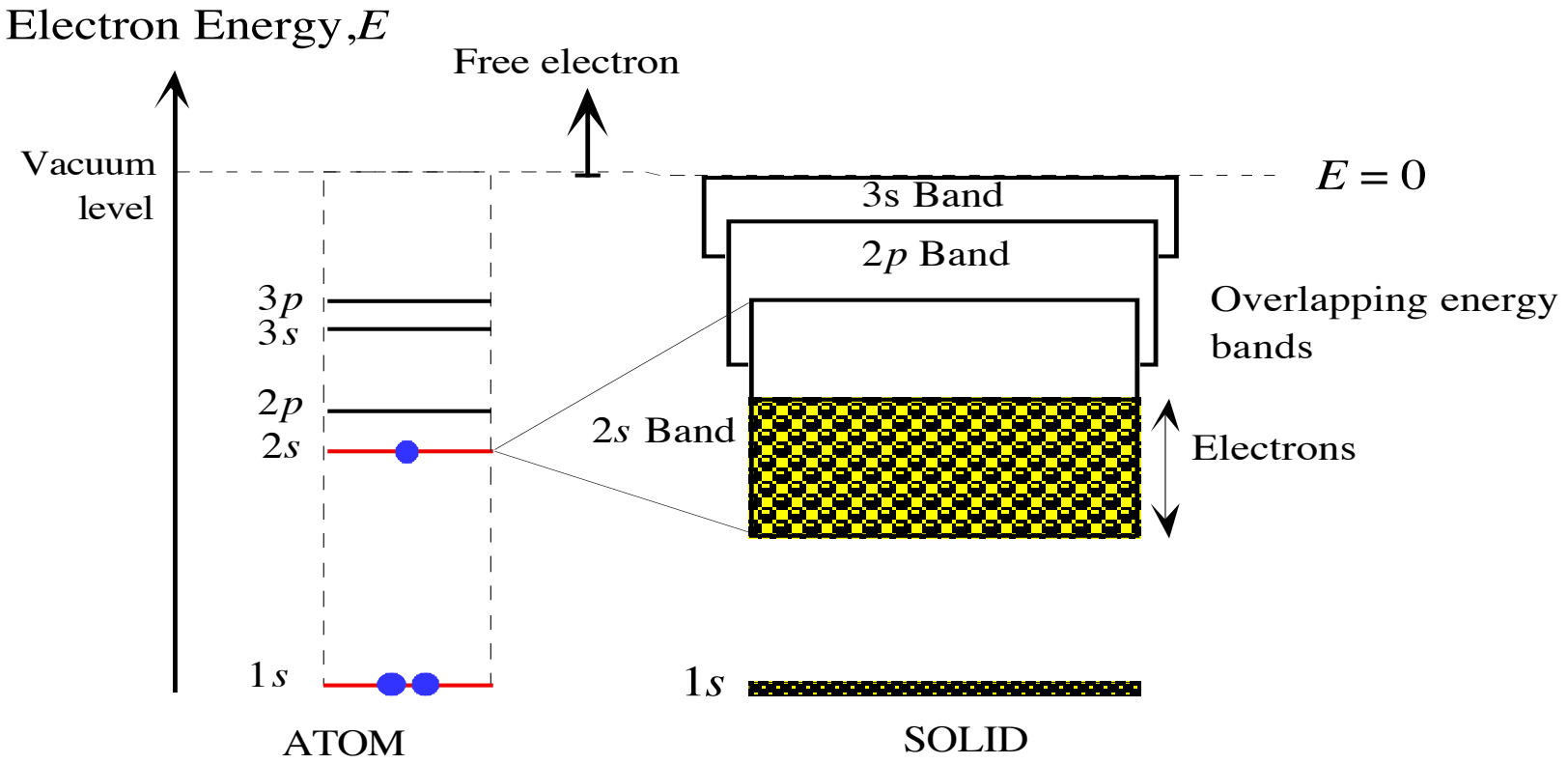
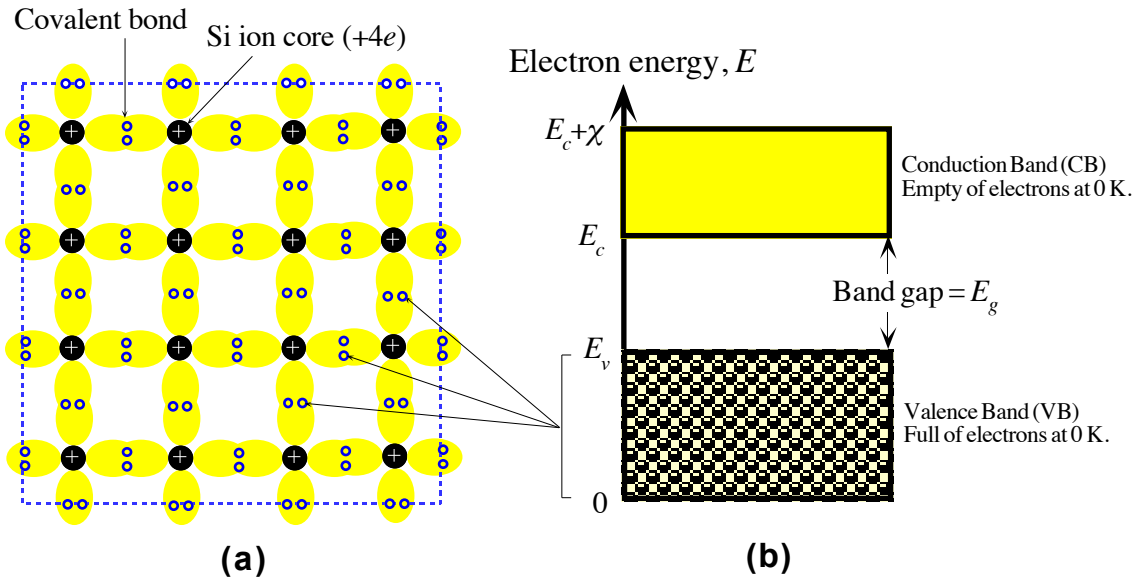
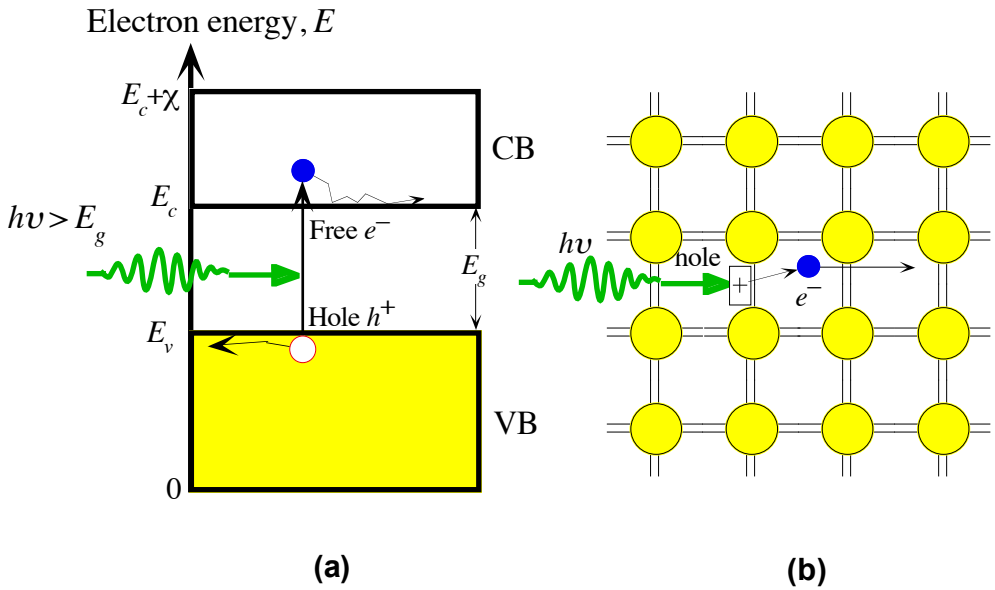


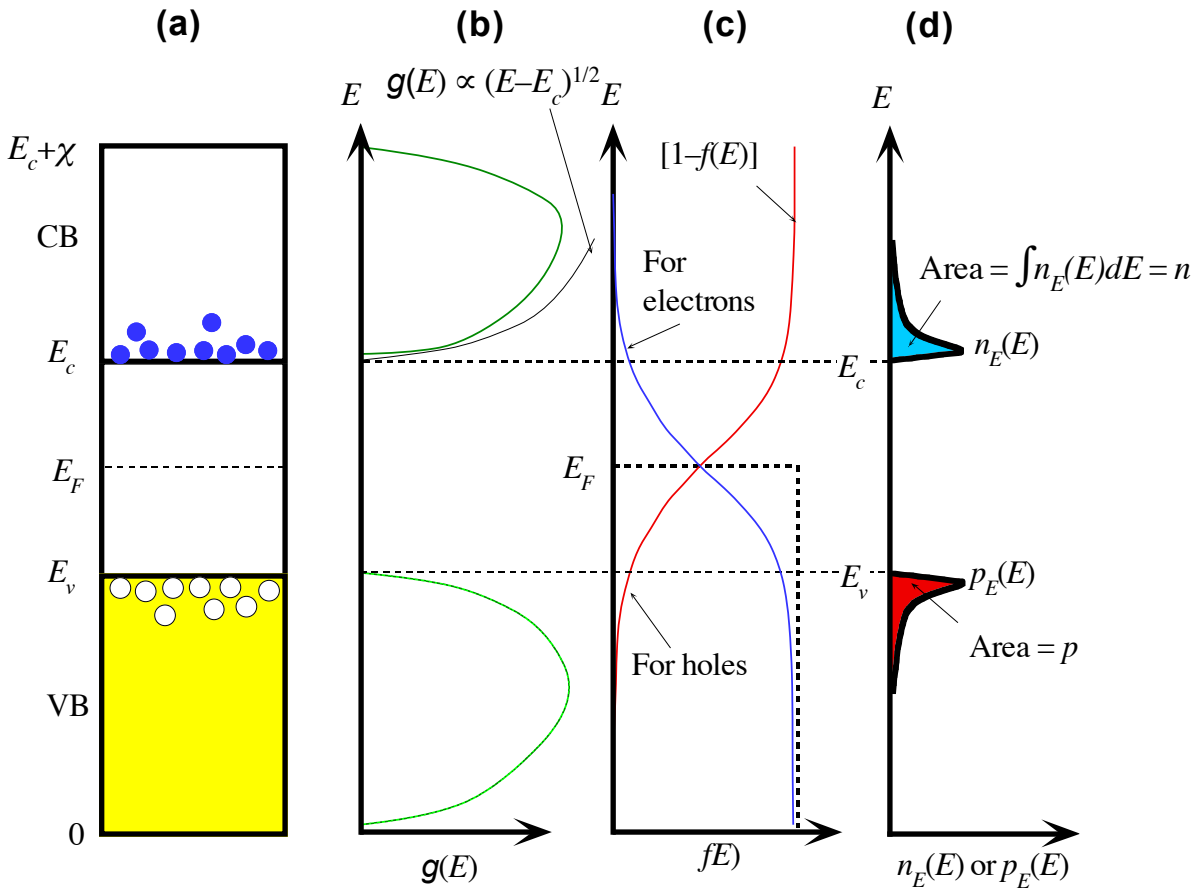
In a metal the various energy bands overlap to give a single band of energies that is only partially full of electrons. There are states with energies up to the vacuum level where the electron is free.



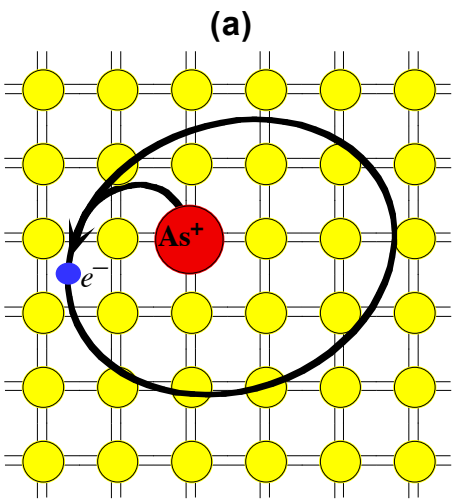
(a) A simplified two dimensional view of a region of the Si crystal showing covalent bonds. (b) The energy band diagram of electrons in the Si crystal at absolute zero of temperature.



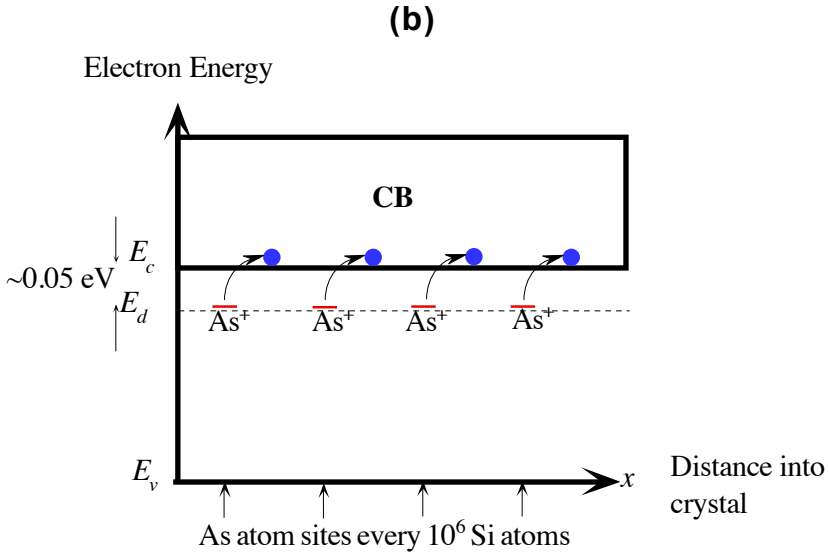
(a) A photon with an energy greater than E_g can excite an electron from the VB to the CB. (b) Each line between Si-Si atoms is a valence electron in a bond. When a photon breaks a Si-Si bond, a free electron and a hole in the Si-Si bond is created.



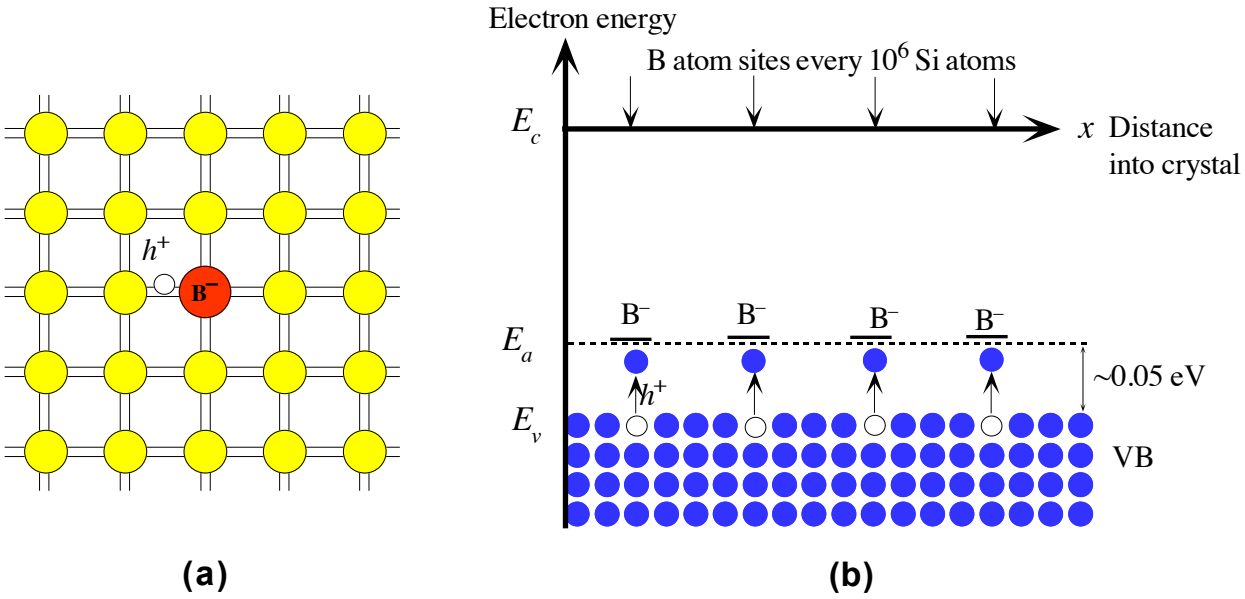
(a) Energy band diagram. (b) Density of states (number of states per unit energy per unit volume). (c) Fermi-Dirac probability function (probability of occupancy of a state). (d) The product of $g(E)$ and $f(E)$ is the energy density of electrons in the CB (number of electrons per unit energy per unit volume). The area under $n_E(E)$ vs. E is the electron concentration.



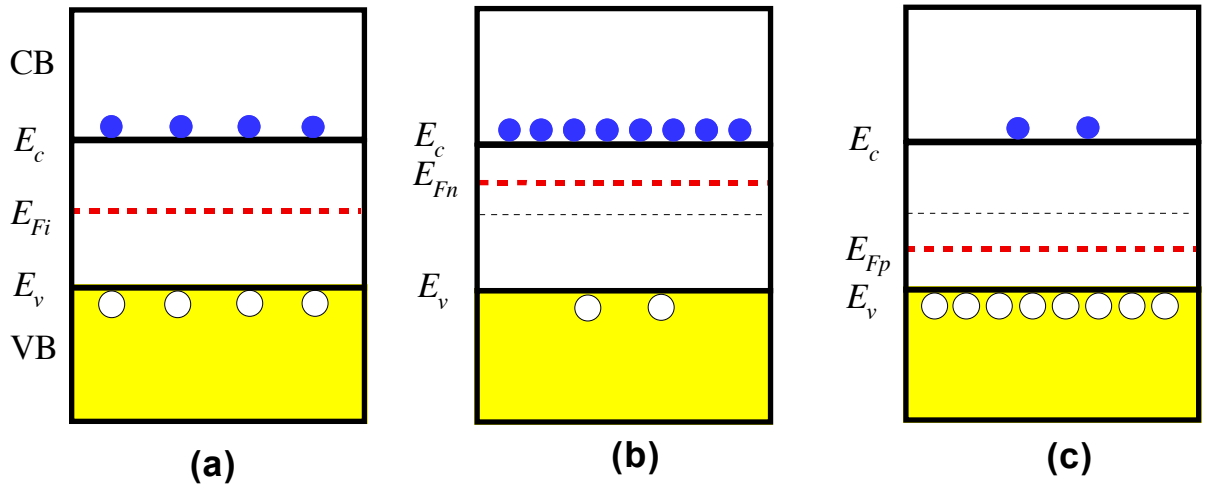
(a) The four valence electrons of As allow it to bond just like Si but the fifth electron is left orbiting the As site. The energy required to release to free fifth-electron into the CB is very small.



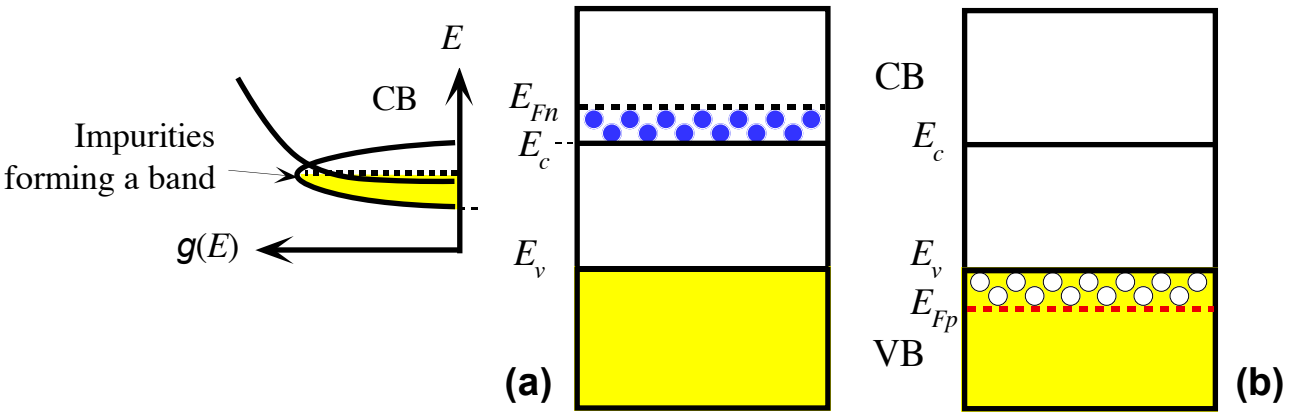
(b) Energy band diagram for an *n*-type Si doped with 1 ppm As. There are donor energy levels just below E_c around As+ sites.



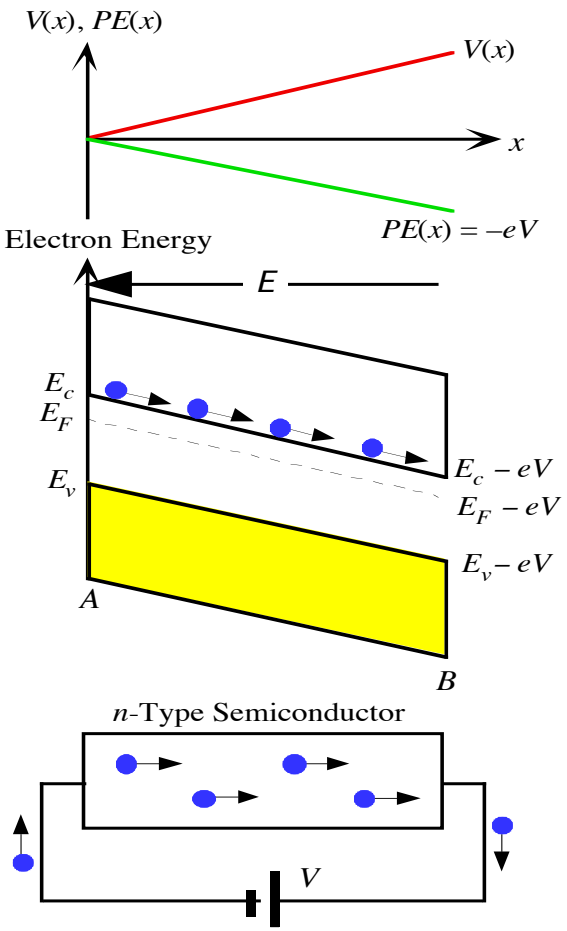
(a) Boron doped Si crystal. B has only three valence electrons. When it substitutes for a Si atom one of its bonds has an electron missing and therefore a hole. (b) Energy band diagram for a *p*-type Si doped with 1 ppm B. There are acceptor energy levels just above E_v around B⁻ sites. These acceptor levels accept electrons from the VB and therefore create holes in the VB.



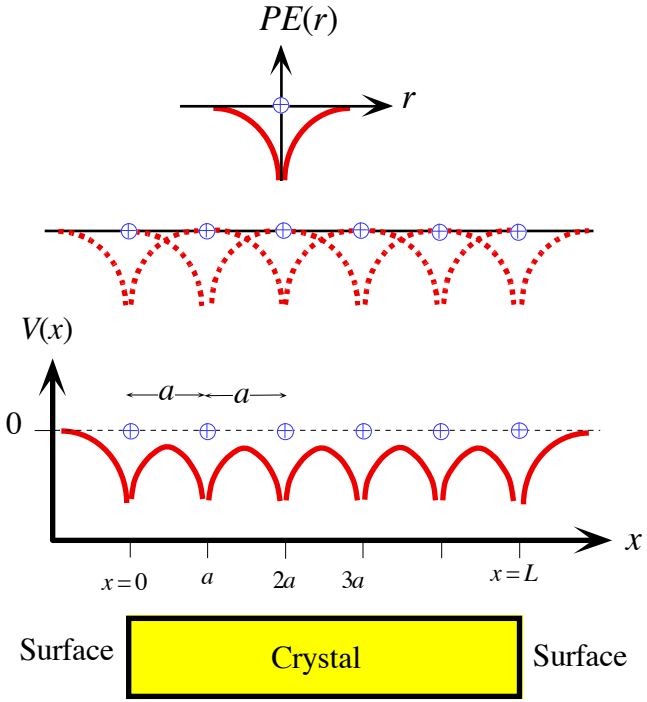
Energy band diagrams for (a) intrinsic (b) *n*-type and (c) *p*-type semiconductors. In all cases, $np = n_i^2$. Note that donor and acceptor energy levels are not shown.



(a) Degenerate *n*-type semiconductor. Large number of donors form a band that overlaps the CB. (b) Degenerate *p*-type semiconductor.



Energy band diagram of an *n*-type semiconductor connected to a voltage supply of V volts. The whole energy diagram tilts because the electron now has an electrostatic potential energy as well

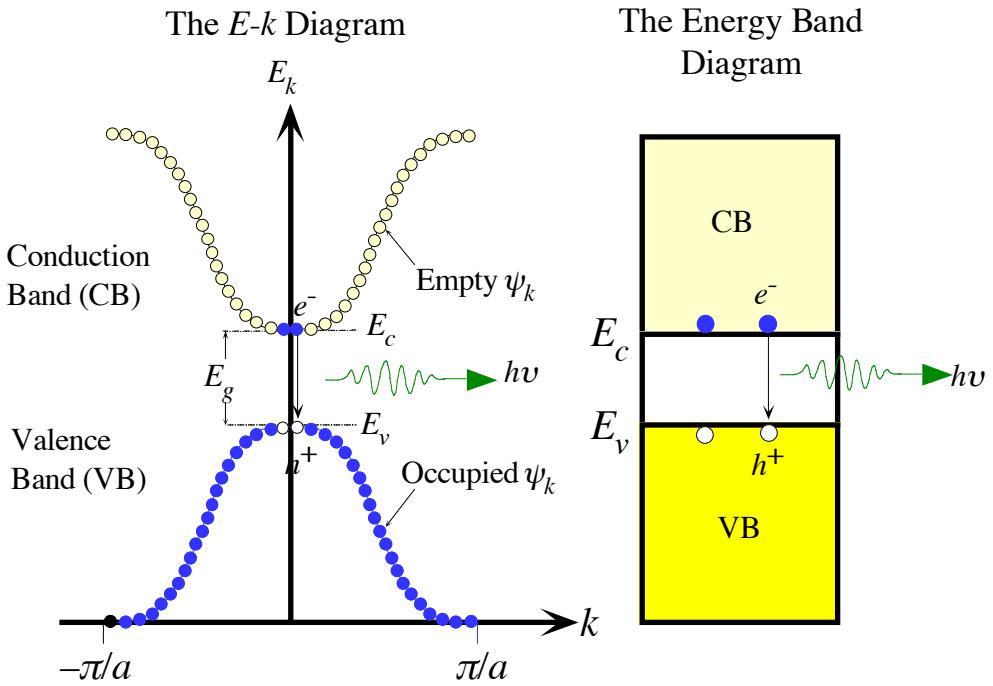


PE of the electron around an isolated atom

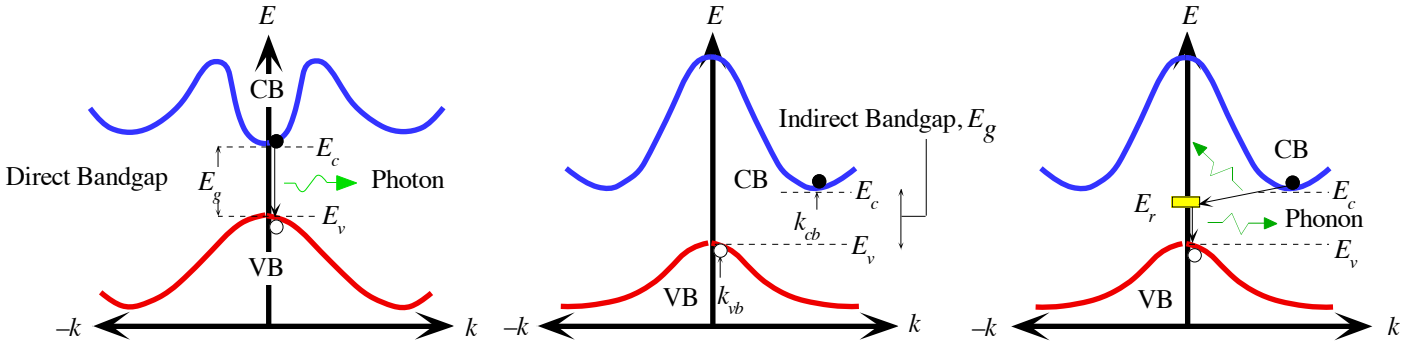
When *N* atoms are arranged to form the crystal then there is an overlap of individual electron *PE* functions.

PE of the electron, $V(x)$, inside the crystal is periodic with a period a.

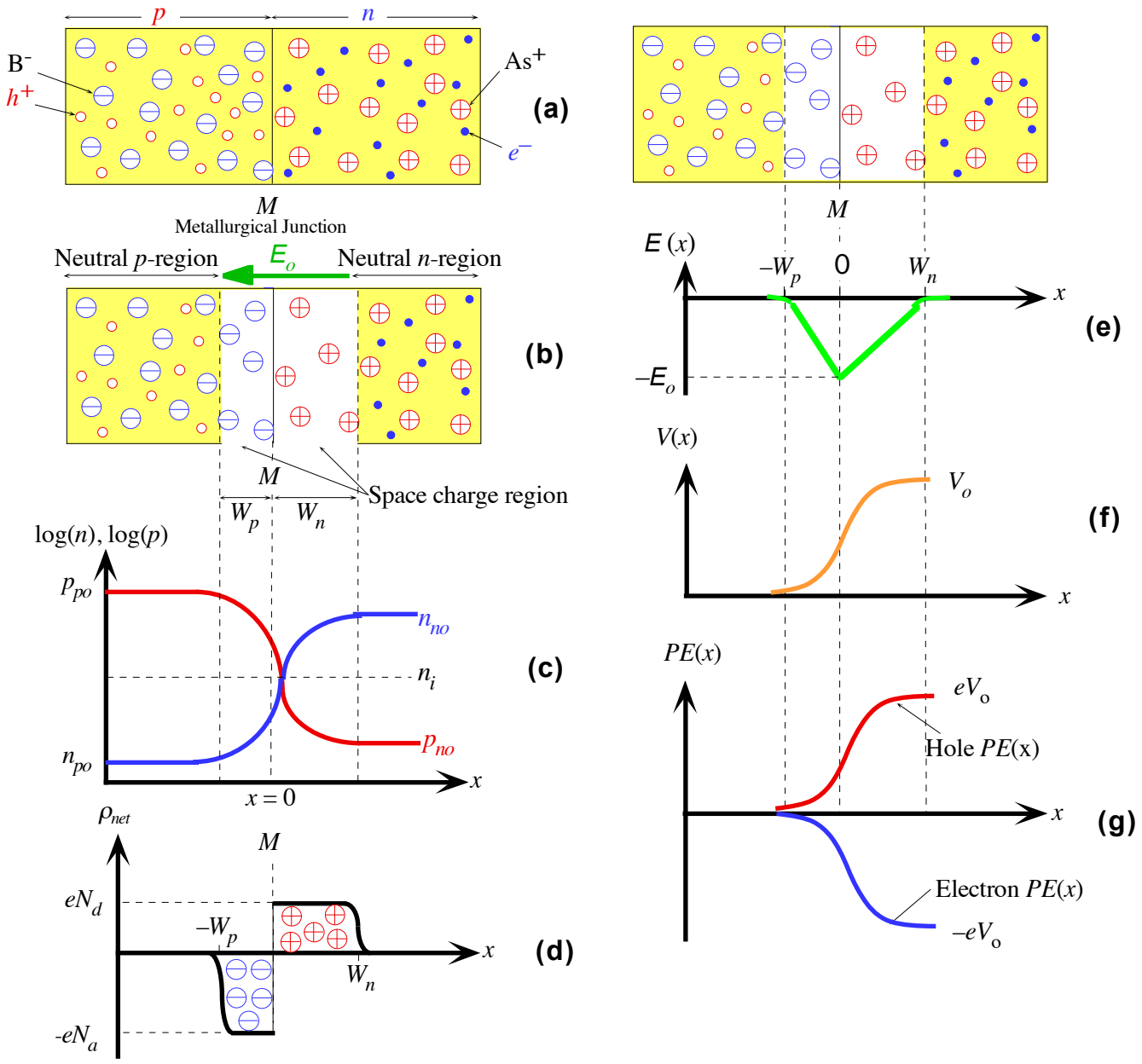
The electron potential energy (*PE*), $V(x)$, inside the crystal is periodic with the same periodicity as that of the crystal, a. Far away outside the crystal, by choice, $V = 0$ (the electron is free and $PE = 0$).



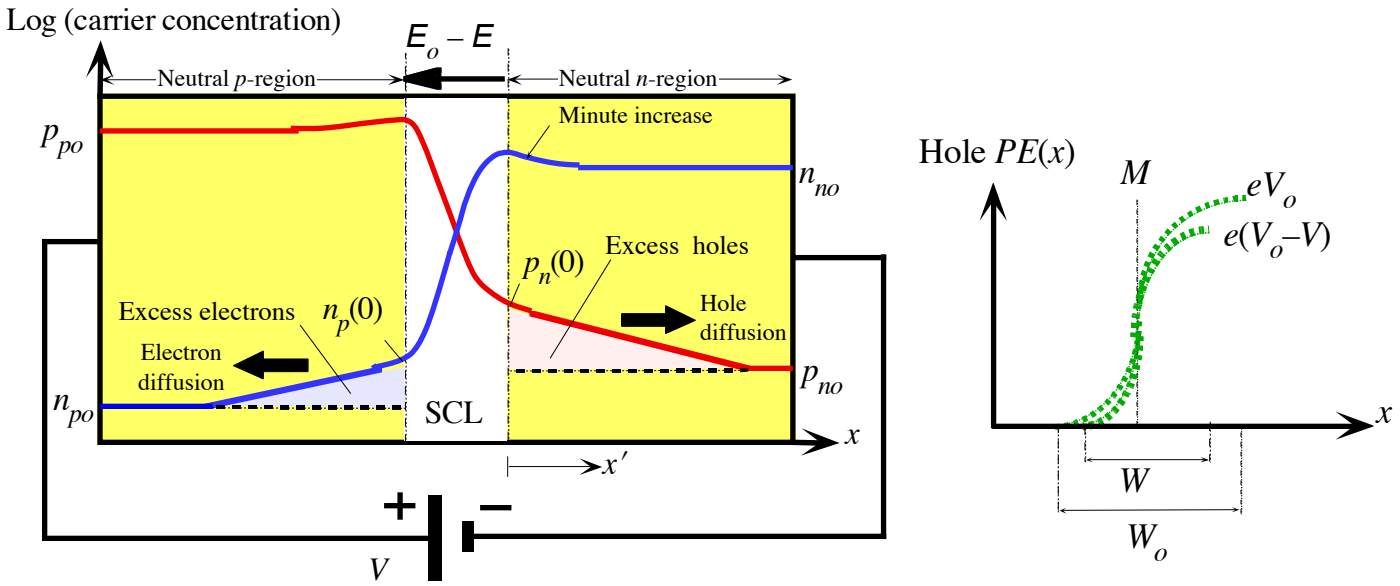
The *E-k* diagram of a direct bandgap semiconductor such as GaAs. The *E-k* curve consists of many discrete points with each point corresponding to a possible state, wavefunction $\psi_k(x)$, that is allowed to exist in the crystal. The points are so close that we normally draw the *E-k* relationship as a continuous curve. In the energy range E_v to E_c there are no points ($\psi_k(x)$ solutions).



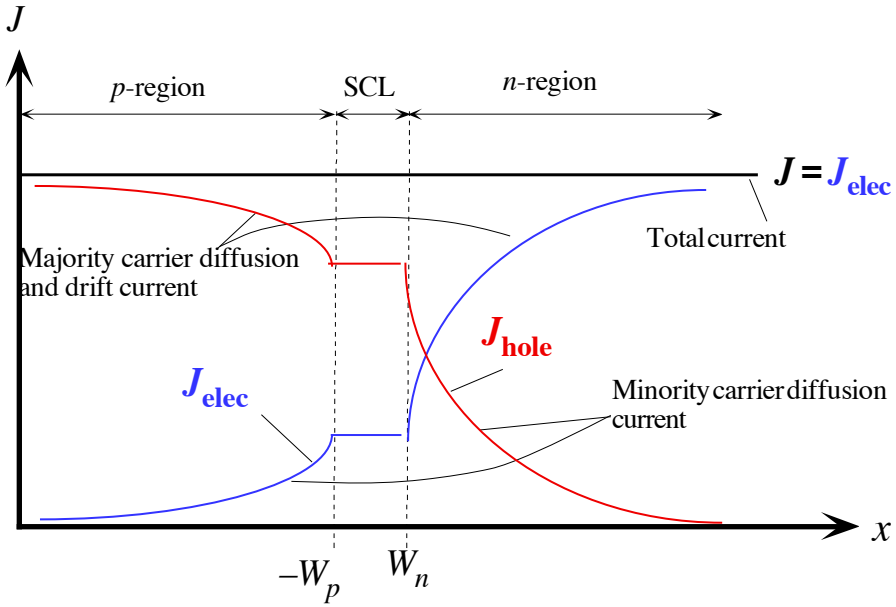
(a) In GaAs the minimum of the CB is directly above the maximum of the VB. GaAs is therefore a direct bandgap semiconductor. (b) In Si, the minimum of the CB is displaced from the maximum of the VB and Si is an indirect bandgap semiconductor. (c) Recombination of an electron and a hole in Si involves a recombination center .



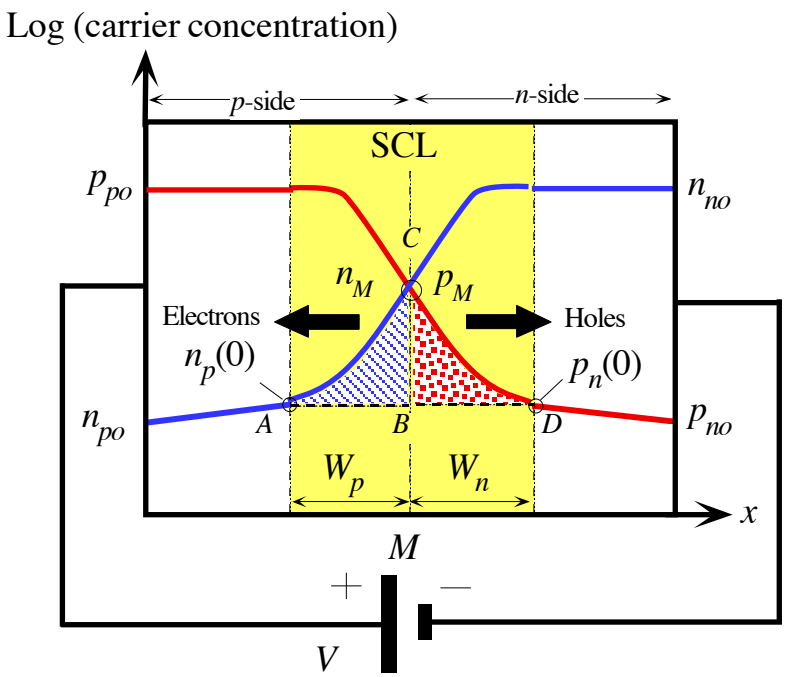
Properties of the *pn* junction.



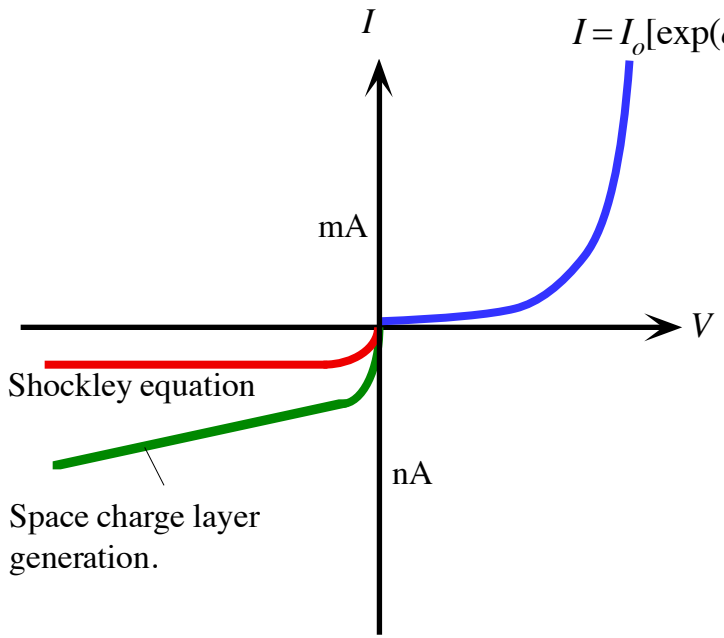
Forward biased *pn* junction and the injection of minority carriers (a) Carrier concentration profiles across the device under forward bias. (b). The hole potential energy with and without an applied bias. *W* is the width of the SCL with forward bias



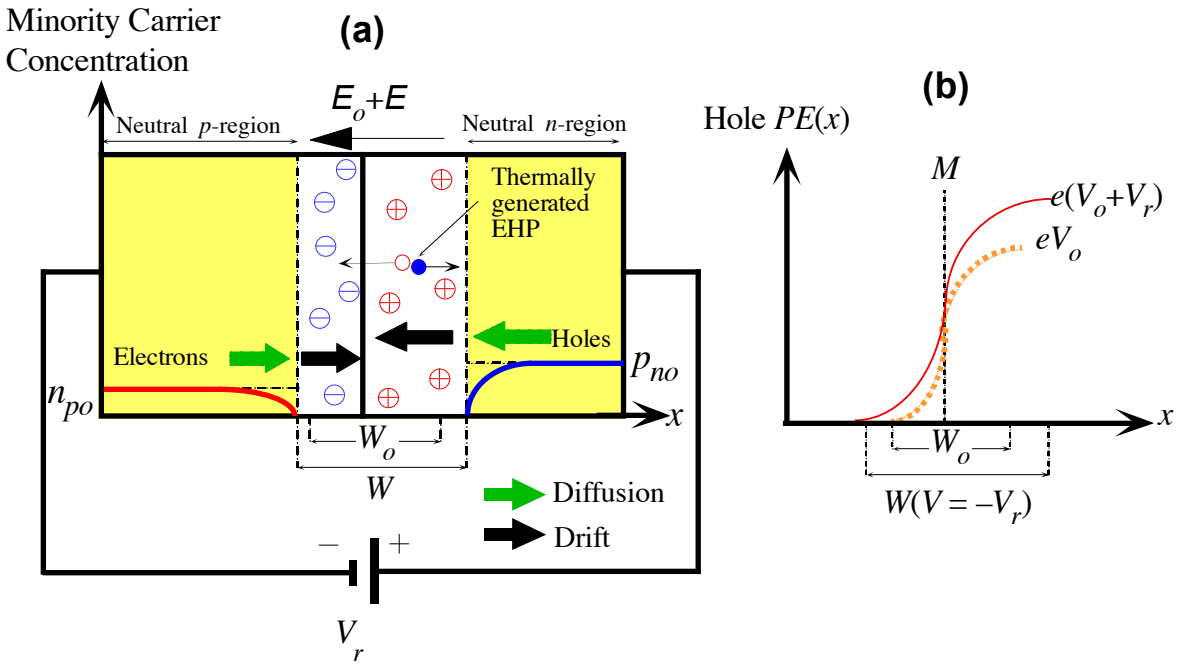
The total current anywhere in the device is constant. Just outside the depletion region it is due to the diffusion of minority carriers.



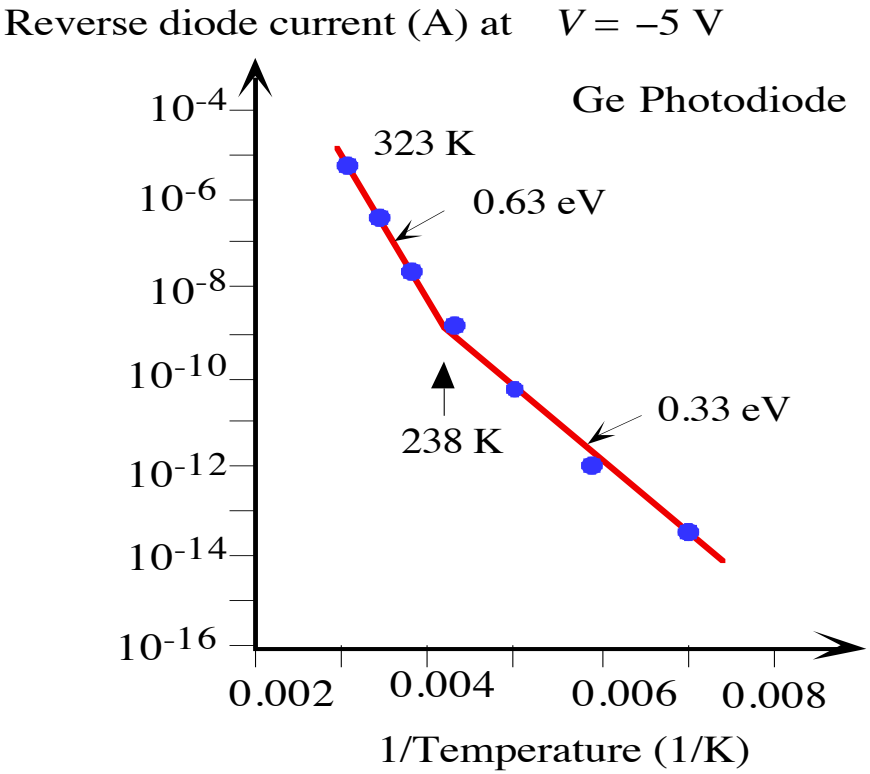
Forward biased *pn* junction and the injection of carriers and their recombination in the SCL.



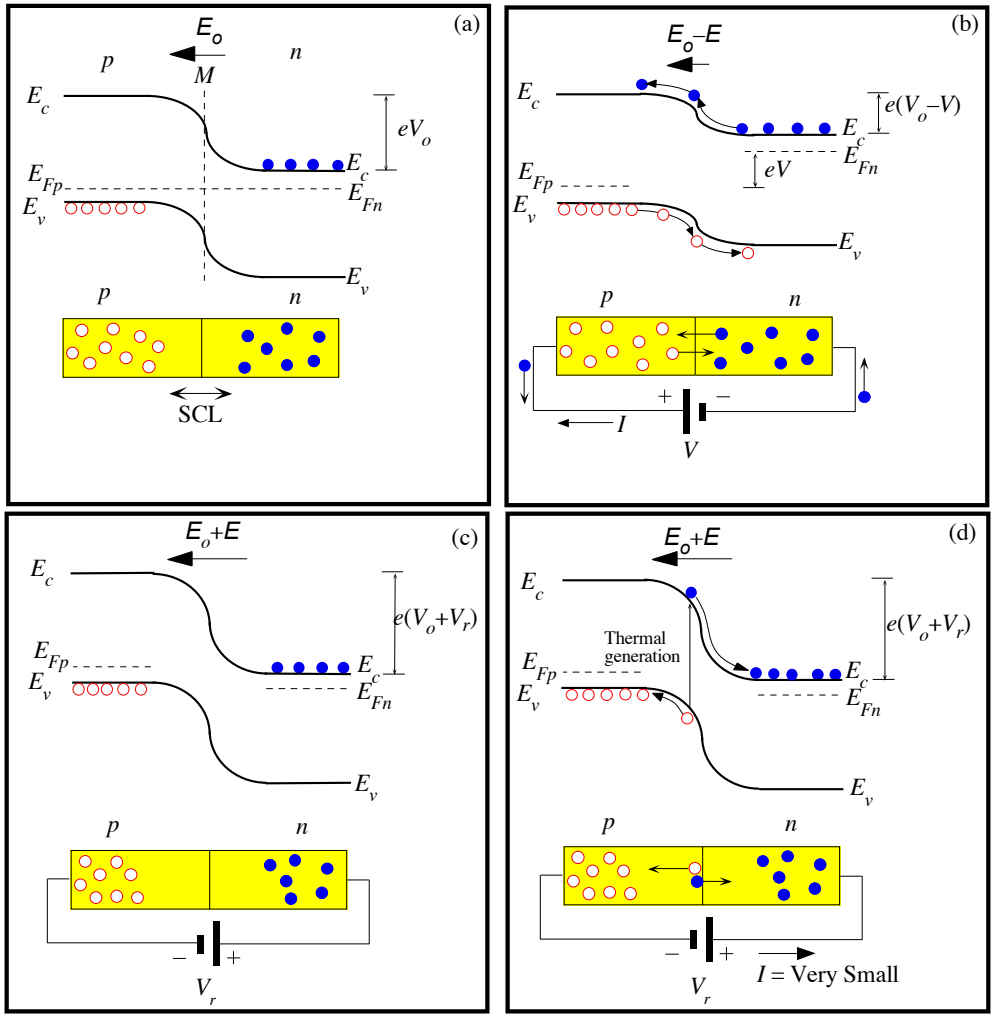
Reverse *I-V* characteristics of a *pn* junction (the positive and negative current axes have different scales)



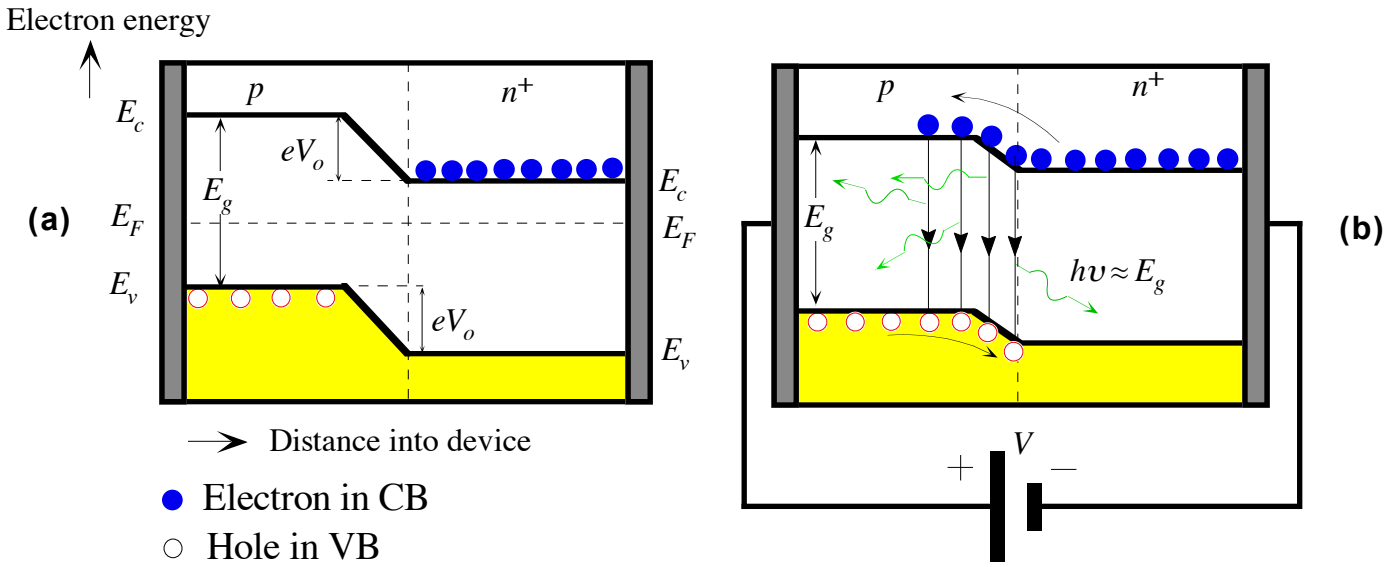
Reverse biased *pn* junction. (a) Minority carrier profiles and the origin of the reverse current. (b) Hole *PE* across the junction under reverse bias



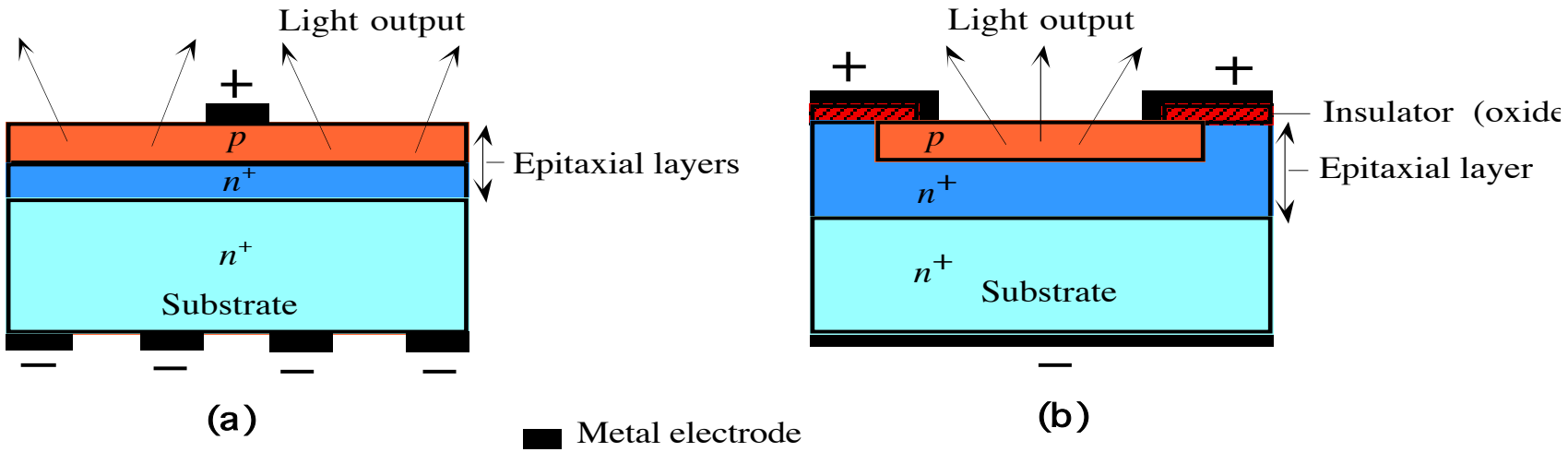
Reverse diode current in a Ge *pn* junction as a function of temperature in a $\ln(I_{rev})$ vs. $1/T$ plot. Above 238 K, I_{rev} is controlled by n_i^2 and below 238 K it is controlled by n_i. The vertical axis is a logarithmic scale with actual current values. (From D. Scansen and S.O. Kasap, *Cnd. J. Physics*. **70**, 1070-1075. 1992.)



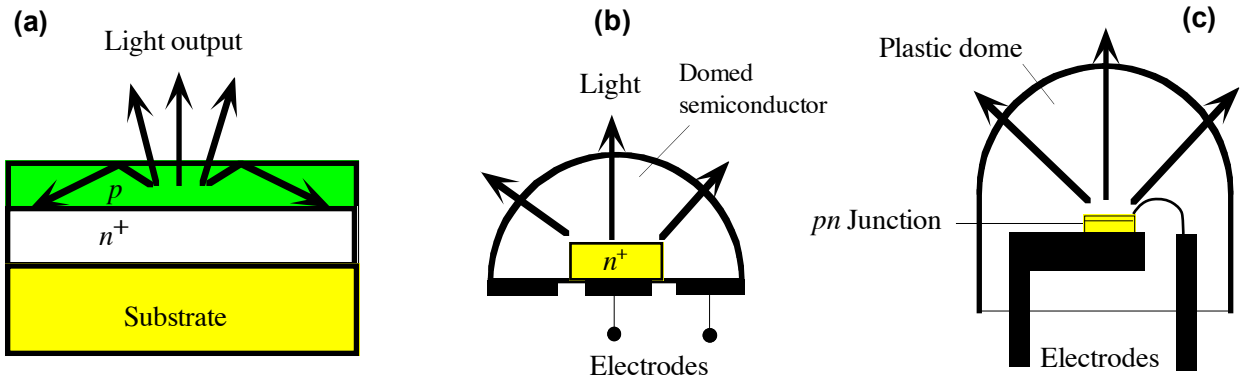
Energy band diagrams for a *pn* junction under (a) open circuit, (b) forward bias and (c) reverse bias conditions. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.



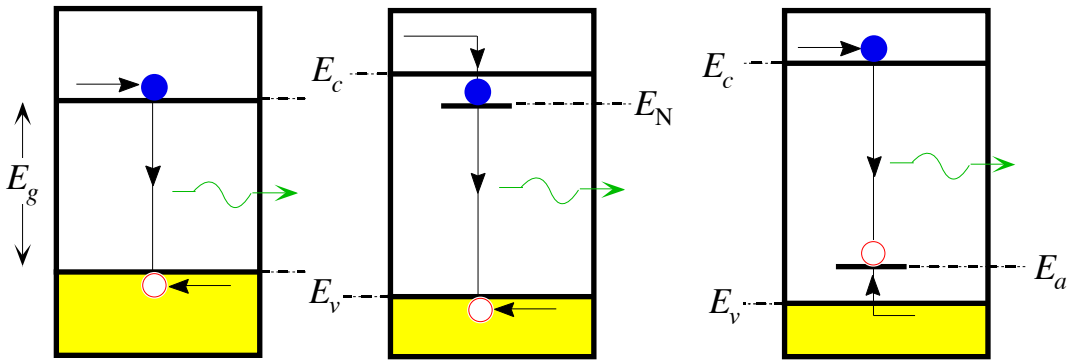
(a) The energy band diagram of a p-n^+ (heavily n-type doped) junction without any bias. Built-in potential V_o prevents electrons from diffusing from n^+ to p side. (b) The applied bias reduces V_o and thereby allows electrons to diffuse, be injected, into the p-side. Recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission.



A schematic illustration of typical planar surface emitting LED devices. (a) p-layer grown epitaxially on an n^+ substrate. (b) First n^+ is epitaxially grown and then p region is formed by dopant diffusion into the epitaxial layer.

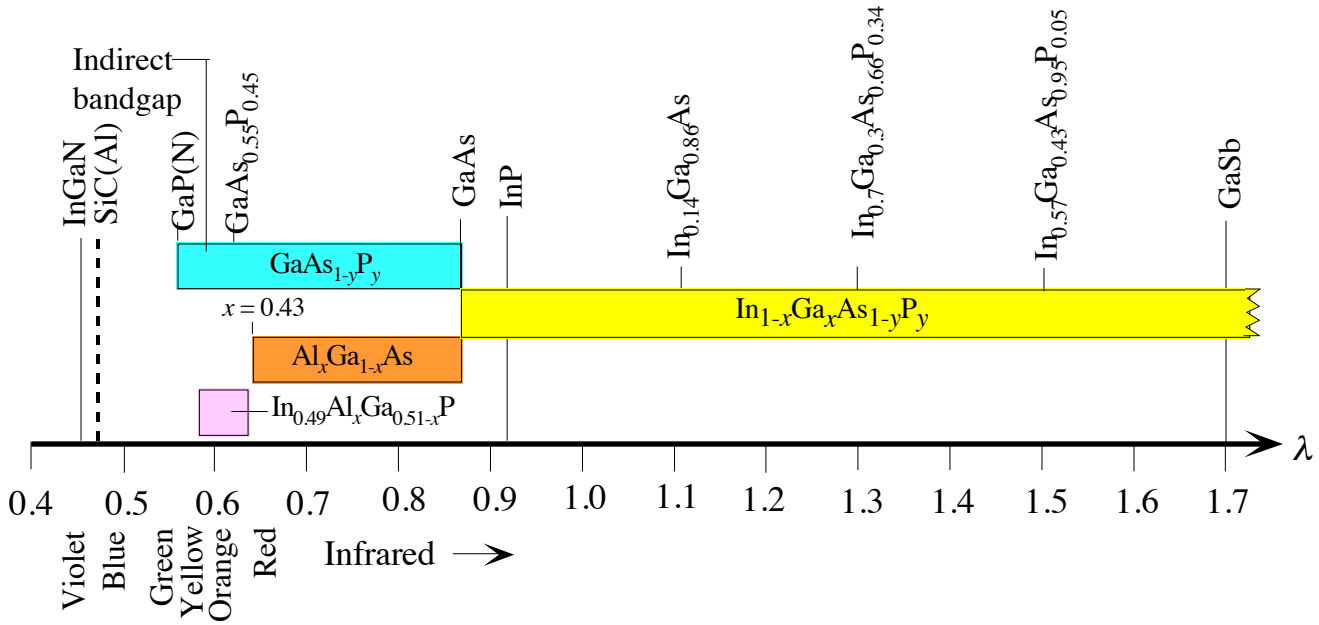


(a) Some light suffers total internal reflection and cannot escape. (b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle. (b) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

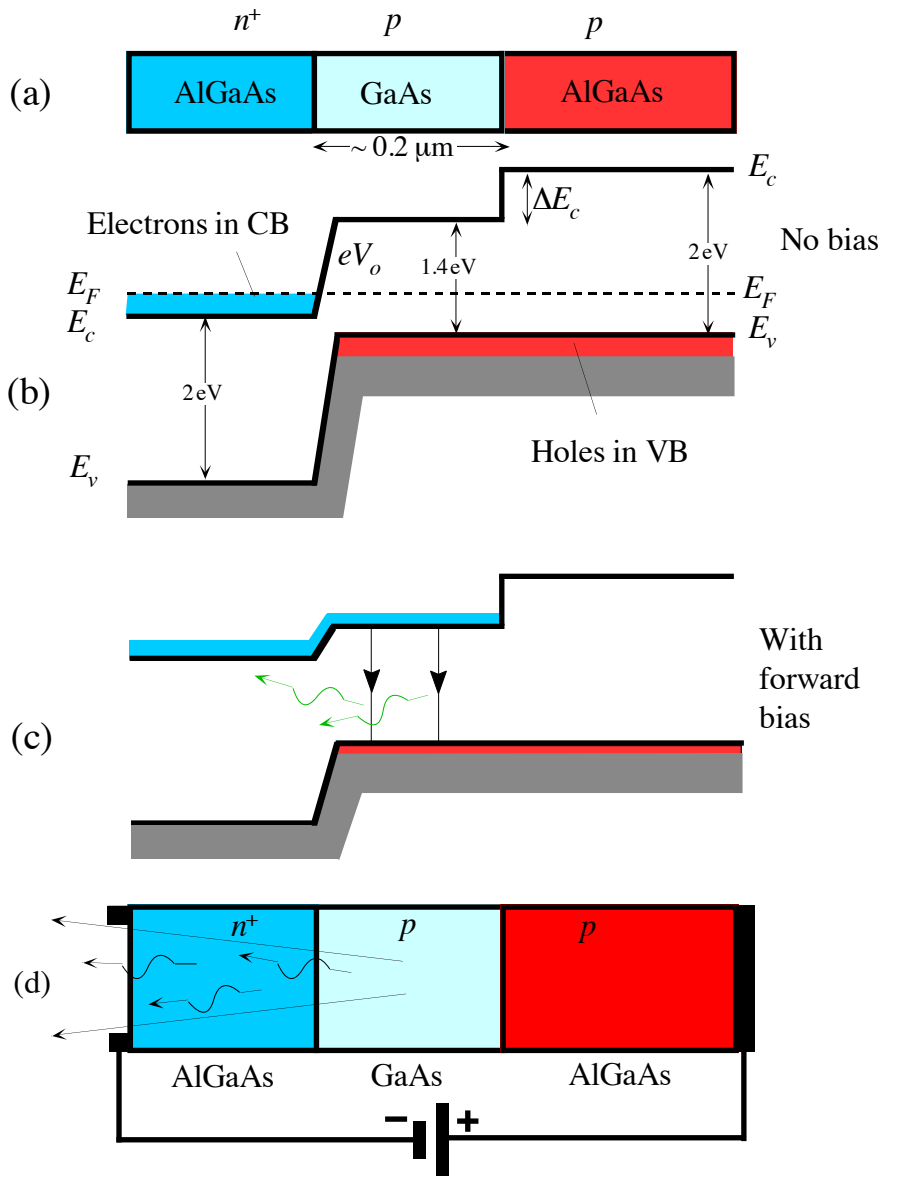


(a) $GaAs_{1-y}P_y$ $y < 0.45$ (b) N doped GaP (c) Al doped SiC

(a) Photon emission in a direct bandgap semiconductor. (b). GaP is an indirect bandgap semiconductor. When doped with nitrogen there is an electron trap at E_N. Direct recombination between a trapped electron at E_N and a hole emits a photon. (c) In Al doped SiC, EHP recombination is through an acceptor level like E_a.



Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials.

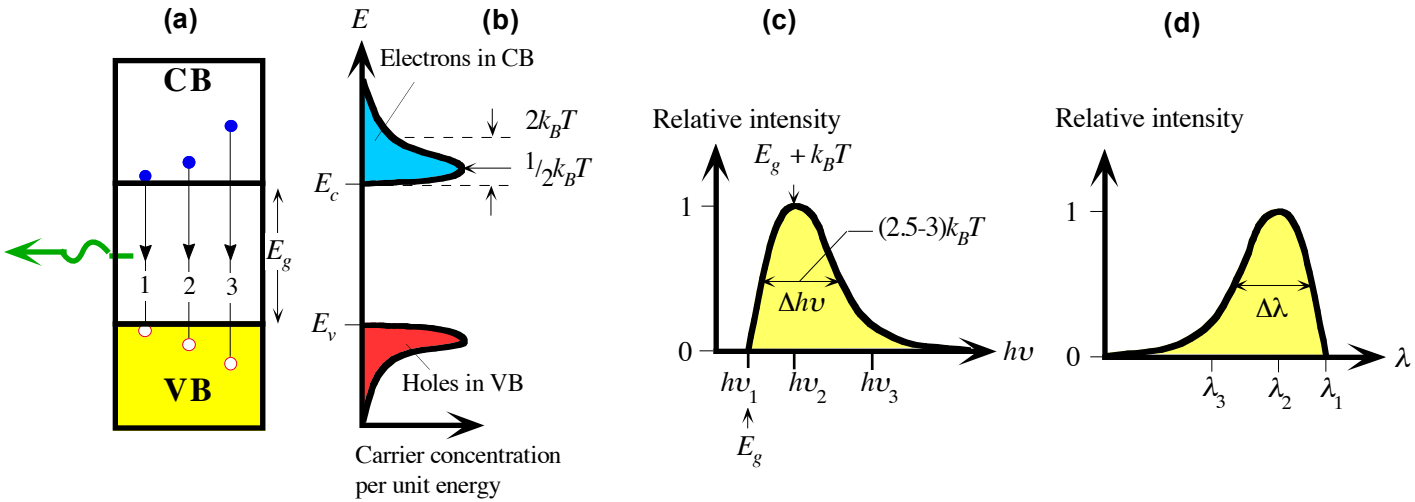


(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs)

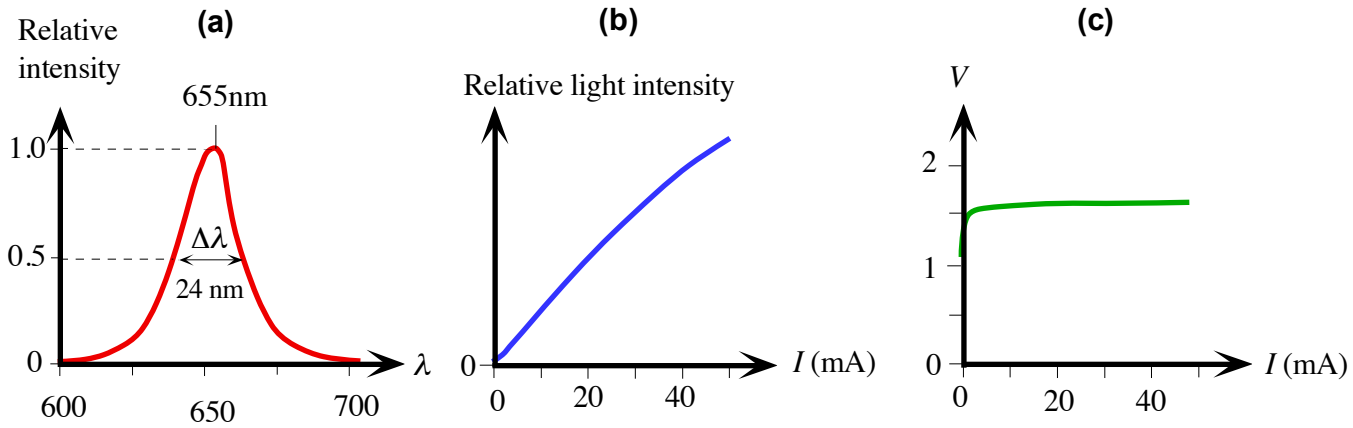
(b) A simplified energy band diagram with exaggerated features. E_F must be uniform.

(c) Forward biased simplified energy band diagram.

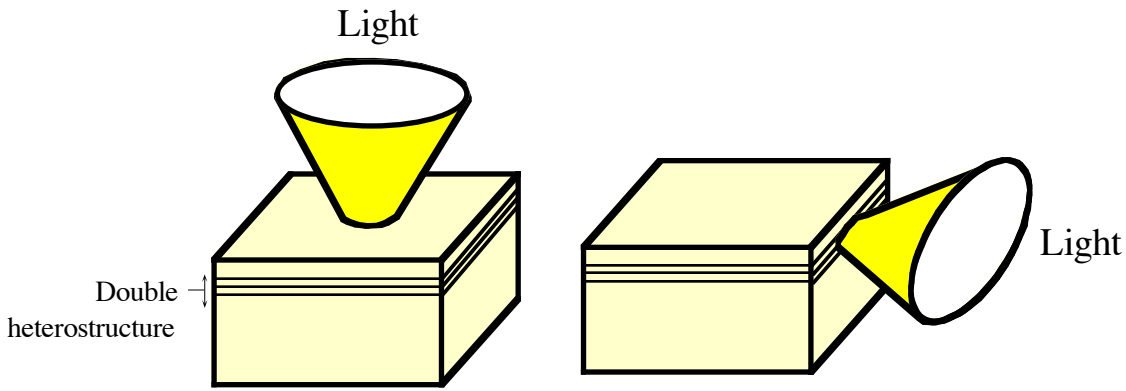
(d) Forward biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.



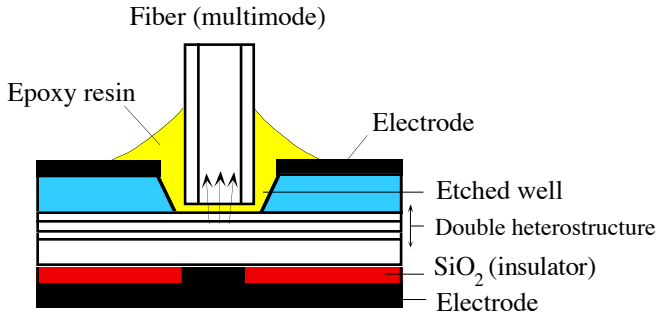
(a) Energy band diagram with possible recombination paths. (b) Energy distribution of electrons in the CB and holes in the VB. The highest electron concentration is $(1/2)k_BT$ above E_c . (c) The relative light intensity as a function of photon energy based on (b). (d) Relative intensity as a function of wavelength in the output spectrum based on (b) and (c).



(a) A typical output spectrum (relative intensity vs wavelength) from a red GaAsP LED. (b) Typical output light power vs. forward current. (c) Typical I-V characteristics of a red LED. The turn-on voltage is around 1.5V.

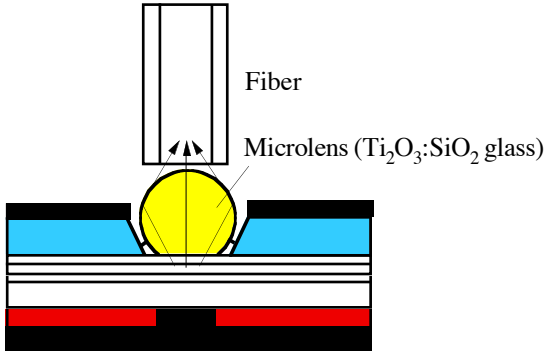


(a) Surface emitting LED (b) Edge emitting LED



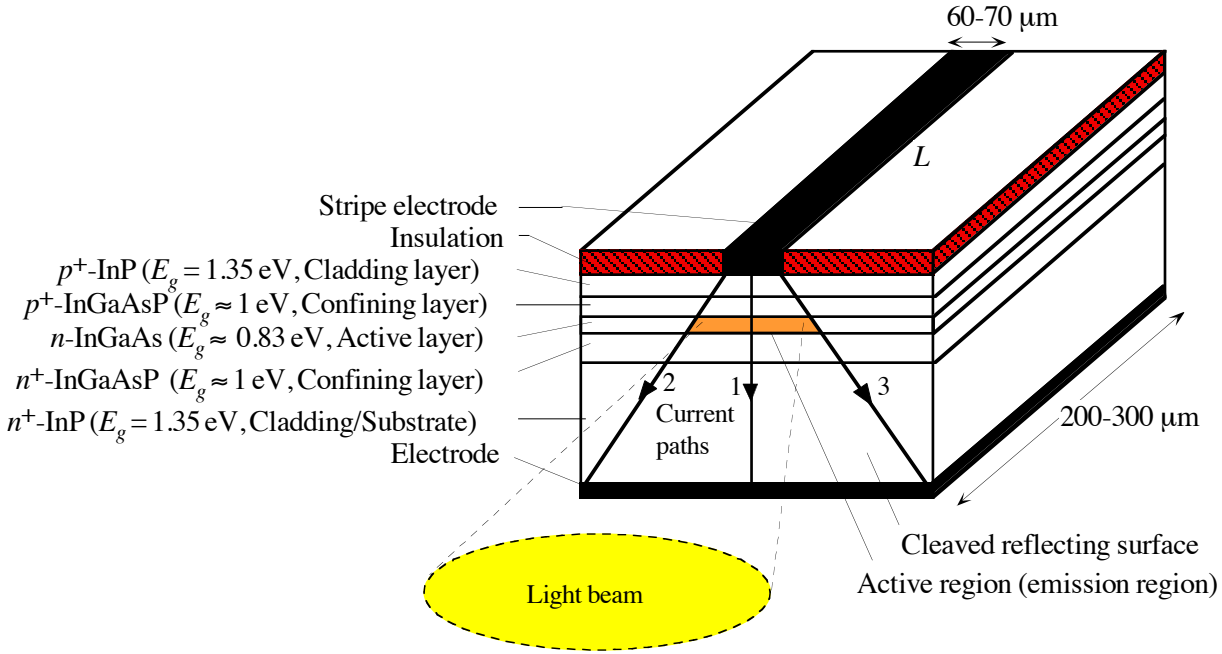
(a)

Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure.

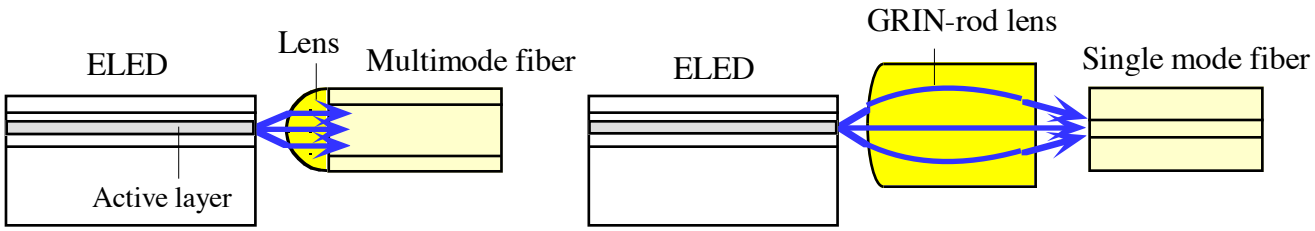


(b)

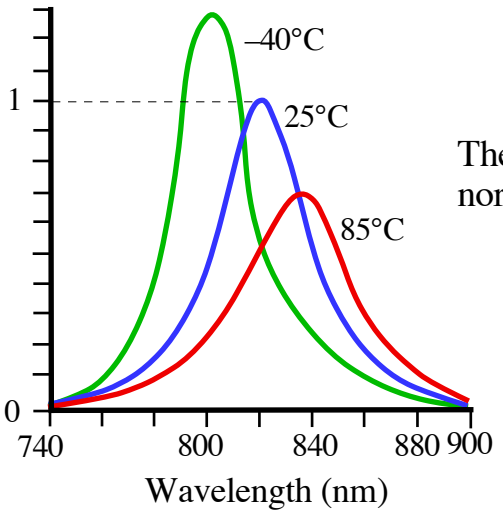
A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.



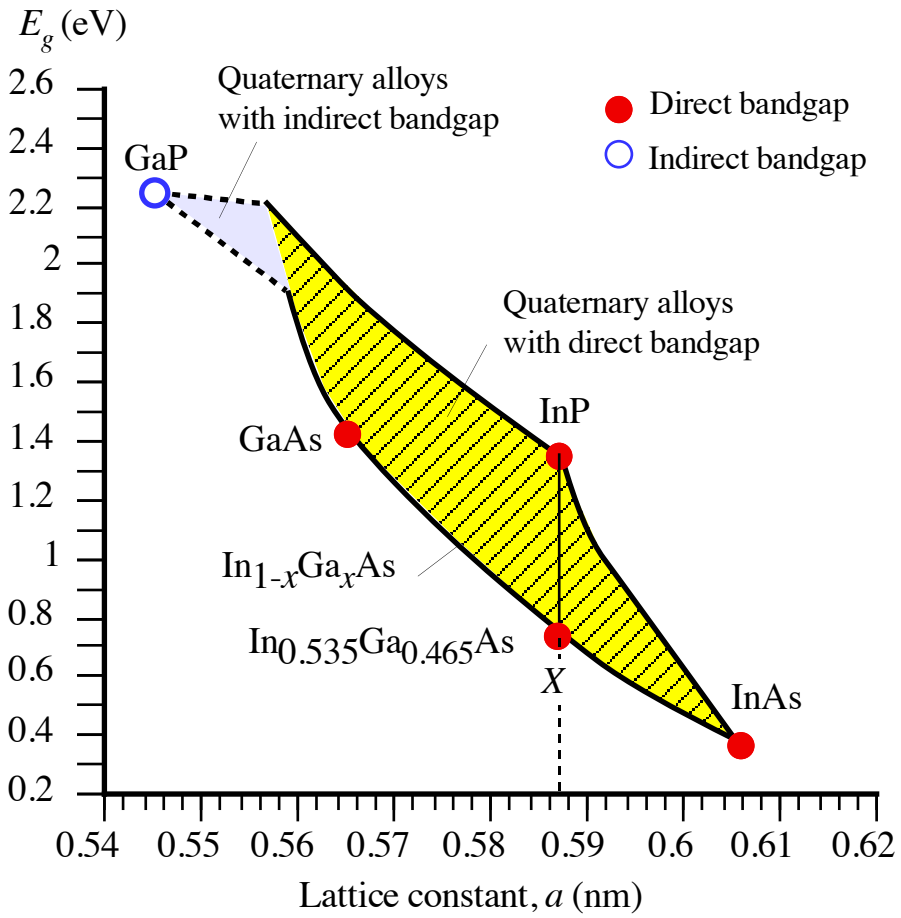
Schematic illustration of the the structure of a double heterojunction stripe contact edge emitting LED



Light from an edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens.



The output spectrum from AlGaAs LED. Values normalized to peak emission at 25°C.



Bandgap energy E_g and lattice constant a for various III-V alloys of GaP, GaAs, InP and InAs. A line represents a ternary alloy formed with compounds from the end points of the line. Solid lines are for direct bandgap alloys whereas dashed lines for indirect bandgap alloys. Regions between lines represent quaternary alloys. The line from X to InP represents quaternary alloys $In_{1-x}Ga_xAs_{1-y}P_y$ made from $In_{0.535}Ga_{0.465}As$ and InP which are lattice matched to InP.