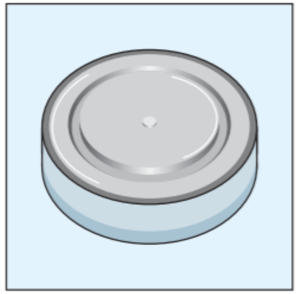

Power (stud) diode


Power (planar) diode


Beam lead pin diode


Flat chip surface mount diode


Power diode

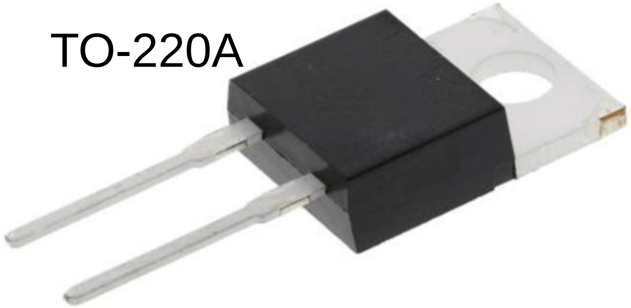

Power (disc, puck) diode

Diodes

DO-14

DO-203AB

TO-220A



DO-21

SOD-123
SOT-23

SOD-323
SMA/DO-214AC

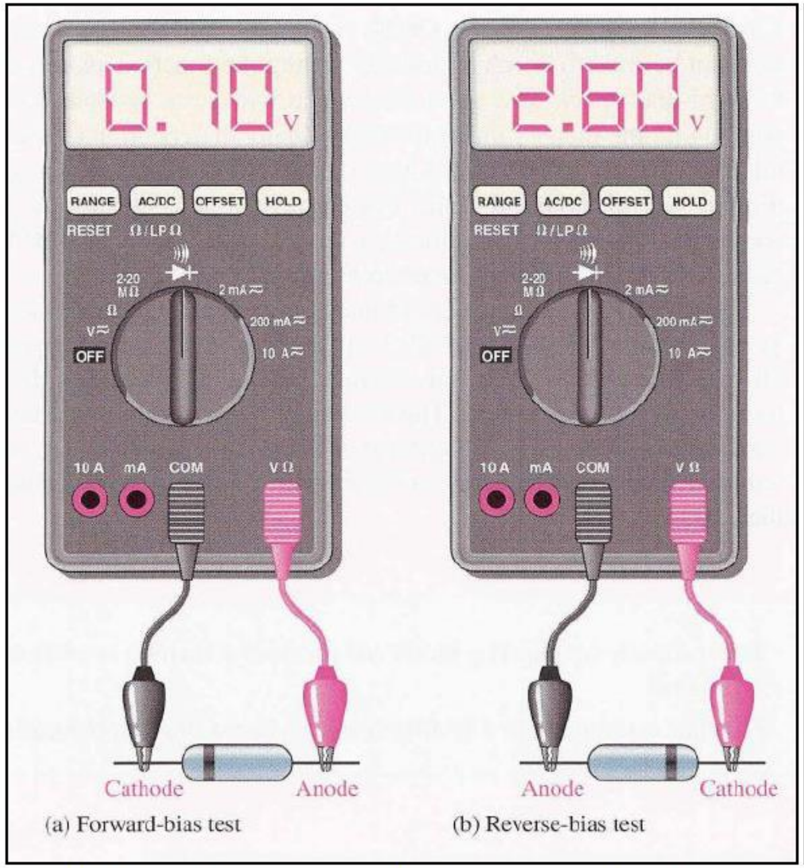
339-02

194-04

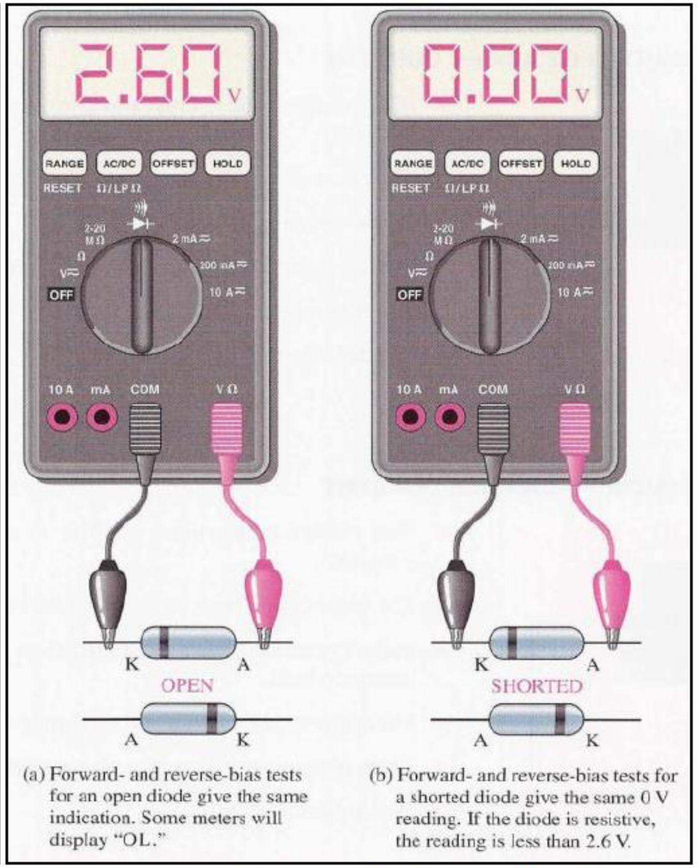
Diode Testing

- The condition of a diode can be determined quickly using a:
  1. Digital display meter (DDM) / Digital Multimeter (DMM)
  2. Ohmmeter section of a multimeter
  3. Curve Tracer

Diode Testing

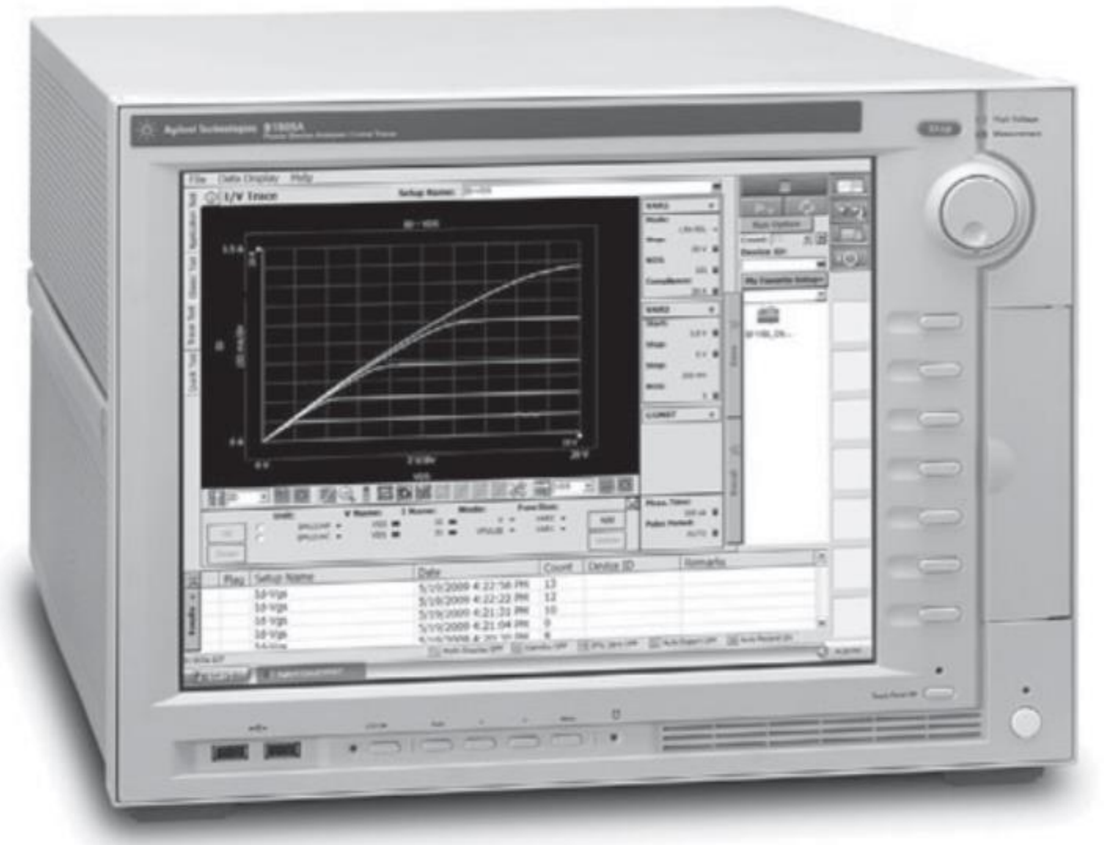


DMM test for a properly functioning diode

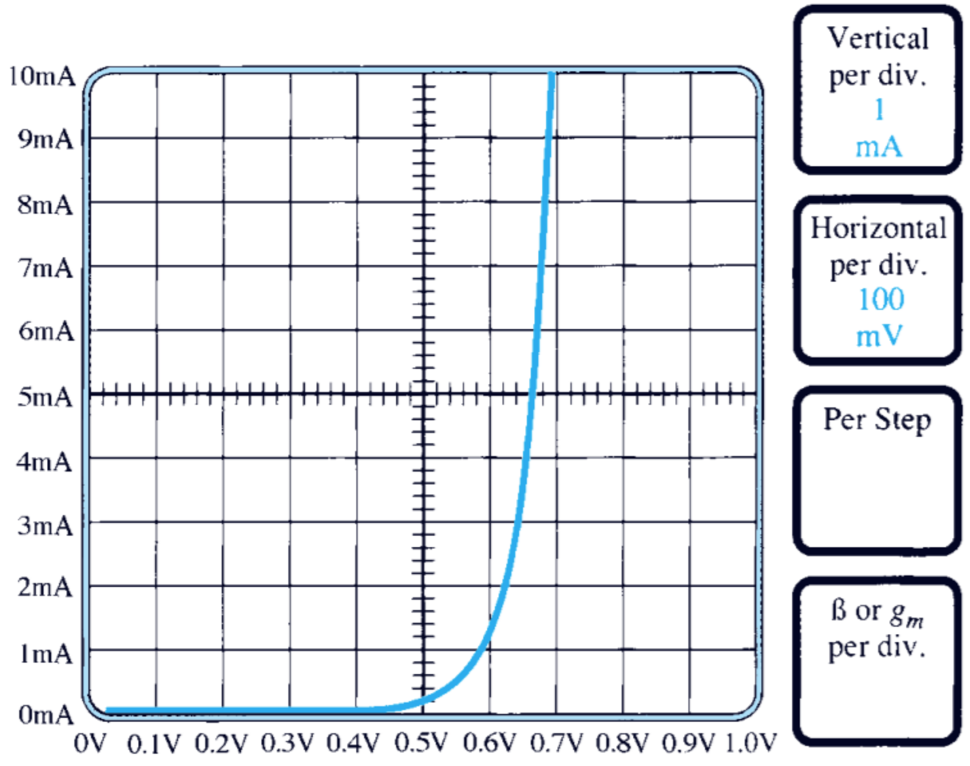


Testing a Defective Diode

Curve Tracer



Agilent Curve Tracer



Curve Tracer Output

Conclusions and Concepts

- The characteristics of an **ideal diode** are a close match with those of a **simple switch** except for the important fact that an **ideal diode can conduct in only one direction.**
- The ideal diode is a **short** in the **region of conduction** and an **open circuit** in the **region of nonconduction**.
- The region near the junction of a diode that has **very few carriers** is called the **depletion region**.
- In the **absence of any externally applied bias**, the diode **current is zero**.
- In the **forward-bias region** the diode **current increases exponentially** with **increase in voltage** across the diode.
- In the **reverse-bias region** the diode **current is the very small** reverse saturation current **until Zener breakdown** is reached and **current will flow in the opposite** direction through the diode.
- The **reverse saturation current** I_S will just about **double in magnitude** for every **10-fold increase in temperature**.
- The **dc resistance** of a diode is determined by the **ratio of the diode voltage and current** at the point of interest and is not sensitive to the shape of the curve. The **dc resistance** decreases with **increase in diode current or voltage**.
- The **ac resistance** of a diode is **sensitive to the shape of the curve** in the region of interest and **decreases for higher levels of diode current or voltage**.
- The **threshold voltage** is about **0.7 V** for silicon diodes and **0.3 V** for germanium diodes.
- The **maximum power dissipation** level of a diode is equal to the **product of the diode voltage and current**.
- The **capacitance** of a diode increases exponentially with **increase in the forward-bias voltage**. Its **lowest levels are in the reverse-bias region**.

End