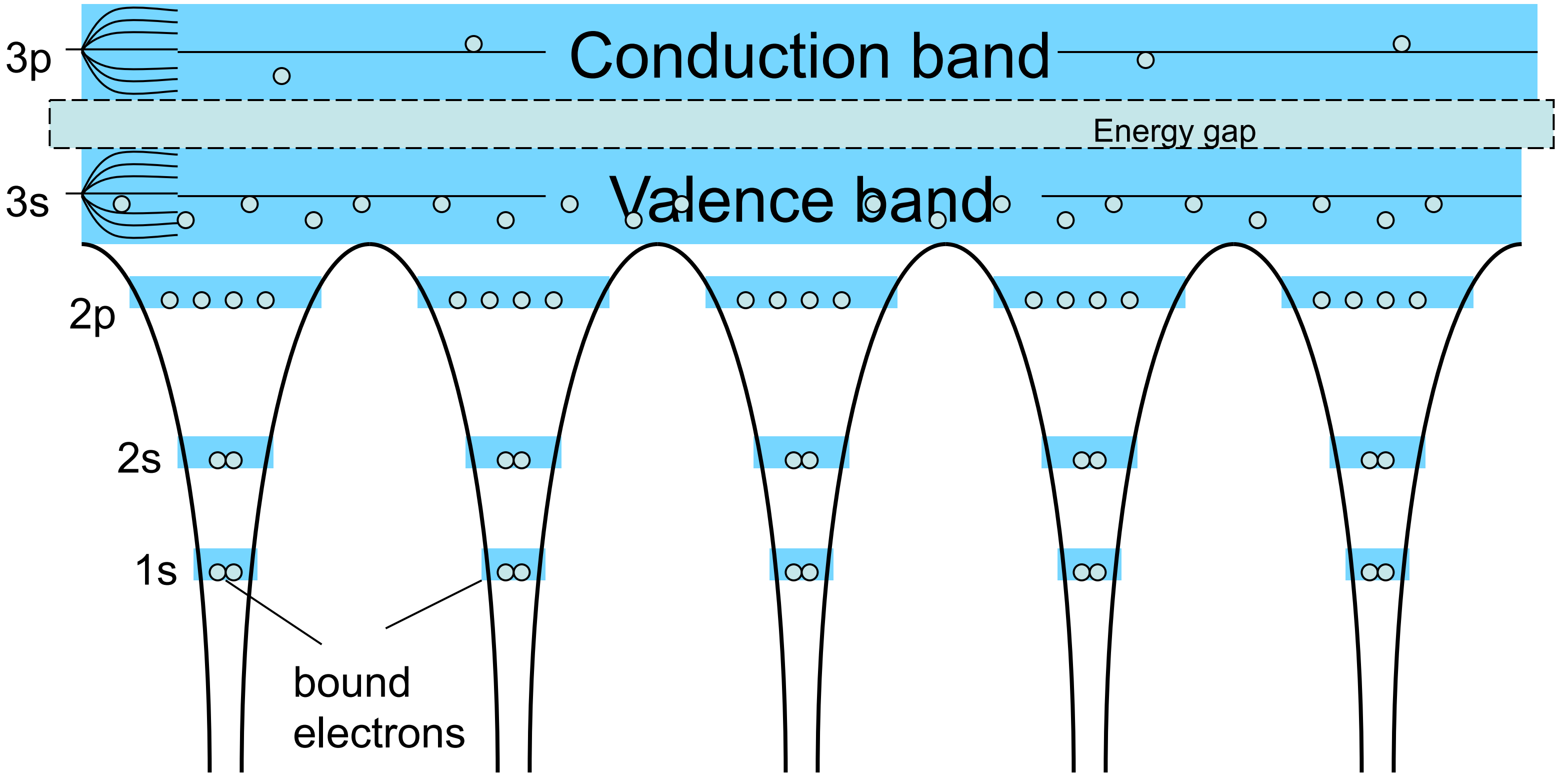
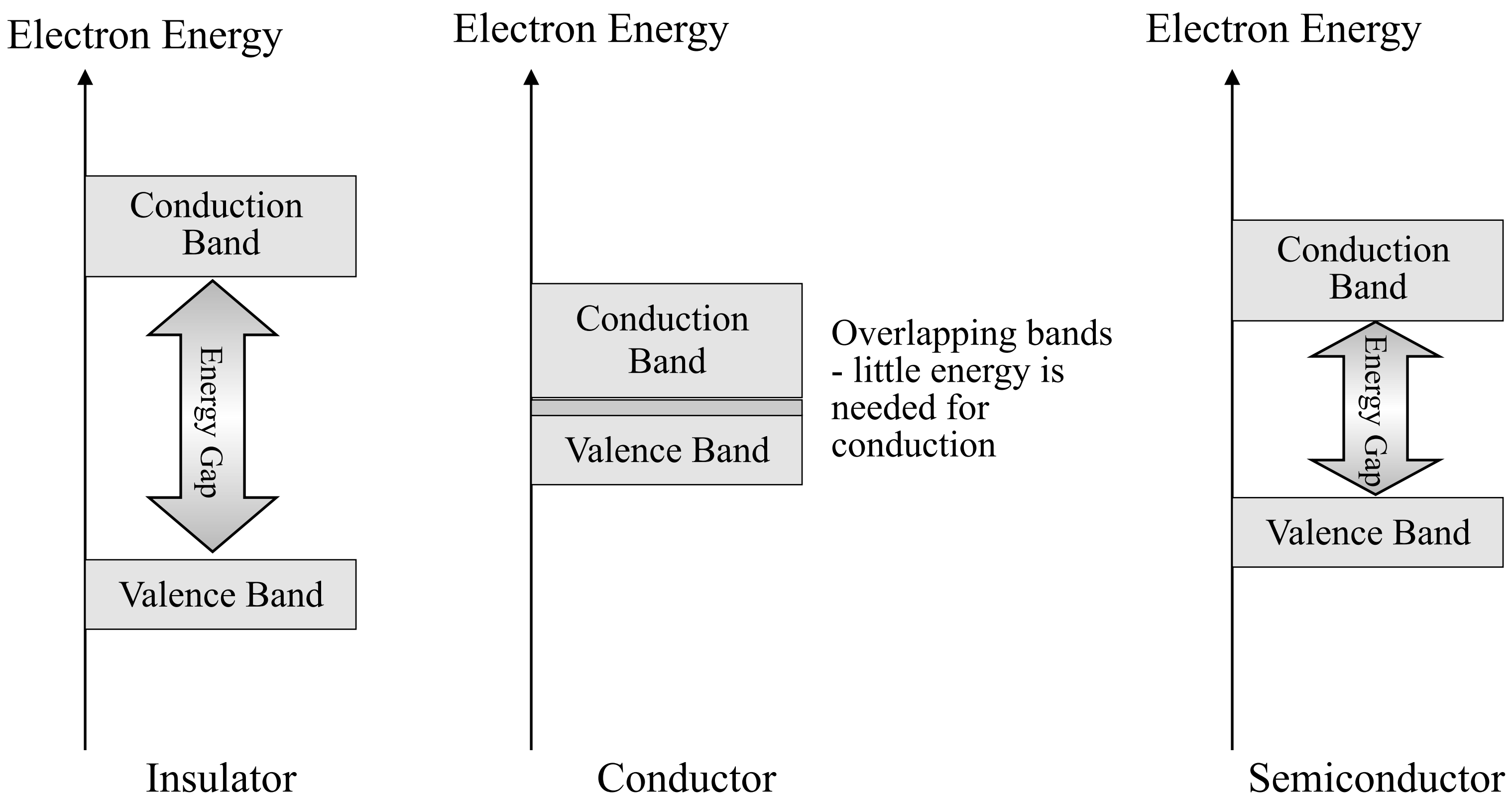
Electrons in Solids



When atoms form a crystalline structure (metals, semiconductors,) the valence electrons loose their attraction to a local atom and form an band of ~equivalent charges- **valence band**. The **conduction band** lies within or above the valence band.

Energy Bands



Electron Energy

Conduction Band

Energy Gap

Valence Band

Insulator

Electron Energy

Conduction Band

Valence Band

Overlapping bands - little energy is needed for conduction

Conductor

Electron Energy

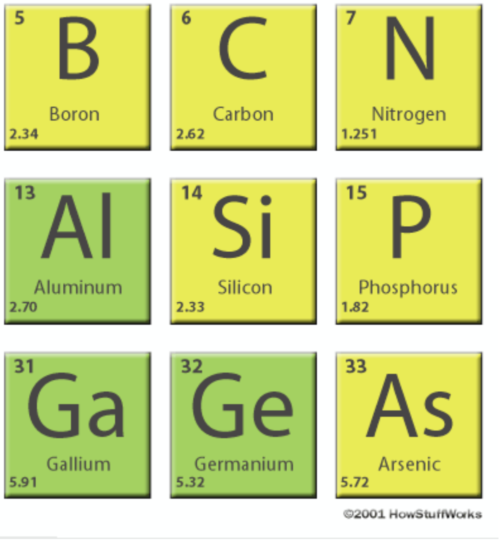
Conduction Band

Energy Gap

Valence Band

Semiconductor

Semiconductors and Impurity Dopants



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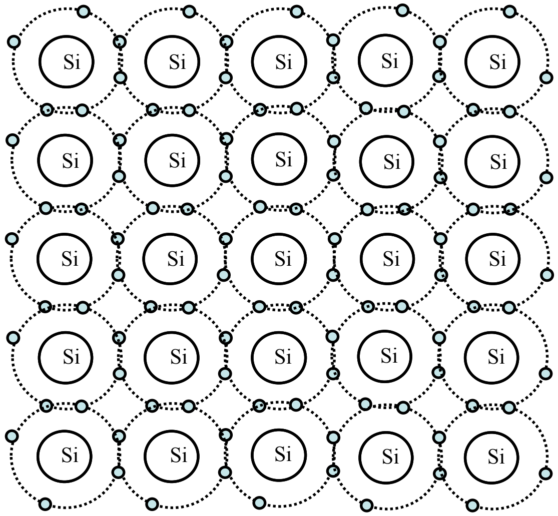
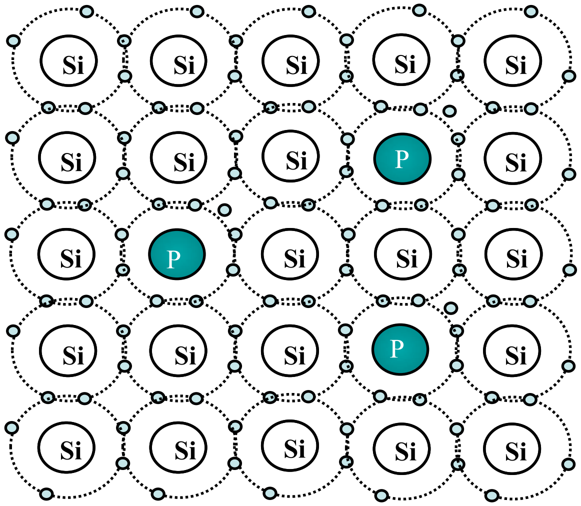
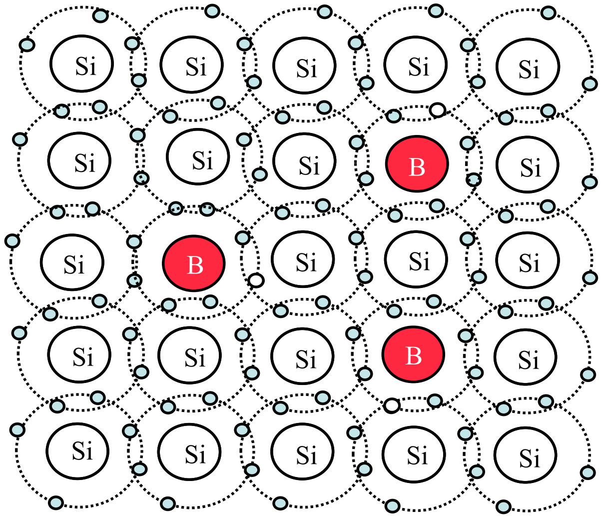
Silicon atoms share valence electrons to form insulator-like bonds.



Phosphorus atom serves as n-type dopant

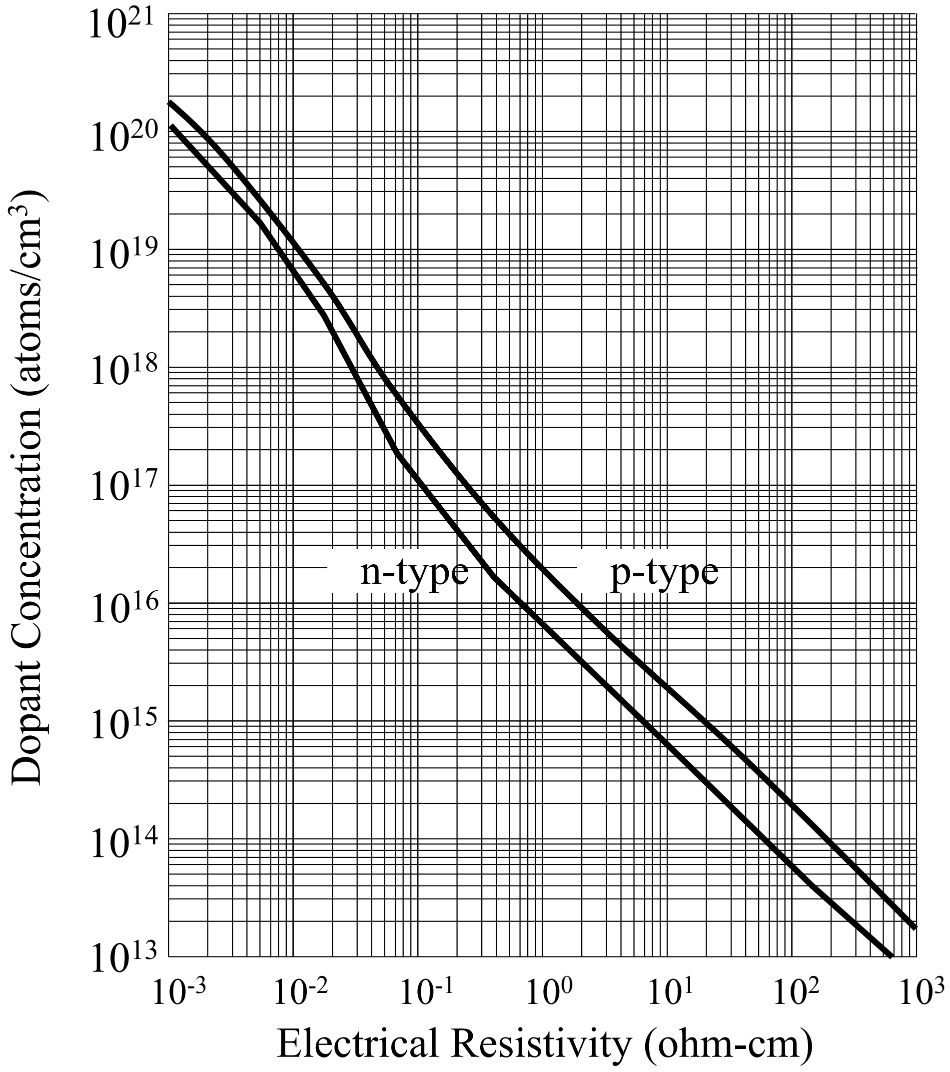


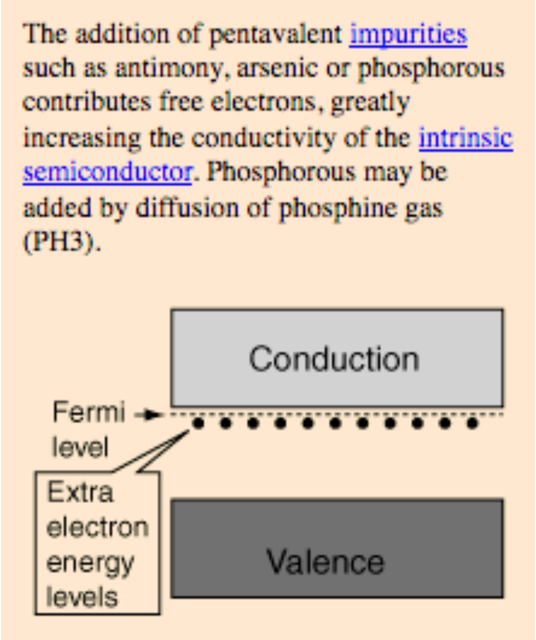
Boron atom serves as p-type dopant



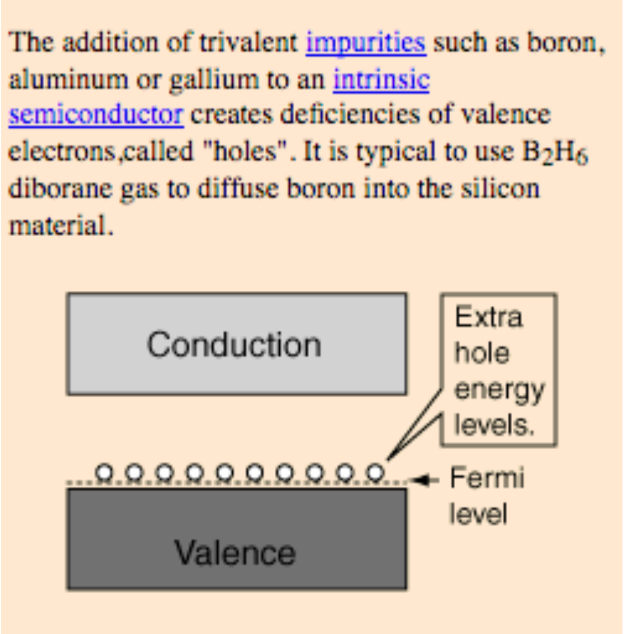
Silicon Resistivity Versus Dopant Concentration

http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/dope.html



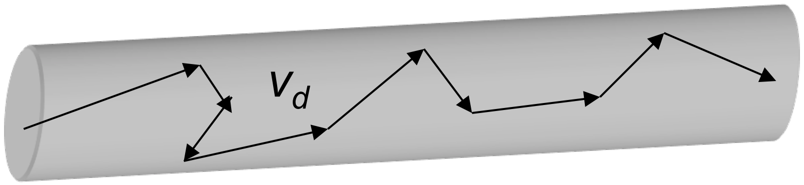


The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the intrinsic semiconductor. Phosphorous may be added by diffusion of phosphine gas (PH3).



The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons,called "holes". It is typical to use B_2H_6 diborane gas to diffuse boron into the silicon material.

Resistivity ρ =1/σ



METAL

$$\rho_m = \frac{m}{ne^2}\frac{1}{\tau}$$

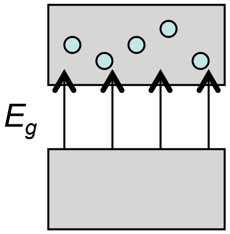
- $j\ = n\ q\ v\ \ (A/m^2)$ *current density*
- $E = j \cdot \rho$ *Ohm's Law*

$(\ j = I/A \quad R = \rho \cdot (L/A) \quad E = V/L\ )$

- *Electrons will collide on average* τ *seconds apart.*

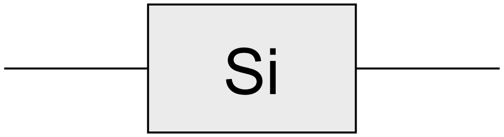
$\tau \equiv$ *collision time (relaxation time)*

- *Drift velocity of electrons* $v_d = a \cdot \tau = \frac{qE}{m} \cdot \tau$
- $\rho = \frac{E}{j} = \frac{m}{ne^2}\frac{1}{\tau} = \frac{m}{ne^2}\left(\frac{1}{\tau_{crystal}} + \frac{1}{\tau_{impurities}}\right)$



SEMICONDUCTOR

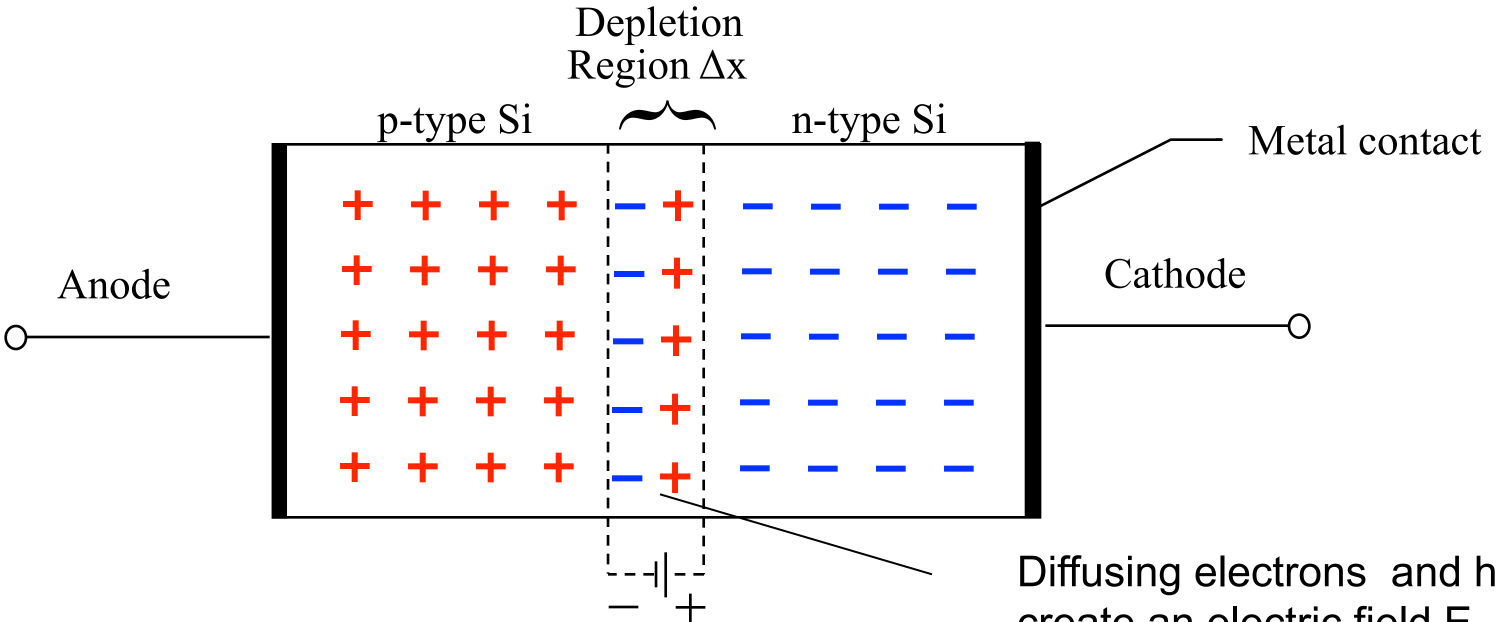
$$\rho_{sc} = \rho_m\ (T/T_0)^{-3/2}\ e^{E_g/2kT}$$



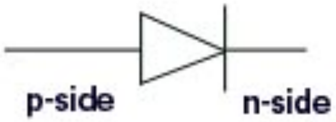
DIODE or PN JUNCTION

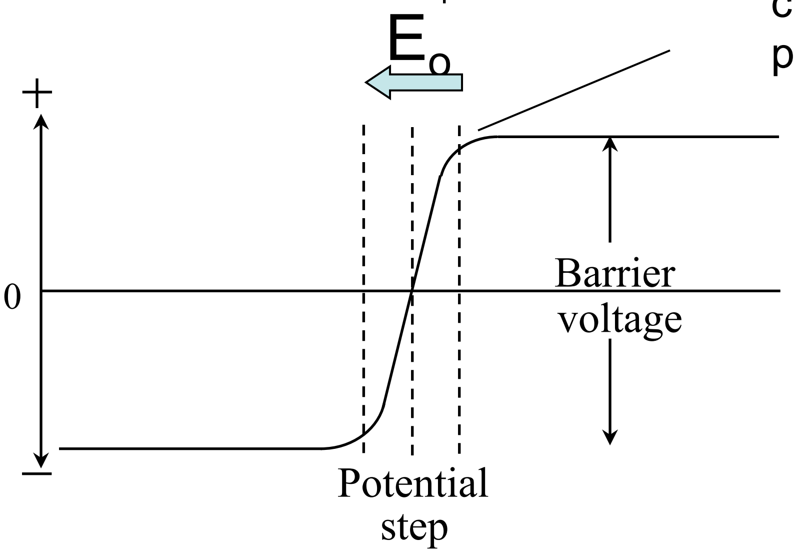
$$I = I_0\left\lfloor e^{eV/kT} - 1 \right\rfloor$$

Diode Action

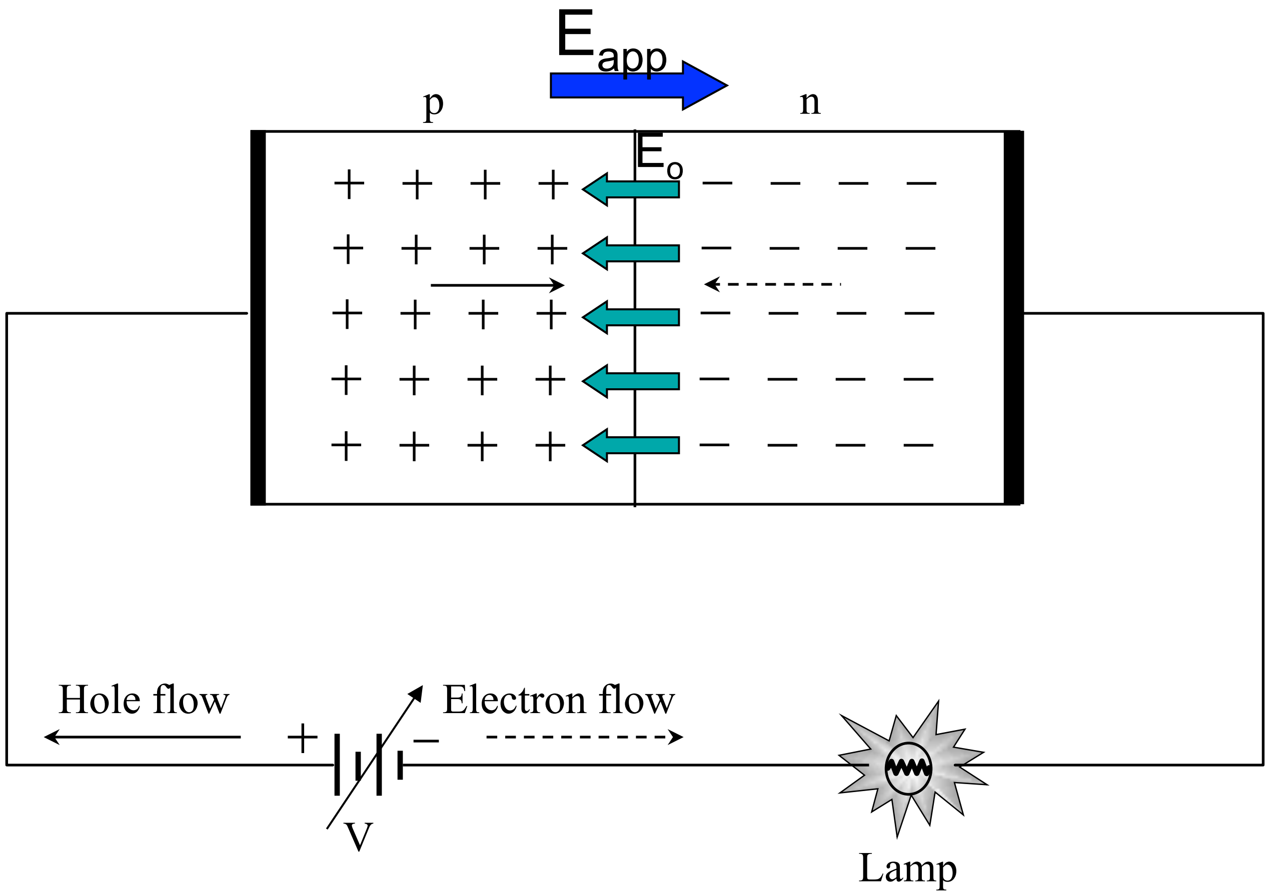


Diffusing electrons and holes create an electric field E_o and potential step at the junction.



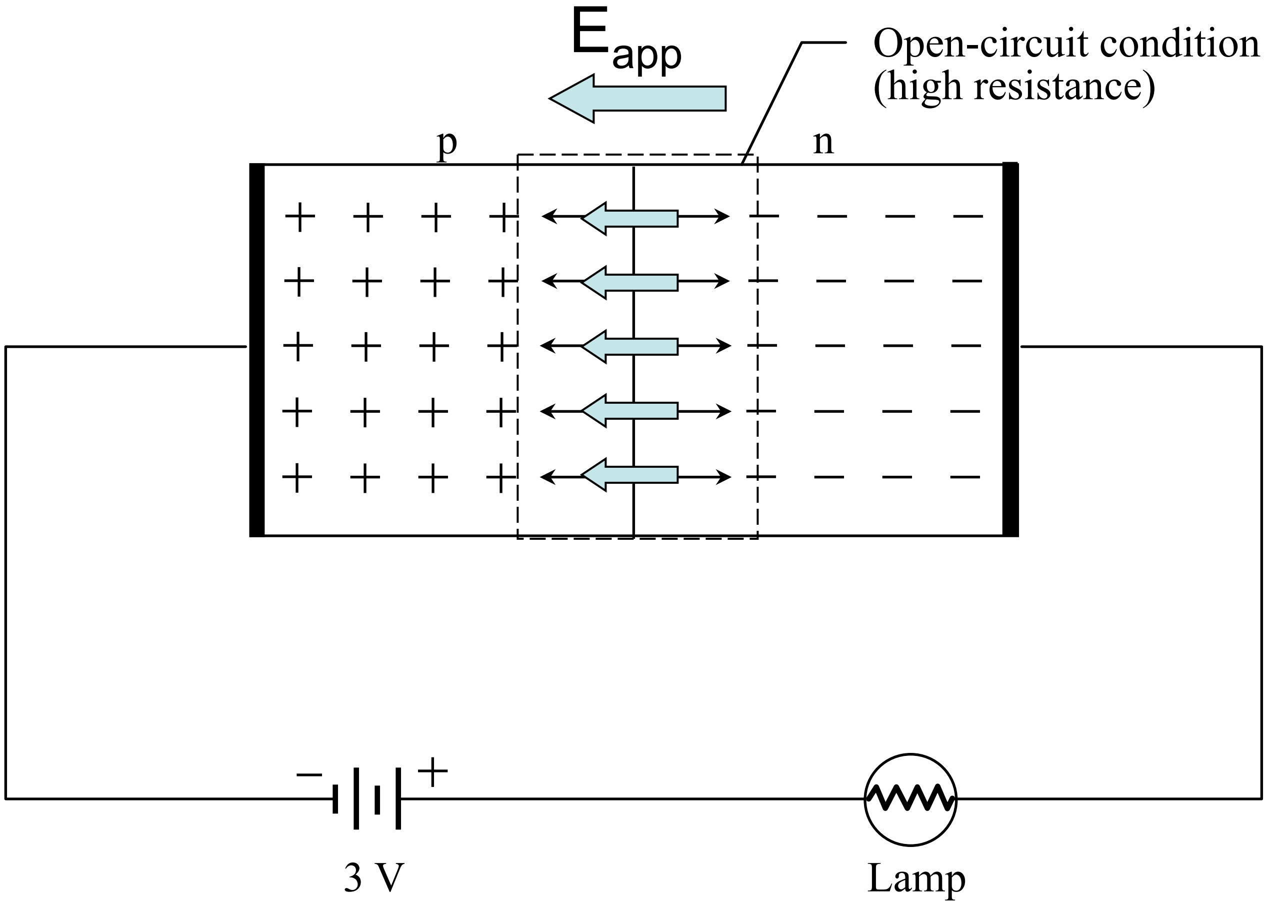


Forward-Biased PN Junction Diode



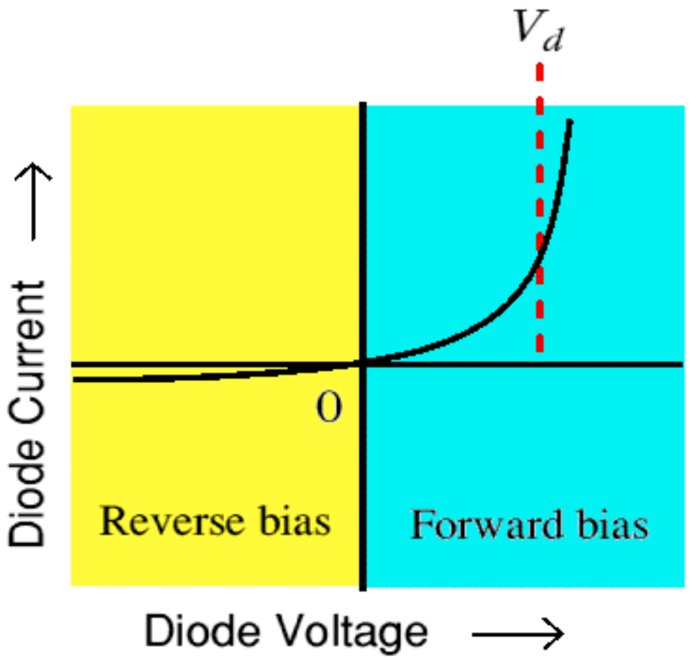
In **forward bias** the applied E-field cancels internal electric field and charges begin flowing across the junction when $E_{app}>E_o$ or $V_{app}>\sim0.6V$.

Reverse-Biased PN Junction Diode



In the **reverse bias** the external E-field increases the size of the depletion zone until all charge carries are near the contacts - **fully depleted**.

Diodes



$$I = I_0\left(\mathrm{Exp}\left\{\frac{eV}{kT}\right\} - 1\right)$$

I = Current through diode in Amps

I_0 = The diode's 'Saturation Current' value

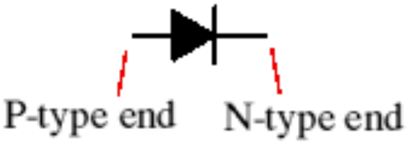
e = electron charge, $1{\cdot}602 \times 10^{-19}$ C

T = temperature in degrees Kelvin

V = Applied voltage in Volts

k = Boltzmann's constant, $1{\cdot}380 \times 10^{-23}$ J/K

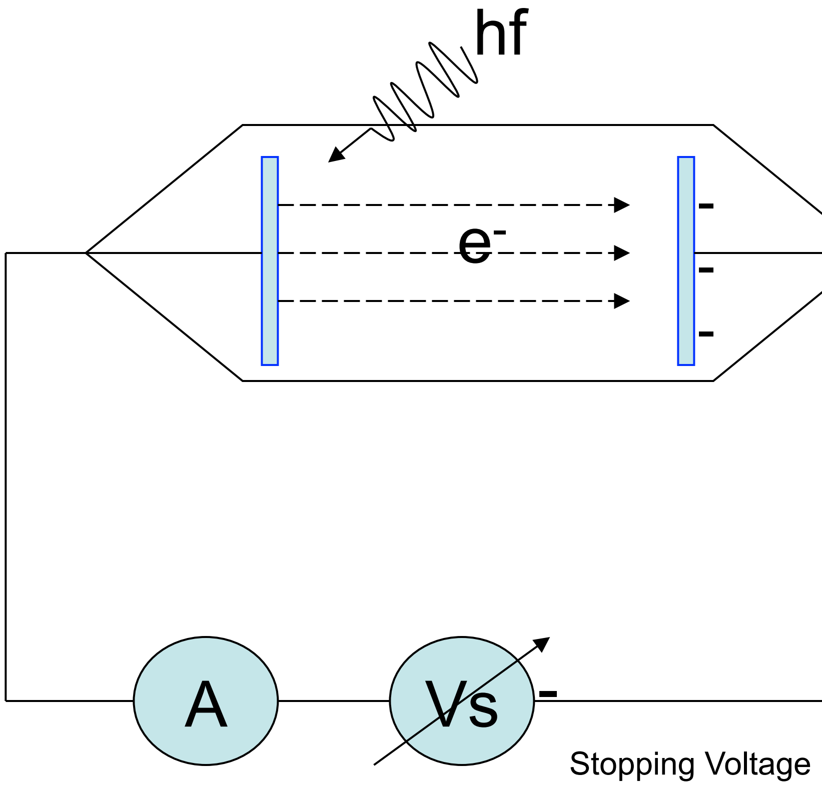
Standard diode symbol



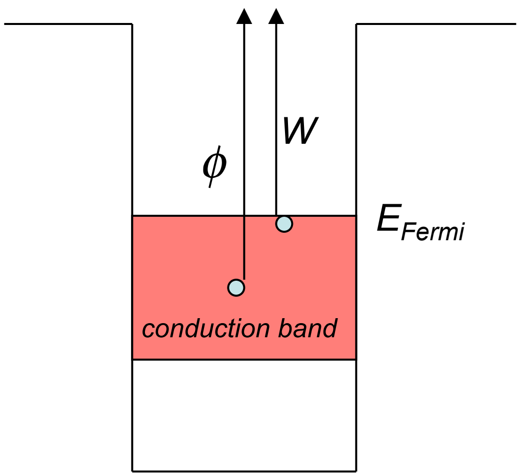
DIODE or PN JUNCTION

$$I = I_0\left\lfloor \mathrm{e}^{e(V-V_g)/kT} - 1\right\rfloor = I_0\, e\left(V - V_g\right)/\,kT$$

Photo-Electric Effect in a Metal

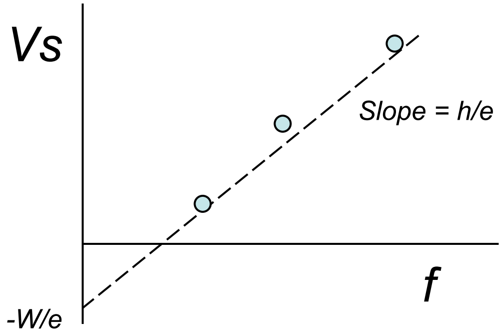


$KE = hf - \phi$

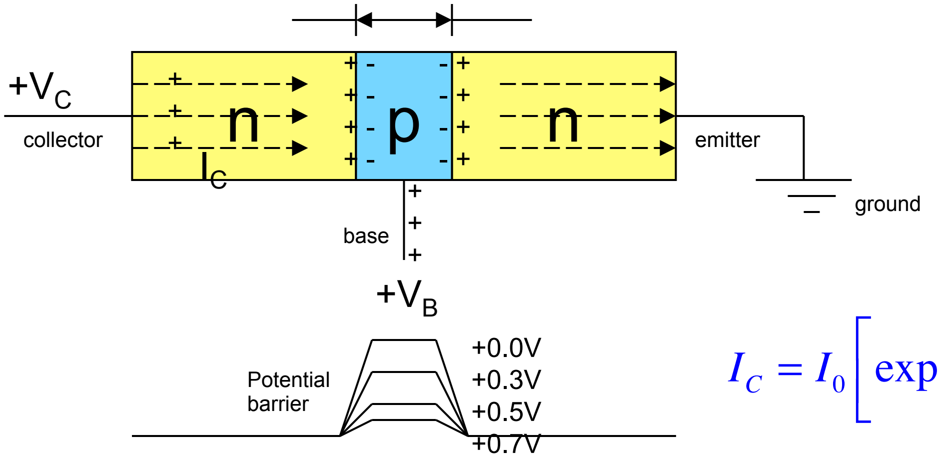


$$KE_{\max} = eV_S = hf - W$$

$$W \equiv work \;\; function \;\; of \;\; the \;\; metal$$



Transistor Action

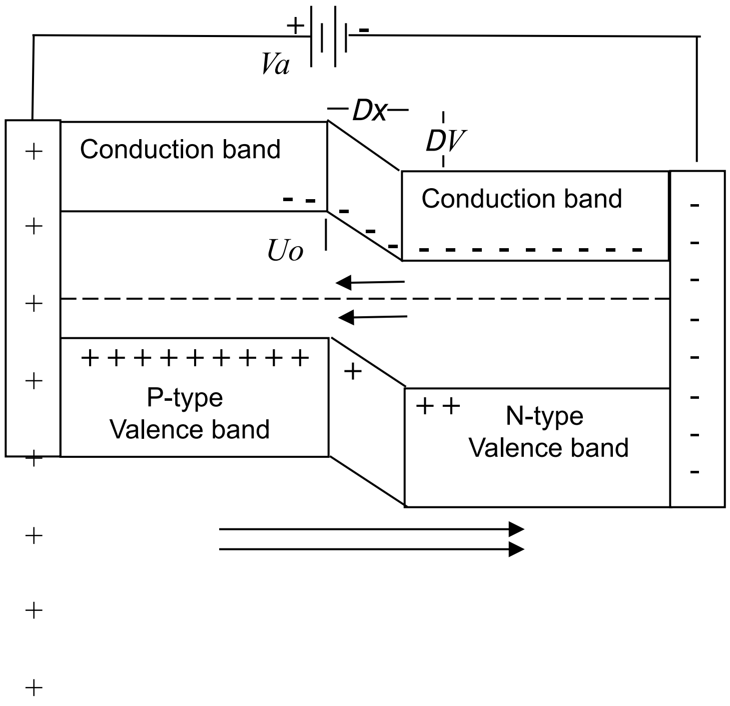


$$I_C = I_0\left[\exp(\frac{qV_B}{kT}) - 1\right]$$

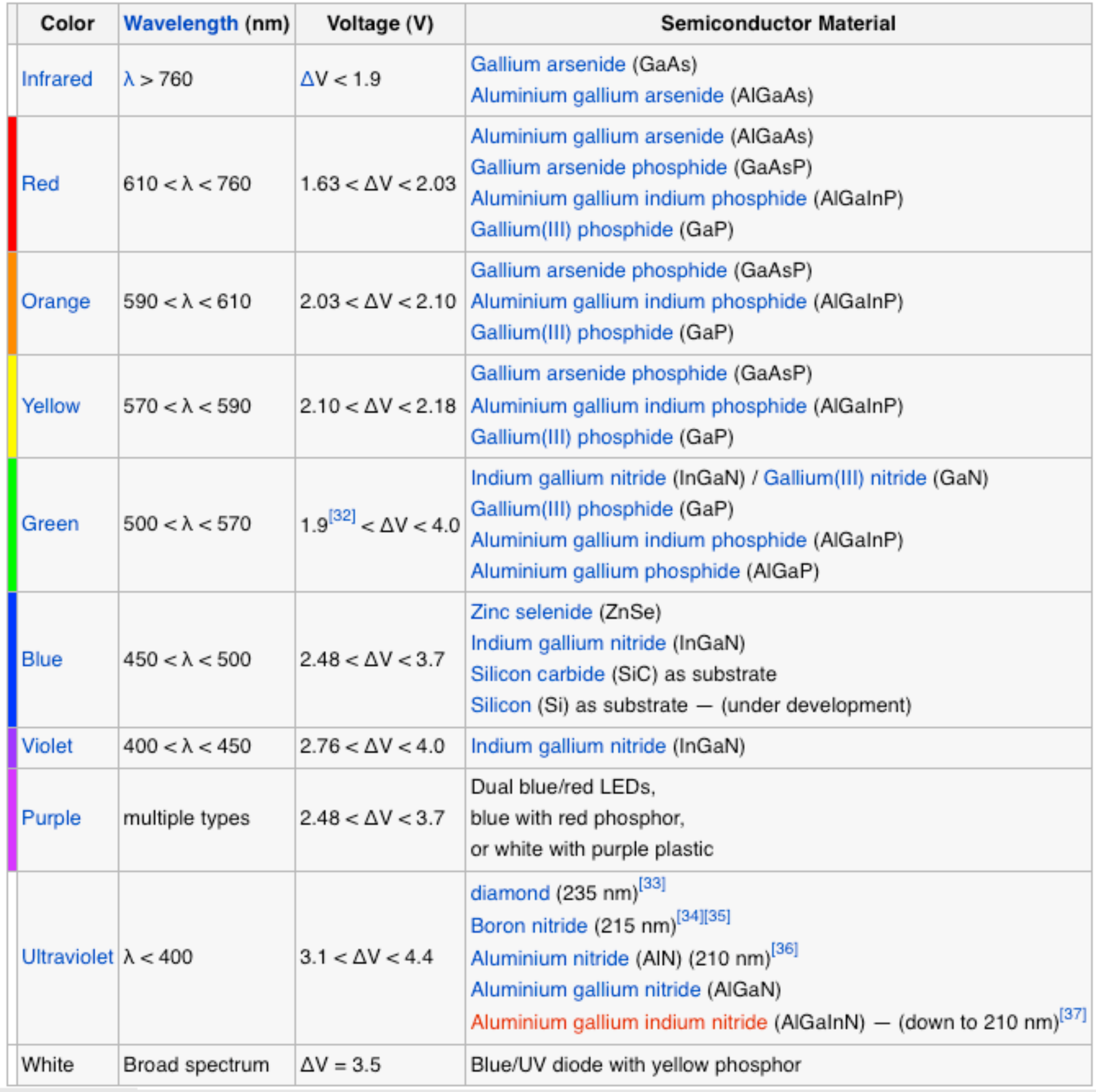
- A transistor is constructed by opposing two diodes structures n-p-n or p-n-p.
- No collector current can flow through the collector-base junction (reverse diode).
- By increasing the base voltage $+V_B$ to about +0.7V the potential barrier is lowered and a large collector current can cross to ground ($\rho_{transistor}$--> 0).
- By modulating the V_B one can form an amplifier $A = I_C / I_B$. (Analogue electronics)
- If V_B >> 1V then the transistor saturates to a digital pulse (Digital electronics).

Light Emitting Diodes

- A PN junction is characterized by a contact diffusion voltage U_0 which developes across the diode depletion zone.
- In forward bias condition electrons and holes can annihilate in the zone emitting a photon of energy hf = $U_{0..}$ U_0 can be engineered to produce different color emissions.
- An LED is special in that the diode is transparent to this photon emission. In a normal diode e-p annihilation energy returns to heating the diode.

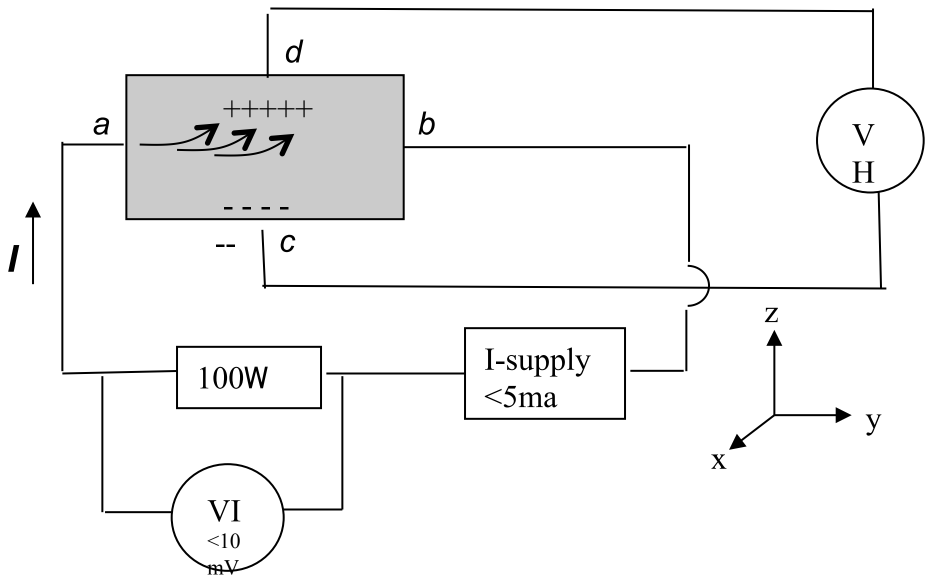


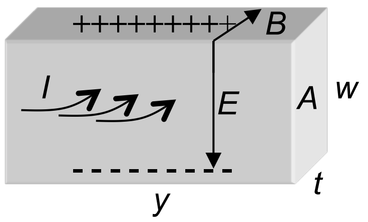
http://en.wikipedia.org/wiki/Light-emitting_diode



	Color	Wavelength (nm)	Voltage (V)	Semiconductor Material
	Infrared	$\lambda > 760$	$\Delta V < 1.9$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
🟥	Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟧	Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟨	Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟩	Green	$500 < \lambda < 570$	1.9[32] $< \Delta V < 4.0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
🟦	Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
🟪	Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
🟪	Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
	Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	diamond (235 nm)[33] Boron nitride (215 nm)[34][35] Aluminium nitride (AlN) (210 nm)[36] Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN) — (down to 210 nm)[37]
	White	Broad spectrum	$\Delta V = 3.5$	Blue/UV diode with yellow phosphor

Hall Effect in p-Germanium





$\vec{j} = nq\vec{v}_d$ *current density = I / area*

$m\frac{\vec{v}_d}{\tau} = q\left(\vec{E} + \vec{v}_d \times \vec{B}\right) = 0$ *equilibrium*

$E_z = -v_d B_x \rightarrow V_y / w = \frac{I}{wt}\frac{1}{nq}B_x$

$V_H = \left(\frac{B_x}{nq\ t}\right)I$ *Hall Voltage*

$R_H = \frac{E_z}{j_y\ B_x} = \frac{1}{nq}$ *Hall Coefficient*

- *n* is the number of free charge carriers in the sample.
- In a semiconductor the free charge carriers *n* are both electrons and holes.
- By measuring the Hall voltage V_H vs I at a known value of *B* we can measure *n* for the sample.
- Slope = (1/nq) (B/t) where R_H=1/nq .
- Since $B = t \times I / R_H$ one can use the Hall effect to measure magnetic fields - Hall Probe!