Diodes

EE223 Digital & Analogue Electronics

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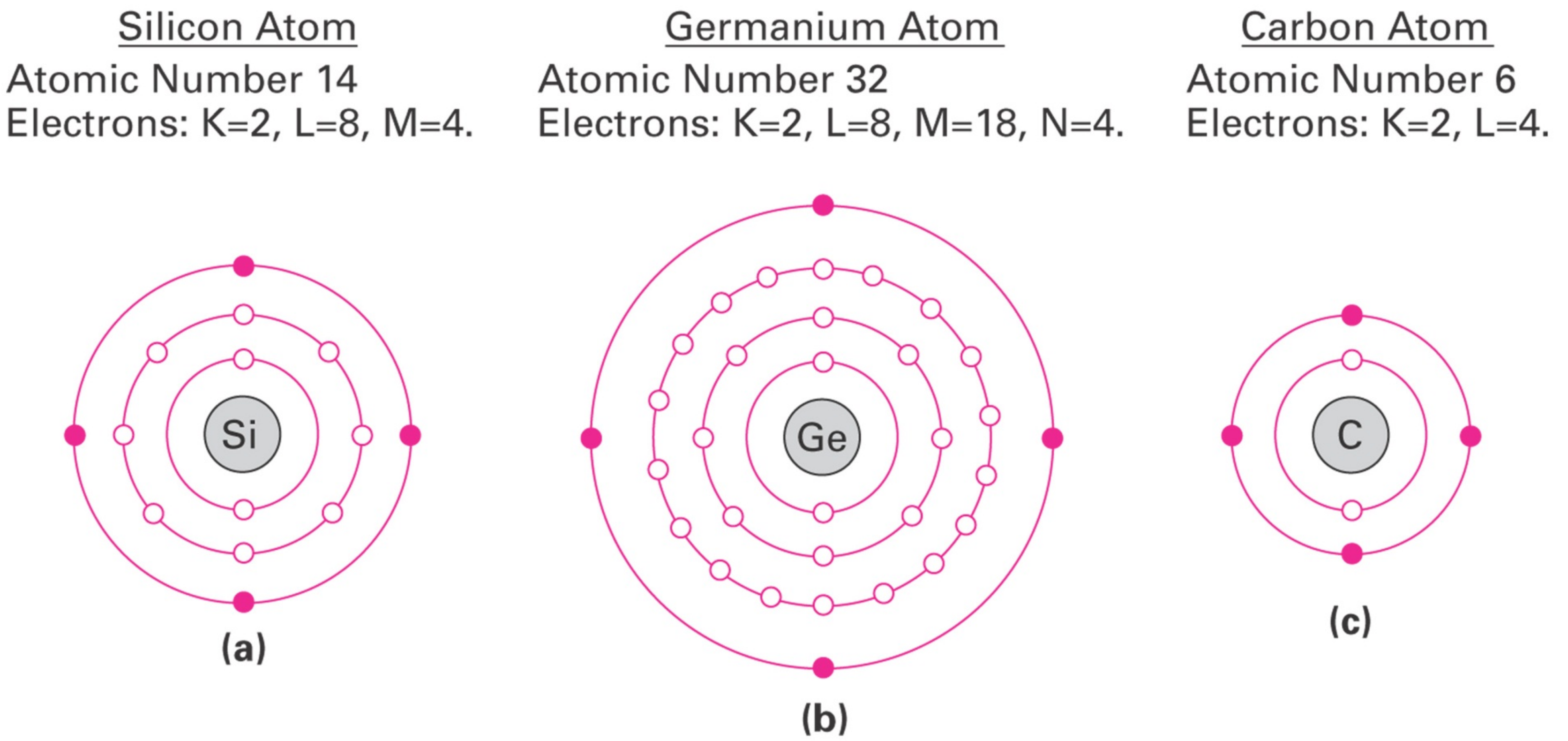
Diodes: A Semiconductor?

- Conductors
  - Such as copper, aluminium have a cloud of free electrons – weak bound **valence electrons** in the outermost orbit of their atoms. If an electric field is applied, current will flow.
- Insulators
  - Such as plastics, valence electrons are tightly bound to the nuclei of the atoms and few are able to break free to conduct a current. If an electric field is applied, current will not flow as there are no mobile charge carriers.

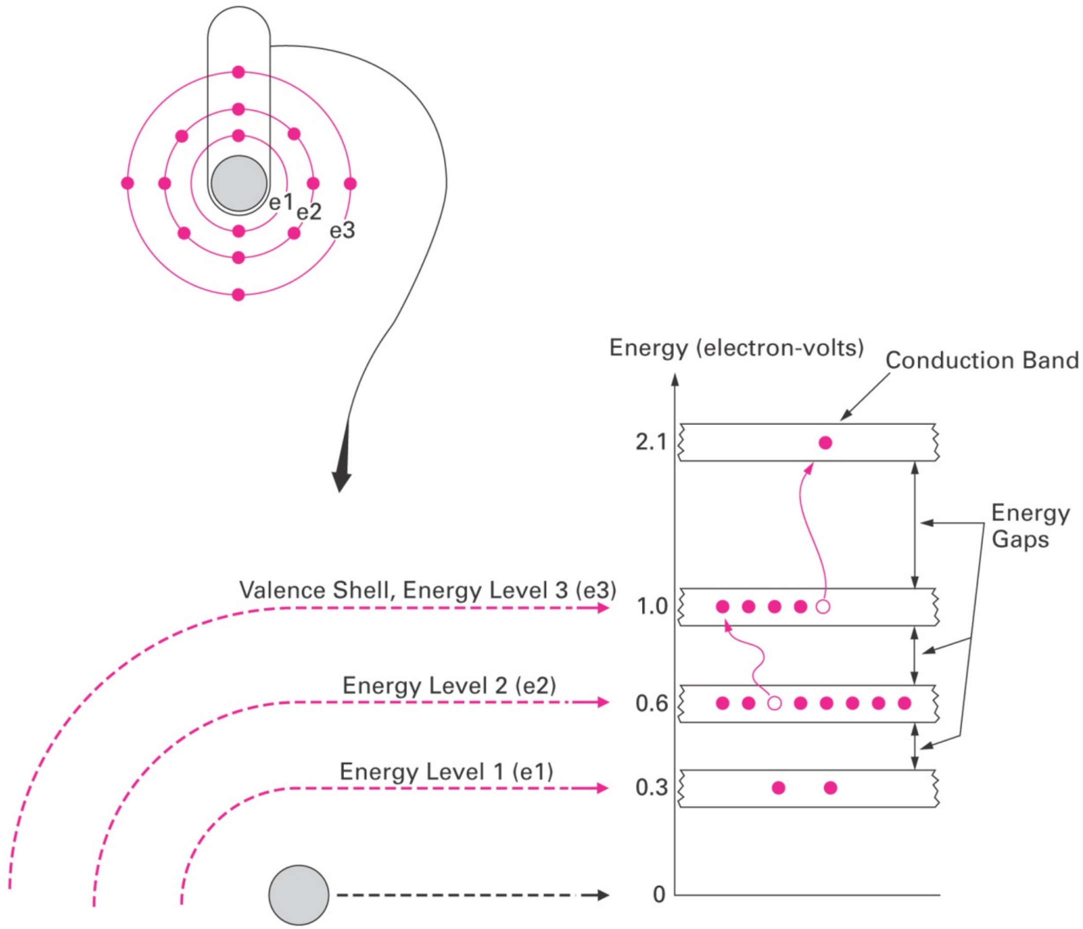
Diodes: A Semiconductor?

- Semiconductor (Semi-conductor!)
  - Such as silicon - at low temperatures semiconductors have the properties of an insulator, but at higher temperatures some electrons are free to move and so it takes on the properties of a conductor. It isn’t a very good conductor unless we dope the silicon (we will see this later)

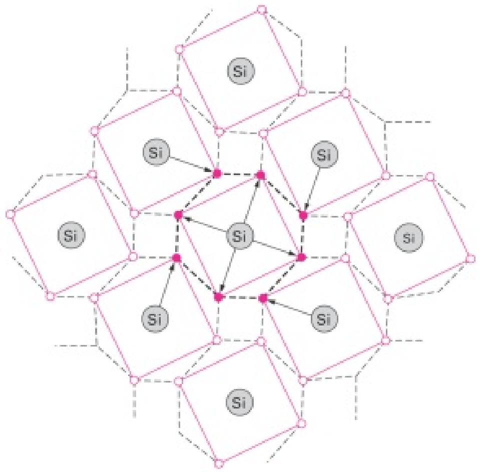
Diodes: Semiconductor atoms with their four valence shell electrons



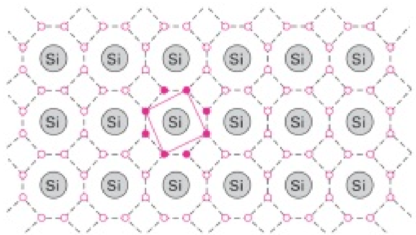
Diodes: An atom's orbital shell energy levels.



Diodes: Covalent bonding



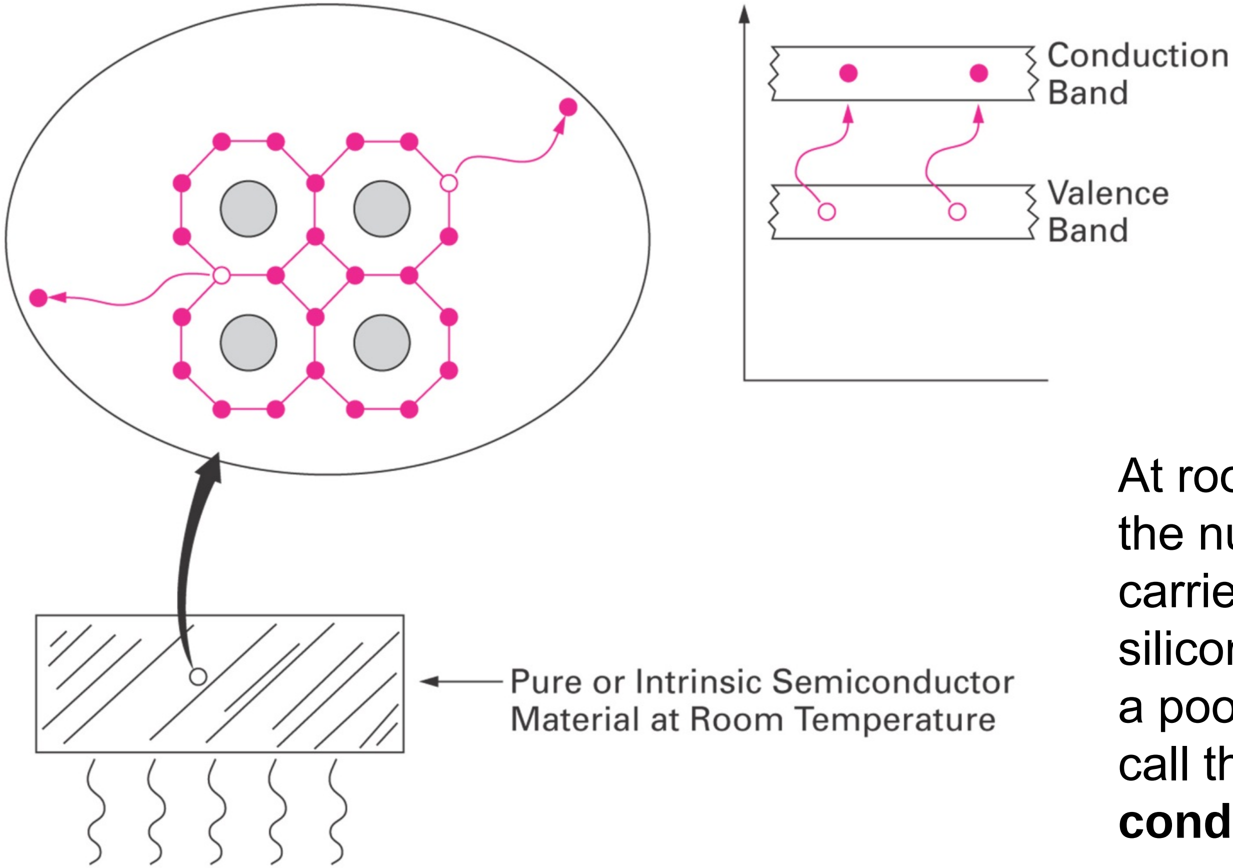
(a)



(b)

- Pure Silicon
  - Silicon is a **tetravalent** (4 valence electrons) material. Outermost electron shell can accommodate 8 electrons and the atom is stable when it is in this form.
- At low Temperatures:
  - Tight bonding means no electrons free to conduct current.
- At higher Temperatures:
  - Thermal vibration of the crystal lattice results in some of the bonds being broken, generating **free electrons** and leaving behind **holes**.

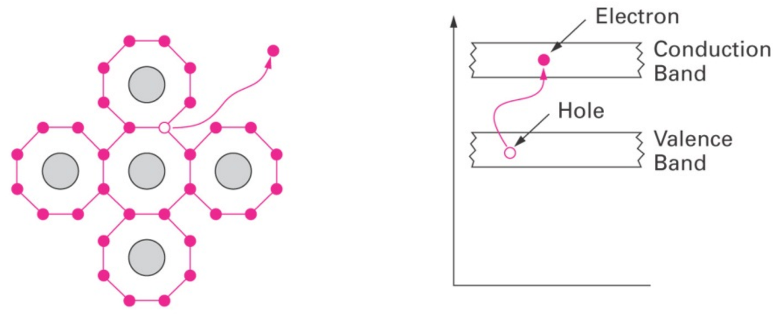
Diodes: Temperature effects on semiconductor materials



At room temperature the number of charge carriers present in pure silicon is small and it is a poor conductor – we call this **intrinsic conduction.**

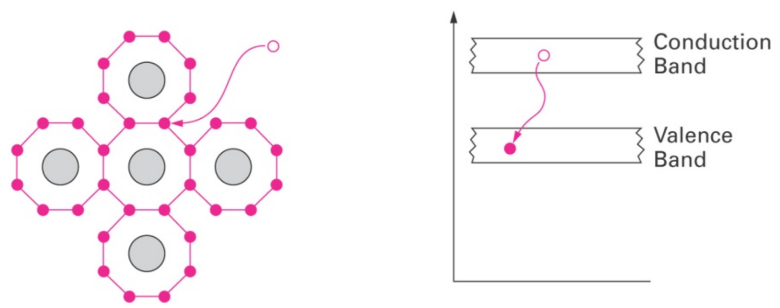
Diodes: Pure Silicon Valence band and conduction band actions.

- Higher Temperatures: Generating an Electron-Hole Pair.



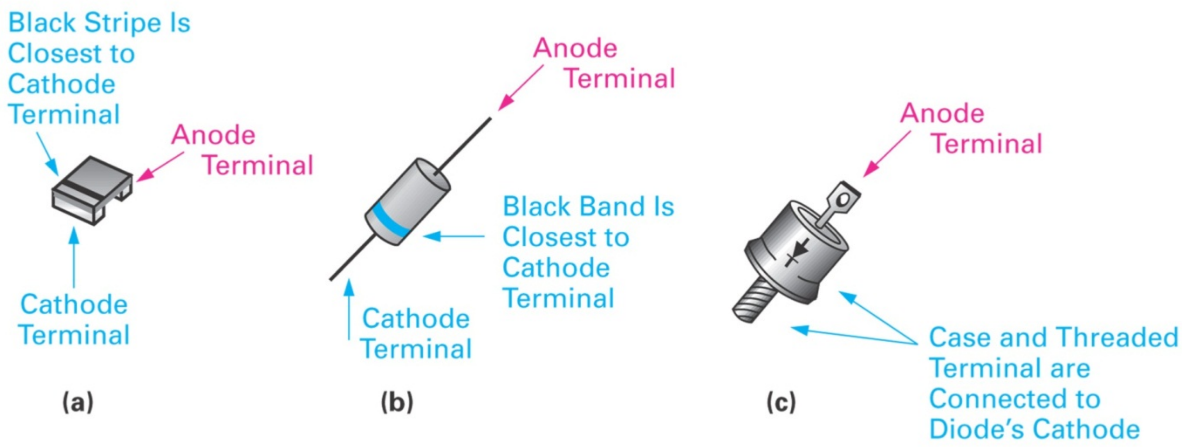
(a)

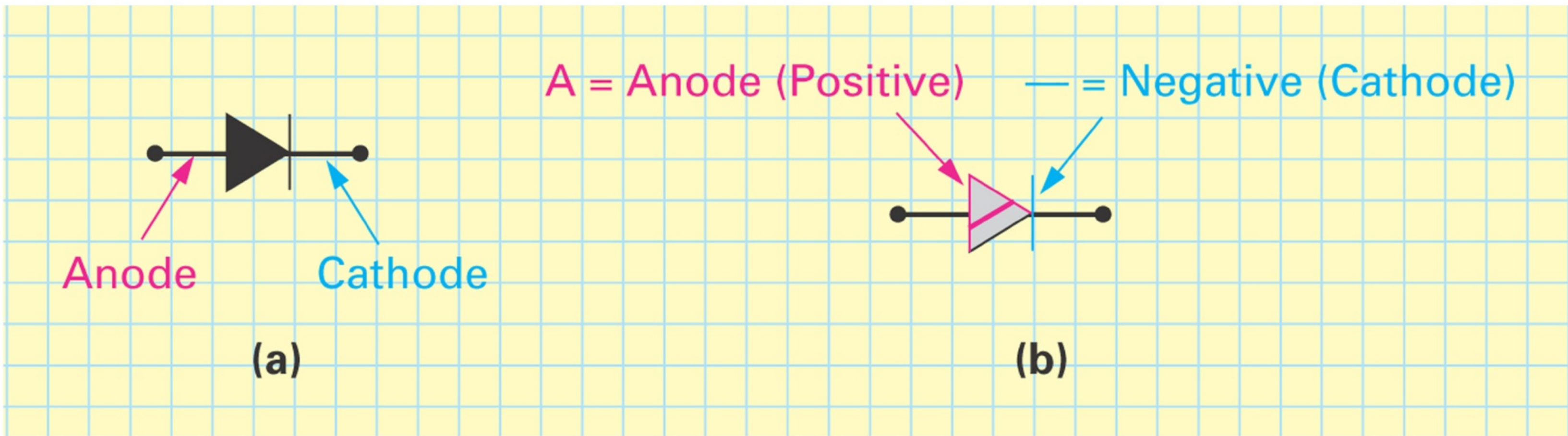
- Cooling Temperature again: Recombination



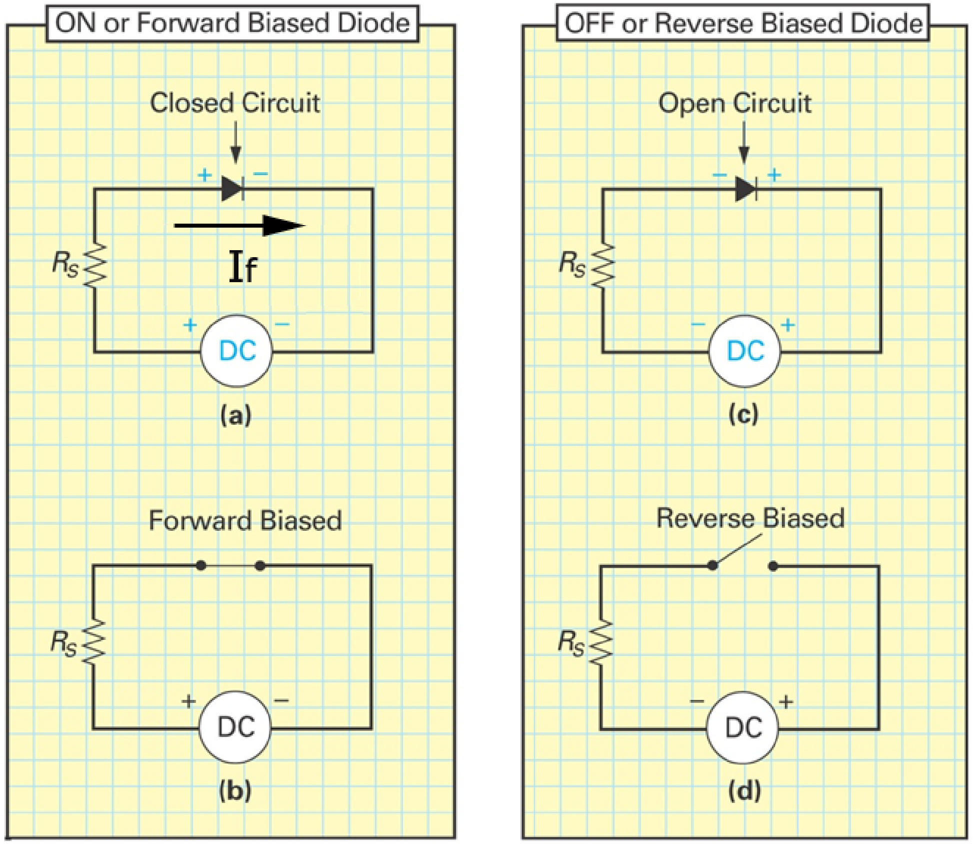
(b)

Diodes: Packaging & Schematic





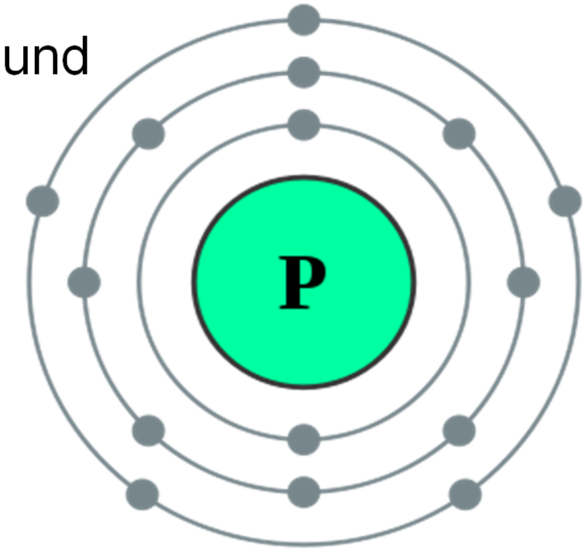
Diode: Operation



(a)(b) Forward Biased (ON) Diode. (c)(d) Reverse Biased (OFF) Diode

Diodes: Doping

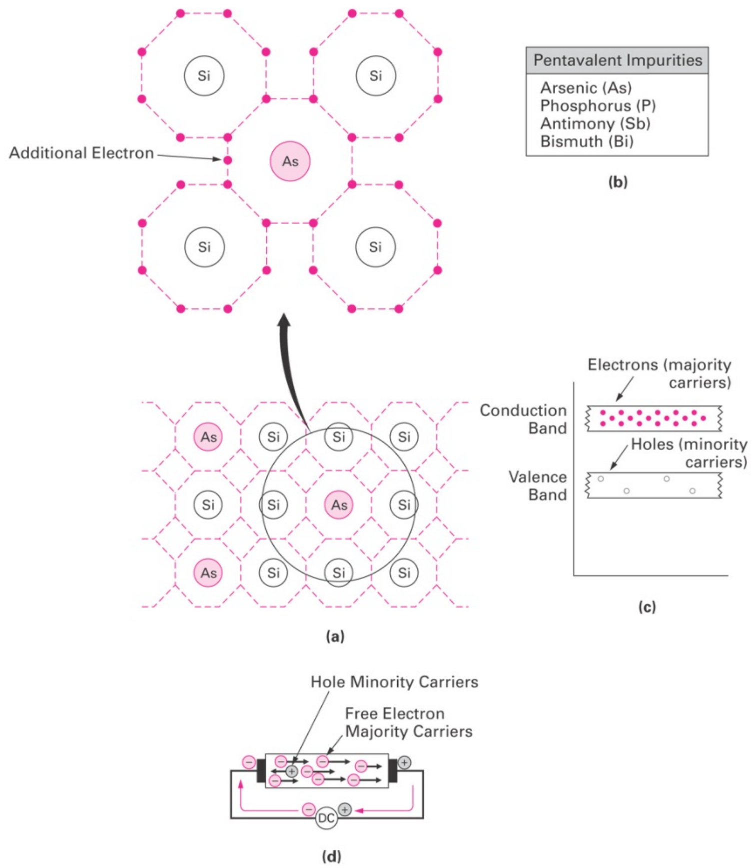
- Adding small amounts of impurities to silicon
  - Can hugely affect its properties – especially if it can fit within the crystal lattice but has a different number of valence electrons. For example: Phosphorus
  - Its fifth valence electron is very weakly bound
  - Has an excess of free electrons



  - Called **n-type semiconductors** as they have free negative charge carriers

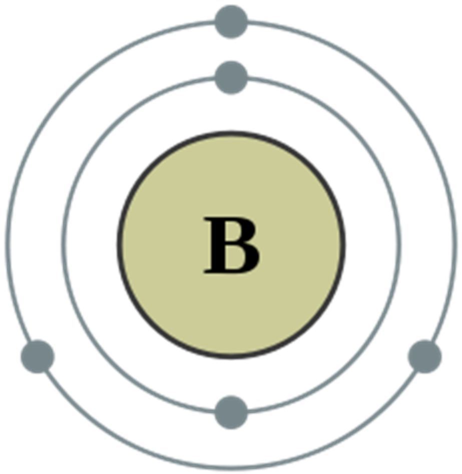
Diodes: An *n*-Type semiconductor material

- Negative Charge Carriers (n-Type)
- Adding pentavalent impurities to create an *n*-Type semiconductor material
- Has greater conductivity than pure silicon
- Majority charge carrier in n-type material is electrons



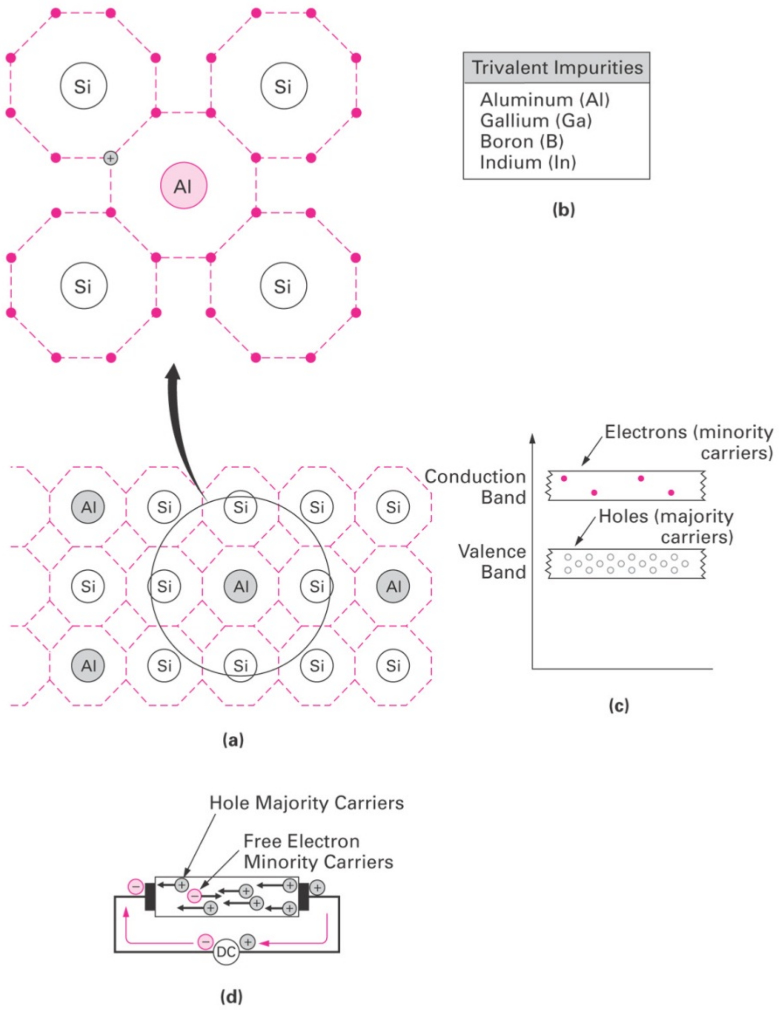
Diodes: p-Type Doping

- A ‘hole’ ?
  - If we add a trivalent doping such as Boron and it fits in the silicon lattice, then the absence of an electron in the outer shell leaves a **‘hole’**
  - This hole can move from atom to atom and acts like a positive charge carrier (just like an electron)
  - These are called **p-Type semiconductors** as they have free **positive charge carriers**

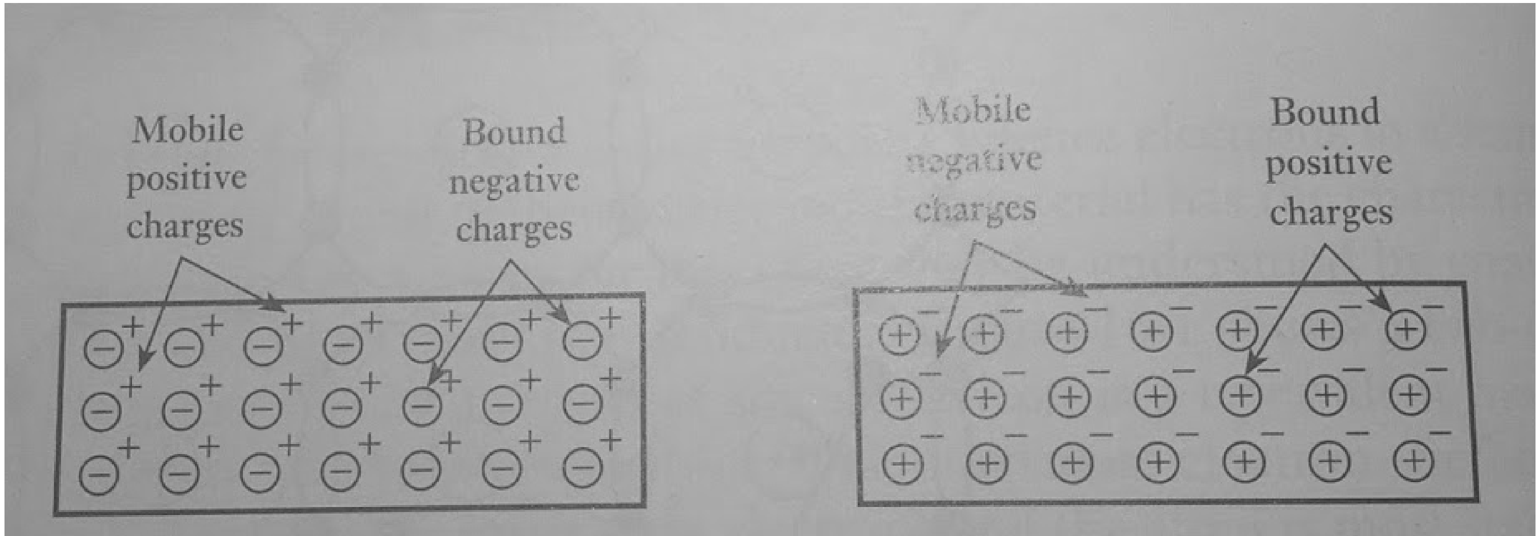


A *p*-Type semiconductor material

- Adding trivalent impurities to create a *p*-Type semiconductor material



Diode: Putting it together…

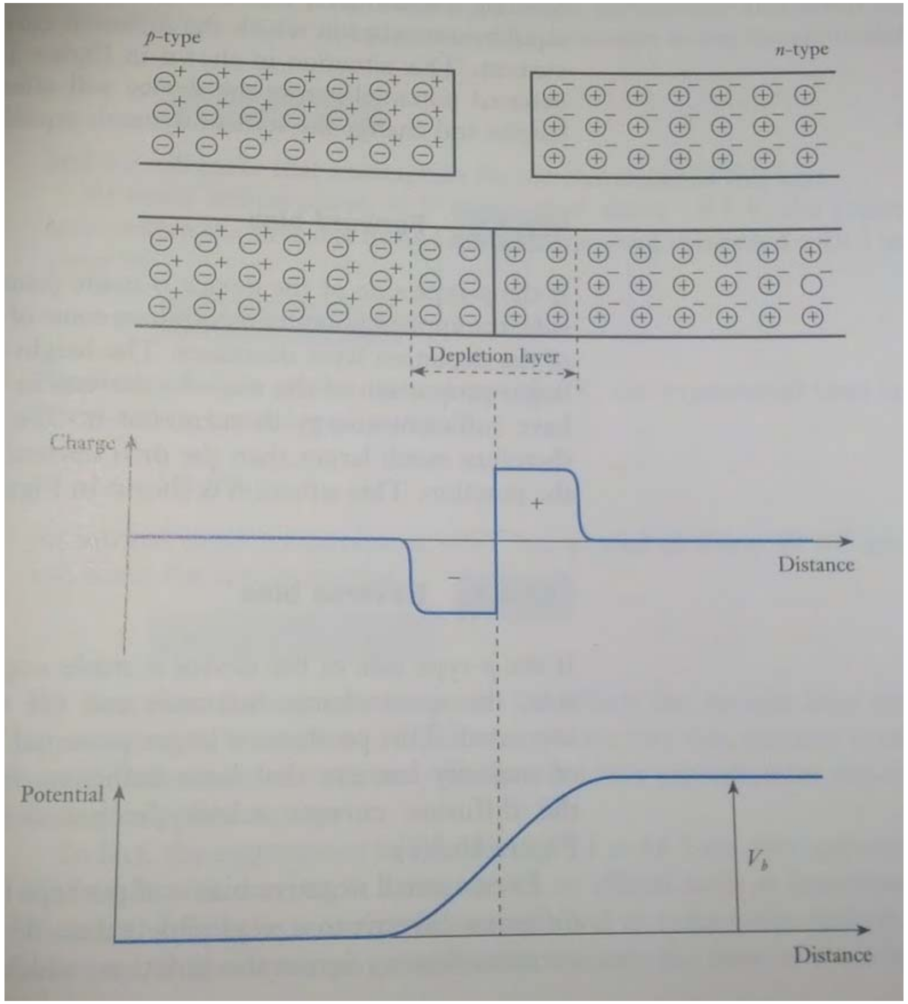


(a) *p*-type semiconductor (b) *n*-type semiconductor

Figure directly from: "Electronics A Systems Approach", 4th edition, by Neil Storey, Pearson (Prentice Hall)

Doped silicon is also electrically neutral (like non-doped silicon) – each mobile charge carrier is matched by an equal number of bound charge carriers of the opposite polarity. The dominant charge carriers (electrons in n-type, holes in p-type) are called **majority charge carriers**.

Diode: Putting it together…



However, when we join p-type and n-type doped silicon to create a pn or np junction:

- n-type electrons diffuse across the joint and recombine with free holes
- p-type holes diffuse to the n-type side and combine with free electrons
- We end up with a **depletion layer**, where there are few mobile charge carriers
- We now have a **potential barrier** that charge carriers must overcome to cross the barrier!

Figure directly from: “Electronics A Systems Approach”, 4th edition, by Neil Storey, Pearson (Prentice Hall)

Diode: With No Applied Voltage…

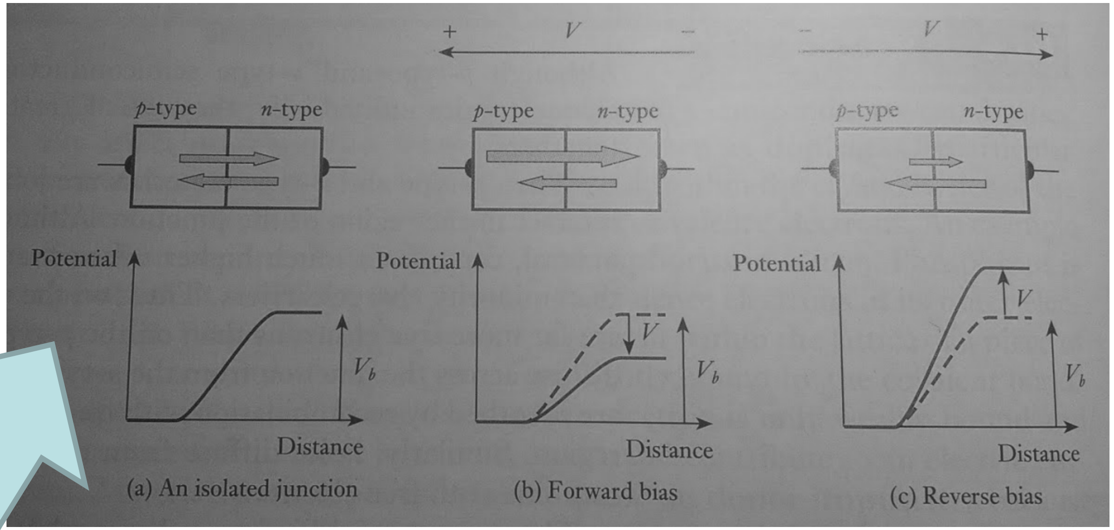


Figure directly from: “Electronics A Systems Approach”, 4th edition, by Neil Storey, Pearson (Prentice Hall)

- **In Isolation (no applied voltage)**, some majority charge carriers cross the depletion layer, creating a small **diffusion current** (moving from areas of high concentration to areas of low concentration without an electric field); however there is exactly equivalent movement of minority charge carriers in the opposite direction (a **drift current**). The drift current cancels out the diffusion current.

Diode: Forward Bias…

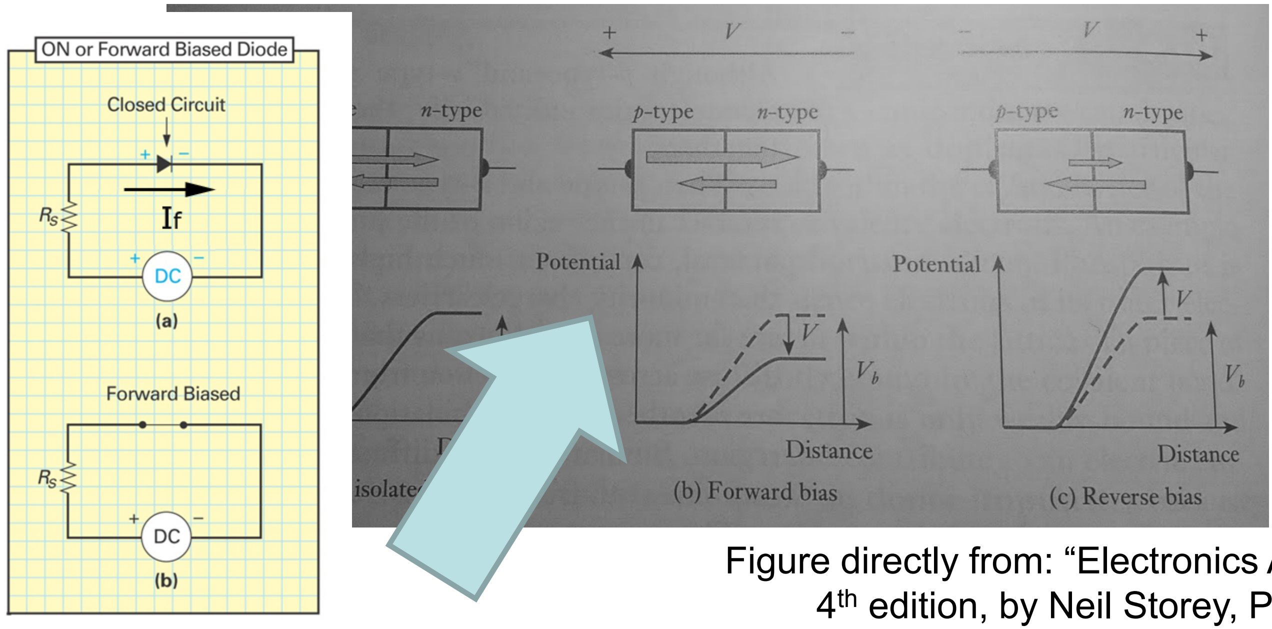
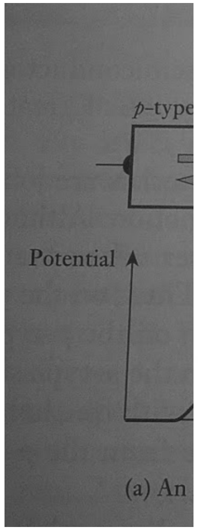
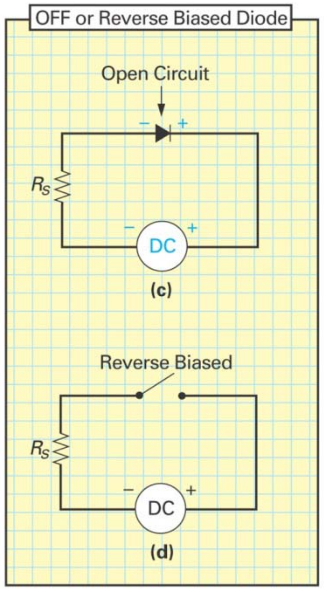


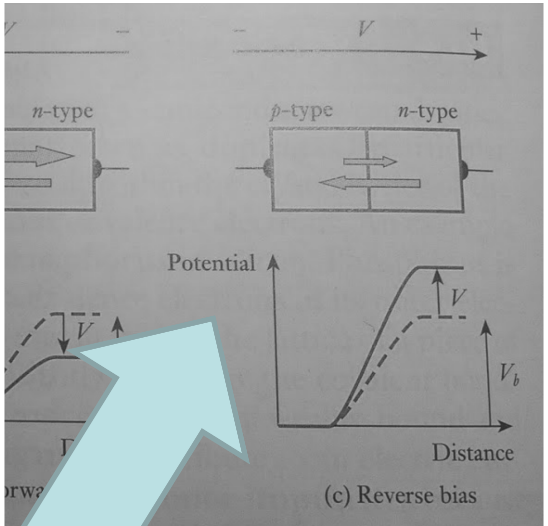
Figure directly from: "Electronics A Systems Approach", 4th edition, by Neil Storey, Pearson (Prentice Hall)

- In **Forward Bias** - the p-type side is made positive with respect to the n-type side and the **depletion layer shrinks.** The height of the potential barrier decreases and majority carriers can now cross the barrier.
- **Diffusion current > Drift current** and there is a net current flow.

Diode: Reverse Bias…







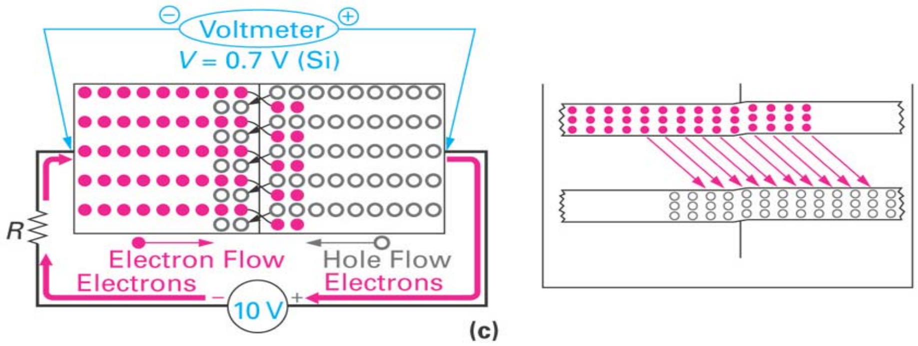
Fi[illegible] directly from: “Electronics A Systems Approach”, 4th edition, by Neil Storey, Pearson (Prentice Hall)

- **In Reverse Bias** - the p-type side is made negative with respect to the n-type side and the **depletion layer expands**. The height of the potential barrier increases and this reduces the number of majority charge carriers that can cross the junction.
- **Diffusion current < Drift current** and the drift current dominates; however, drift current is determined by the rate of thermal generation of minority carriers and at room temperature this is only a few nano-Amps (in small devices)

Forward Biasing a PN-Junction

Passing current through in a forward direction

- When device conducting (current flow n→p), threshold voltage appears as voltage drop across junction
  → e.g. Si junction, voltmeter = 0.7V
- N.B.
  V_{Th} for Si = 0.7V
  V_{Th} for Ger = 0.3V



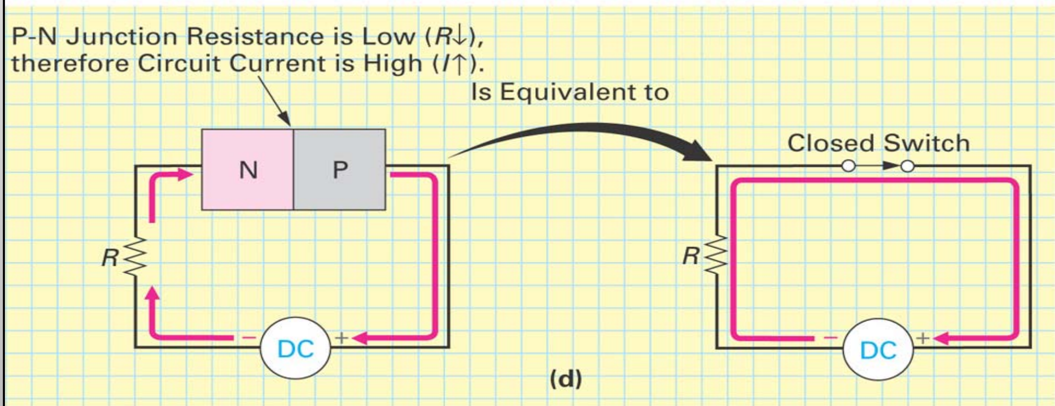
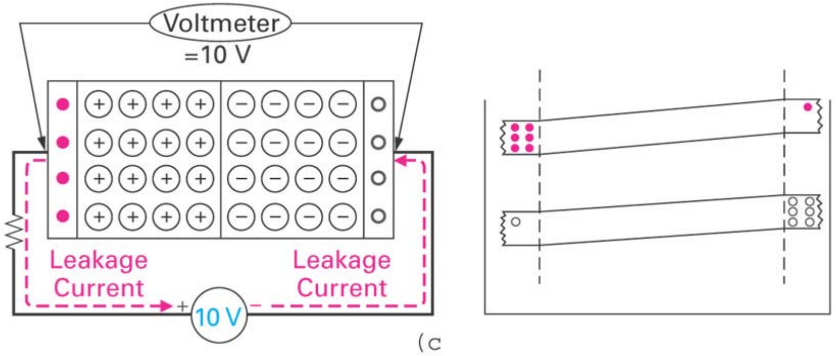


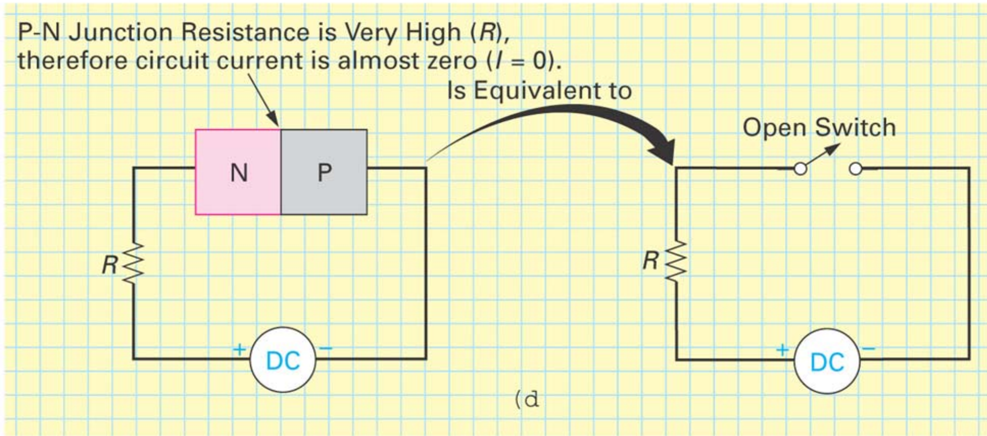
Fig (d)
- Forward-biased PN junction → acts as closed switch with small resistance
  → Switch opens again, when applied voltage drops < V_{Th} needed for n→p

Reverse Biasing a P-N Junction

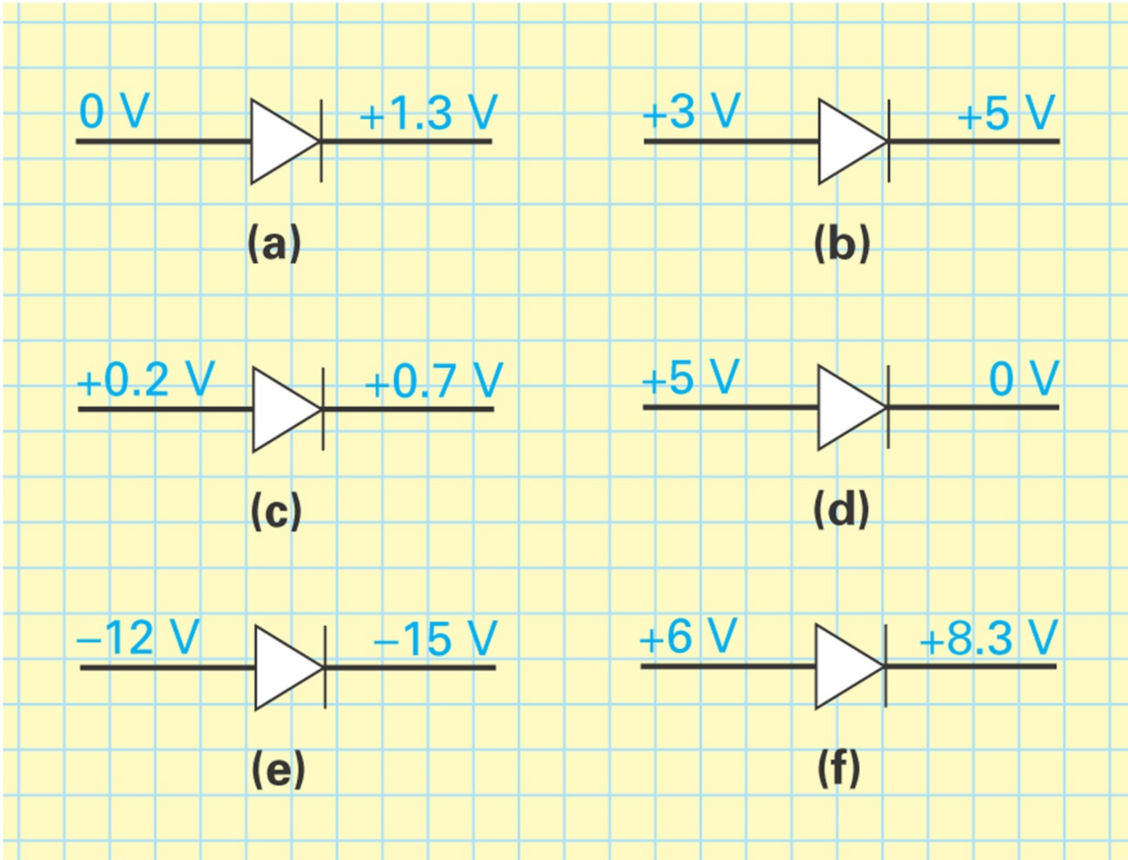
p-side made more negative with respect to the n-side

Reverse-biased PN Junction
- High resistance
- No current flow (leakage)
  => no voltage drop
  (e.g. voltmeter=10V)
- Essentially open switch

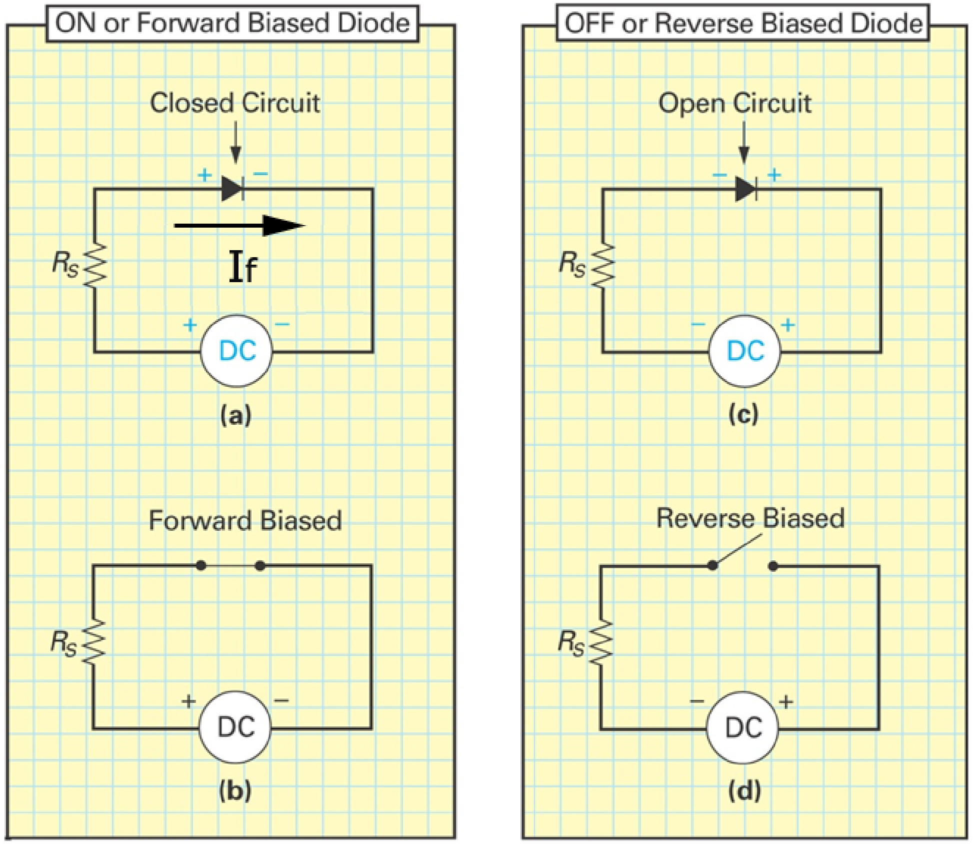




Biased pn-junctions – How biased?

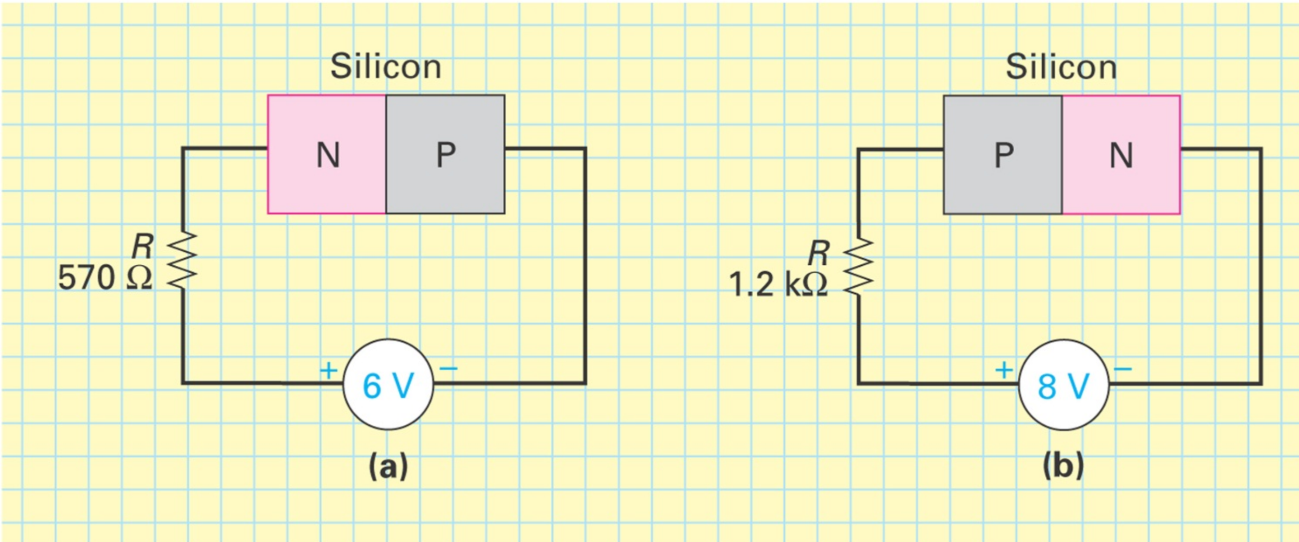


Diode: Operation Summary



(a)(b) Forward Biased (ON) Diode. (c)(d) Reverse Biased (OFF) Diode

Diode: Worked Examples

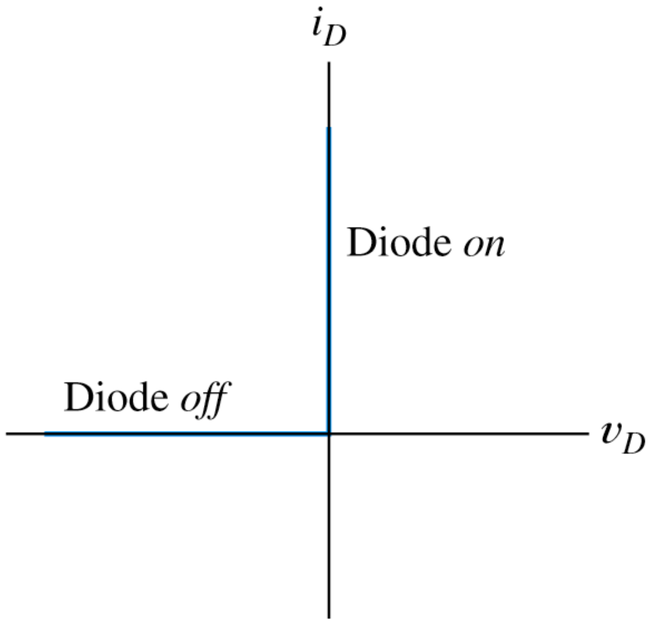


- Solution of (a) I=0mA and V=6V
- Solution of (b) I=(Vs-Vpn)/R

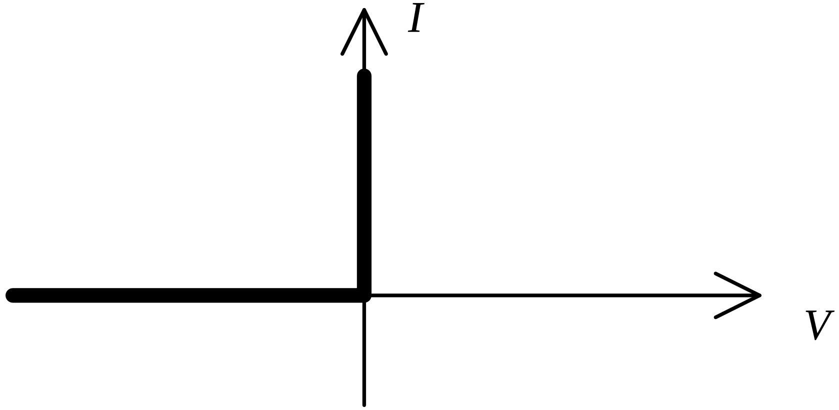
  I=6.08mA (i.e. V_R = 7.3V, taking Vpn=0.7V)

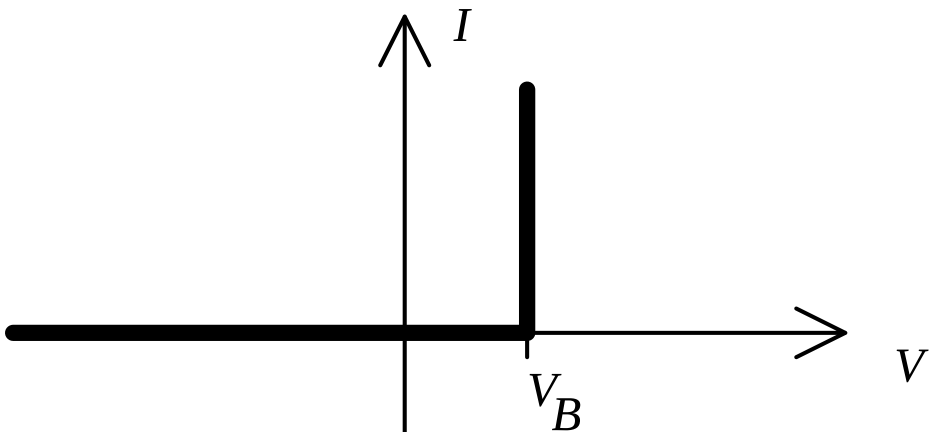
Diode: Simple Ideal-Diode Model

The ideal diode acts as a short circuit for forward currents and as an open circuit with reverse voltage applied.

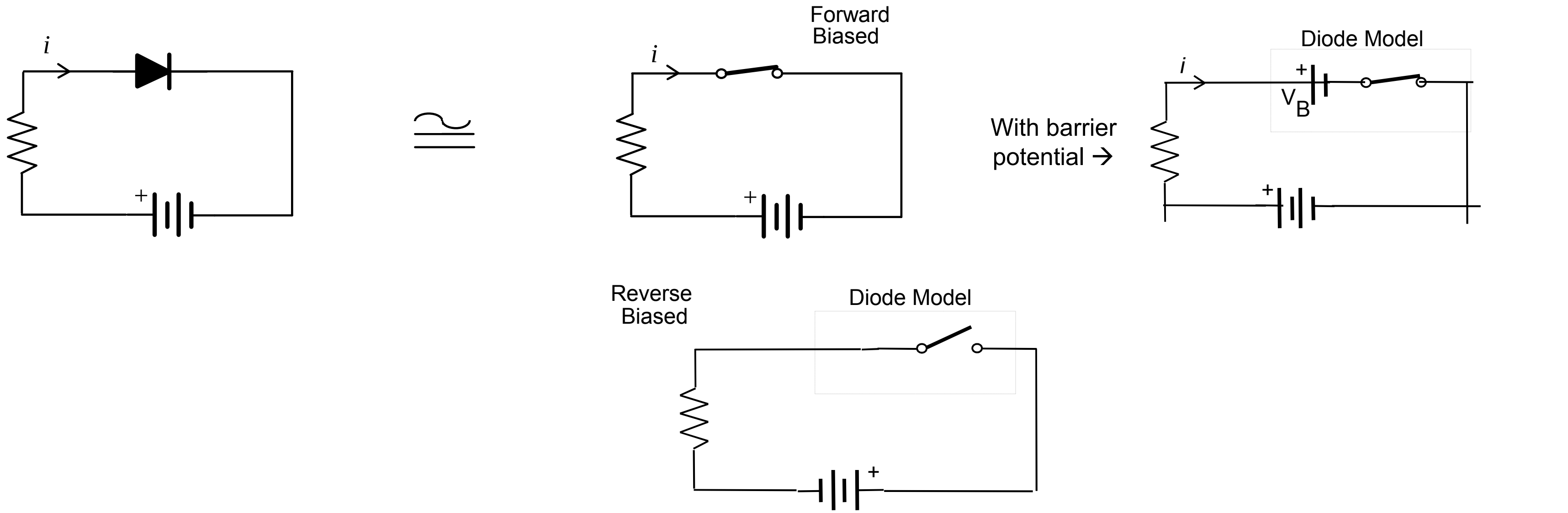


Diode: Forward Characteristic (Ideal-Diode)





including the barrier potential



Diode Voltage/Current Characteristic Summary

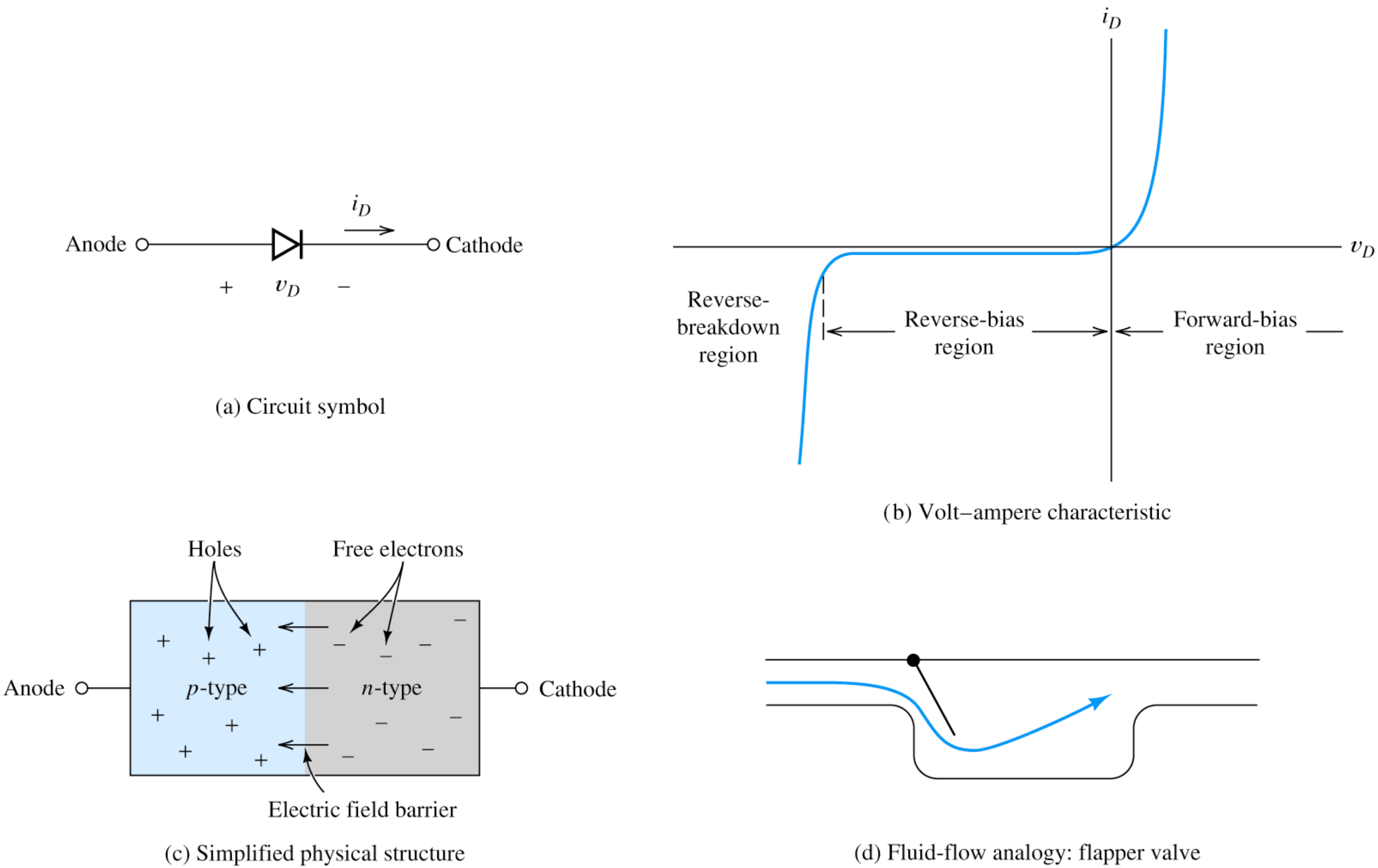


Figure 10.1 Semiconductor diode.

From: "Electrical Engineering: Principles and Applications, 3rd Ed. Allan R. Hambley, 2005 Pearson Education, Inc.

Diode: Voltage/Current characteristic

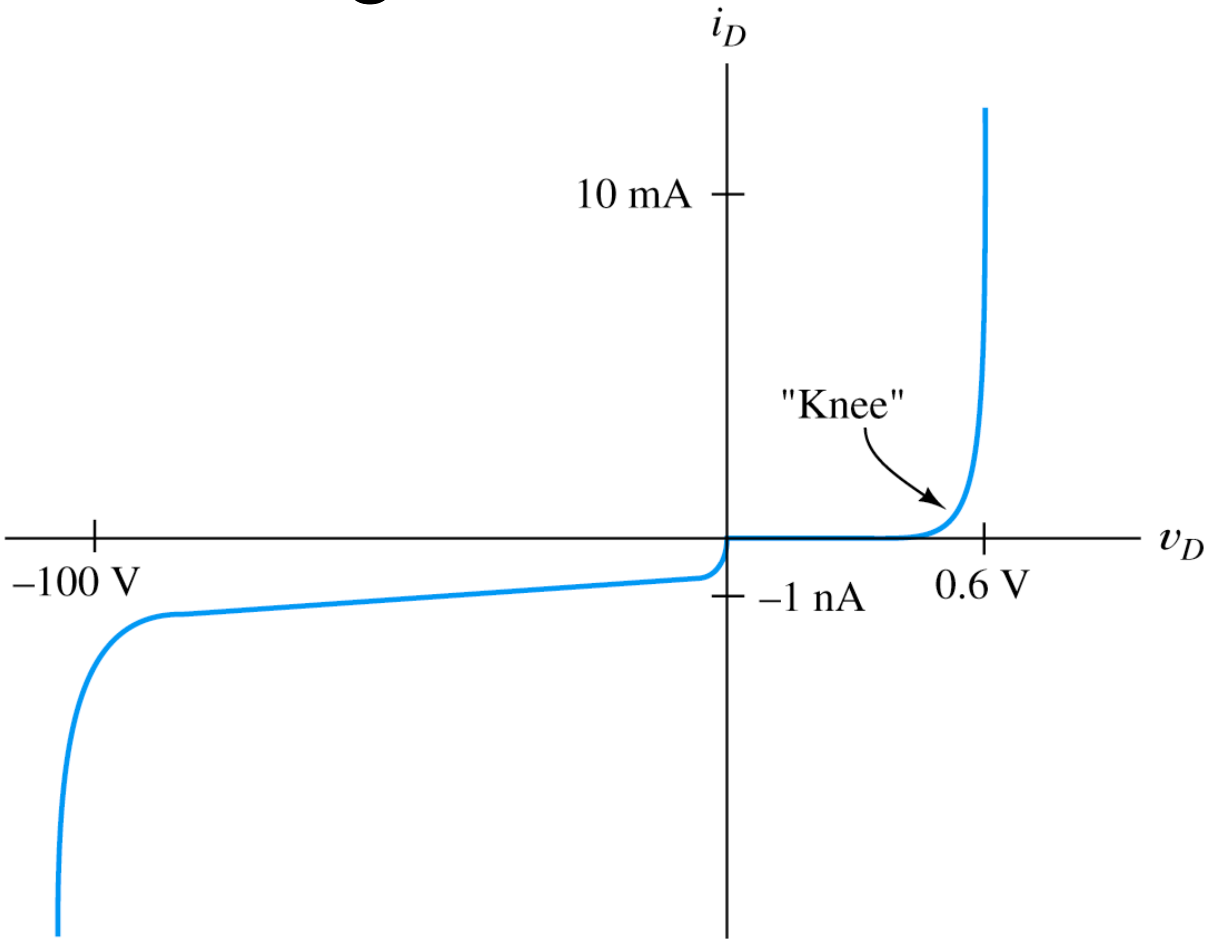
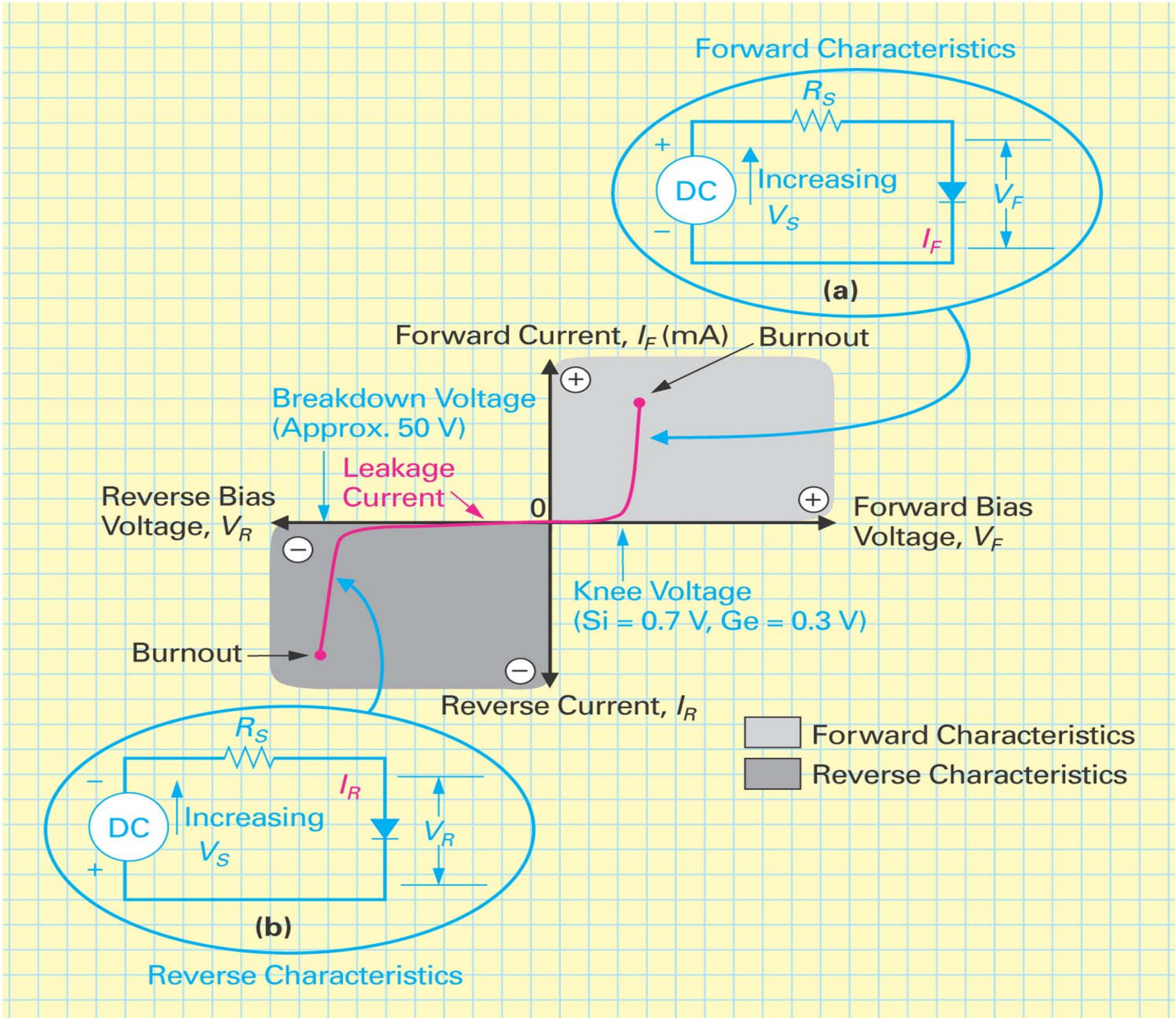


Figure 10.2 Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the change of scale for negative current and voltage.

From: "Electrical Engineering: Principles and Applications, 3rd Ed. Allan R. Hambley, 2005 Pearson Education, Inc.

Diode Voltage/Current characteristic



Diode: Forward/Reverse Current

We can approximately model current through a pn junction as:

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

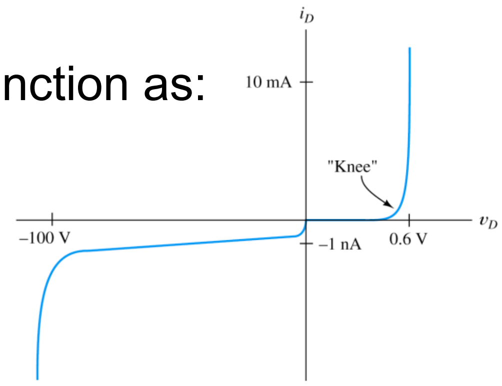


Figure 10.2 Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the change of scale for negative current and voltage.

This is known as the Shockley Equation, where,

I is the current through the junction
I_s is a constant called the reverse saturation current
e is the electronic charge
V is the applied voltage
ɳ (eta) is a constant in the range of 1-2 (for example: 1 for germanium and 1.3 for silicon)
k is Boltzmann's constant (1.38×10^{-23} J/K)
T is the absolute temperature

If we assume that ɳ = 1, then $I = I_s\left(e^{eV/kT} - 1\right)$

In Reverse bias: At room temperatures if *V* is less than -0.1 then the exponential is very small, so: $I = I_s(0 - 1) \Rightarrow I = -I_s$

In Forward bias: At room temperatures if *V* is greater than +0.1 then the exponential is large compared to -1, so: $I = I_s\left(e^{eV/kT}\right)$
At room temperatures e/kT = 40V^{-1} so we can say: $I = I_s\left(e^{40V}\right)$

Figure From: "Electrical Engineering: Principles and Applications, 3rd Ed. Allan R. Hambley, 2005 Pearson Education, Inc.

Diode Application: Half-Wave Rectifier

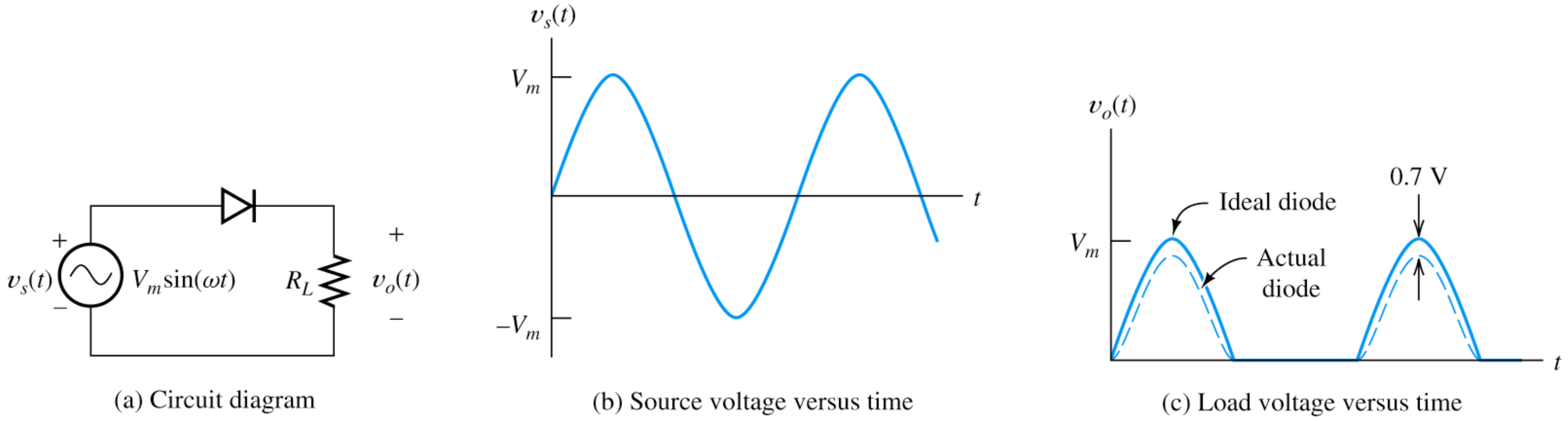


Figure 10.24 Half-wave rectifier with resistive load.

From: "Electrical Engineering: Principles and Applications, 3rd Ed. Allan R. Hambley, 2005 Pearson Education, Inc.

Diode Application: Half-Wave Rectifier (with smoothing)

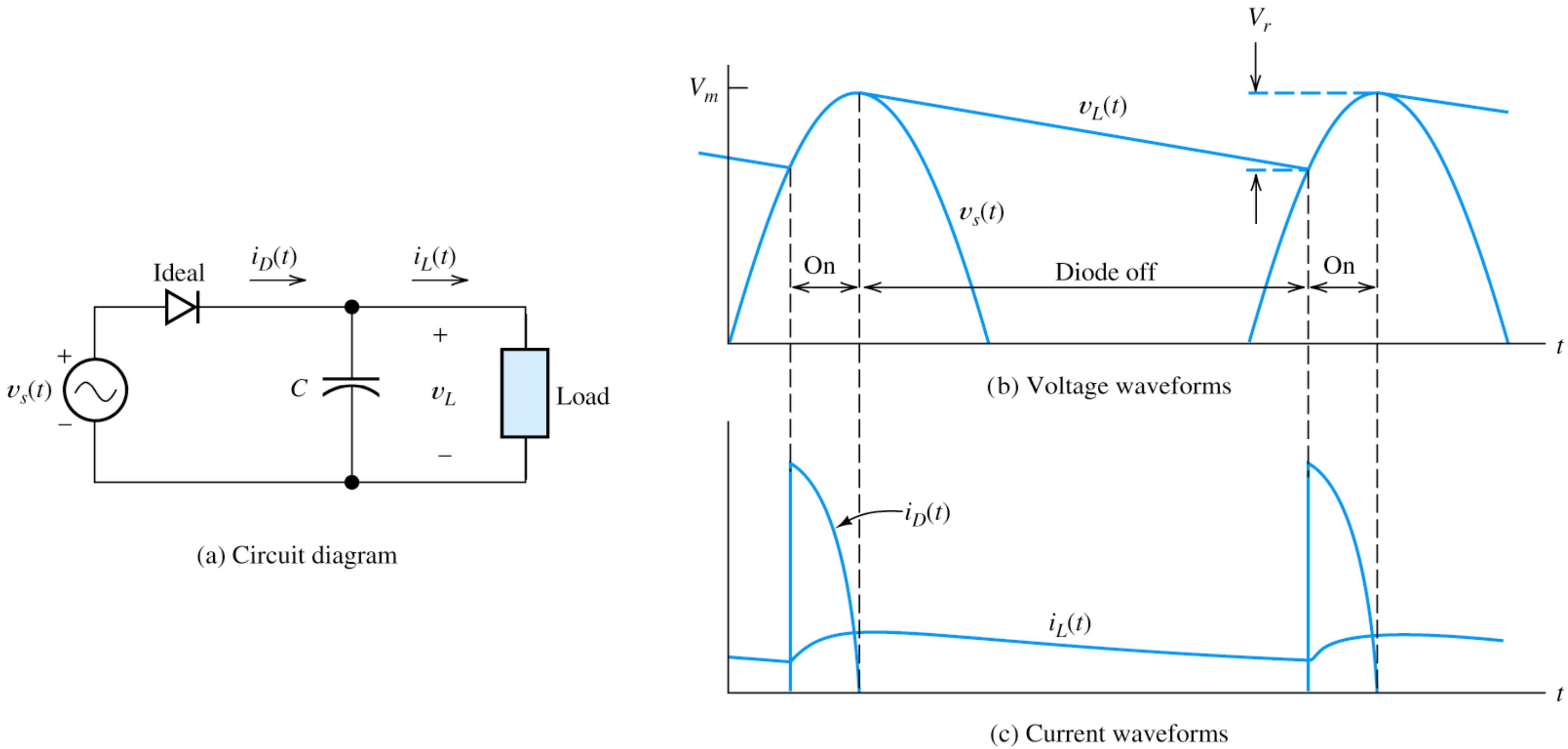


Figure 10.26 Half-wave rectifier with smoothing capacitor.

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Diode Application: Full-Wave Rectifier

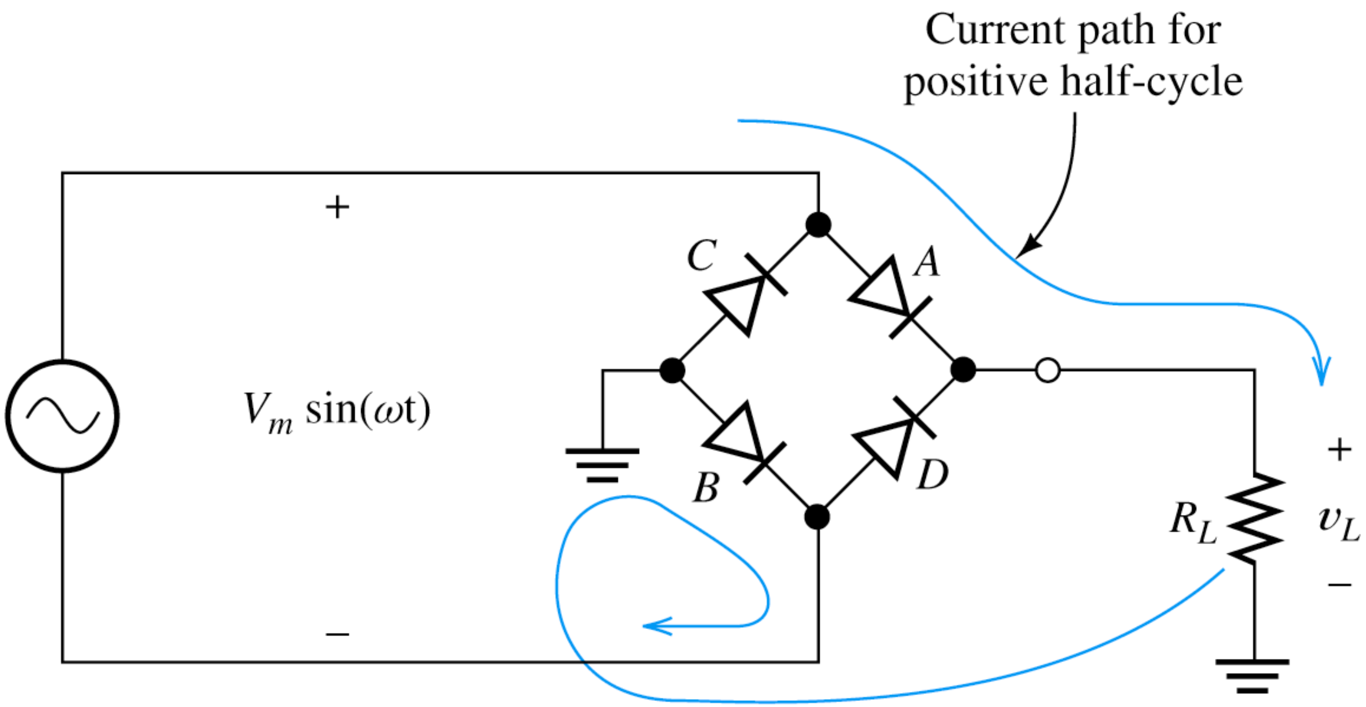

Figure 10.28 Diode-bridge full-wave rectifier.

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Load Line (Slide 1)

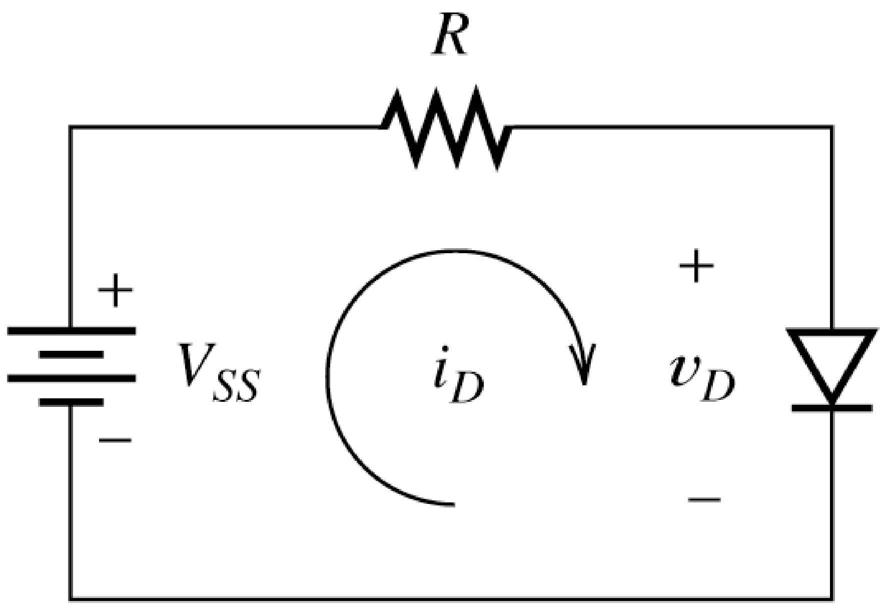


Figure 10.5 Circuit for load-line analysis.

$$V_{SS} = R.i_D + v_D$$

We know *R* and V_{SS}. What are i_D and v_D?

Load Line (Slide 2)

- $V_{SS} = R.i_D + v_D$.
- Need a second equation to solve for both i_D and v_D.
- Can use Shockley equation for this, or draw both on a graph.

Load Line (Slide 3)

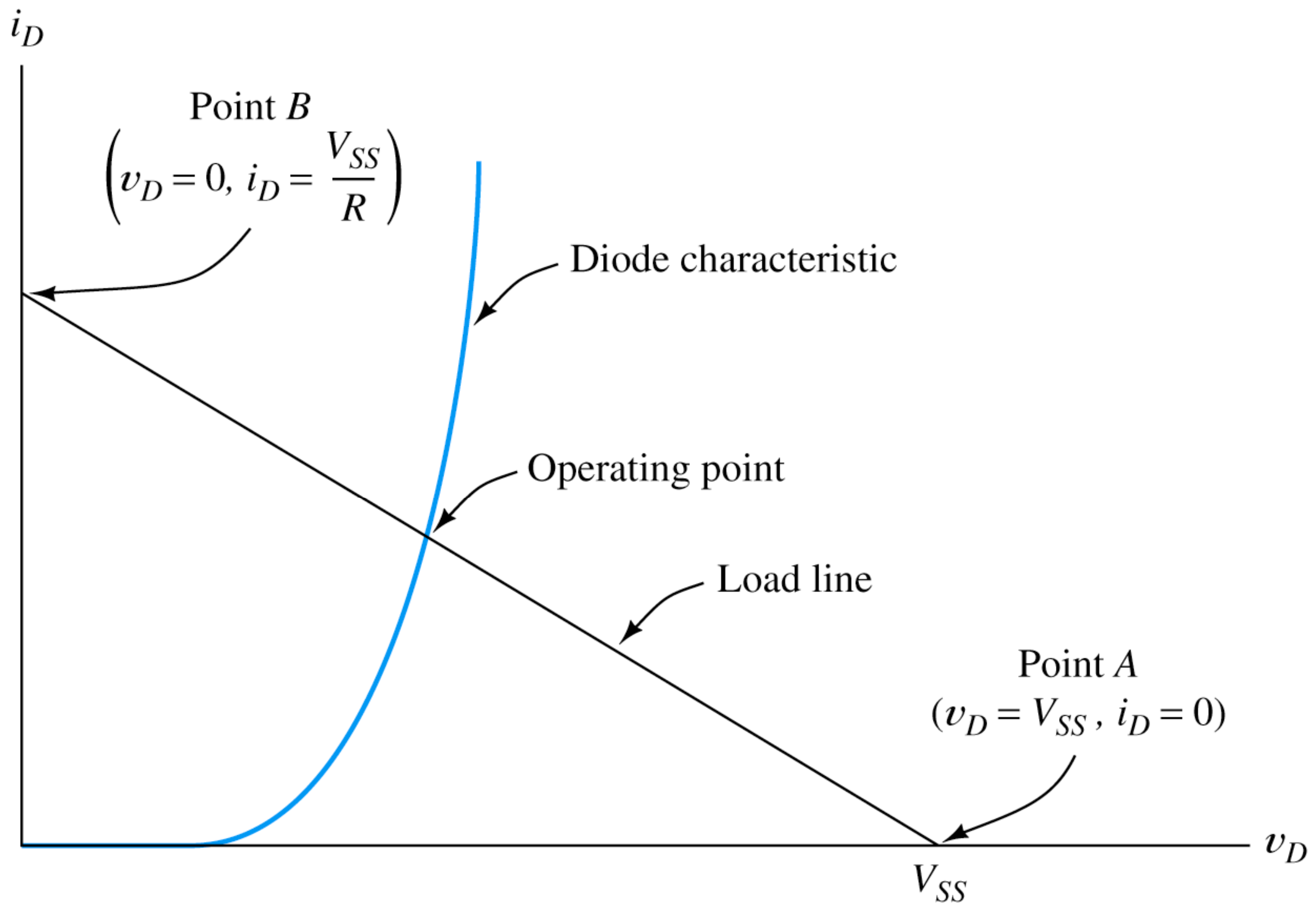


Figure 10.6 Load-line analysis of the circuit of Figure 10.5.

Load Line (Slide 4)

Example 10.1

V_{SS} = 2V, R = 1kΩ. Find i_D and v_D.

Find intercepts of load line with axes:

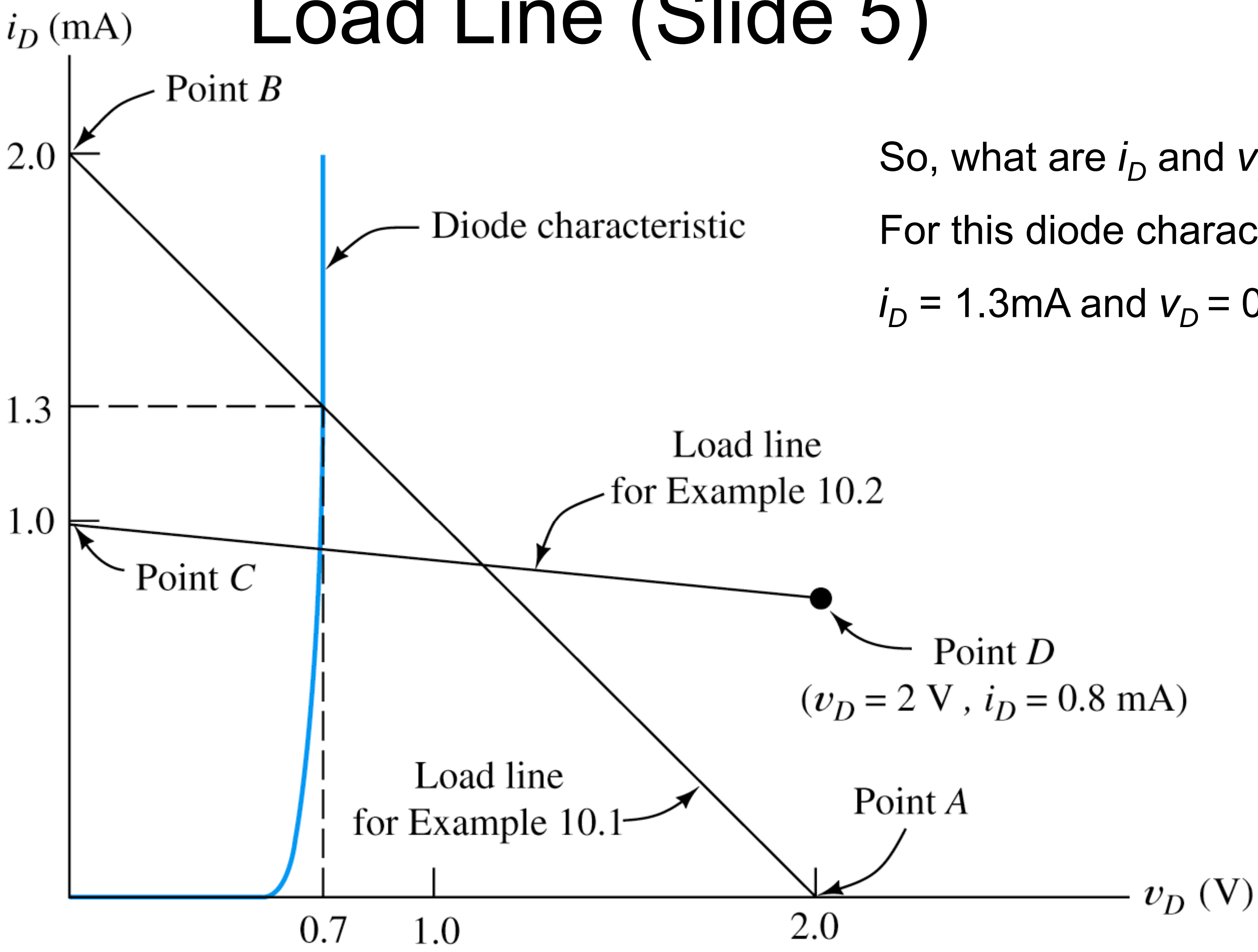
$V_{SS} = R.i_D + v_D$,

so $v_D = 0$

$\rightarrow i_D = V_{SS}/R$ = 2mA.

Similarly $i_D = 0 \rightarrow v_D = 2V$.

Load Line (Slide 5)



So, what are i_D and v_D?

For this diode characteristic:

i_D = 1.3mA and v_D = 0.7V

Figure 10.7 Load-line analysis for Examples 10.1 and 10.2.

Load Line (Slide 6)

Example 10.2

V_{SS} = 10V, R = 10kΩ. Find i_D and v_D.

Find intercepts of load line with axes:

$V_{SS} = R.i_D + v_D$,

so $v_D = 0$, and $i_D = V_{SS} / R$ = 1mA.

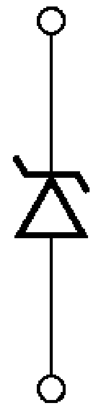
$i_D = 0 \rightarrow v_D = 10V$ *(off the page!)*

so try $v_D = 2$,

which gives i_D = 0.8mA.

Zener Diodes

Diodes that are intended to operate in the breakdown region are called **Zener diodes**.



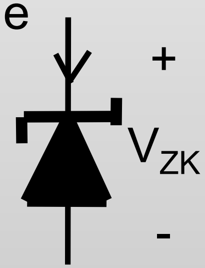
Zener diode

Recall for a regular diode:

- Reverse biased diode: No Current flow
  - → Unless $V_{RB} > V_{breakdown}$ (50V)
- Reverse breakdown
  - → Large reverse current
    - → If not limited, diode burnout!

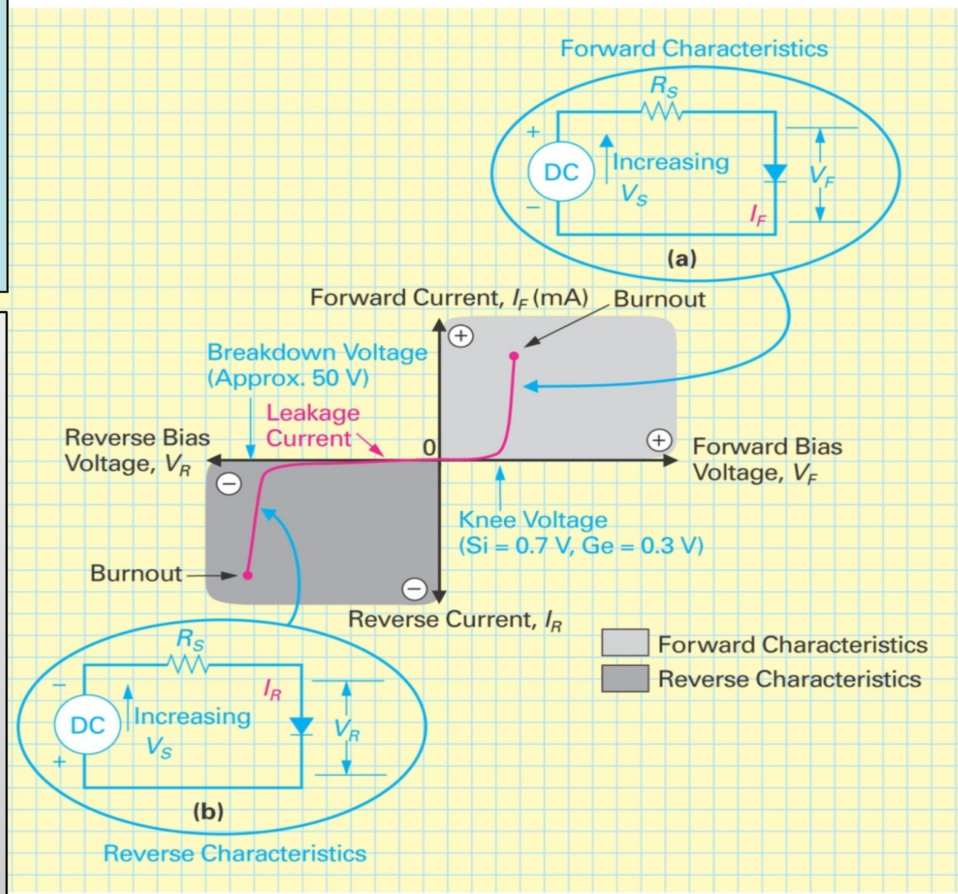
Now: A Zener Diode

- Same as regular Diode
- But designed to allow <u>controlled</u> reverse Current flow with reduced breakdown voltage ('Zener Voltage' - V_{ZK})
  - → E.g. V_{ZK} = 10V



- Reverse conducting mode
  - → V_{ZK} appears across device (remember V_{Th} appearing across forward conducting diode)
  - → Exploit constant voltage, e.g. voltage regulation

Regular Diode Voltage/Current Transfer Characteristic



Zener Diodes 1

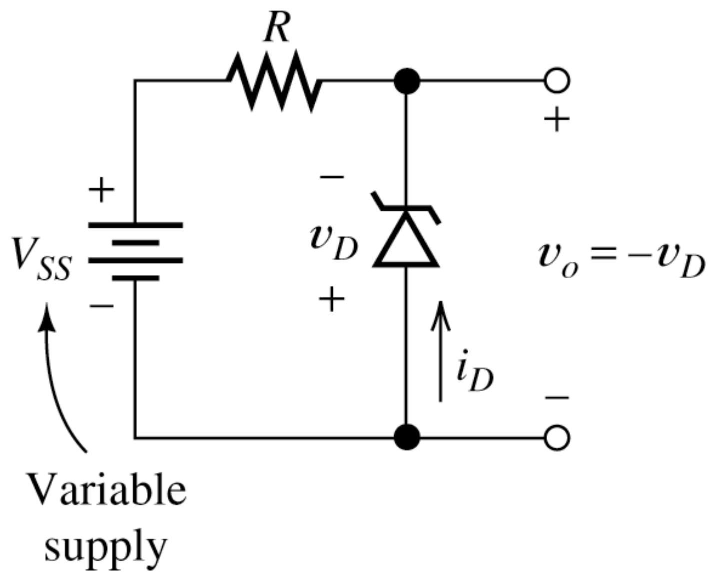


Figure 10.9 A simple regulator circuit that provides a nearly constant output voltage v_o from a variable supply voltage.

Zener Diodes 2

- $V_{SS} + R.i_D + v_D = 0$

(note that i_D is in anode-cathode direction.)

If we change V_{SS}, v_D remains nearly constant.

- *Acts as "voltage regulator".*

Zener Diodes 3

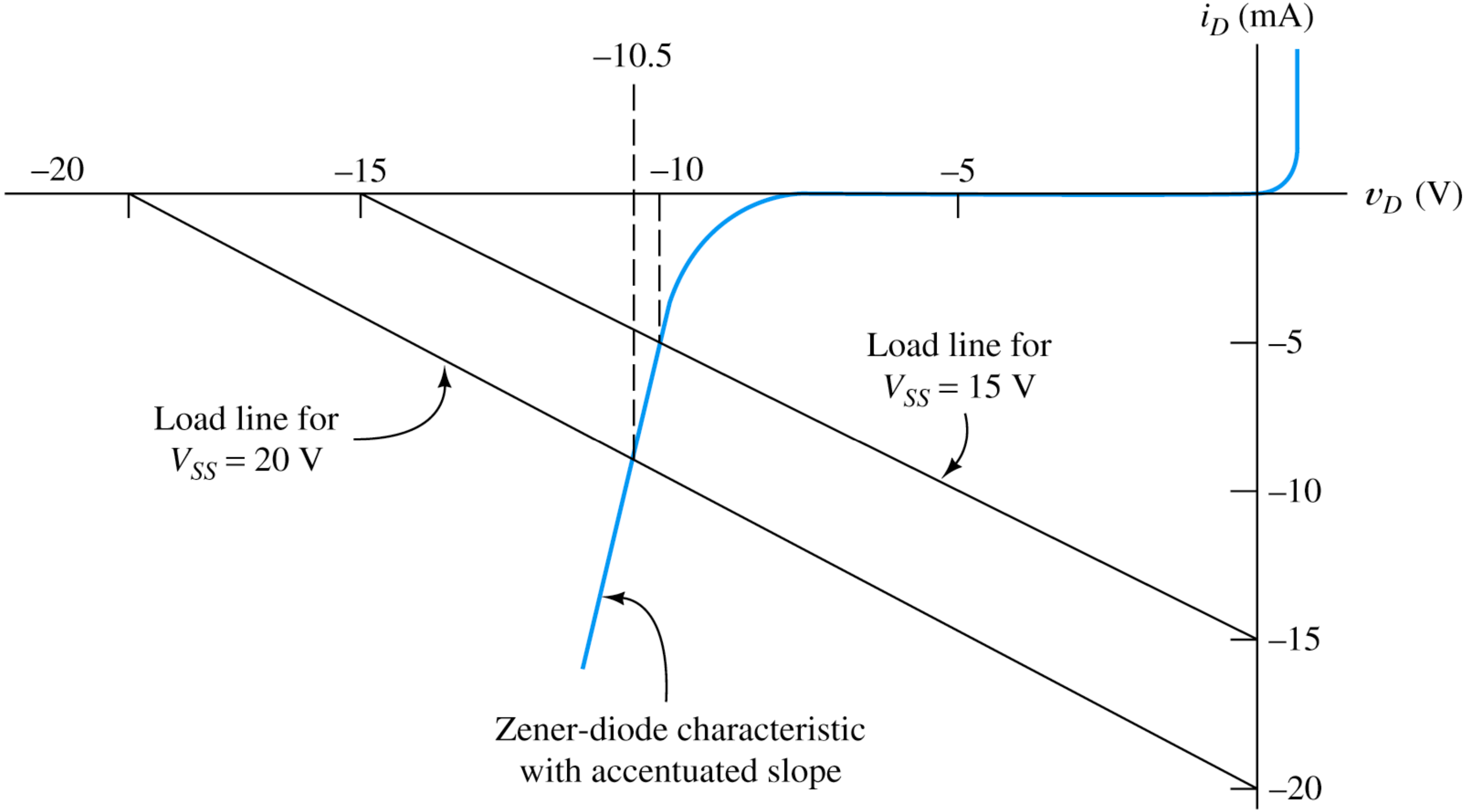


Figure 10.10 See Example 10.3.

Zener Diodes 4

Example 10.3

R = 1kΩ; find v_D *for* V_{SS} *= 15V and for* V_{SS} *= 20V.*

Although V_{SS} changes by 5V,
v_D changes by only 0.5V;

this is called **regulation**.