Semiconductors, diodes, transistors

(Horst Wahl, QuarkNet presentation, June 2001)

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ELECTRICAL CONDUCTIVITY

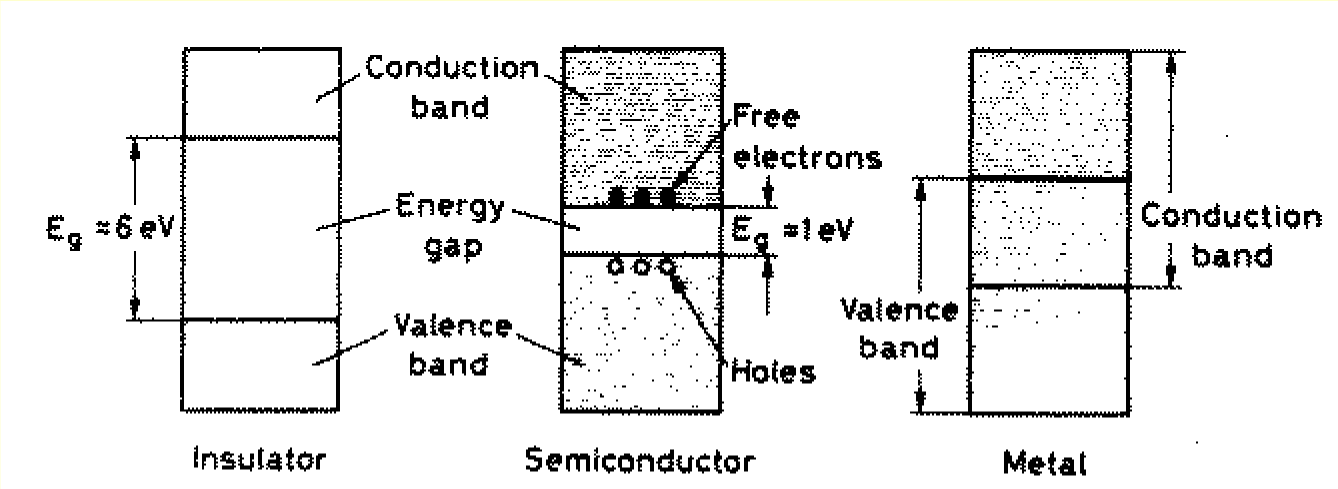
- in order of conductivity: superconductors, conductors, semiconductors, insulators
  - conductors: material capable of carrying electric current, i.e. material which has “mobile charge carriers” (e.g. electrons, ions,..)
    e.g. metals, liquids with ions (water, molten ionic compounds), plasma
  - insulators: materials with no or very few free charge carriers; e.g. quartz, most covalent and ionic solids, plastics
  - semiconductors: materials with conductivity between that of conductors and insulators; e.g. germanium Ge, silicon Si, GaAs, GaP, InP
  - superconductors: certain materials have zero resistivity at very low temperature.
- some representative resistivities (ρ):
  - $R = \rho L/A$, R = resistance, L = length, A = cross section area; resistivity at 20° C

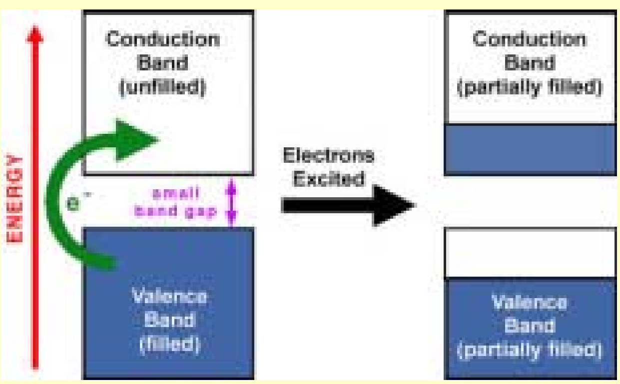
	resistivity in Ω m	resistance(in Ω)(L=1m, diam =1mm)
aluminum	2.8×10^{-8}	3.6×10^{-2}
brass	$\approx 8\times10^{-8}$	10.1×10^{-2}
copper	1.7×10^{-8}	2.2×10^{-2}
platinum	10×10^{-8}	12.7×10^{-2}
silver	1.6×10^{-8}	2.1×10^{-2}
carbon	3.5×10^{-5}	44.5
germanium	0.45	5.7×10^{5}
silicon	≈ 640	$\approx 6\times10^{8}$
porcelain	10^{10} - 10^{12}	10^{16} - 10^{18}
teflon	10^{14}	10^{20}
blood	1.5	1.9×10^{6}
fat	24	3×10^{7}

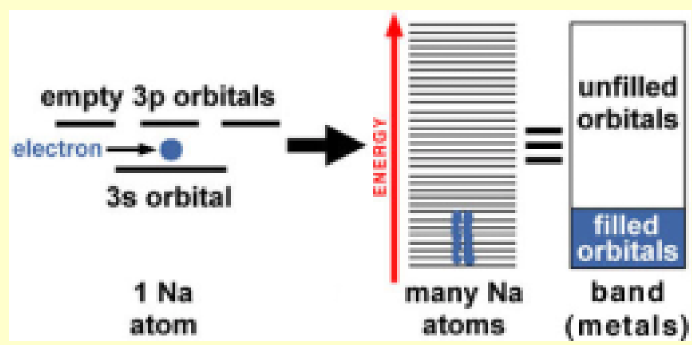
ENERGY BANDS IN SOLIDS:

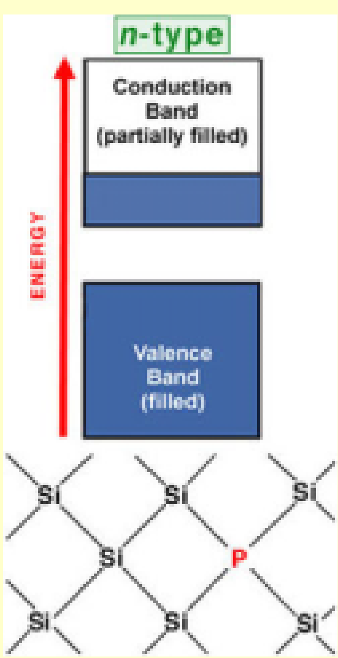
- In solid materials, electron energy levels form bands of allowed energies, separated by forbidden bands
- valence band = outermost (highest) band filled with electrons ("filled" = all states occupied)
- conduction band = next highest band to valence band (empty or partly filled)
- "gap" = energy difference between valence and conduction bands, = width of the forbidden band
- Note:
  - electrons in a completely filled band cannot move, since all states occupied (Pauli principle); only way to move would be to "jump" into next higher band - needs energy;
  - electrons in partly filled band can move, since there are free states to move to.
- Classification of solids into three types, according to their band structure:
  - insulators: gap = forbidden region between highest filled band (valence band) and lowest empty or partly filled band (conduction band) is very wide, about 3 to 6 eV;
  - semiconductors: gap is small - about 0.1 to 1 eV;
  - conductors: valence band only partially filled, or (if it is filled), the next allowed empty band overlaps with it

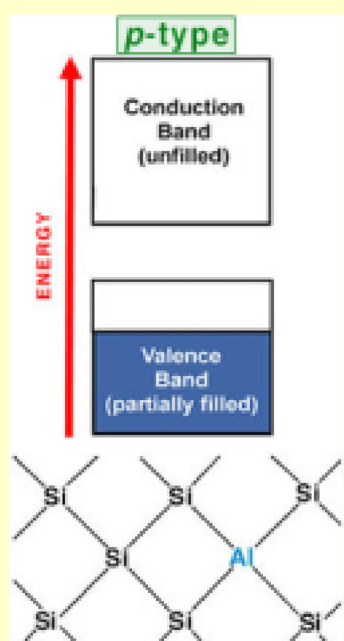
Band structure and conductivity







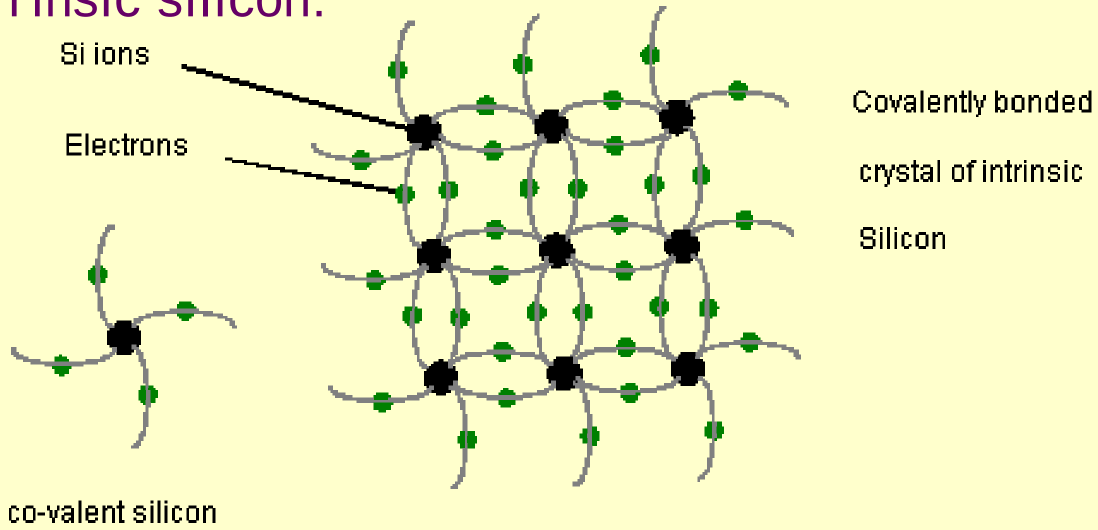




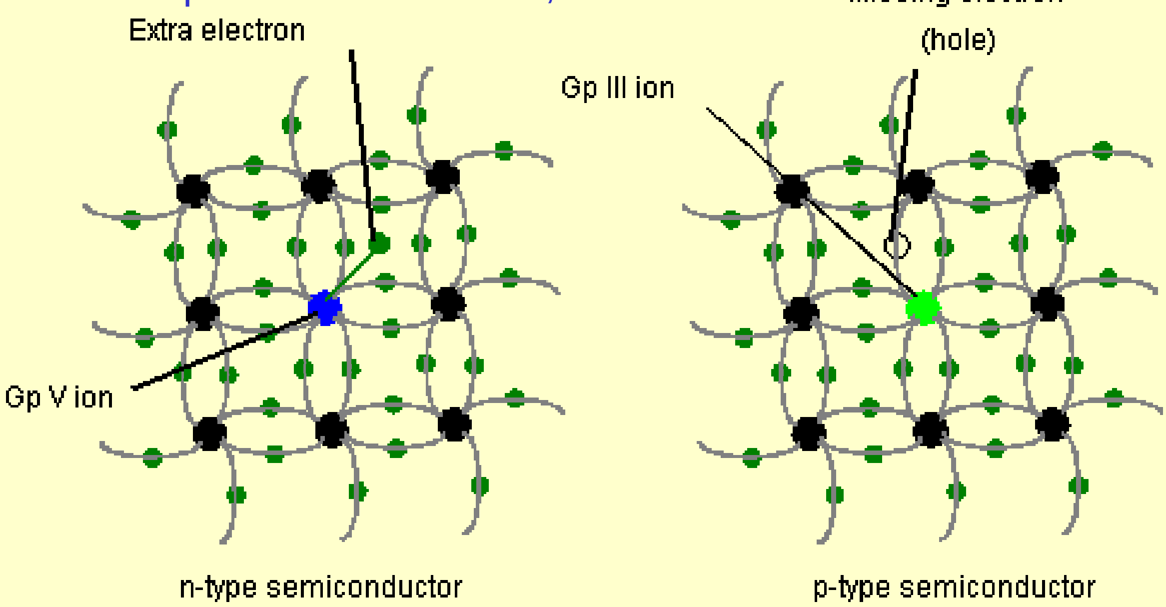
INTRINSIC SEMICONDUCTORS

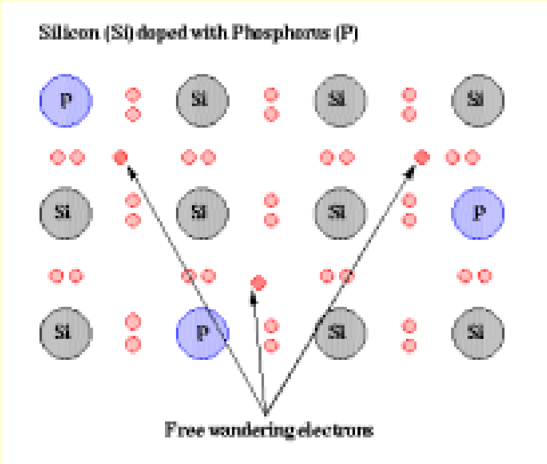
- semiconductor = material for which gap between valence band and conduction band is small;
  (gap width in Si is 1.1 eV, in Ge 0.7 eV).
- at T = 0, there are no electrons in the conduction band, and the semiconductor does not conduct (lack of free charge carriers);
- at T > 0, some fraction of electrons have sufficient thermal kinetic energy to overcome the gap and jump to the conduction band;
  fraction rises with temperature;
  e.g. at 20^o C (293 K), Si has 0.9×10^{10} conduction electrons per cubic centimeter; at 50^o C (323 K) there are 7.4×10^{10} .
- electrons moving to conduction band leave "hole" (covalent bond with missing electron) behind;
  under influence of applied electric field, neighboring electrons can jump into the hole, thus creating a new hole, etc. $\Rightarrow$ holes can move under the influence of an applied electric field, just like electrons;
  both contribute to conduction.
- in pure Si and Ge, there are equally many holes ("p-type charge carriers") as there are conduction electrons ("n-type charge carriers");
- pure semiconductors also called "intrinsic semiconductors".

- Intrinsic silicon:



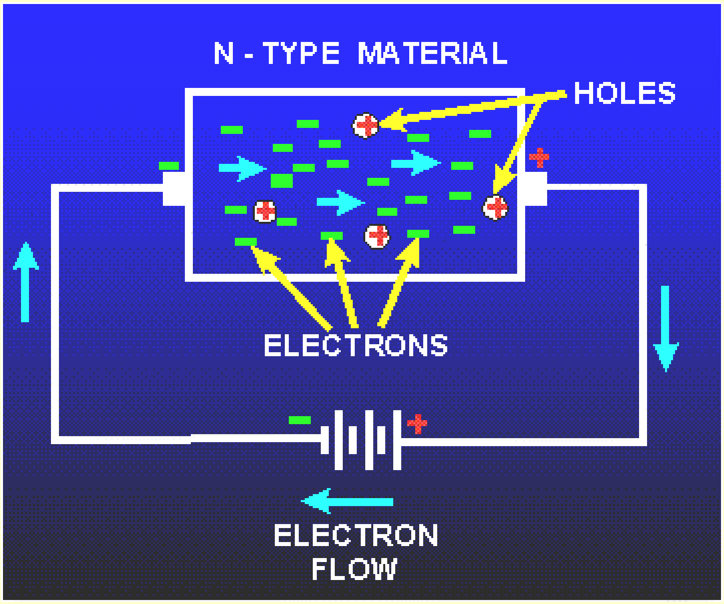
- DOPED SEMICONDUCTORS:
  - "doped semiconductor": (also "impure", "extrinsic") = semiconductor with small admixture of trivalent or pentavalent atoms;





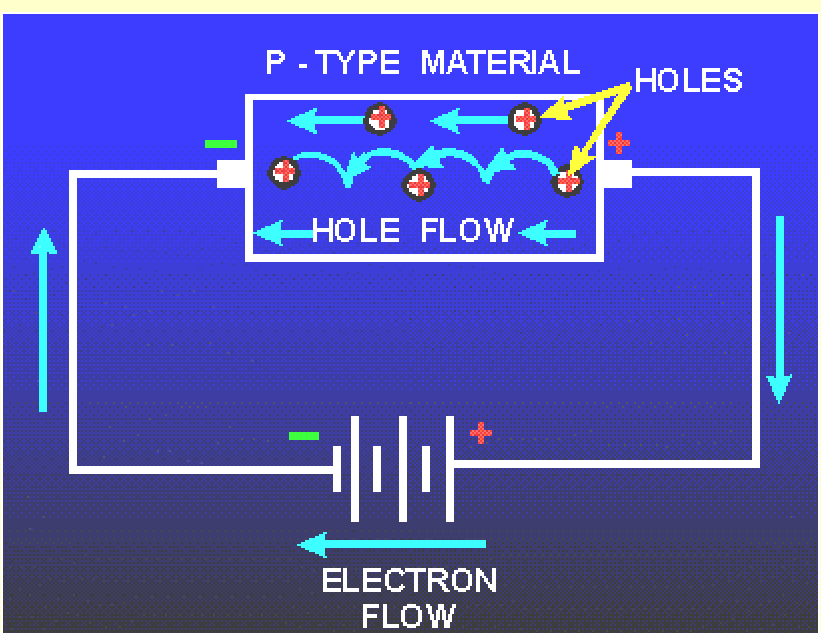
n-type material

- ***donor (n-type) impurities***:
  - dopant with 5 valence electrons (e.g. P, As, Sb)
  - 4 electrons used for covalent bonds with surrounding Si atoms, one electron "left over";
  - left over electron is only loosely bound ⇒ only small amount of energy needed to lift it into conduction band (0.05 eV in Si)
  - ⇒ "*n-type semiconductor*", has conduction electrons, no holes (apart from the few intrinsic holes)
  - example: doping fraction of 10^{-8} Sb in Si yields about 5×10^{16} conduction electrons per cubic centimeter at room temperature, i.e. gain of 5×10^{6} over intrinsic Si.



p-type material

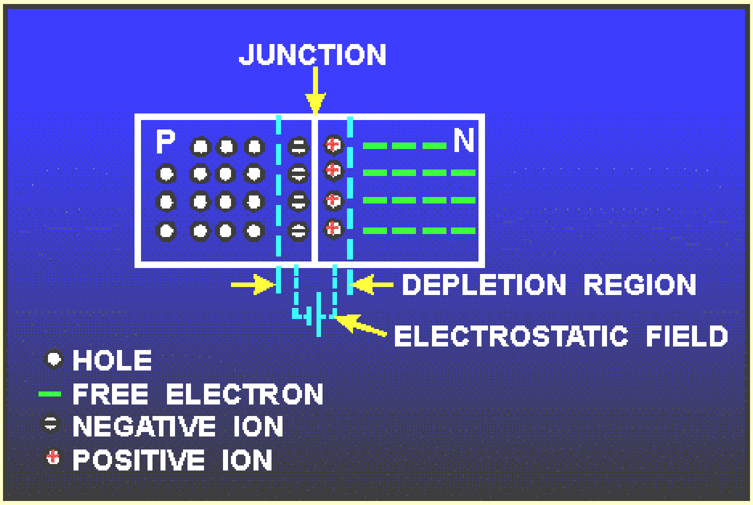
- ***acceptor (p-type) impurities***:
  - dopant with 3 valence electrons (e.g. B, Al, Ga, In) ⇒ only 3 of the 4 covalent bonds filled ⇒ vacancy in the fourth covalent bond ⇒ hole
  - "*p-type semiconductor*", has mobile holes, very few mobile electrons (only the intrinsic ones).
- advantages of doped semiconductors:
  - can"tune" conductivity by choice of doping fraction
  - can choose "majority carrier" (electron or hole)
  - can vary doping fraction and/or majority carrier within piece of semiconductor
  - can make "p-n junctions" (diodes) and "transistors"



DIODES AND TRANSISTORS

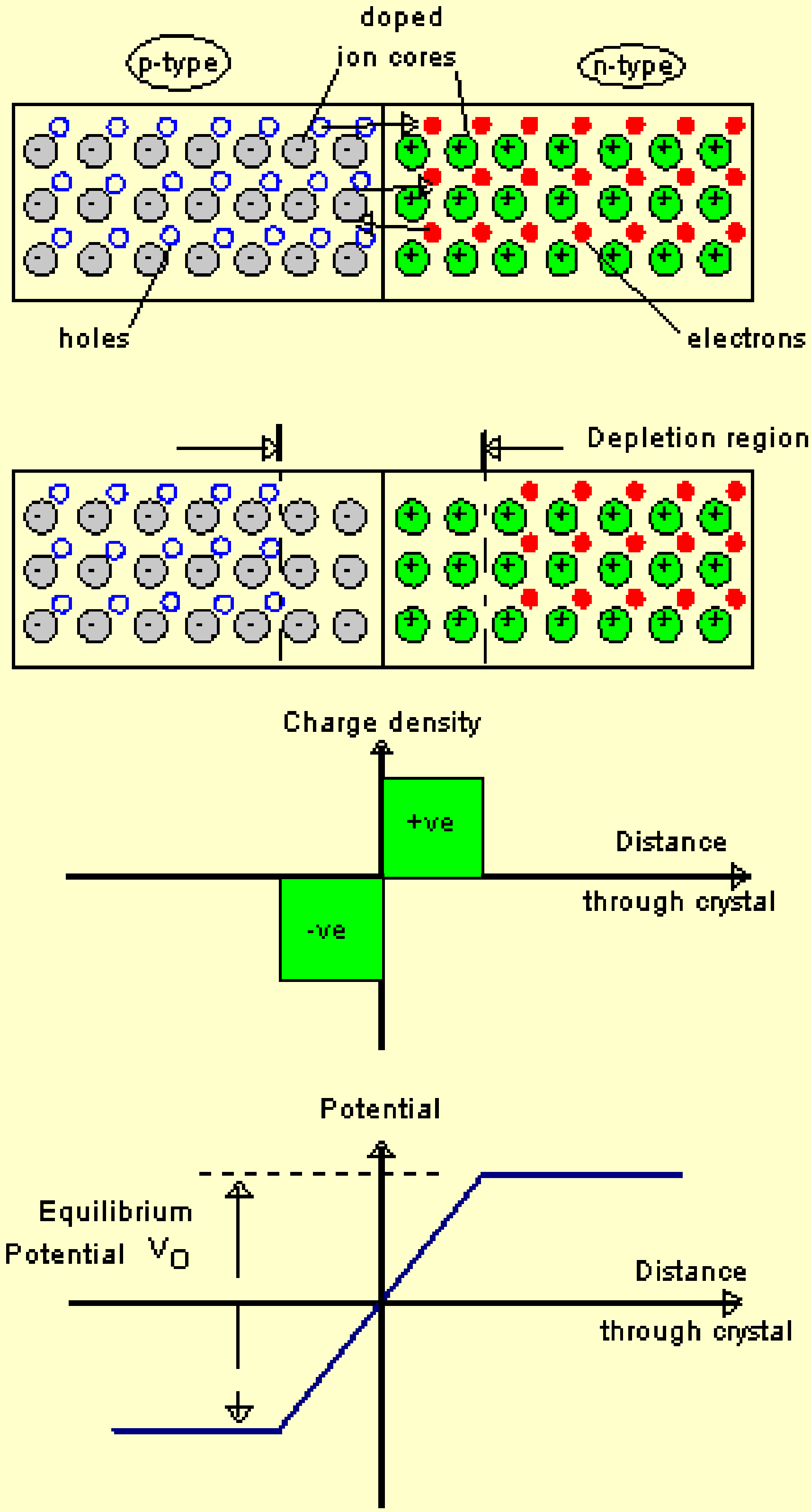
- **p-n JUNCTION:**
  - p-n junction = semiconductor in which impurity changes abruptly from p-type to n-type ;
  - “diffusion” = movement due to difference in concentration, from higher to lower concentration;
  - in absence of electric field across the junction, holes “diffuse” towards and across boundary into n-type and capture electrons;
  - electrons diffuse across boundary, fall into holes (“*recombination of majority carriers*”);

    $\Rightarrow$ formation of a “depletion region”
    (= region without free charge carriers)
    around the boundary;
  - charged ions are left behind (cannot move):
    - negative ions left on p-side $\Rightarrow$ net negative charge on p-side of the junction;
    - positive ions left on n-side $\Rightarrow$ net positive charge on n-side of the junction
    - $\Rightarrow$ electric field across junction which prevents further diffusion.



Pn junction

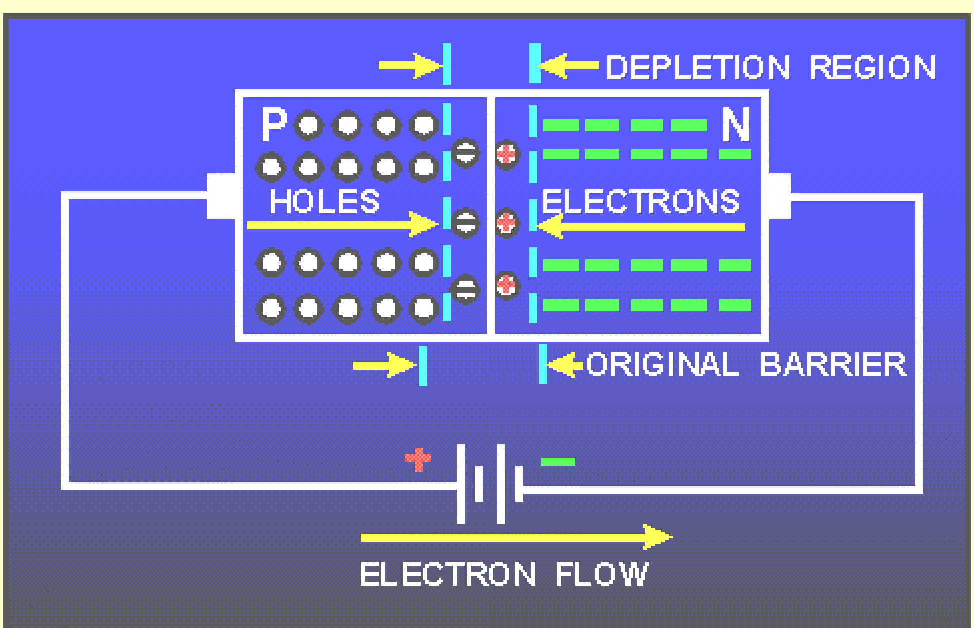
- Formation of depletion region in pn-junction:



DIODE

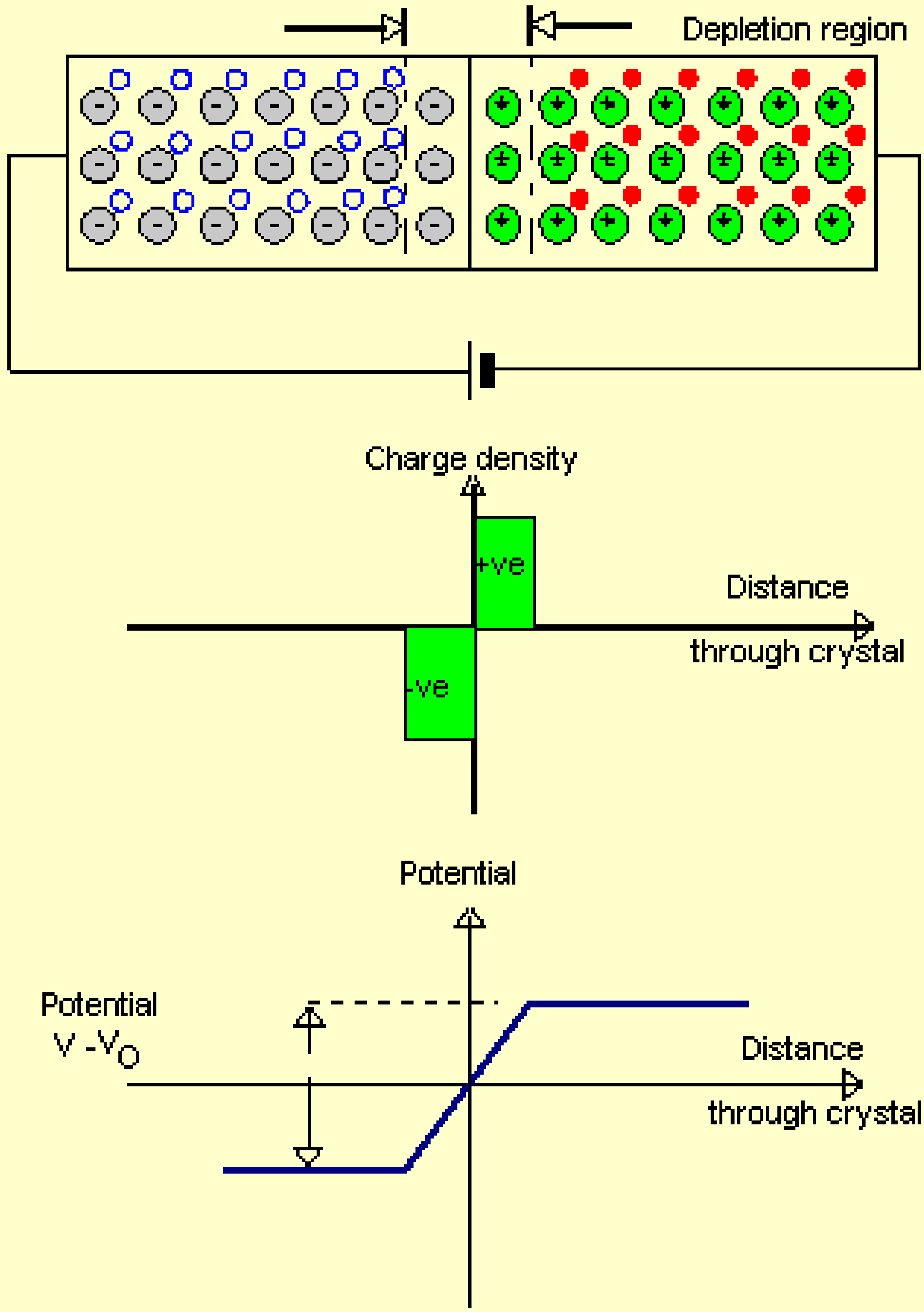
- diode = "biased p-n junction", i.e. p-n junction with voltage applied across it
- "forward biased": p-side more positive than n-side;
- "reverse biased": n-side more positive than p-side;
- forward biased diode:
  - the direction of the electric field is from p-side towards n-side
  - ⇒ p-type charge carriers (positive holes) in p-side are pushed towards and across the p-n boundary,
  - n-type carriers (negative electrons) in n-side are pushed towards and across n-p boundary

⇒ current flows across p-n boundary



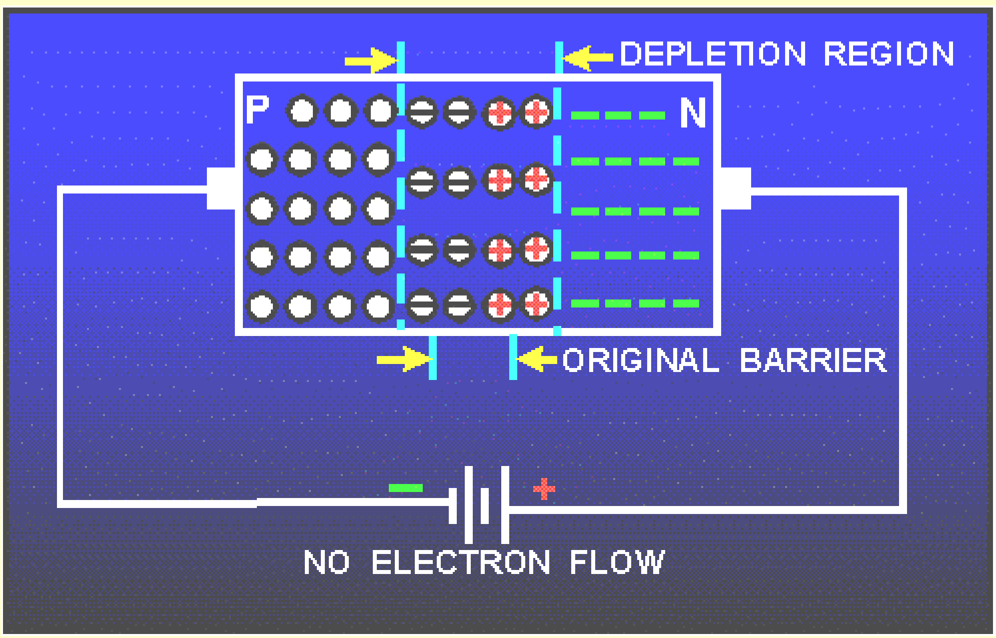
Forward biased pn-junction

- Depletion region and potential barrier reduced



Reverse biased diode

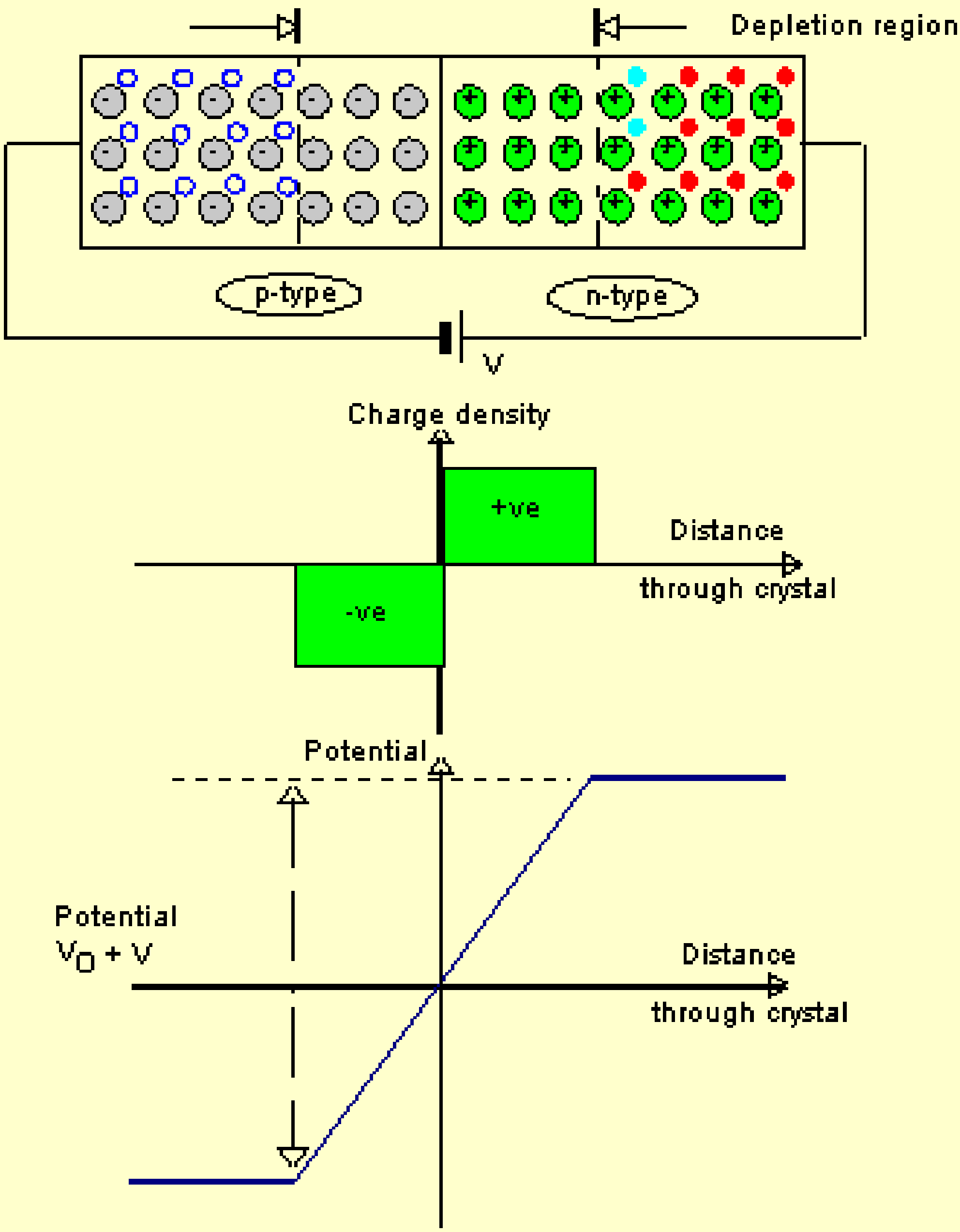
- reverse biased diode: applied voltage makes n-side more positive than p-side
  - ⇒ electric field direction is from n-side towards p-side
  - ⇒ pushes charge carriers away from the p-n boundary
  - ⇒ depletion region widens, and no current flows



- **diode only conducts when positive voltage applied to p-side and negative voltage to n-side**
- diodes used in “rectifiers”, to convert ac voltage to dc.

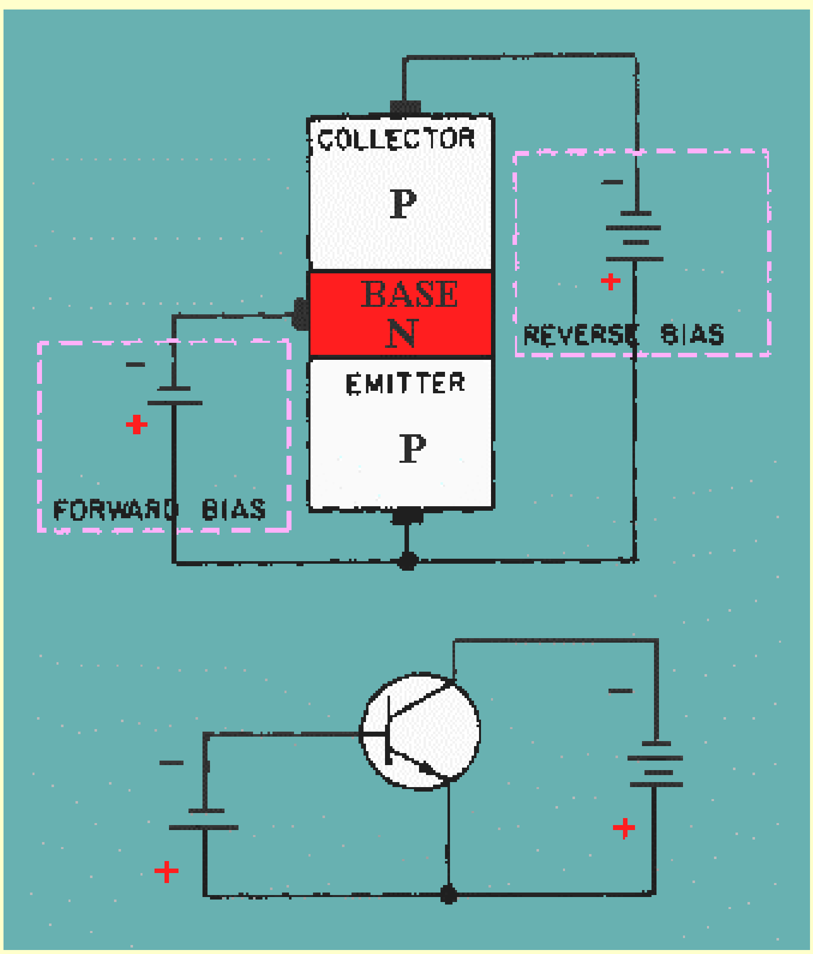
Reverse biased diode

- Depletion region becomes wider,
  barrier potential higher

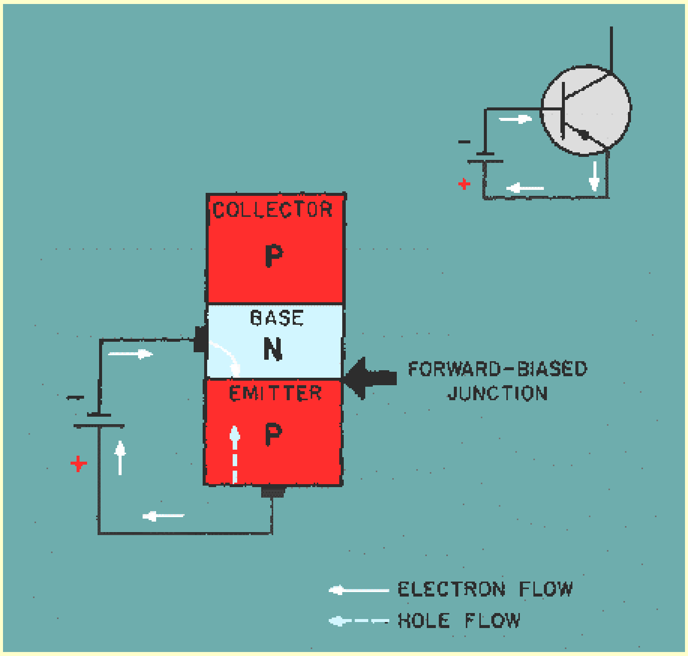


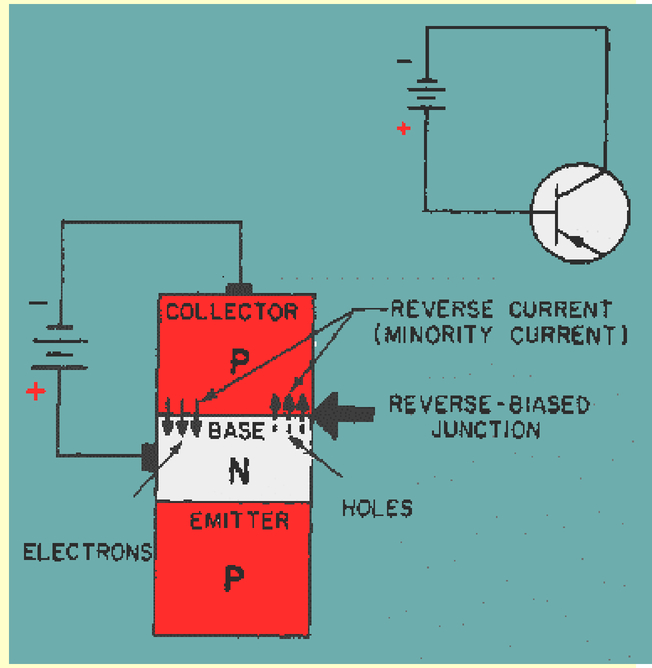
TRANSISTORS

- (bipolar) transistor = combination of two diodes that share middle portion, called “base” of transistor; other two sections: “emitter'' and “collector”;
- usually, base is very thin and lightly doped.
- two kinds of bipolar transistors: pnp and npn transistors
- “pnp” means emitter is p-type, base is n-type, and collector is p-type material;
- in “normal operation of pnp transistor, apply positive voltage to emitter, negative voltage to collector;



operation of pnp transistor:



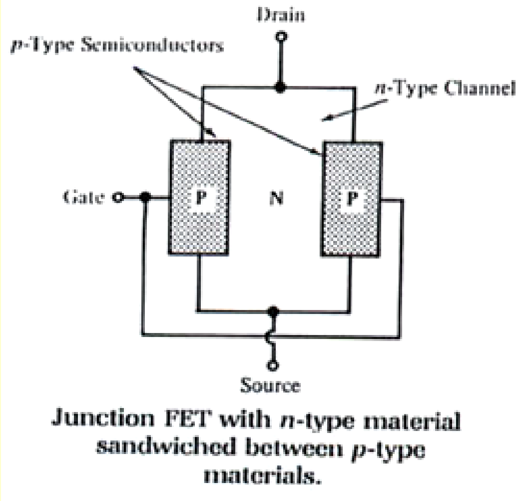


- if emitter-base junction is forward biased, "holes flow" from battery into emitter, move into base;
- some holes annihilate with electrons in n-type base, but base thin and lightly doped $\Rightarrow$ most holes make it through base into collector,
- holes move through collector into negative terminal of battery; i.e. "collector current" flows whose size depends on how many holes have been captured by electrons in the base;
- this depends on the number of n-type carriers in the base which can be controlled by the size of the current (the "base current") that is allowed to flow from the base to the emitter; the base current is usually very small; small changes in the base current can cause a big difference in the collector current;

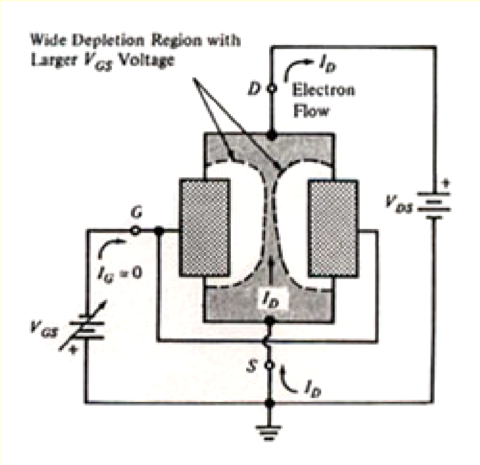
Transistor operation

- **transistor acts as amplifier of base current**, since *small changes in base current cause big changes in collector current*.
- **transistor as switch**: if voltage applied to base is such that emitter-base junction is reverse-biased, no current flows through transistor -- transistor is "off"
- therefore, a *transistor can be used as a voltage-controlled switch*; computers use transistors in this way.

- "field-effect transistor" (FET)
  - in a pnp FET, current flowing through a thin channel of n-type material is controlled by the voltage (electric field) applied to two pieces of p-type material on either side of the channel (current depends on electric field).



Junction FET with *n*-type material sandwiched between *p*-type materials.



  - Many different kinds of FETs
  - FETs are the kind of transistor most commonly used in computers.