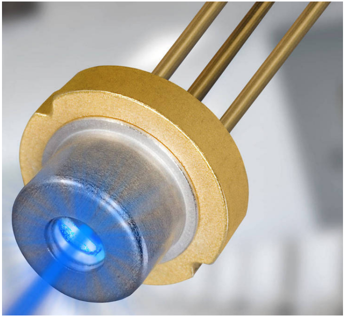
Chapter 9 - Condensed Matter Physics



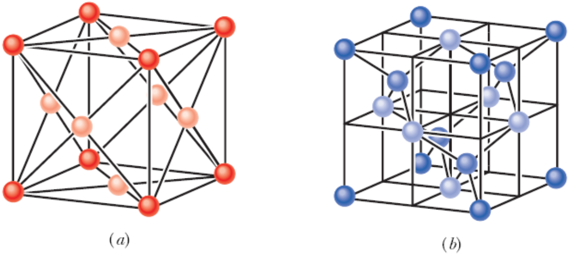
"Being virtually killed by a virtual laser in a virtual space is just as effective as the real thing, because you are as dead as you think you are."

-Douglas Adams, *Mostly Harmless*

David J. Starling
Penn State Hazleton
PHYS 214

Electrical Properties

Condensed Matter deals with the properties of materials made up of particles that adhere to each other.



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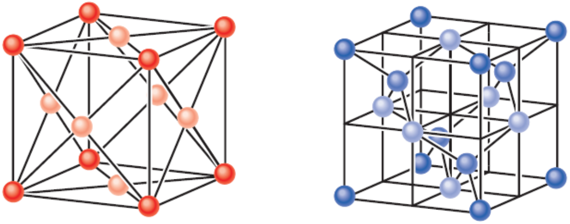

(a) (b)

Copper is face-centered cubic (a) and Carbon or Silicon is in a diamond lattice (b).

Electrical Properties

Measurable electrical properties can be understood by analyzing the lattice structure and valence electrons.

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- **number density of charge carriers:** measured via hall effect, n

Electrical Properties

Electrical properties of solids can vary by many orders of magnitude.

Some Electrical Properties of Two Materials[a]

Property	Unit	Material: Copper	Material: Silicon
Type of conductor		Metal	Semiconductor
Resistivity, ρ	$\Omega \cdot m$	2×10^{-8}	3×10^{3}
Temperature coefficient of resistivity, α	K^{-1}	$+4 \times 10^{-3}$	-70×10^{-3}
Number density of charge carriers, n	m^{-3}	9×10^{28}	1×10^{16}

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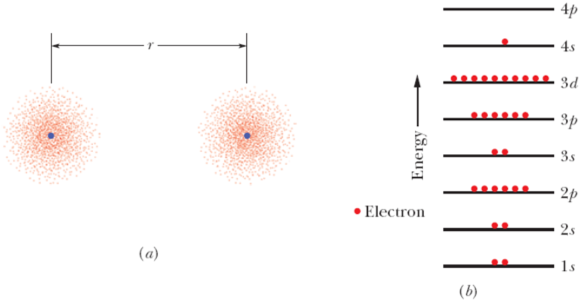
Copper and silicon are the two most common electrical components.

Energy Levels

When (e.g., copper) atoms come together, their electron clouds and their energy levels begin to overlap.



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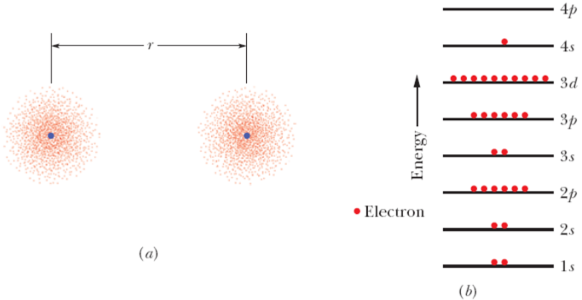
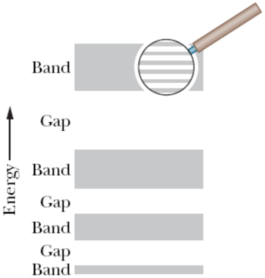


Due to the Pauli exclusion principle, the overlapping levels spread into "bands."

Energy Levels

These bands are just like energy levels, and can be occupied by electrons.



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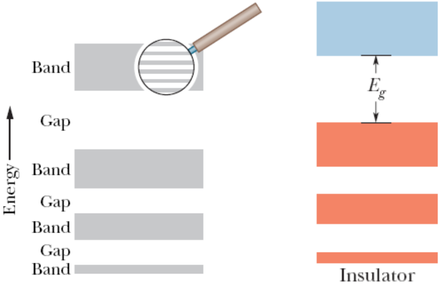
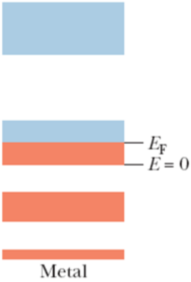


If the highest occupied band is full (red), and there is a large gap to an unoccupied band (blue), we have an insulator.

Energy Levels

If the occupied and unoccupied bands are close in energy, we have a conductor.



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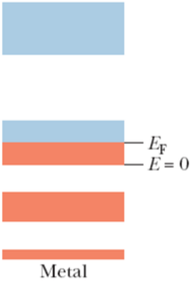
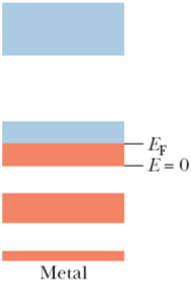


Here, $T = 0$ and we set $E = U + K = 0$ at the bottom of the highest occupied band.

Energy Levels

The Fermi level is defined as the highest occupied level, with Fermi energy E_F corresponding to kinetic energy of an electron at the Fermi level.



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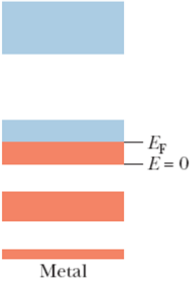

For copper, the Fermi energy is 7.0 eV with a speed of 1.6×10^6 m/s.

Energy Levels

Lecture Question 9.1

Which of the following features is the main difference between insulators and semiconductors?

(a) The energy gap between the conduction band and the valence band is larger for insulators.

(b) The energy gap between the conduction band and the valence band is smaller for insulators.

(c) The width of the valence band is larger for semiconductors.

(d) The width of the conduction band is larger for semiconductors.

(e) The width of the conduction band is smaller for semiconductors.

Occupied States

Key concepts for counting:

- M_{sam} - mass of the sample
- N - number of atoms in a sample
- V - volume of sample
- n - number of atoms per unit volume
- m - atomic mass, mass of one atom
- M - molar mass, mass of one mole of atoms
- $N_A = 6.02 \times 10^{23}$ atoms/mol

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Here's how they are connected:

$$n = \frac{N}{V} = \frac{1}{V} \times \left(\frac{M_{sam}}{m} \right) = \frac{1}{V} \times \left(\frac{M_{sam}}{M/N_A} \right)$$

Occupied States

To find the number of **conduction electrons** *in a metal we multiply by the number of valence electrons in each atom* N_V.

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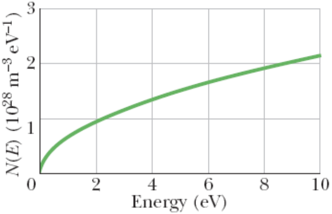
Copper, for example, has $N_V = 1$ valence electron.

Occupied States

In order to calculate the Fermi energy, we must know how the electrons are distributed.



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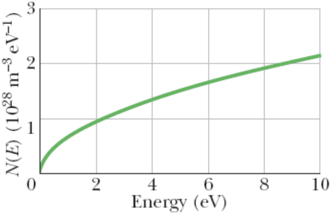

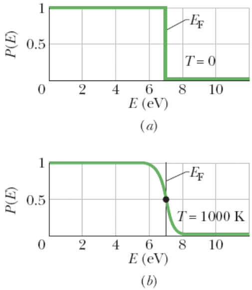

- The number of levels per volume per energy rises as a square root.
- The occupancy probability depends on temperature.

Occupied States

We can derive (but won't) the equations for these curves.

$$
\begin{aligned}
N(E) &= \frac{8\sqrt{2}\pi m^{3/2}}{h^3}\sqrt{E} \\
P(E) &= \frac{1}{e^{(E-E_F)/kT}+1}
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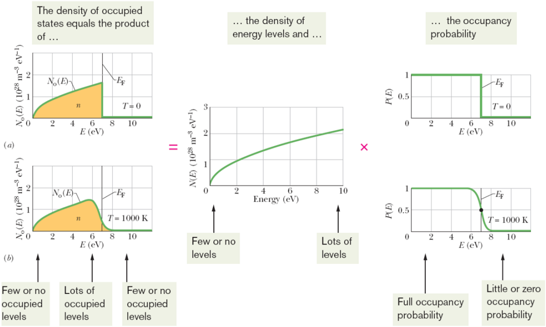

Occupied States

Using the measurable occupied states n, electron mass m and constants, we can find the Fermi energy (at T = 0).

$$n = \int_0^{E_F} N_0(E) dE$$

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Occupied States

Lecture Question 9.2

Determine how many conduction electrons there are in a sample of pure sodium occupying 1.0×10^5 m^3. Each sodium atom contributes one electron.

(a) 7.9×10^{22}

(b) 2.5×10^{23}

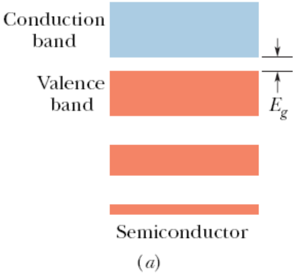
(c) 4.2×10^{23}

(d) 6.4×10^{23}

(e) 1.0×10^{24}

Semiconductors

Semiconductors are similar to conductors, but the bandgap is considerably smaller.



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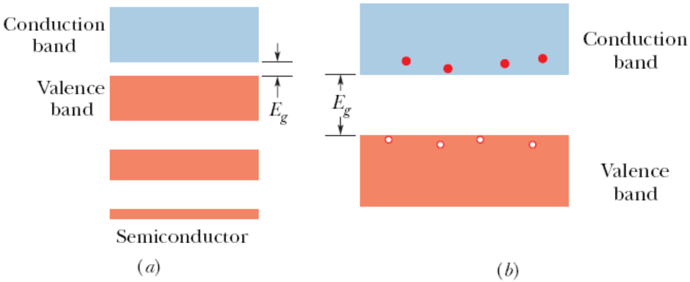
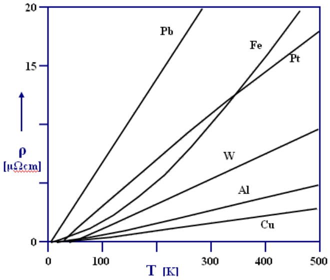


Thermal agitation is enough to knock some electrons into the **conduction band**. **Holes** are left behind.

Semiconductors

Metals tend to have higher resistivity at higher temperatures.

$$\alpha = \frac{1}{\rho}\frac{d\rho}{dT} > 0$$



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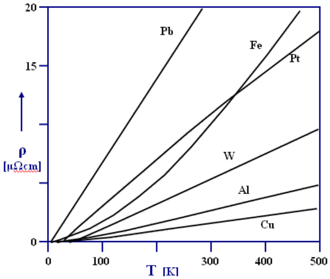
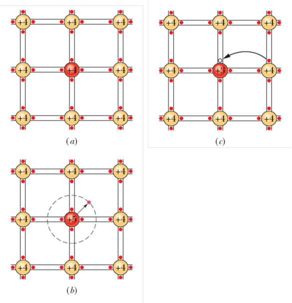


For semiconductors, this is not true; higher temperature equates to more charge carriers. So $\alpha < 0$.

Semiconductors

Semiconductors are typically **doped** *with impurities to enhance their conductivity.*



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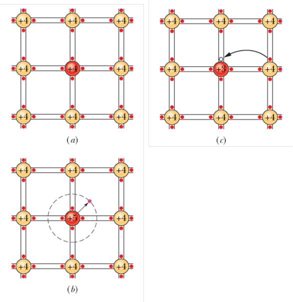

- **n-type**: a pentavalent (donor) atom is added (e.g., phosphorus), the extra electron can migrate.

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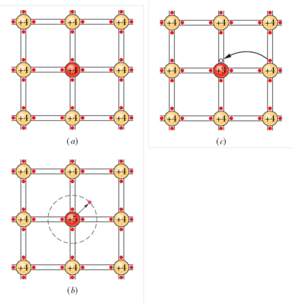
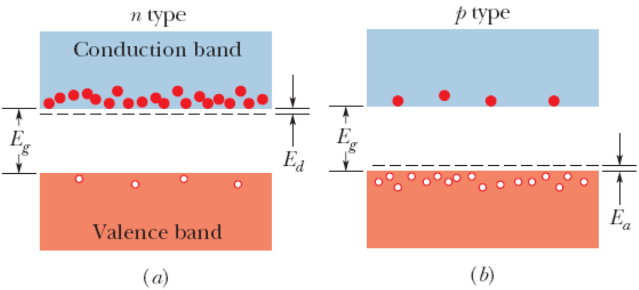


- **n-type**: a pentavalent (donor) atom is added (e.g., phosphorus), the extra electron can migrate.
- **p-type**: a trivalent (acceptor) atom is added (e.g., aluminum), the hole can migrate

Semiconductors

The dopant introduces a new energy level near the band structure of the semiconductor material.



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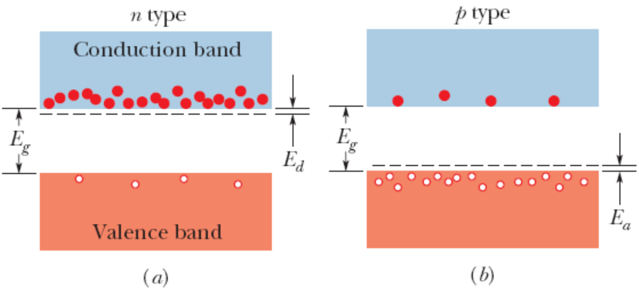

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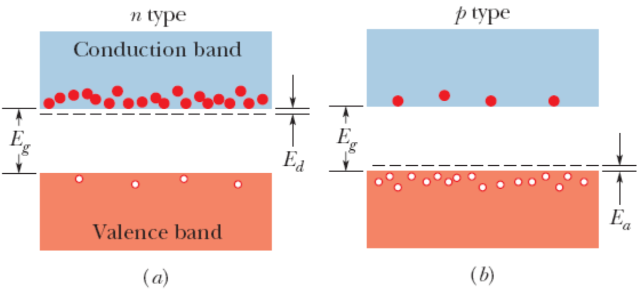
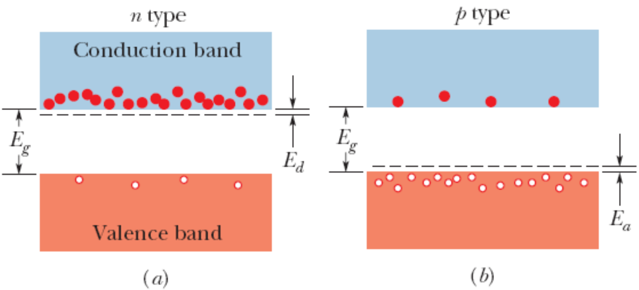


- **n-type**: electrons jump from dashed level of donor atom
- **p-type**: electrons jump from semiconductor to acceptor atom

Semiconductors

Currents flows differently in n- and p-type semiconductors.



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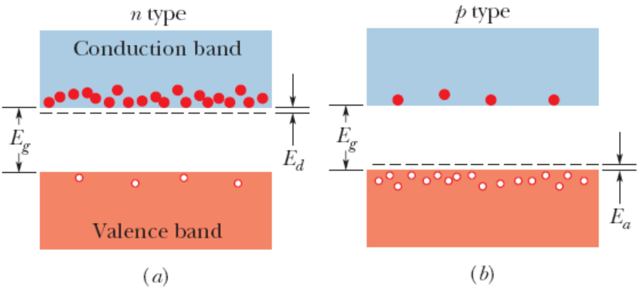

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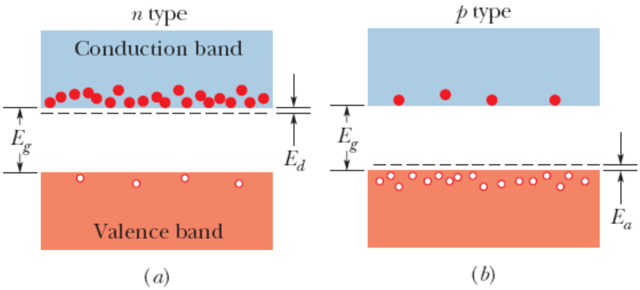


- **n-type**: electrons are the majority carriers
- **p-type**: holes are the majority carriers

Semiconductors

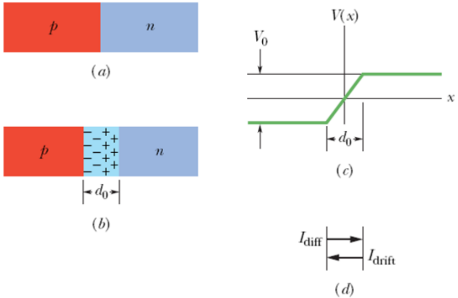
How do n- and p-type semiconductors compare?

Properties of Two Doped Semiconductors

Property	Type of Semiconductor: *n*	Type of Semiconductor: *p*
Matrix material	Silicon	Silicon
Matrix nuclear charge	$+14e$	$+14e$
Matrix energy gap	1.2 eV	1.2 eV
Dopant	Phosphorus	Aluminum
Type of dopant	Donor	Acceptor
Majority carriers	Electrons	Holes
Minority carriers	Holes	Electrons
Dopant energy gap	$E_d = 0.045$ eV	$E_a = 0.067$ eV
Dopant valence	5	3
Dopant nuclear charge	$+15e$	$+13e$
Dopant net ion charge	$+e$	$-e$

Semiconductors

A p-n junction is made by fabricating a semiconductor with both types of dopants.



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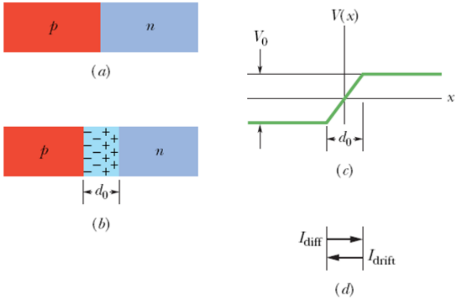
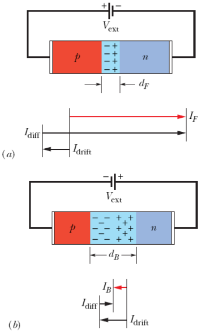


Near the junction, electrons move from the n-type material to fill in the holes in the p-type material and a **depletion region** is formed.

Semiconductors

When a forward or reverse bias voltage is applied, the p-n junction behaves differently.



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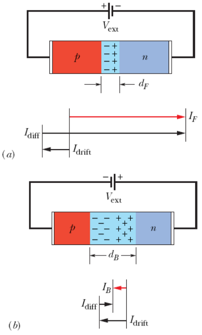
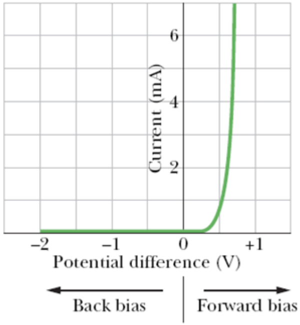
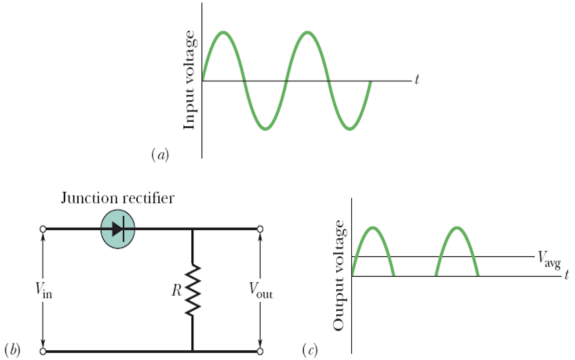




Reverse bias widens the depletion region, limiting current flow.

Semiconductors

These junctions can be used to create a variety of devices.



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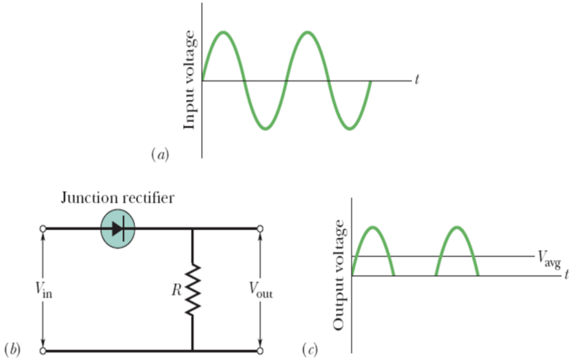
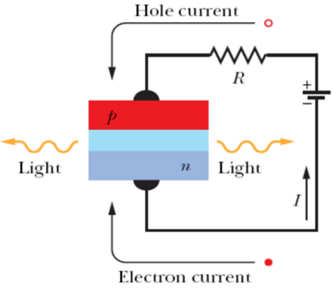
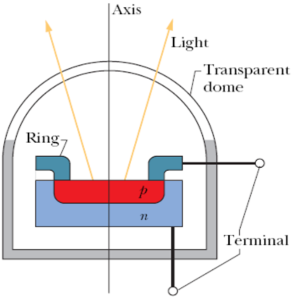


The rectifier removes negative voltages.

Semiconductors

The Light Emitting Diode (LED) is tuned to emit visible light when holes and electrons recombine.





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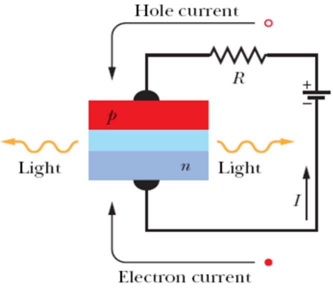
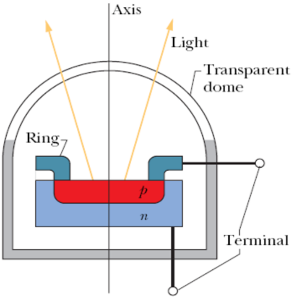
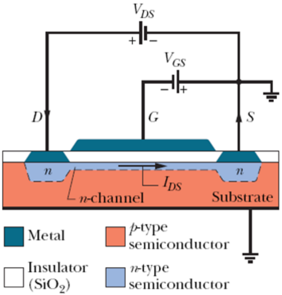


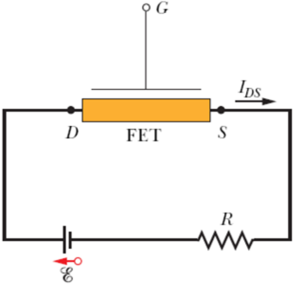


Different materials produce different colors.

Semiconductors

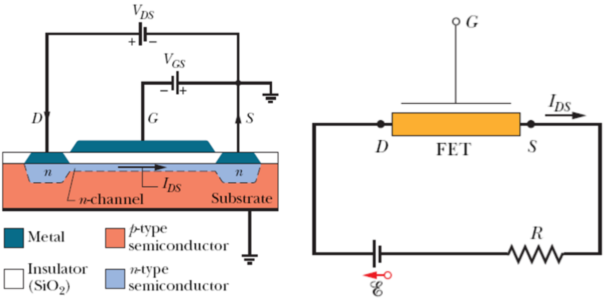
A field effect transistor (FET) uses a voltage to control current through the n-channel of a semiconductor.





Semiconductors

A field effect transistor (FET) uses a voltage to control current through the n-channel of a semiconductor.



Drain (D), Source (S) and Gate (G) are common terminology with transistor technology.

Semiconductors

Lecture Question 9.3

Which one of the following materials would be in a p-type semiconductor?

(a) germanium doped with antimony

(b) germanium doped with arsenic

(c) silicon doped with phosphorus

(d) silicon doped with arsenic

(e) silicon doped with boron