LED lecture

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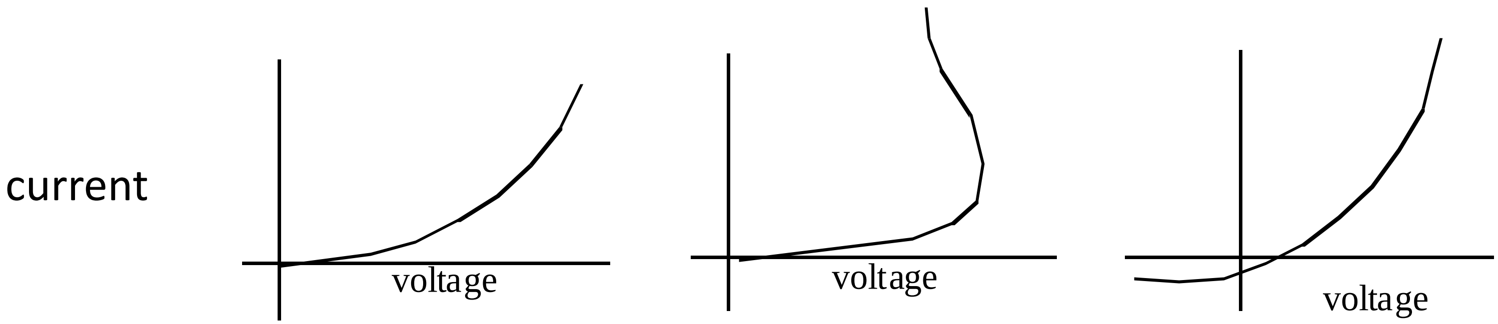
Linear and Nonlinear electronics



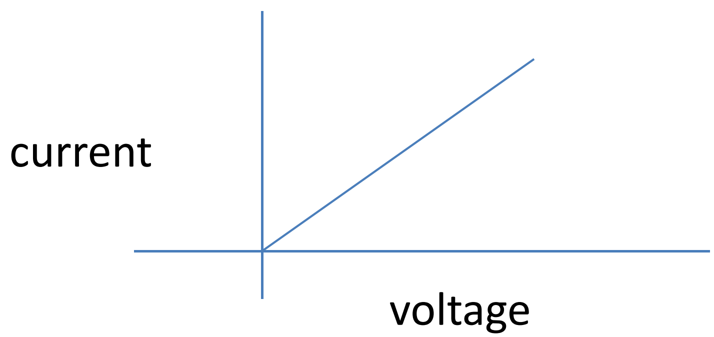
Vaccum tube
(i.e. type 2A3)

Thermistor

(large negative temperature coefficient of resistivity)

Diode
(i.e. PN diode, LED, laser diode, phtodiode)

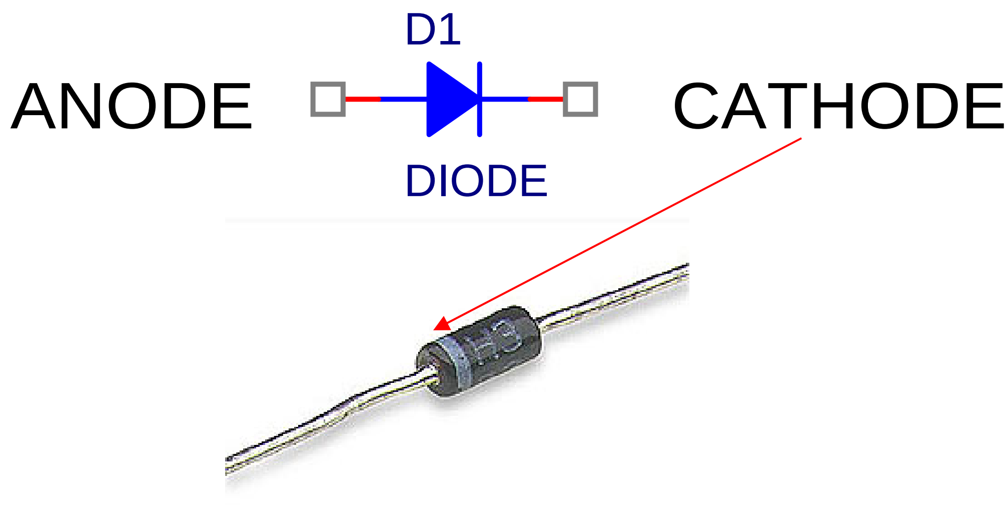
$$i_D = I_S\left(e^{v_D/nV_T} - 1\right)$$



Normal resistor

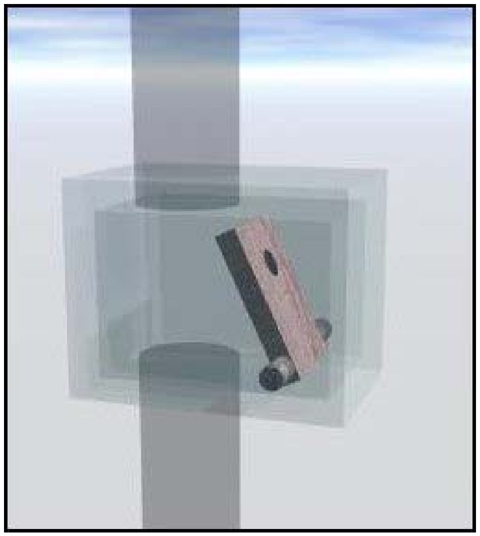
Ohm's Law: *i=v/R*

Introduction to Diodes



- A diode can be considered to be an electrical one-way valve.
- They are made from a large variety of materials including silicon, germanium, gallium arsenide, silicon carbide …

Introduction to Diodes

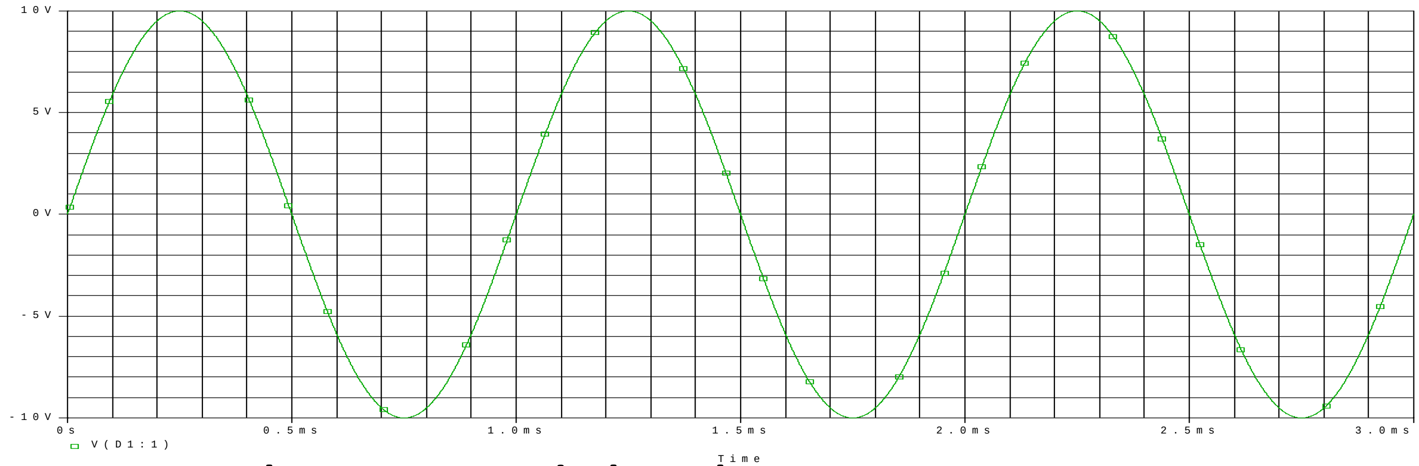


- In effect, diodes act like a flapper valve
  - Note: this is the simplest possible model of a diode

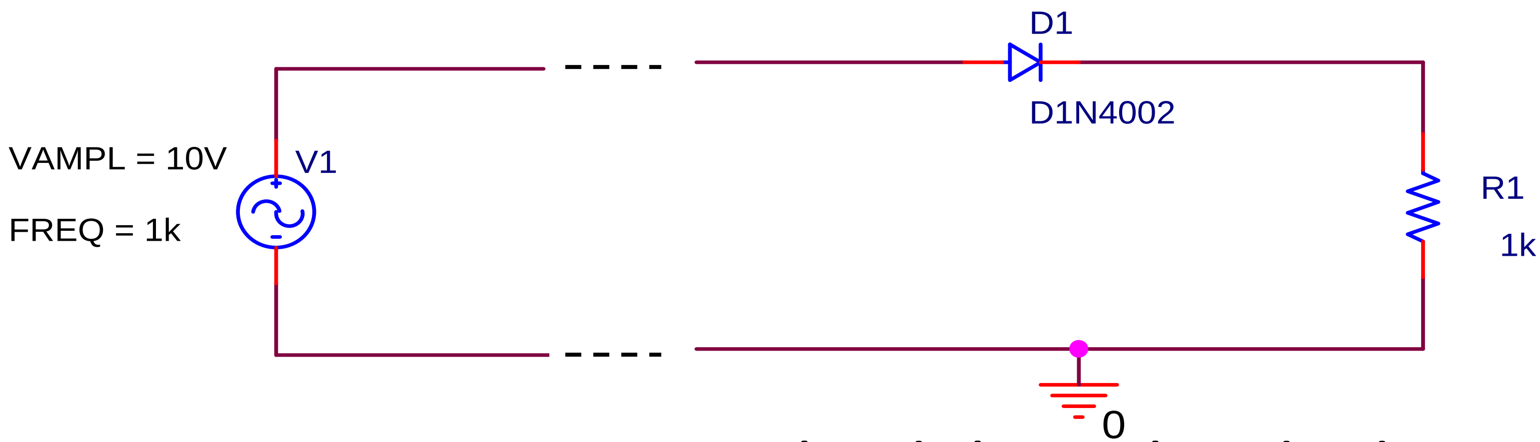
Introduction to Diodes

- For the flapper valve, a small positive pressure is required to open.
- Likewise, for a diode, a small positive voltage is required to turn it on. This voltage is like the voltage required to power some electrical device. It is used up turning the device on so the voltages at the two ends of the diode will differ.
  - The voltage required to turn on a diode is typically around 0.6 - 0.8 volt for a standard silicon diode and a few volts for a light emitting diode (LED)

Introduction to Diodes

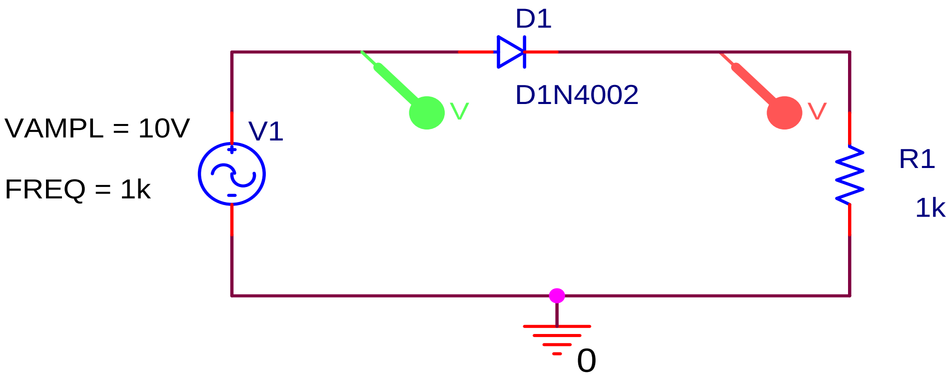


- 10 volt sinusoidal voltage source

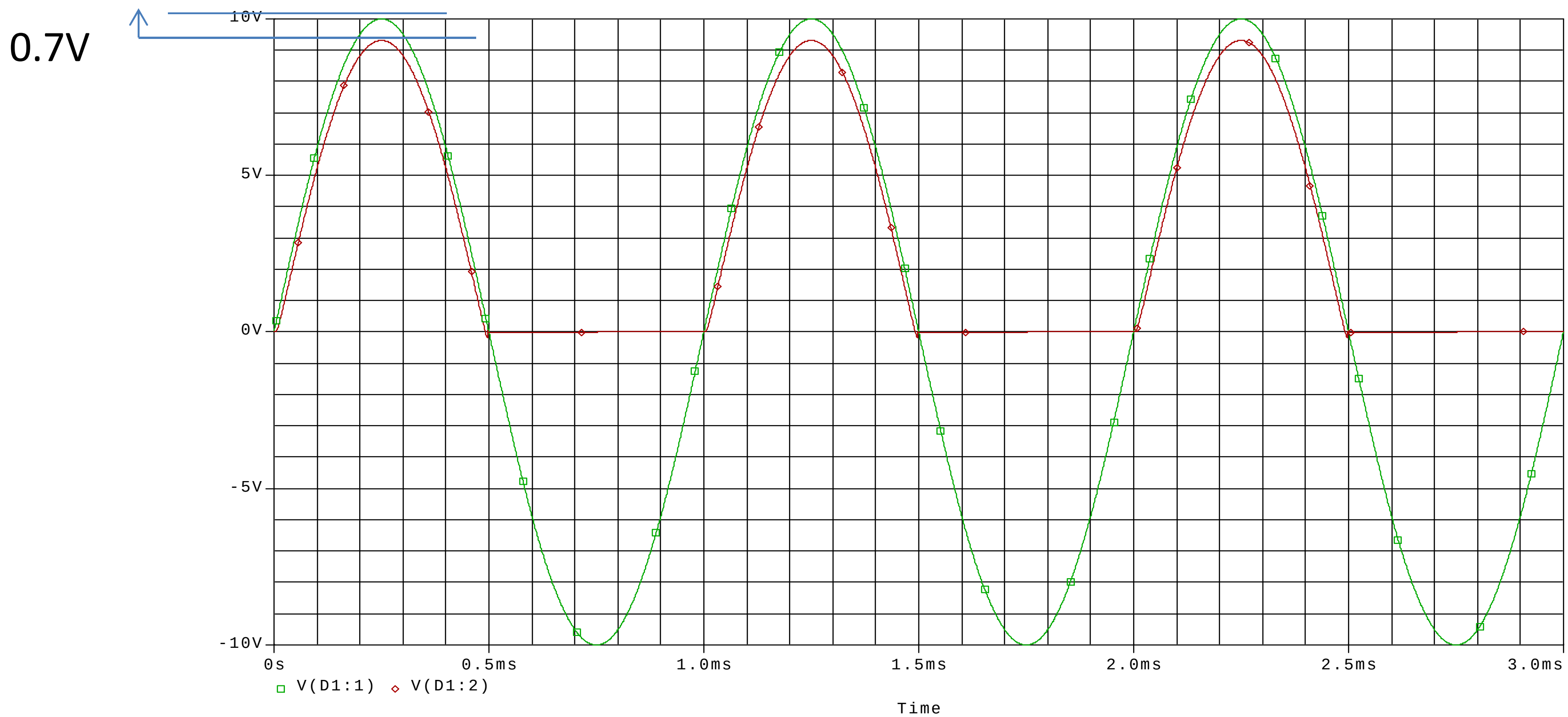


- Connect to a resistive load through a diode

Introduction to Diodes



Only positive current flows



Semiconductor

Variable conductivity

A pure semiconductor is a poor electrical conductor as a consequence of having just the right number of electrons to completely fill its valence bonds. Through various techniques (e.g., doping or gating), the semiconductor can be modified to have excess of electrons (becoming an ***n*-type semiconductor**) or a deficiency of electrons (becoming a ***p*-type semiconductor**). In both cases, the semiconductor becomes much more conductive (the conductivity can be increased by a factor of one million, or even more). Semiconductor devices exploit this effect to shape electrical current.

Junctions

When doped semiconductors are joined to metals, to different semiconductors, and to the same semiconductor with different doping, the resulting junction often strips the electron excess or deficiency out from the semiconductor near the junction. This depletion region is rectifying (only allowing current to flow in one direction), and used to further shape electrical currents in semiconductor devices.

Energetic electrons travel far

Electrons can be excited across the energy band gap (see *Physics* below) of a semiconductor by various means. These electrons can carry their excess energy over distance scales of microns before dissipating their energy into heat, significantly longer than is possible in metals. This effect is essential to the operation of bipolar junction transistors.

Light energy conversion

Electrons in a semiconductor can absorb light, and subsequently retain the energy from the light for a long enough time to be useful for producing electrical work instead of heat. This principle is used in the photovoltaic cell.

Conversely, in certain semiconductors, electrically excited electrons can relax by emitting light instead of producing heat. This is used in the light emitting diode.

Thermal energy conversion

Semiconductors are good materials for thermoelectric coolers and thermoelectric generators, which convert temperature differences into electrical power and vice versa. Peltier coolers use semiconductors for this reason.

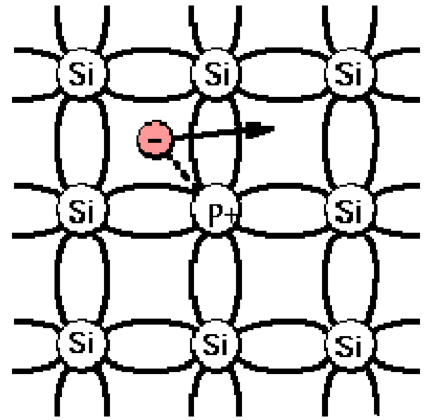
P type and N type Materials

The semiconductor can be modified to have
excess of electrons (becoming an ***n*-type semiconductor**)
or a deficiency of electrons (becoming a ***p*-type semiconductor**).

In both cases, the semiconductor becomes much more conductive (the conductivity can be increased by a factor of one million, or even more). Semiconductor devices exploit this effect to shape electrical current.

Donor (n type semiconductors)

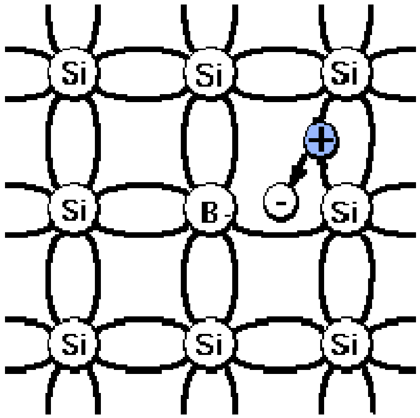
In semiconductor physics, a **donor** is a dopant atom that, when added to a semiconductor, can form a n-type region. For example, when silicon (Si), having four valence electrons, needs to be doped as an n-type semiconductor, elements from group V like phosphorus (P) or arsenic (As) can be used because they have five valence electrons. A dopant with five valence electrons is also called a pentavalent impurity. Other pentavalent dopants are antimony (Sb) and bismuth (Bi). When substituting a Si atom in the crystal lattice, four of the valence electrons of phosphorus form covalent bonds with the neighbouring Si atoms but the fifth one remains weakly bonded. At room temperature, all the fifth electrons are liberated, can move around the Si crystal and can carry a current and thus act as charge carriers. The initially neutral donor becomes positively charged (ionised).



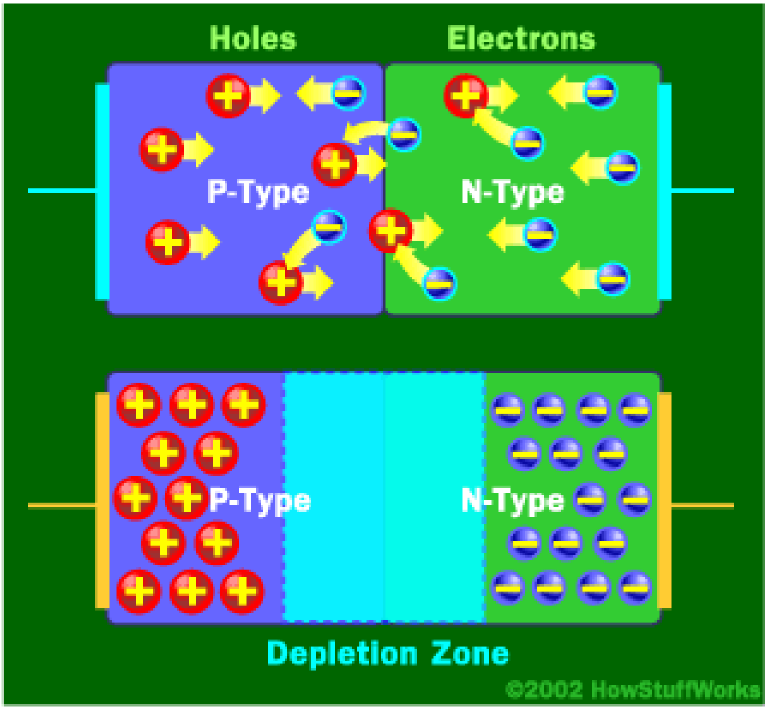
Acceptor (P type semiconductors)

In semiconductor physics, an **acceptor** is a dopant atom that when added to a semiconductor can form a p-type region. For example, when silicon (Si), having four valence electrons, needs to be doped as a p-type semiconductor, elements from group III like boron (B) or aluminium (Al), having three valence electrons, can be used. The latter elements are also called trivalent impurities. Other trivalent dopants include indium (In) and gallium (Ga).

When substituting a Si atom in the crystal lattice, the three valence electrons of boron form covalent bonds with three of the Si neighbours but the bond with the fourth neighbour remains unsatisfied. The unsatisfied bond attracts electrons from the neighbouring bonds. At room temperature, an electron from the neighbouring bond will jump to repair the unsatisfied bond thus leaving a hole (a place where an electron is deficient). The hole will again attract an electron from the neighbouring bond to repair this unsatisfied bond. This chain-like process results in the hole moving around the crystal and able to carry a current thus acting as a charge carrier. The initially electroneutral acceptor becomes negatively charged (ionised).

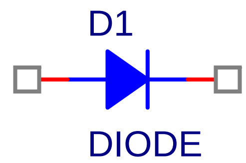


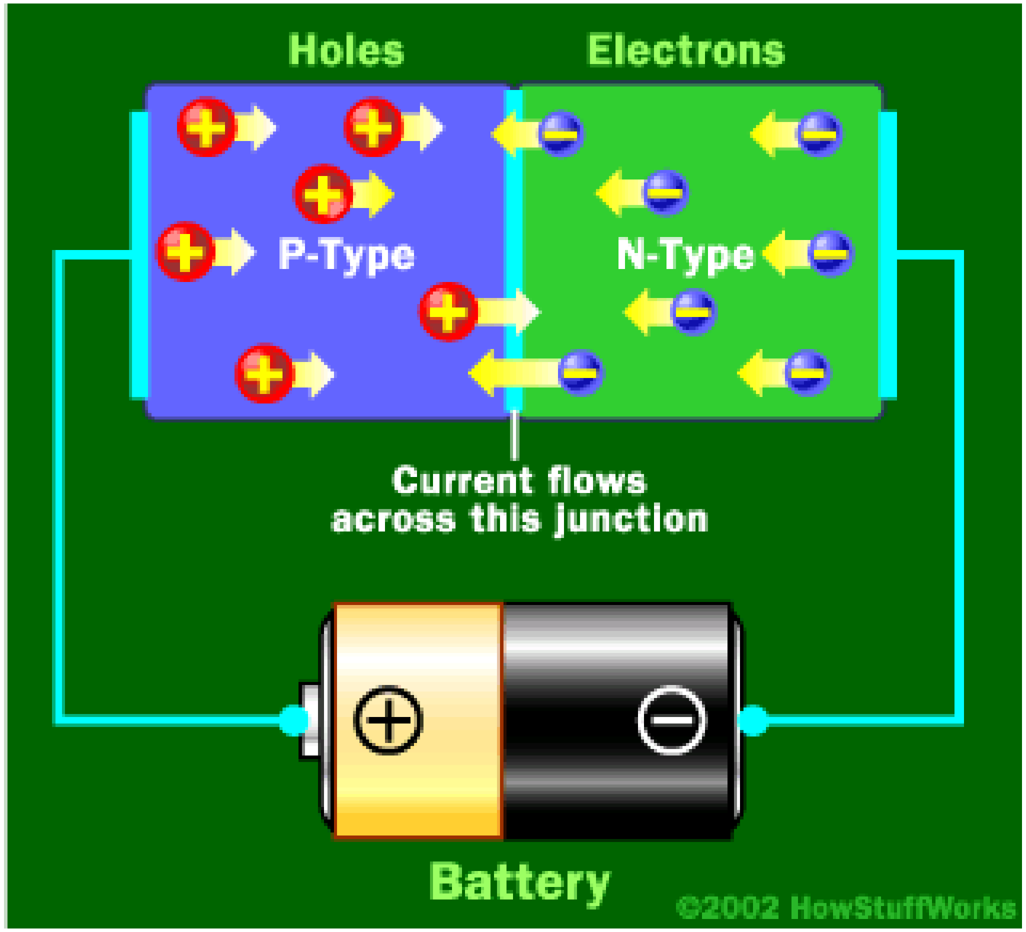
How Diodes Work



When put two materials together, free electrons from the N-type material fill holes from the P-type material. This creates an insulating layer in the middle of the diode called the depletion zone.

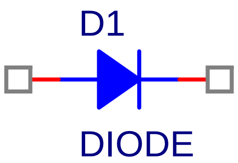
How Diodes Work

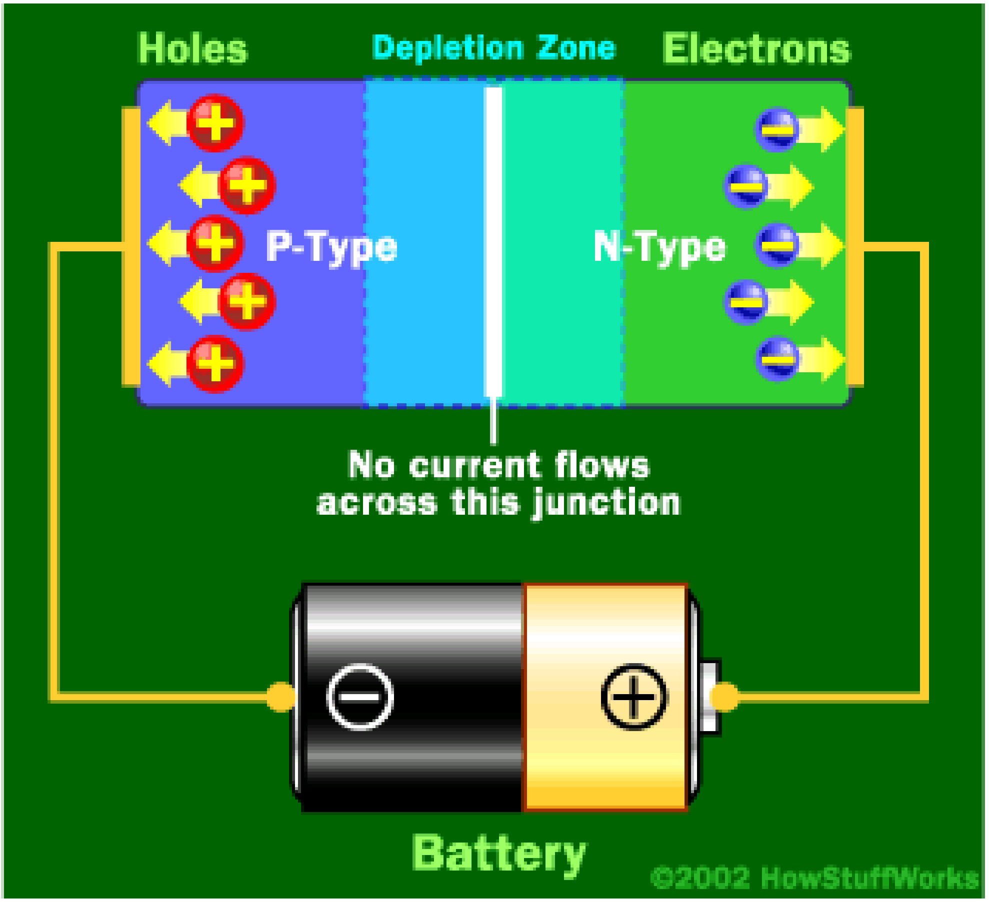
ANODE  CATHODE



When the negative end of the circuit is hooked up to the N-type layer and the positive end is hooked up to P-type layer, electrons and holes start moving and the depletion zone disappears.

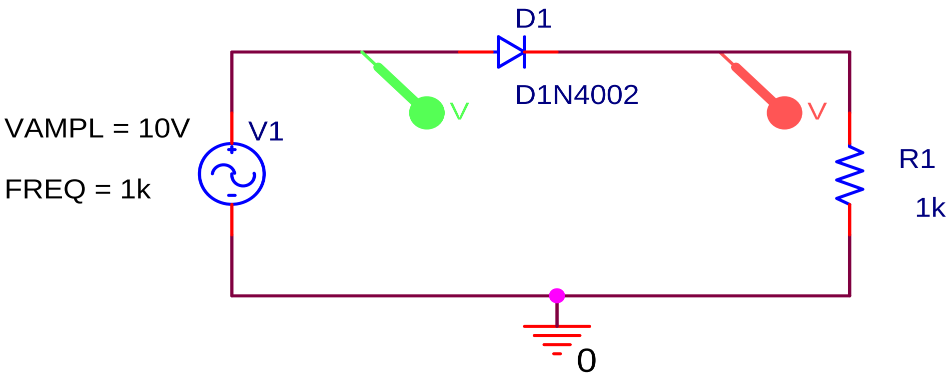
How Diodes Work

ANODE  CATHODE

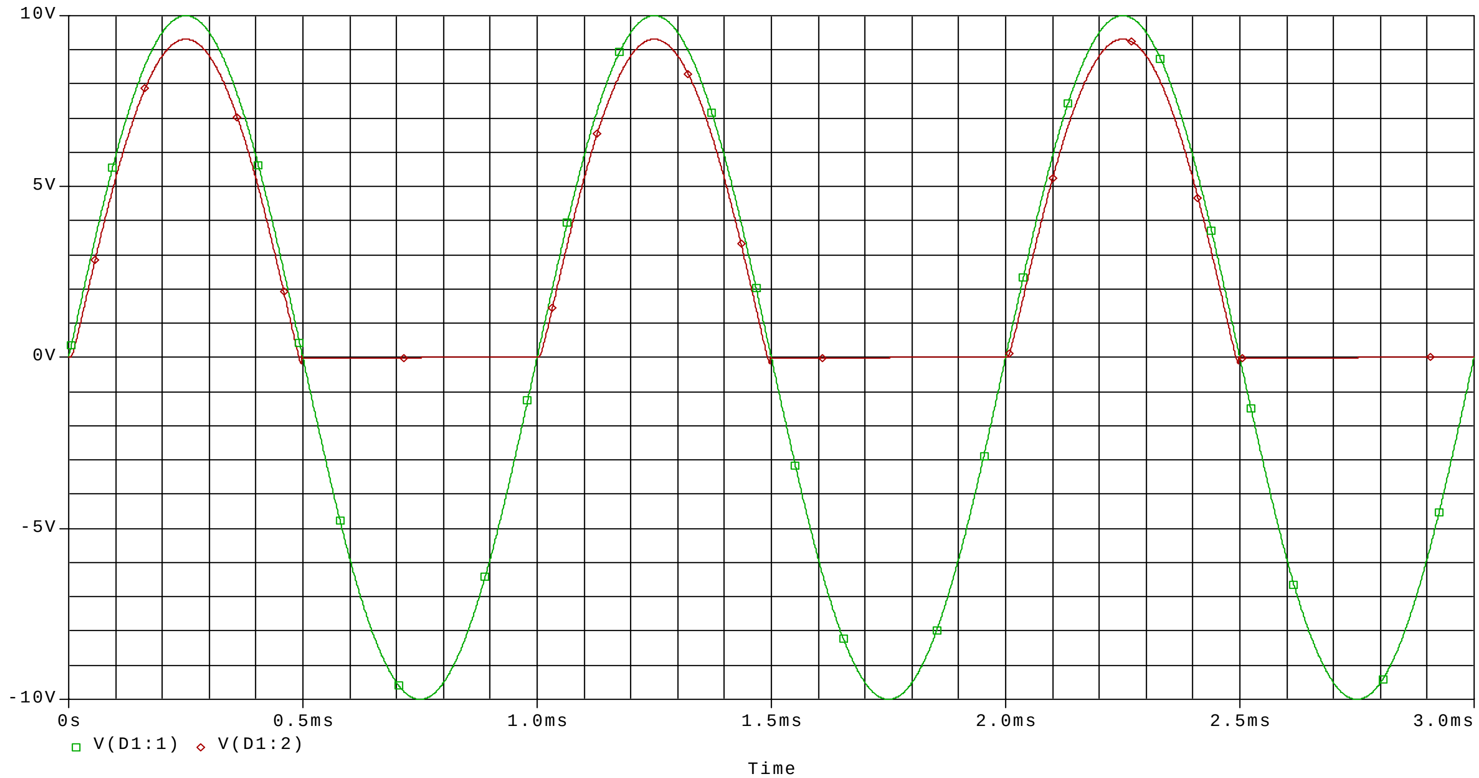


When the positive end of the battery is hooked up to the N-type layer and the negative end is hooked up to the P-type layer, free electrons collect on one end of the diode and holes collect on the other. The depletion zone gets bigger and no current flows.

Introduction to Diodes



Only positive current flows

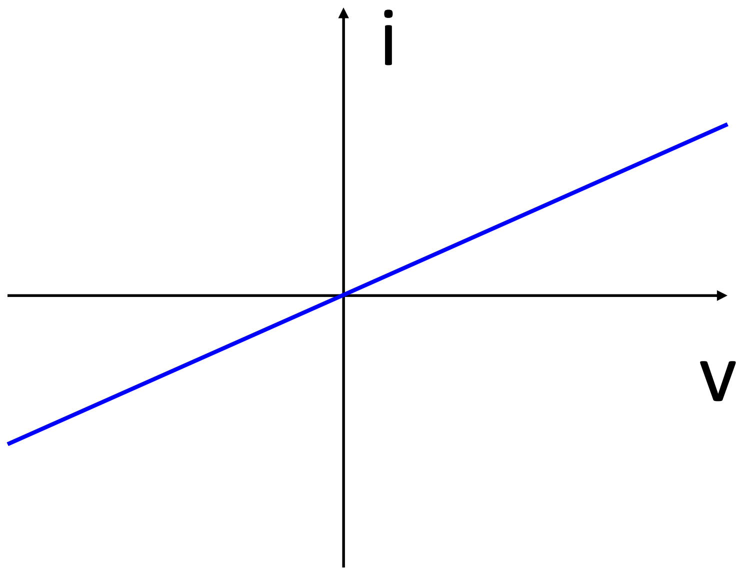


Part A: Diode i-v Characteristic Curves

- What is a i-v characteristic curve?
- i-v curve of an ideal diode
- i-v curve of a real diode

What is an i-v characteristic curve?

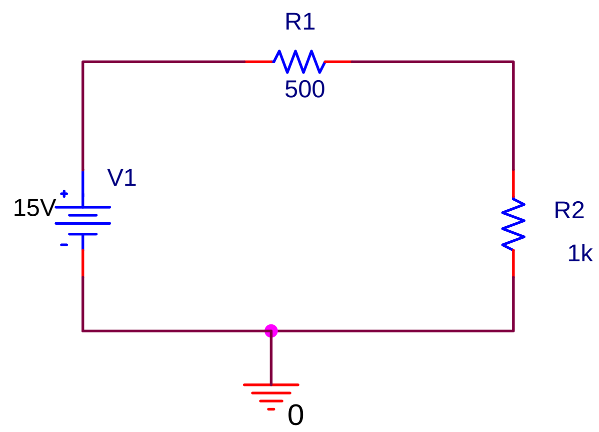
- Recall that the *i-v* relationship for a resistor is given by Ohm's Law: *i=v/R*
- If we plot the voltage across the resistor vs. the current through the resistor, we obtain

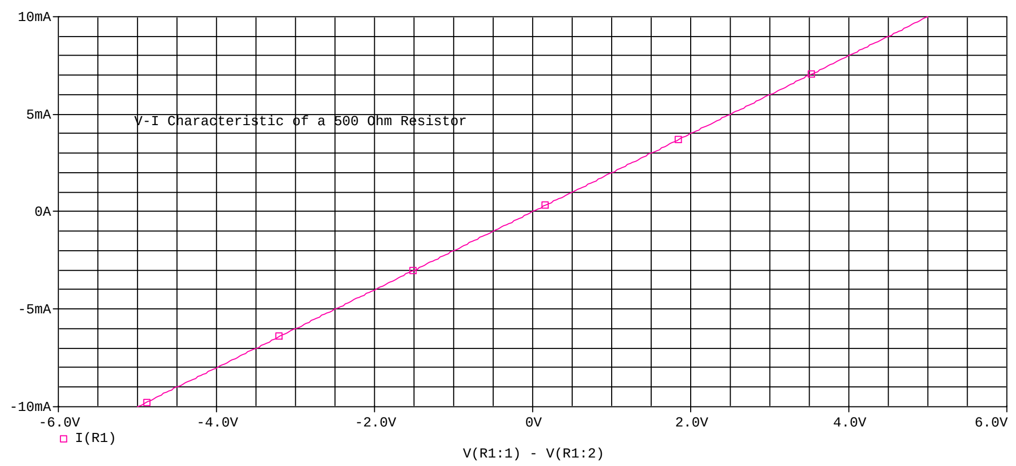


The slope of the straight line is given by 1/R

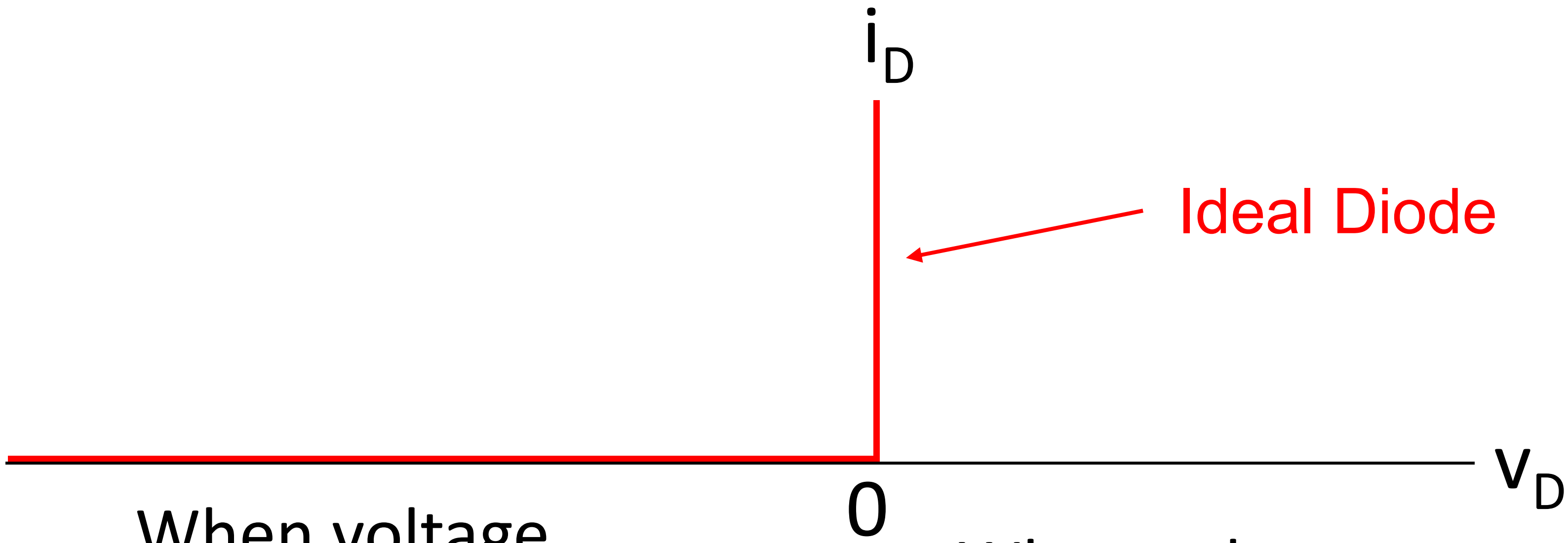
What is an i-v characteristic curve?

If we change the axis variables, we can obtain *i-v* characteristic curves.





i-v characteristic for an ideal diode

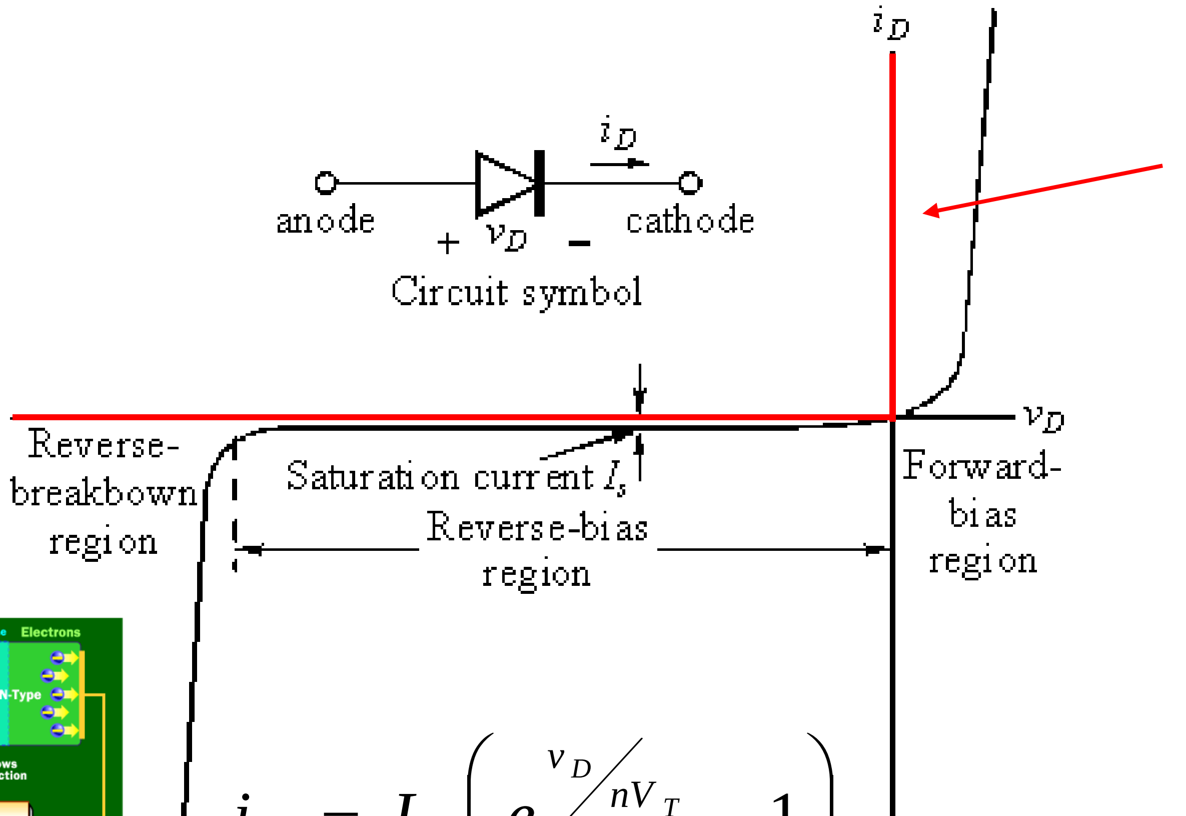


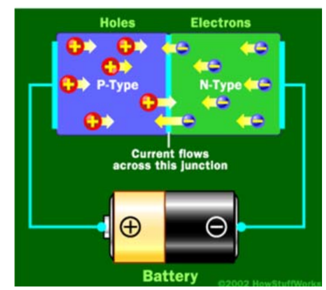
When voltage across the diode is negative, the diode looks like an open circuit.

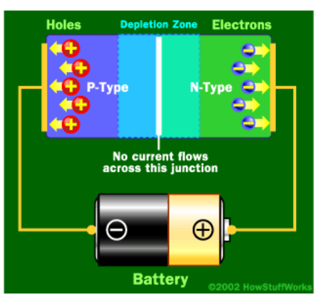
When voltage across the diode is positive, the diode looks like a short.

i-v characteristic of a real diode

- Real diode is close to ideal

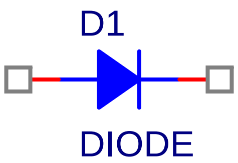


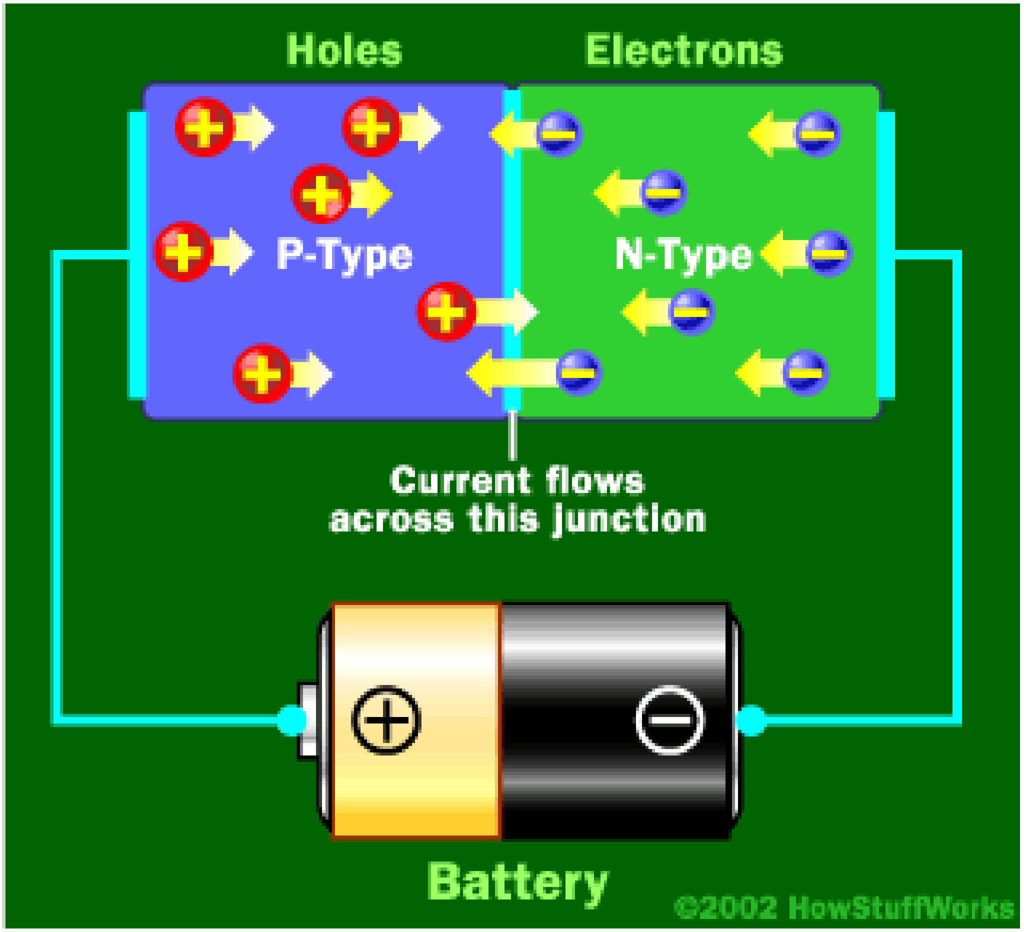




$$i_D = I_S\left(e^{v_D/nV_T} - 1\right)$$

How Diodes Work

ANODE  CATHODE



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How Diodes Work

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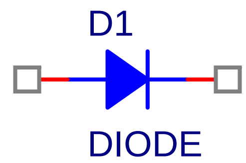
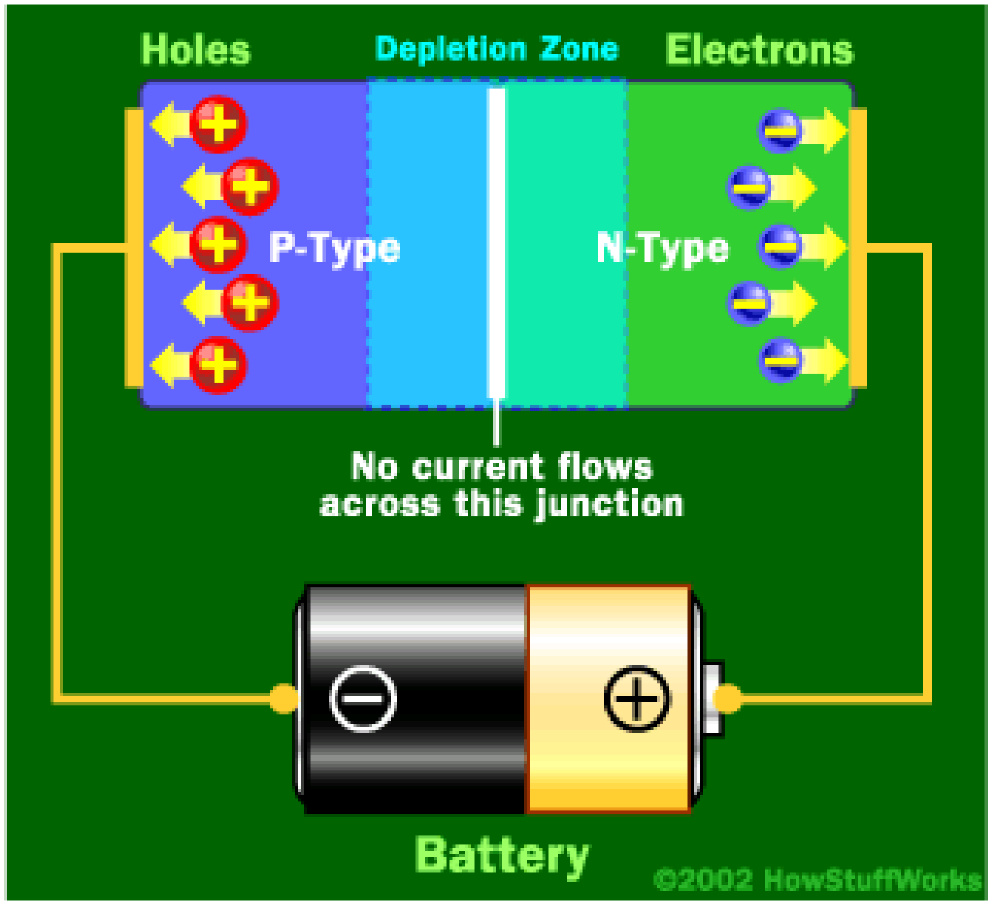


CATHODE



When the positive end of the battery is hooked up to the N-type layer and the negative end is hooked up to the P-type layer, free electrons collect on one end of the diode and holes collect on the other. The depletion zone gets bigger and no current flows.

Real diode characteristics

- A very large current can flow when the diode is forward biased. For power diodes, currents of a few amps can flow with bias voltages of 0.6 to 1.5V. Note that the textbook generally uses 0.6V as the standard value, but 0.7V is more typical for the devices.
- Reverse breakdown voltages can be as low as 50V and as large as 1000V.
- Reverse saturation currents I_s are typically 1nA or less.

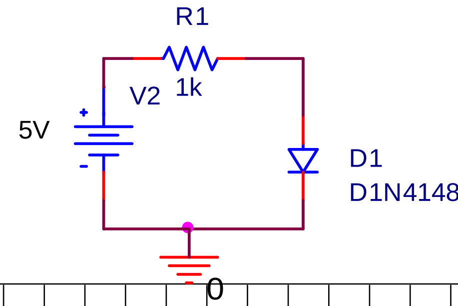
The diode equation

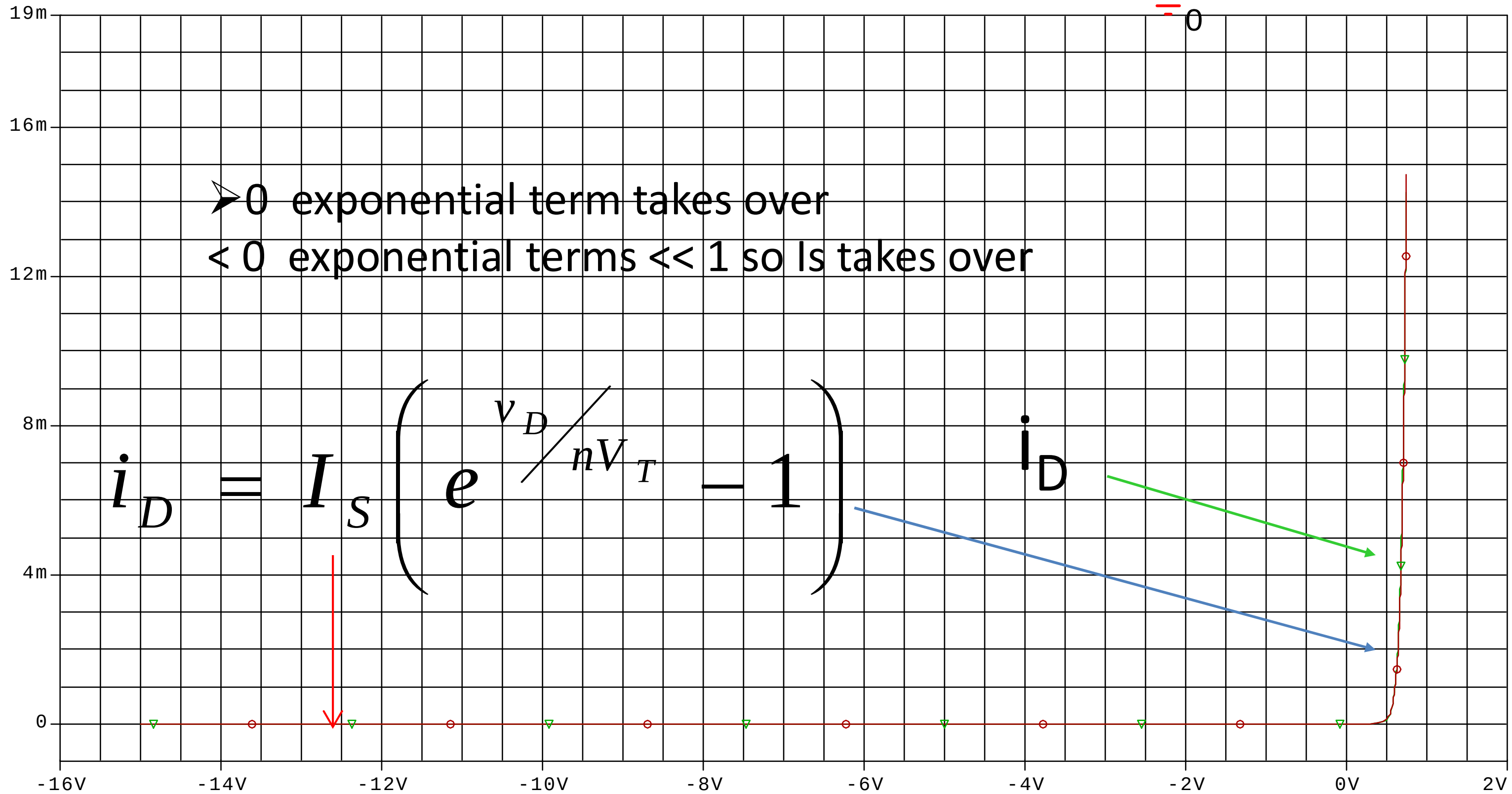
- The i_D-v_D relationship (without breakdown) can be written simply as:

$$i_D = I_S\left(e^{v_D / nV_T} - 1\right)$$

- v_D is the voltage across the diode and i_D is the current through the diode. n and I_s are constants. V_T is a voltage proportional to the temperature, we use 0.0259V.
- Note that for v_D less than zero, the exponential term vanishes and the current i_D is roughly equal to minus the saturation current.
- For v_D greater than zero, the current increases exponentially.

Diode equation





> 0 exponential term takes over

< 0 exponential terms << 1 so Is takes over

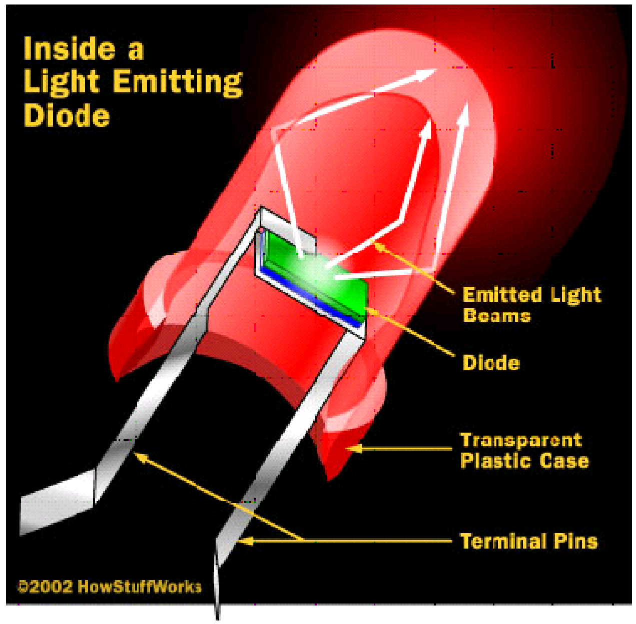
$$i_D = I_S\left(e^{v_D/nV_T} - 1\right)$$

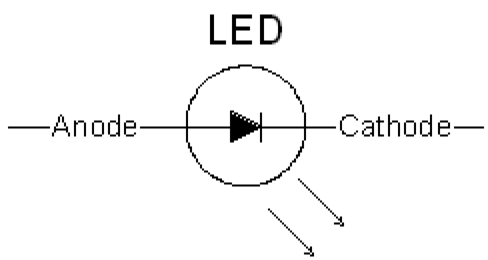
i_D

Both the simulated current vs. voltage (green) and the characteristic equation (red) for the diode are plotted.

Light Emitting Diodes

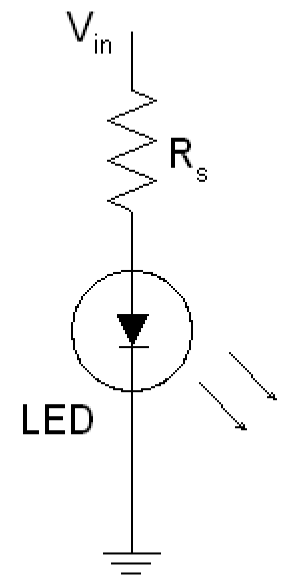
- The Light-Emitting Diode (LED) is a semiconductor pn junction diode that emits visible light or near-infrared radiation when forward biased.
- Visible LEDs emit relatively narrow bands of green, yellow, orange, or red light (tens of nm). Infrared LEDs emit in one of several bands just beyond red light.





Facts about LEDs

- LEDs switch off and on rapidly, are very rugged and efficient, have a very long lifetime, and are easy to use (~ns to μs).
- They are current-dependent sources, and their light output intensity is directly proportional to the forward current through the LED.
- Always operate an LED within its ratings to prevent irreversible damage.
- Use a series resistor (R_s) to limit the current through the LED to a safe value. V_{LED} is the LED voltage drop. It ranges from about 1.3V to about 3.6V.
- I_{LED} is the specified forward current. (Generally 20mA).



$$R_s = \frac{V_{in} - V_{LED}}{I_{LED}}$$

Approximate LED threshold voltages

Diode	V_{LED}		Diode	V_{LED}
infra-red	1.2		blue	3.6
red	2.2		purple	3.6
yellow	2.2		ultra-violet	3.7
green	3.5		white	3.6

How Light Emitting Diodes Work

by Tom Harris

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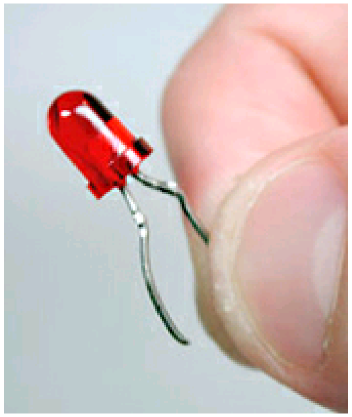
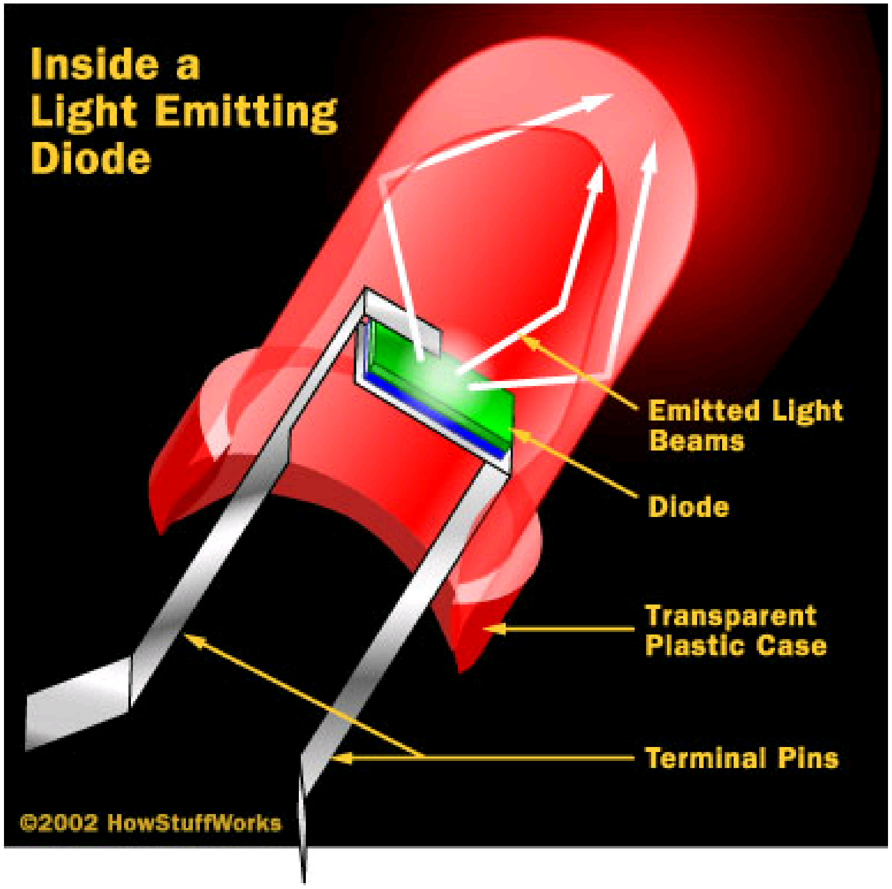
› Introduction to How Light Emitting Diodes Work
› What is a Diode?
› How Can a Diode Produce Light?
› Lots More Information
› What do you think?



Light emitting diodes, commonly called LEDs, are real unsung heroes in the electronics world. They do dozens of different jobs and are found in all kinds of devices. Among other things, they form the numbers on digital clocks, transmit information from remote controls, light up watches and tell you when your appliances are turned on. Collected together, they can form images on a jumbo television screen or illuminate a traffic light.

Basically, LEDs are just tiny light bulbs that fit easily into an electrical circuit. But unlike ordinary incandescent bulbs, they don't have a filament that will burn out, and they don't get especially hot. They are illuminated solely by the movement of electrons in a semiconductor material, and they last just as long as a standard transistor.

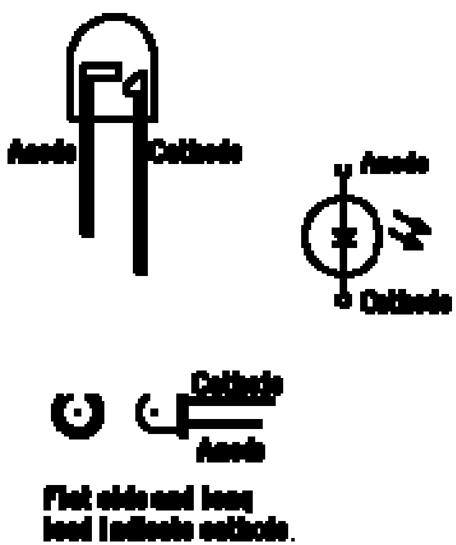


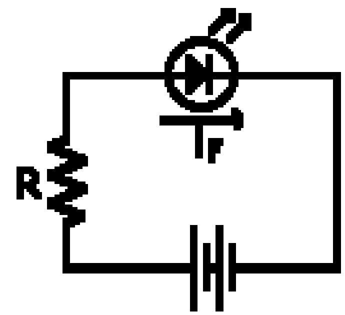
LEDs have several advantages over conventional incandescent lamps. For one thing, they don't have a filament that will burn out, so they last much longer. Additionally, their small plastic bulb makes them a lot more durable. They also fit more easily into modern electronic circuits.

Light Emitting Diode (LED)

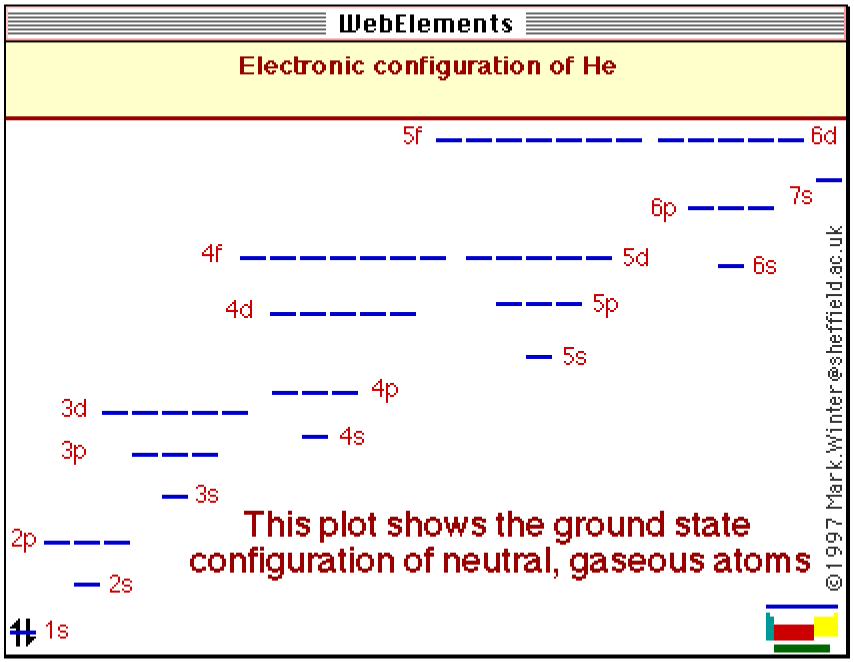
The electroluminescent process of LED is to covert input electrical energy into output optical radiation in the visible or infrared (heat) portion of the spectrum, depending on the semiconductor material.

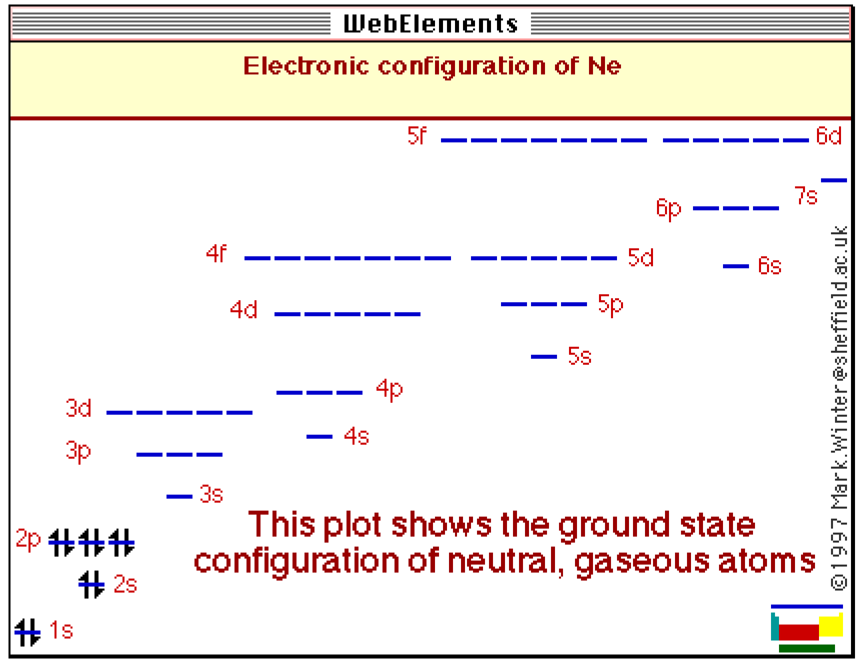
LEDs and laser diodes are very similar devices. In fact, when operating below their threshold current, all laser diodes act as LEDs.





Energy levels



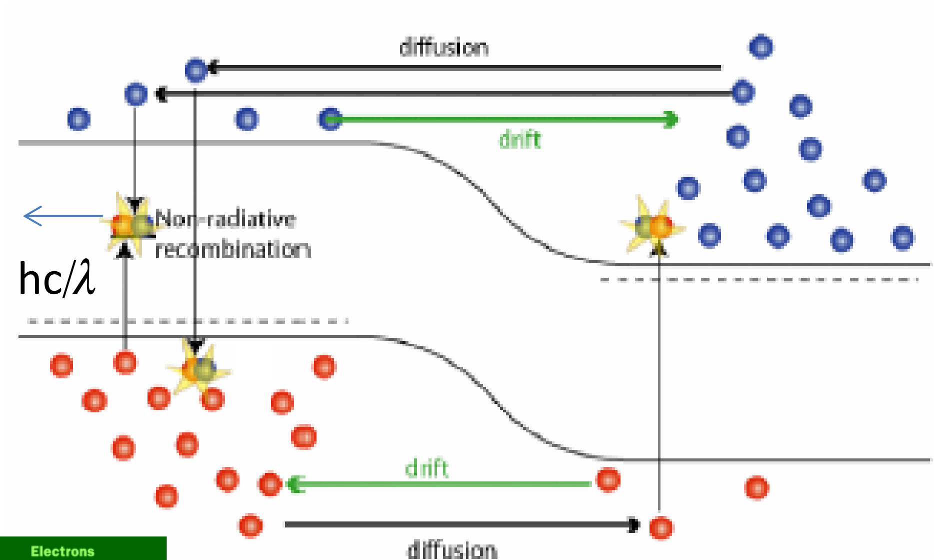


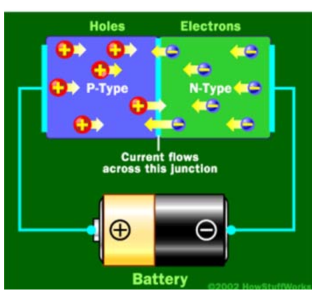
Helium (He) with its two electrons, has filled its s-orbital and its K-shell. Because its outer shell is filled, Helium (He) does not have any valance electrons. As a result, it tends to be nearly perfectly inert or non-reactive

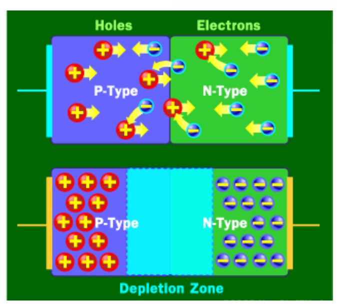
Forward Bias

- Forward bias is a voltage applied to the pn junction that REDUCES the electric field at the barrier, Reverse bias INCREASES the electric field at the junction
- When bias is applied the balance between drift and diffusion current is destroyed – nett current flow
- In forward bias, drift current decreases very slightly (can assume it stays the same) but diffusion current increases – Nett current flow
- In reverse bias opposite occurs with diffusion current decreasing and drift remaining same – Nett current flow (this one isvery small)

$h\upsilon = hc/\lambda$







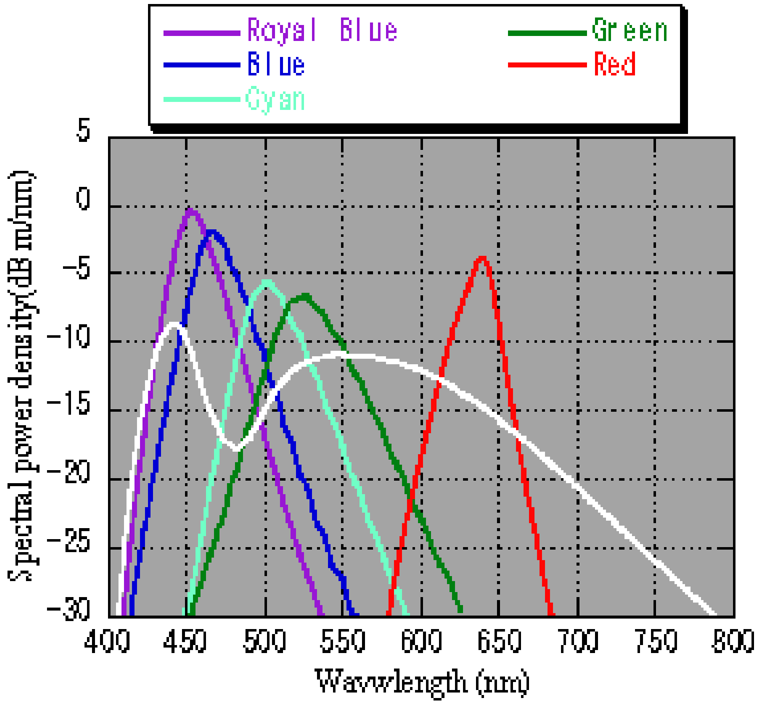
The energy conversion takes place in two stages: first, the energy of carriers in the semiconductor is raised above their equilibrium value by electrical input energy, and second, most of these carriers, after having lived a mean lifetime in the higher energy state, give up their energy as **spontaneous emission** of photons with energy nearly equal to the bandgap E_g of the semiconductor:

$$E_{go} = h\,\upsilon = hc/\lambda$$

where h is plank constant and ν is frequency of emitting light.

The choice of LED materials requires the wavelength light emission to be within visible light or infrared light region. This means that the bandgap of the semiconductor has to be roughly around 2 eV. The most frequency used binary compounds for LED applications are III-V compounds such as GaAs and GaP. In your case, the red diode could be made of a homojunction GaAsP (650nm) diode and the yellow diode made of a homojunction GaAsP:N (585nm) diode, where N representing doping level.

The typical spectral output of a LED might looks like:

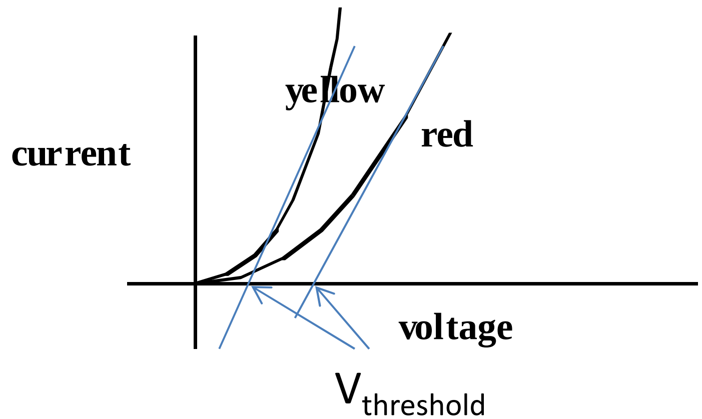


Spectra of different color LEDs

The current-voltage relation of a diode is derived based on the **Boltzman's and Maxwell's equations**. The equation of voltage and current is given:

$$I_d = I_{do}\left(e^{qV_d/2kT} - 1\right)$$

where k=Boltzman's constant= 8.62e-5 eV/°K, T= temperature (°K) and q = single electron charge =1.6e-19 coulombs and I_{do} a function of energy gap. The later term means that different emitting light diodes give different $I_{do.}$ As energy gap increases the current I_{do} increases. This mean the yellow light will increase a lot quicker in current than red when same voltage is applied



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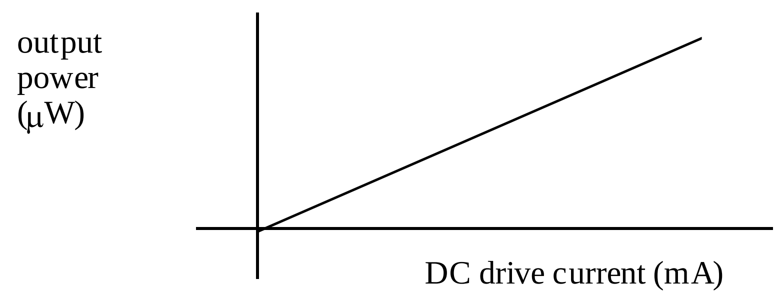
Diode	V_{LED}		Diode	V_{LED}
infra-red	1.2		blue	3.6
red	2.2		purple	3.6
yellow	2.2		ultra-violet	3.7
green	3.5		white	3.6

The output power vs. forward current for the LED appears as a linear function. The relation is given as

$$output\ power = \eta_o I_{inj} \frac{h\upsilon}{q}$$

Where η_o is overall device efficiency=extraction efficient x the radiative efficiency x injection efficiency, *h* is plank constant and n is frequency of emitting light, *q* = single electron charge and $I_{inj} = I_d$. All but $I_{inj} = I_d$ are constant. This linear relation should be verified with your experiment

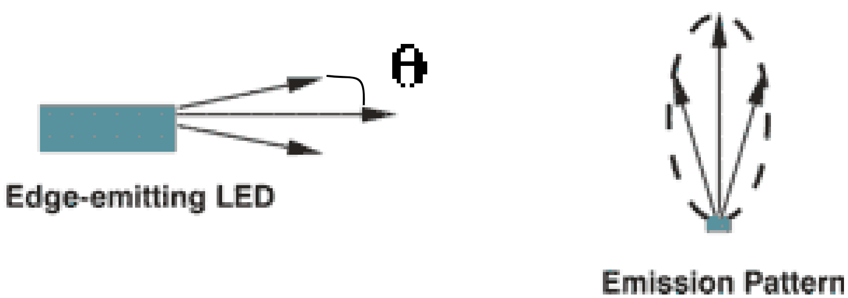


The output power vs. forward current for the LED

LED

There are two basic types of LED structures: edge emitters and surface emitters.

$$P = P_0 \cos\theta$$

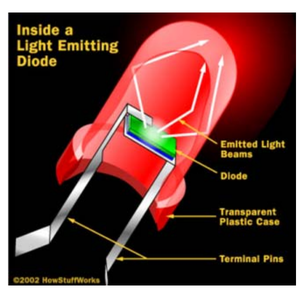


output power is high (emitting spot is very small, typically 30-50 μm)

narrow emission spectra (FWHM is typically about 7% of the central wavelength)

Narrow beam pattern

w.wang



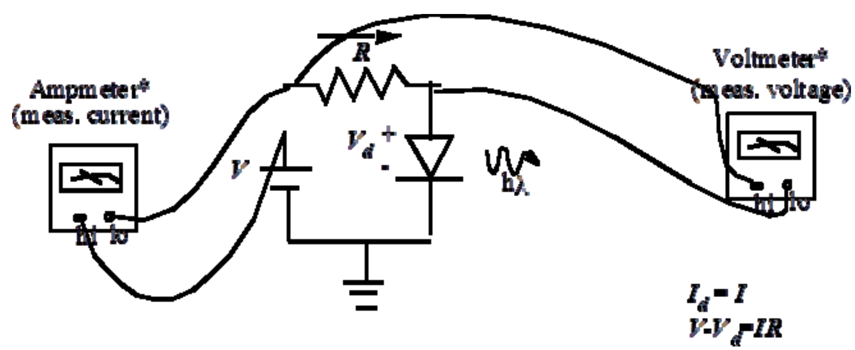
simple structure, are relatively inexpensive, offer low-to-moderate output power levels, and are capable of low-to-moderate operating speeds

output power is as high or higher than the edge-emitting LED, but the emitting area is large, causing poor coupling efficiency to the optical fiber

emit light in all directions

Using the setup as shown in Figure., where the current is provided by the voltage source V is limited by the series resistance R. Under operating conditions, the voltage drop across the LED is V_d , the operating voltage of the device. If operating current is $I=I_d$, then the circuit can be described by

$$V - V_{threshold} = I_d R$$



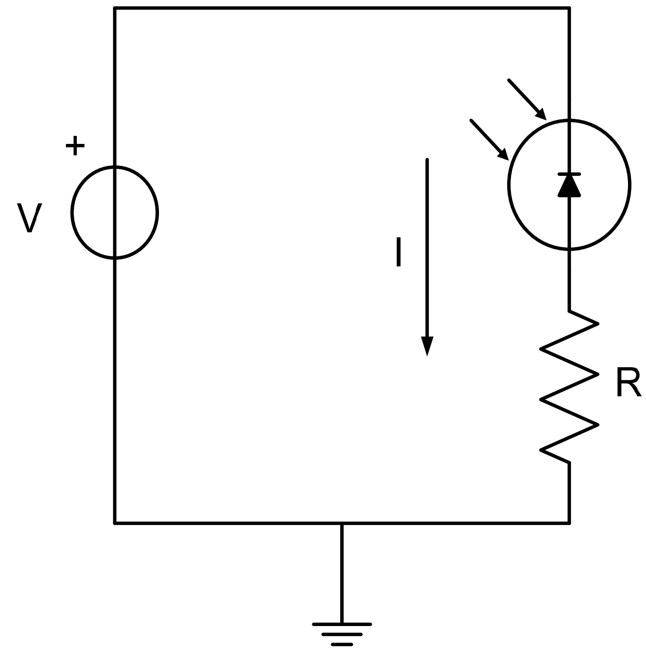
Detector

Photodiodes and Phototransistors

– Photodiodes are designed to detect photons and can be used in circuits to sense light.

– Phototransistors are photodiodes with some internal amplification.

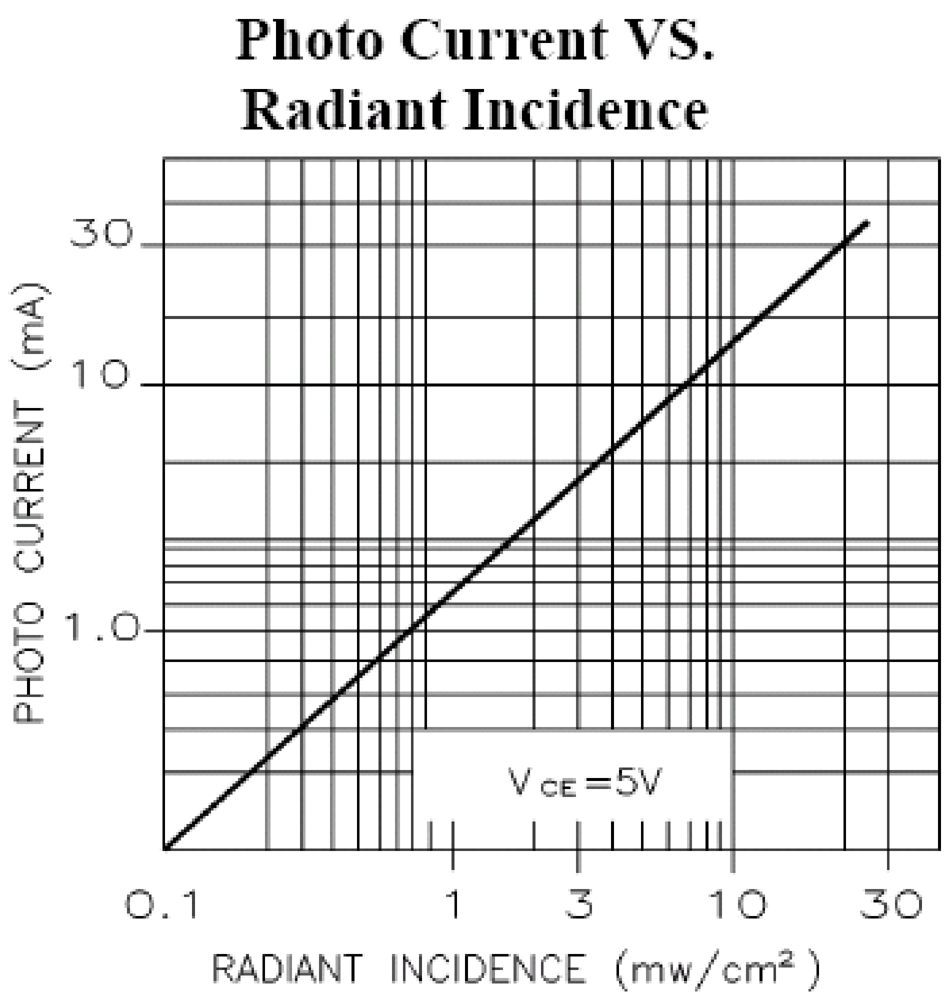
Photodiode Light-detector Circuit



<u>Note</u>:

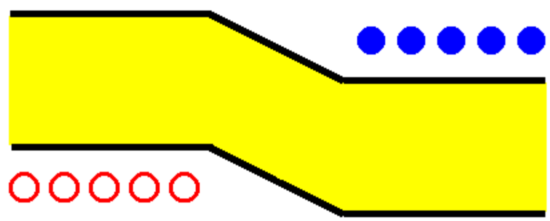
Reverse current flows through the photodiode when it is sensing light.
If photons excite carriers in a reverse-biased pn junction, a very small current proportional to the light intensity flows.
The sensitivity depends on the wavelength of light.

Phototransistor Light Sensitivity



The current through a phototransistor is directly proportional to the intensity of the incident light.

Semicoductor types (interval photoemission)



P-N junction (no bias, short circuit)

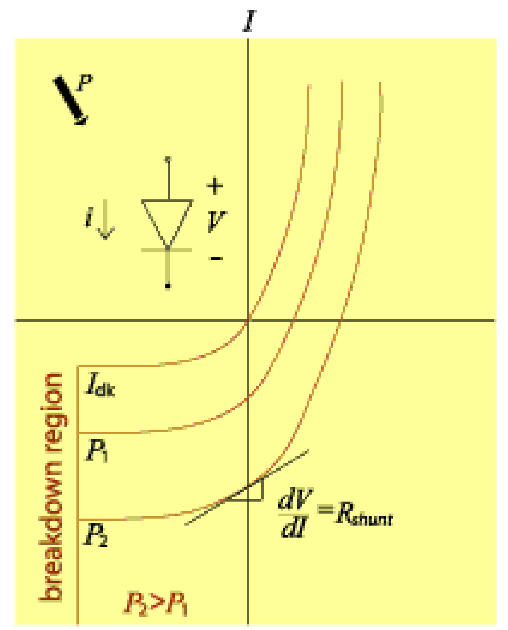
1. Absorbed hν excited e from valence to conduction, resulting in the creation of e-h pair
2. Under the influence of a bias voltage these carriers move through the material and induce a current in the external circuit.
3. For each electron-hole pair created, the result is an electron flowing in the circuit.

Photodiode Operation

A photodiode behaves as a photocontrolled current source in parallel with a semiconductor diode and is governed by the standard diode equation

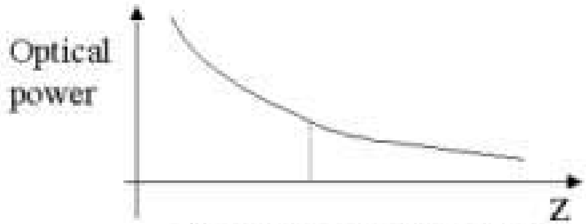
$$I_d = I_{do}\left(e^{qV_d/2kT} - 1\right) + I_p$$

where I is the total device current, I_p is the photocurrent, I_{dk} is the dark current (leakage current), V_0 is the voltage across the diode junction, q is the charge of an electron, k is Boltzmann's constant, and T is the temperature in degrees Kelvin.

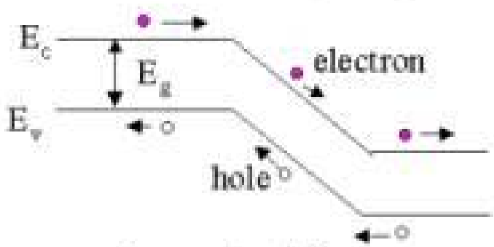


Two significant features to note from both the curve and the equation are that the photogenerated current (I_p) is additive to the diode current, and the dark current is merely the diode's reverse leakage current. Finally, the detector shunt resistance is the slope of the *I-V* curve (*dV/dI*) evaluated at *V*= 0.

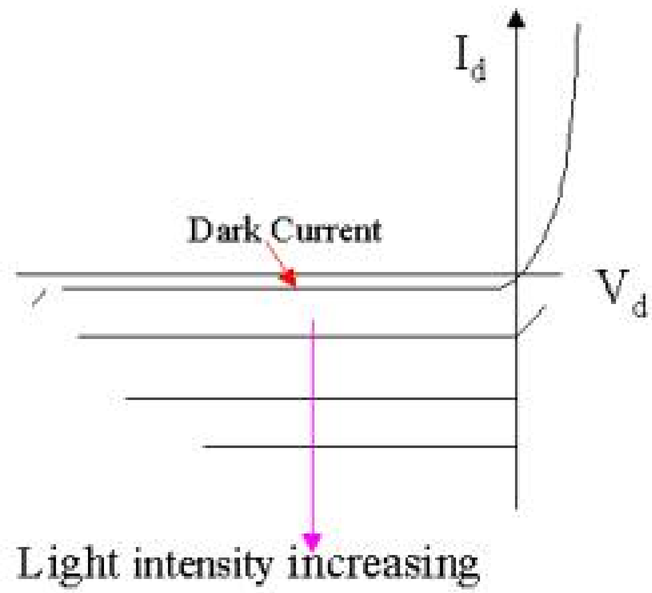
p-n photo diode in reverse bias



Variation of optical power



Energy band diagram



Reverse bias characteristic

- Reverse bias current is mainly due to minority carriers
- Photo current increases significantly in reverse bias –
- diffusion current outside the depletion region

diffusion is slow process <u>(high potential barrier)</u>

Quantum efficiency

A photodiode's capability to convert light energy to electrical energy, expressed as a percentage, is its Quantum Efficiency, (Q.E.).

$$\eta = r_e/r_p = \frac{\text{\# of electrons (holes) collected as } I_p\text{/sec}}{\text{\# of incident photons/sec}}$$

Depends on λ, through absorption coefficient, thickness of layers,
Doping, geometry, etc. Operating under ideal conditions of reflectance, crystal structure and internal resistance, a high quality silicon photodiode of optimum design would be capable of approaching a Q.E. of 80%.

Photodiode Responsivity

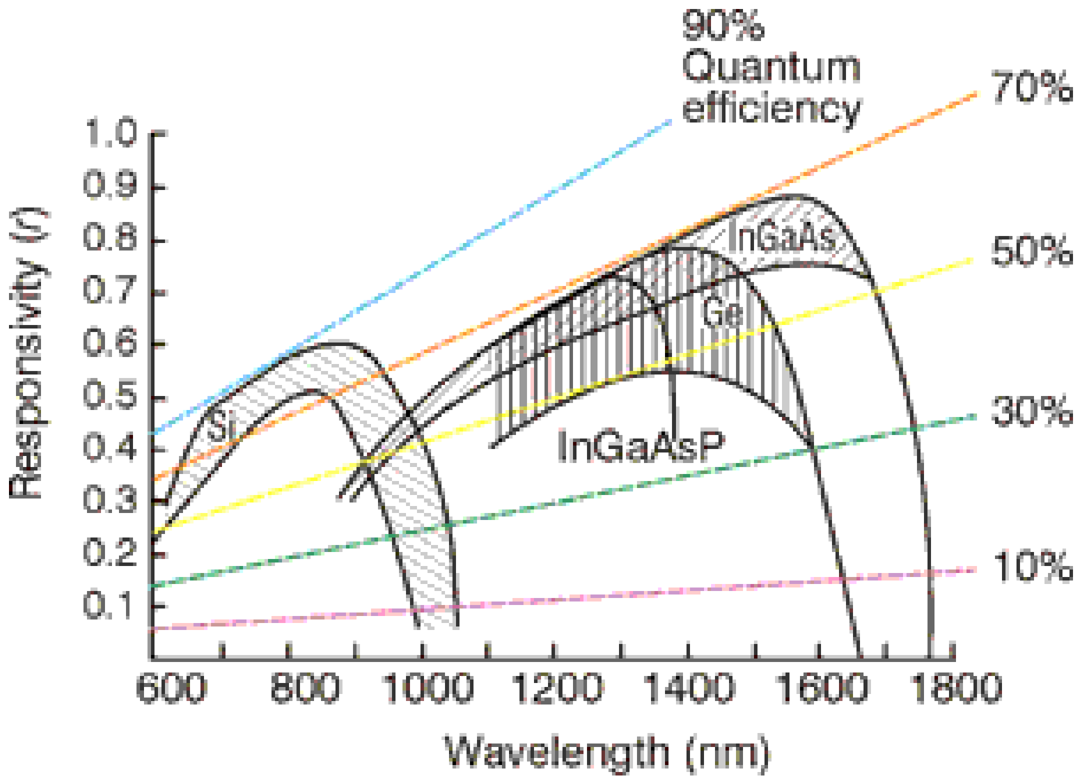
Responsivity R_λ is defined as the ratio of radiant energy (in watts), P, incident on the photodiode to the photocurrent output in amperes I_p. It is expressed as the absolute responsivity in amps per watt. Please note that radiant energy is usually expressed as watts/cm^2 and that photodiode current as amps/cm^2. The cm^2 term cancels and we are left with amps/watt (A/W).

$$R_\lambda = \frac{I_p}{P} \qquad \text{(A/W)}$$

Since $h\upsilon$ = energy of photon, $P = r_p\, h\upsilon$

where r_p = photon flux = $P/\,h\upsilon$ = # photons/ sec

Photodetectors



Electron rate then

$$r_e = \eta r_p = \eta P/(h\nu)$$

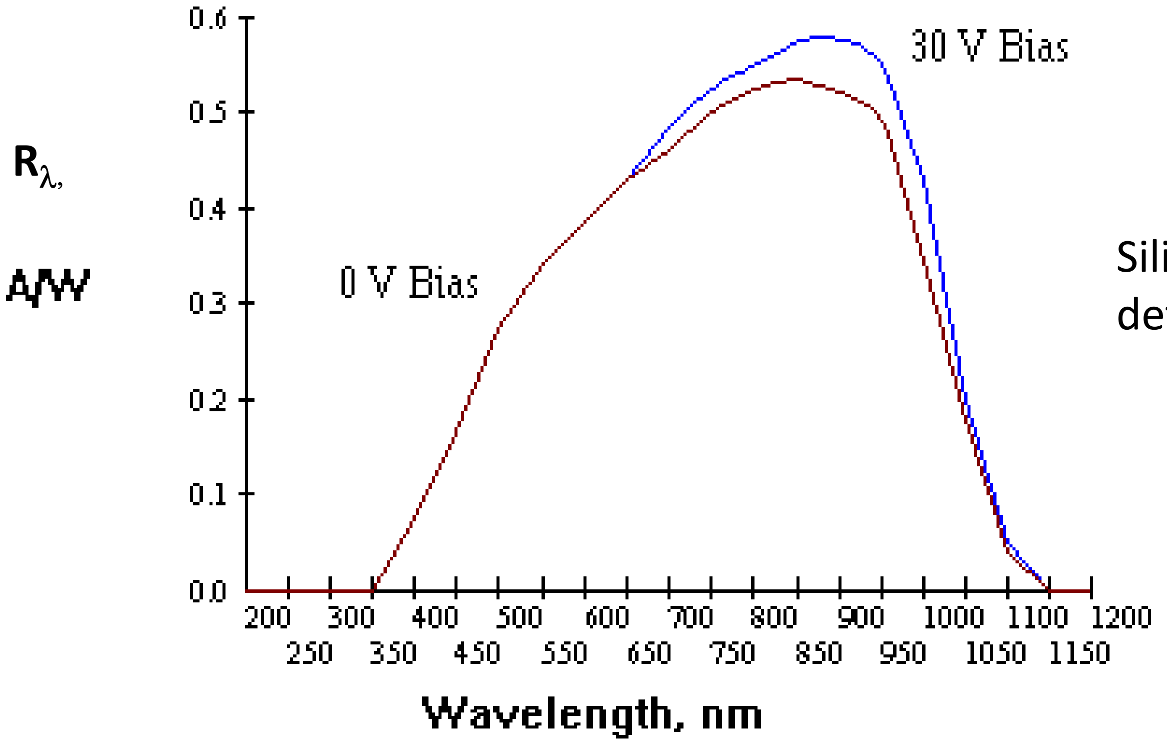
Therefore, the output photo current is

$$I_p = e\eta P/(h\nu)$$

The responsivity may then be written

$$R_\lambda = e\eta/(h\nu) = e\eta\lambda/(hc) = \eta\lambda/1.24 \text{ (A/W)}$$

h= plank constant = 6.63×10^{-34} joule-sec



Silicone based detector

A typical responsivity curve that shows A/W as a function of wavelength

Typical Photodetector Characteristics

Photodetector	Wavelength (nm)	Responsivity (A/W)	Dark Current (nA)	Rise Time (ns)
Silicon PN	550–850	0.41–0.7	1–5	5–10
Silicon PIN	850–950	0.6–0.8	10	0.070
InGaAs PIN	1310–1550	0.85	0.5–1.0	0.005–5
InGaAs APD	1310–1550	0.80	30	0.100
Germanium	1000–1500	0.70	1000	1–2