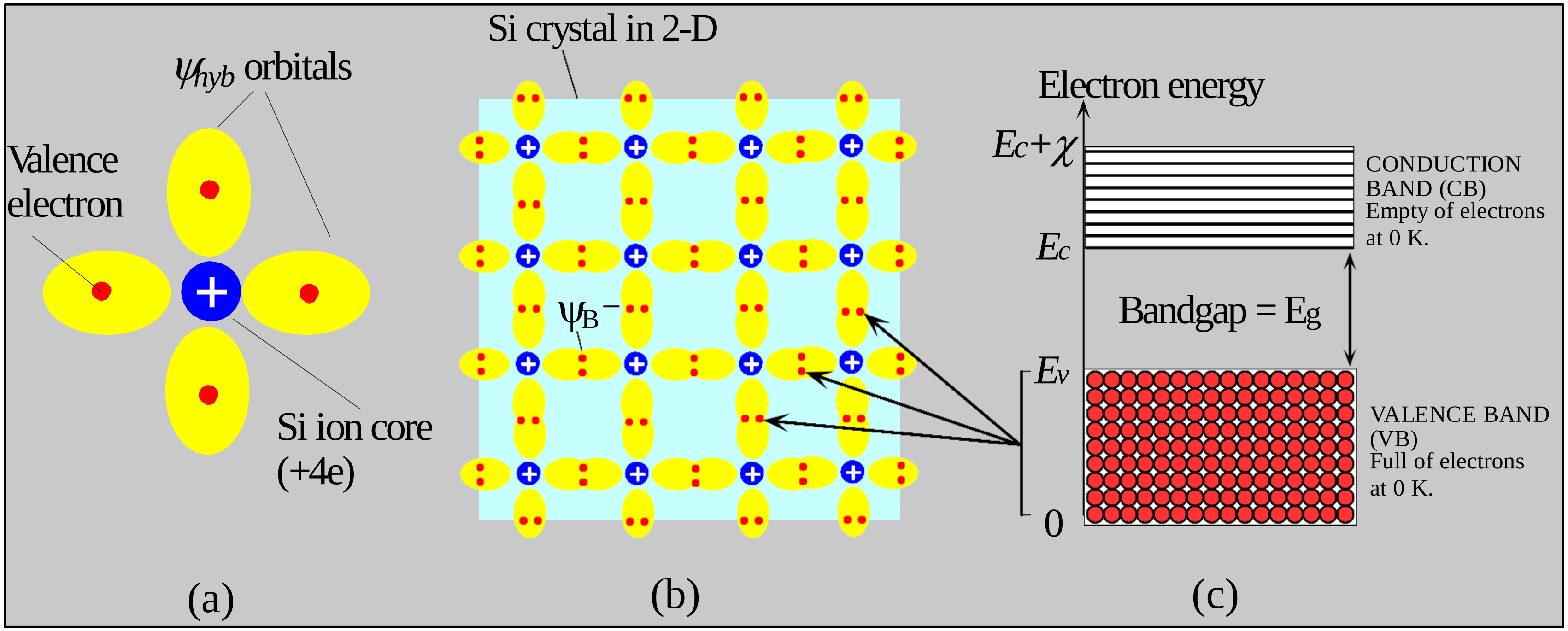
Semiconductor fundamentals:

1. *energy band, carriers, conductivity*
2. *intrinsic semiconductors*
3. *extrinsic semiconductors*

Devices always involve interfaces:

1. *metal-semiconductor interface*
   - *Schottky Junction*
   - *Ohmic Contact*
   - ***Tutorial 1***
2. *semiconductor-semiconductor interface*
   - *pn Junction*
   - *Tutorial 2, MOSFET (short briefing)*

Silicon crystal and energy band diagram



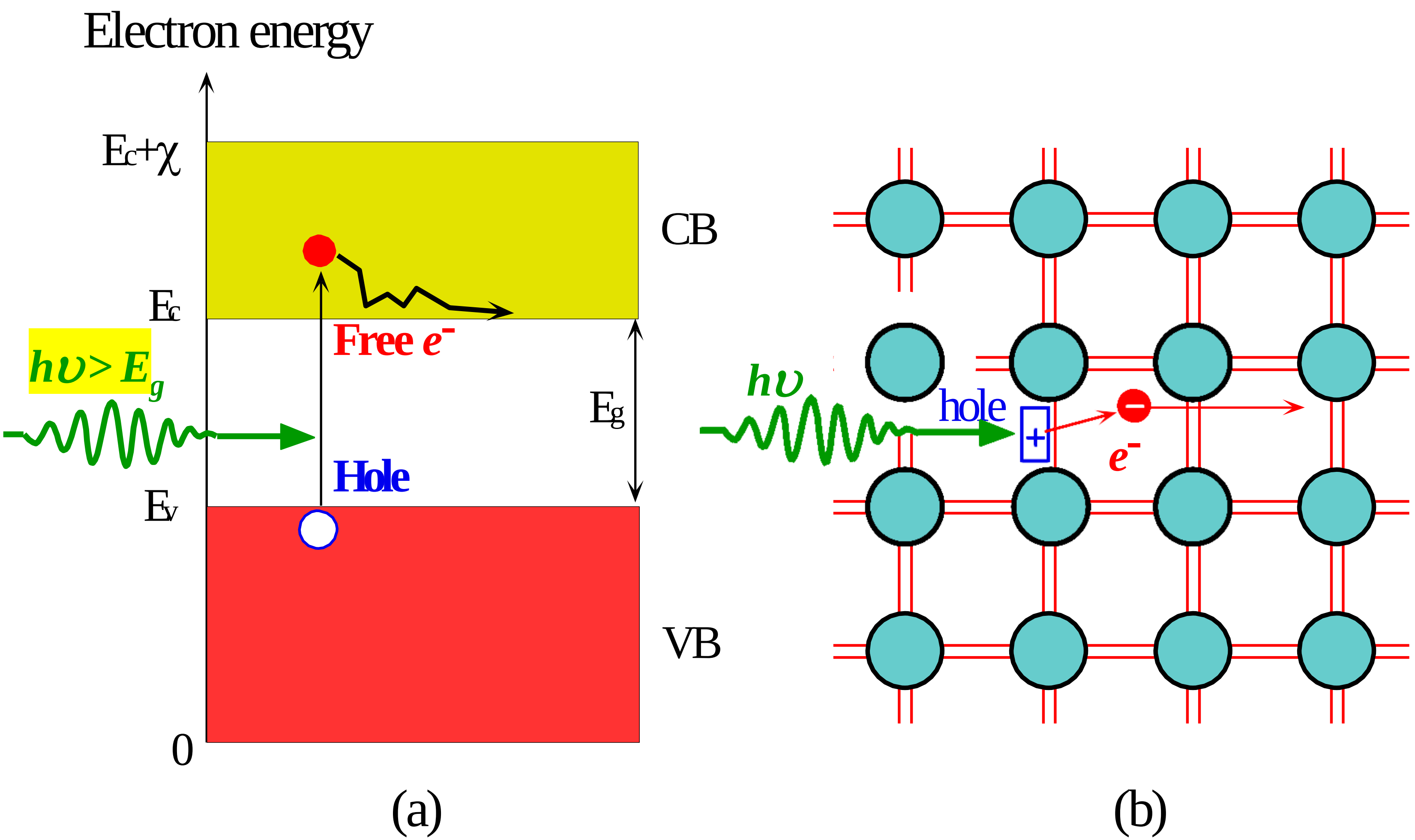
E_g = energy gap (bandgap); E_v = top of the VB; E_c = bottom of the CB

χ = electron affinity;

E_g：能带间隙 (带隙); E_v ：价带顶; E_c ：导带底；χ ：电子亲和能

E_f ：费米能级； Φ：逸出功

Conduction electron due to optical excitation

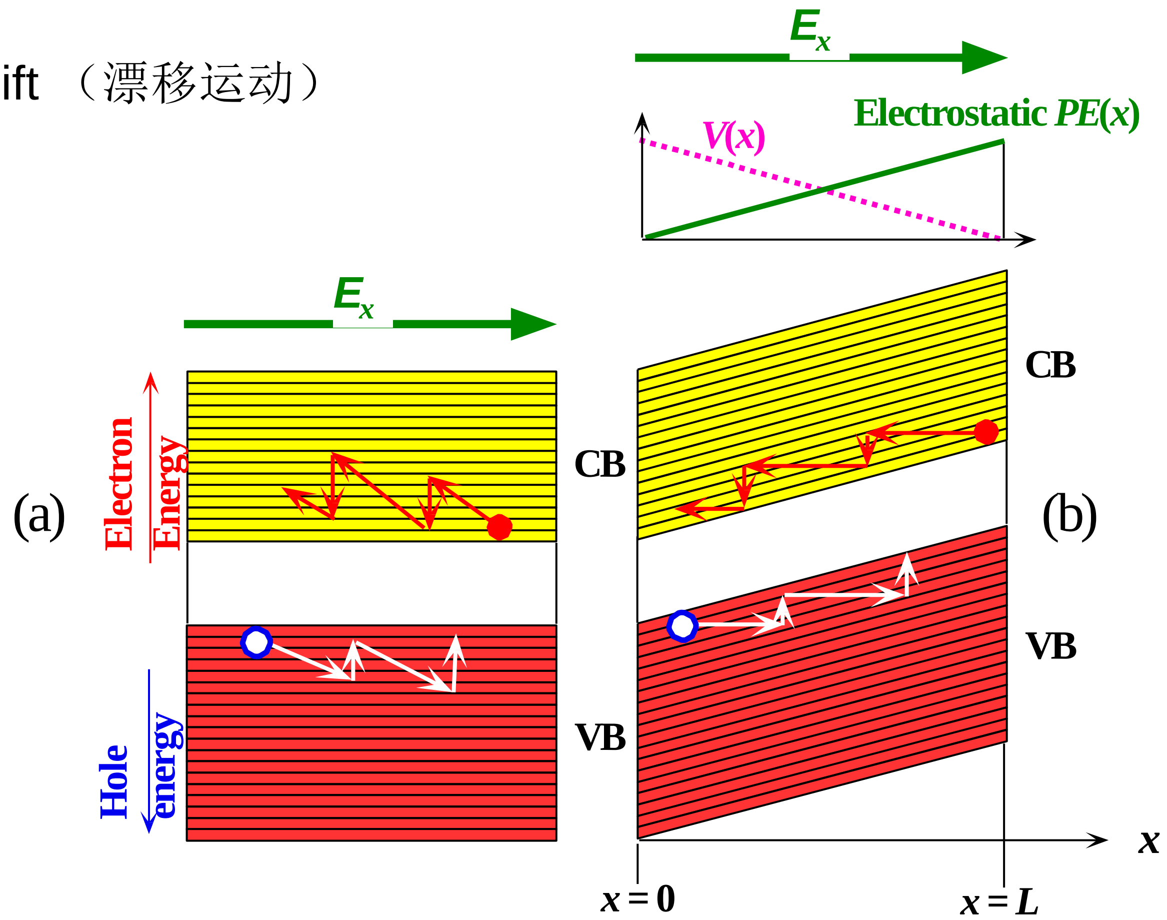


(a) A photon with an energy greater than E_g can excite an electron from the VB to the CB.

(b) When a photon breaks a Si-Si bond, a free **electron** and a **hole** in the Si-Si bond is created.

Conductivity（电导率） in semiconductors

Drift （漂移运动）

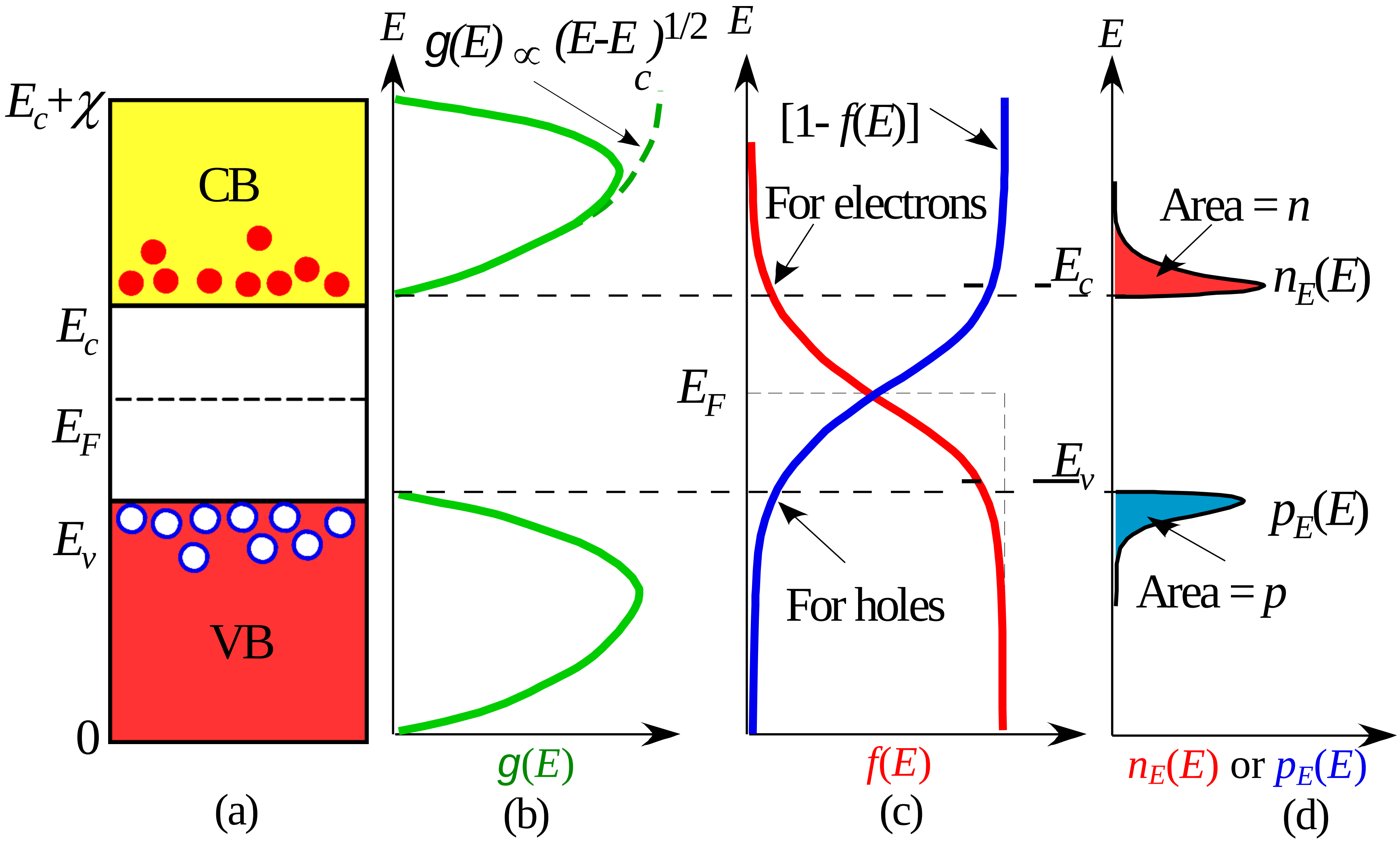


Applied field bends the energy bands, the electrostatic *PE* of the electron is -*eV*(*x*) and *V*(*x*) decreases in the direction of E_x whereas *PE* increases

The conductivity of a semiconductor:

$$\sigma = en\mu_e + ep\mu_h$$

Calculate carrier（载流子）concentration

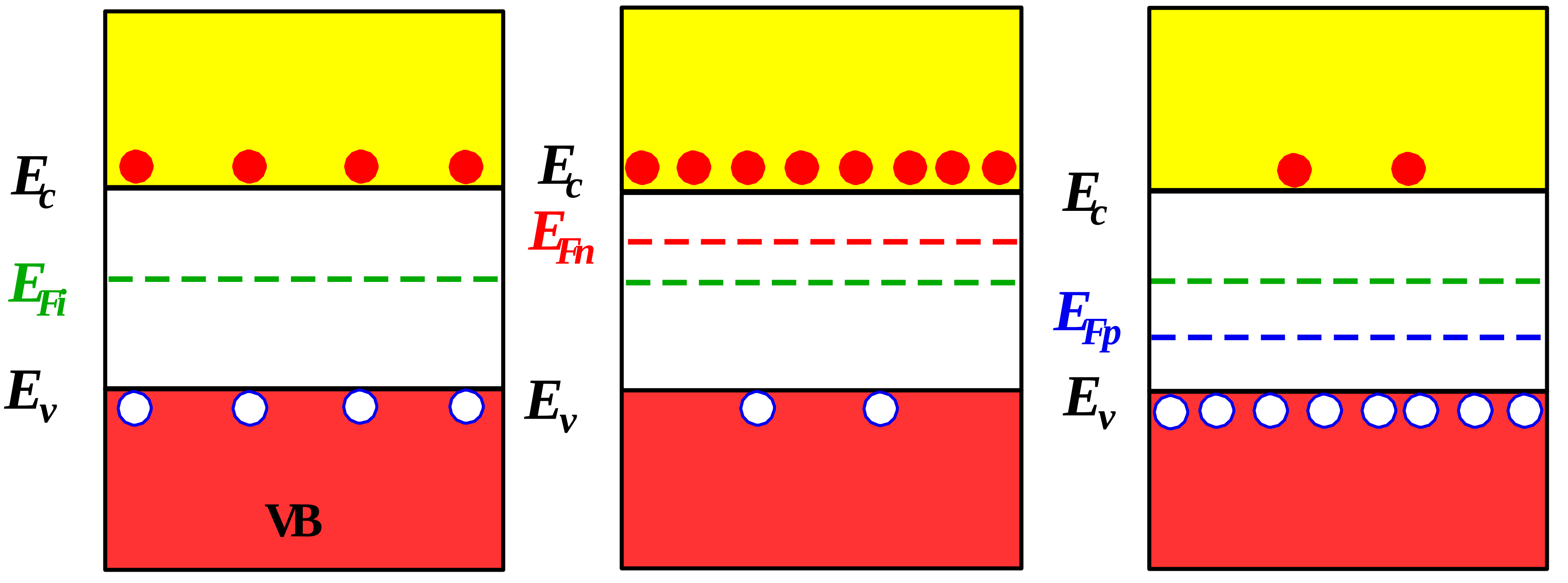


$$n_E dE = g_{cb}(E) f(E) dE$$

$$n = N_c \exp[-\frac{E_c - E_F}{kT}] \qquad p = N_v \exp[-\frac{(E_F - E_v)}{kT}]$$

Energy band diagrams for (a) intrinsic (b) n-type and (c) p-type semiconductors.
In all cases, $np = n_i^2$

$$np = n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$



$$n = p = n_i$$

$$n_i = N_c \exp\left[-\frac{E_c - E_{Fi}}{kT}\right]$$

$$n_i = N_v \exp\left[-\frac{E_{Fi} - E_v}{kT}\right]$$

$$n = N_c \exp\left[-\frac{E_c - E_{Fn}}{kT}\right] = N_d$$

$$p = N_v \exp\left[-\frac{E_{Fp} - E_v}{kT}\right] = N_a$$

For intrinsic Si:

$$n_i = N_c \exp\left[-\frac{E_c - E_{Fi}}{kT}\right]$$

For doped n-type Si:

$$n = N_c \exp\left[-\frac{E_c - E_{Fn}}{kT}\right] = N_d$$

$$\Rightarrow \quad \frac{N_d}{n_i} = \exp\left[\frac{E_{Fn} - E_{Fi}}{kT}\right]$$

For intrinsic Si:

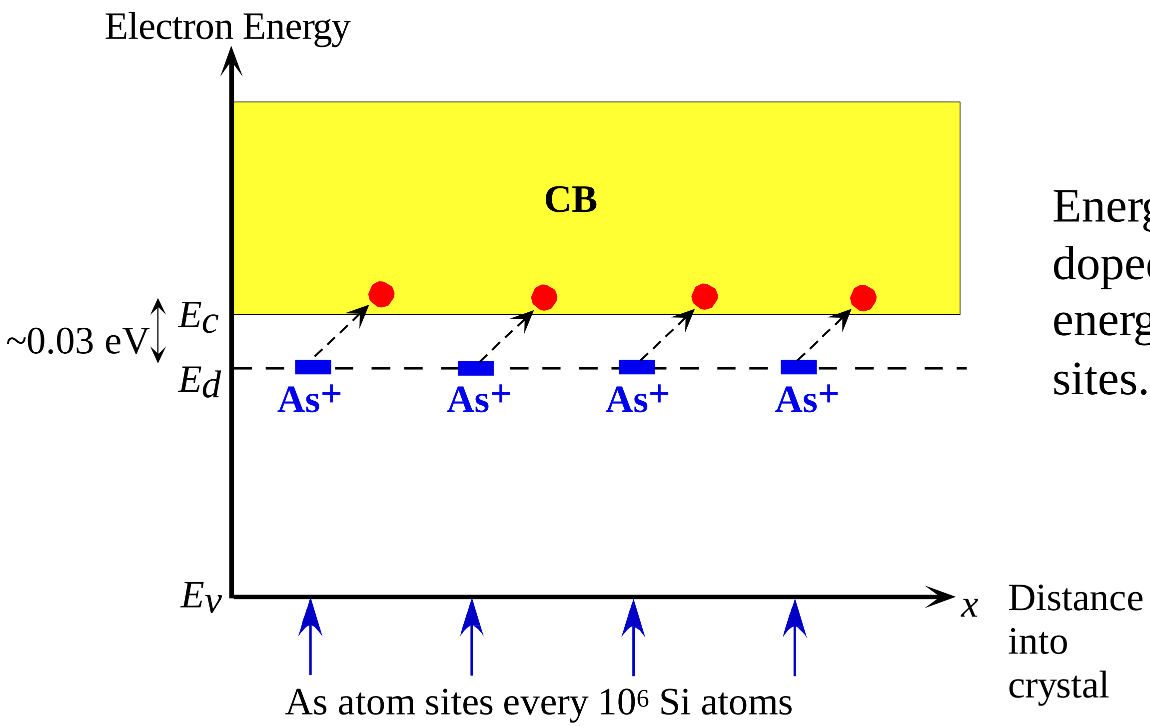
$$n_i = N_v \exp\left[-\frac{E_{Fi} - E_v}{kT}\right]$$

For doped p-type Si:

$$p = N_v \exp\left[-\frac{E_{Fp} - E_v}{kT}\right] = N_a$$

$$\Rightarrow \quad \frac{N_a}{n_i} = \exp\left[-\frac{E_{Fp} - E_{Fi}}{kT}\right]$$

Extrinsic semiconductors, n-type



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.

donor ionization energy

$\Delta E = E_c - E_d$

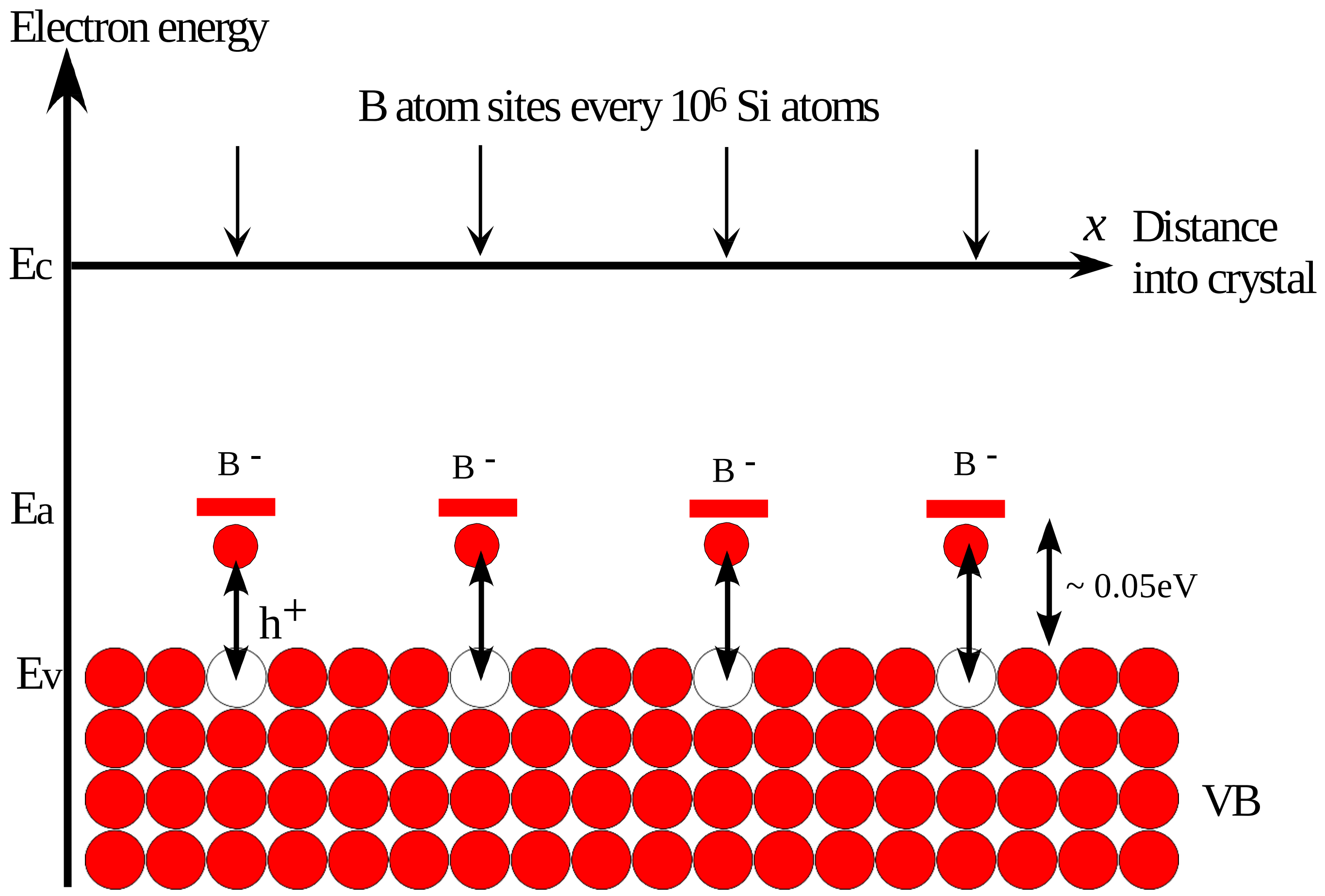
If the N_d is the donor atom concentration in the crystal, then provided that $\mathbf{N_d >> n_i}$, at **room temperature** the electron concentration in the CB will be nearly equal to N_d, that is $\mathbf{n \approx N_d}$.

$$p = \frac{n_i^{2}}{N_d}$$

The conductivity σ :

$$= eN_d\mu_e + e\left(\frac{n_i^2}{N_d}\right)\mu_h \approx eN_d\mu_e$$

Extrinsic semiconductors, p-type



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

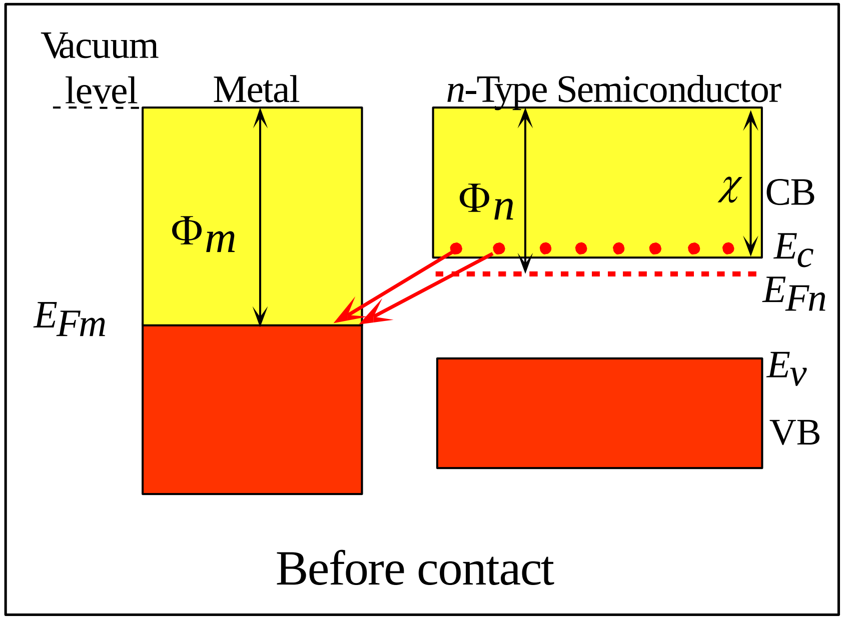
$$p \approx N_a$$

The conductivity σ :

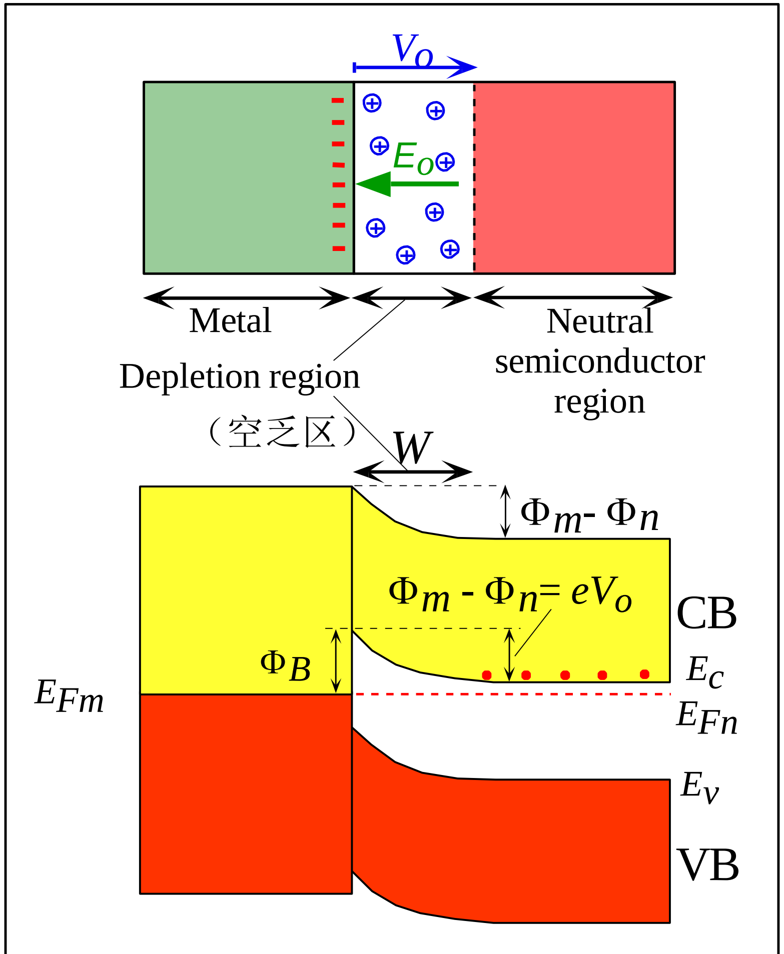
$$= eN_a\mu_h$$

$$n = \frac{n_i^2}{N_a}$$

Metal-Semiconductor Interface: Schottky Junction （肖特基结）



Before contact



After contact

Work function (逸出功):

$\Phi = E_{vacuum} - E_F$

Formation of a Schottky junction:

$\mathbf{\Phi_m > \Phi_n}$

The build-in potential V_o（内置电位）：

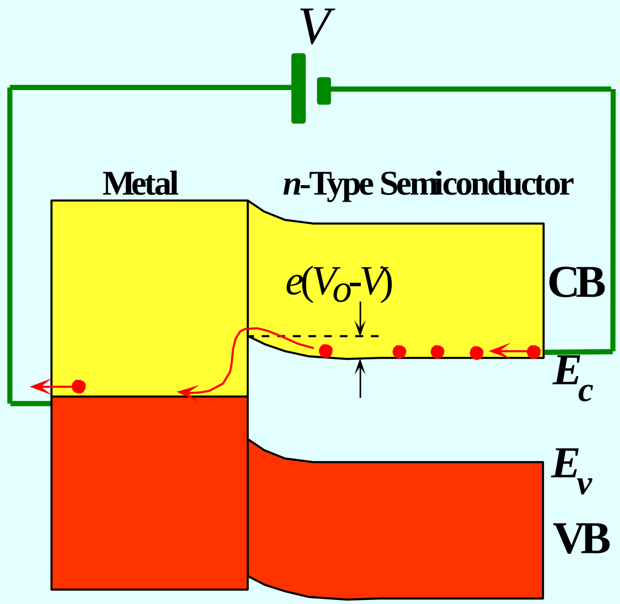
$$V_0 = (\Phi_m - \Phi_n)/e$$

Schottky barrier height Φ_B:

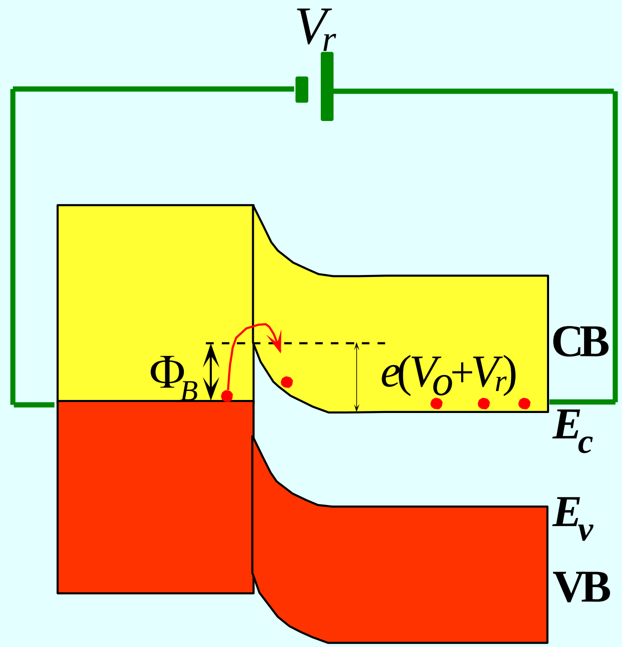
$$\Phi_B = \Phi_m - \chi = eV_0 + (E_c - E_{Fn})$$

The Schottky junction

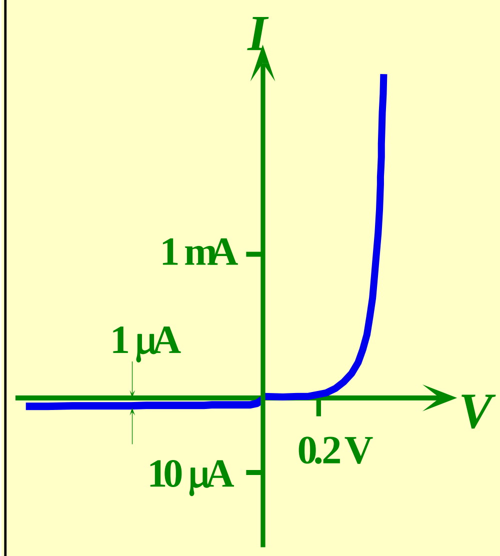
Schottky diode



(a) Forward biased Schottky junction. Electrons in the CB of the semiconductor can readily overcome the small *PE* barrier to enter the metal.



(b) Reverse biased Schottky junction. Electrons in the metal can not easily overcome the *PE* barrier Φ_B to enter the semiconductor.



(c) *I-V* Characteristics of a Schottky junction exhibits rectifying properties (negative current axis is in microamps)

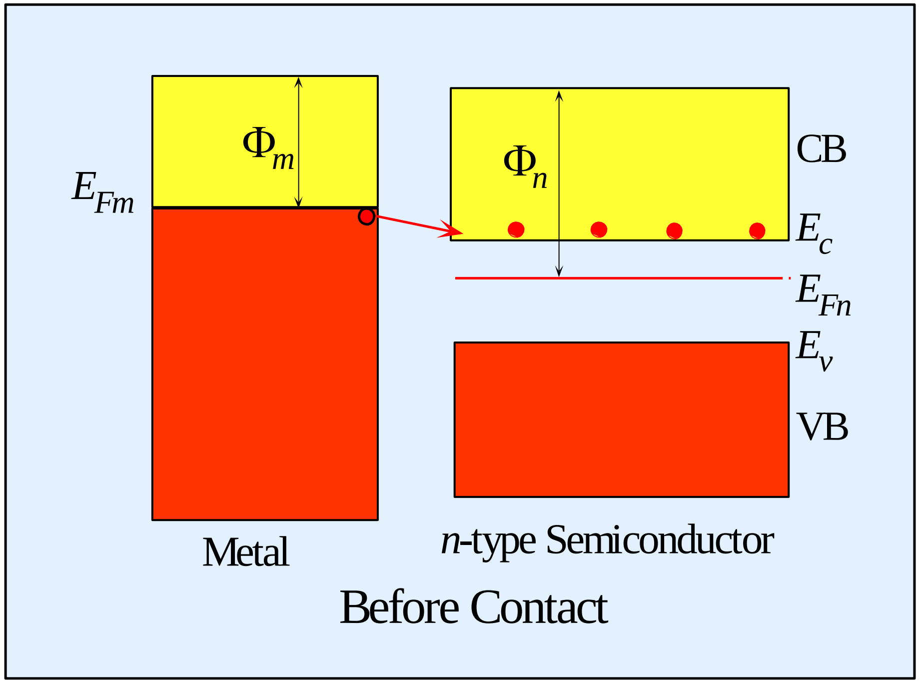
$$J = J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

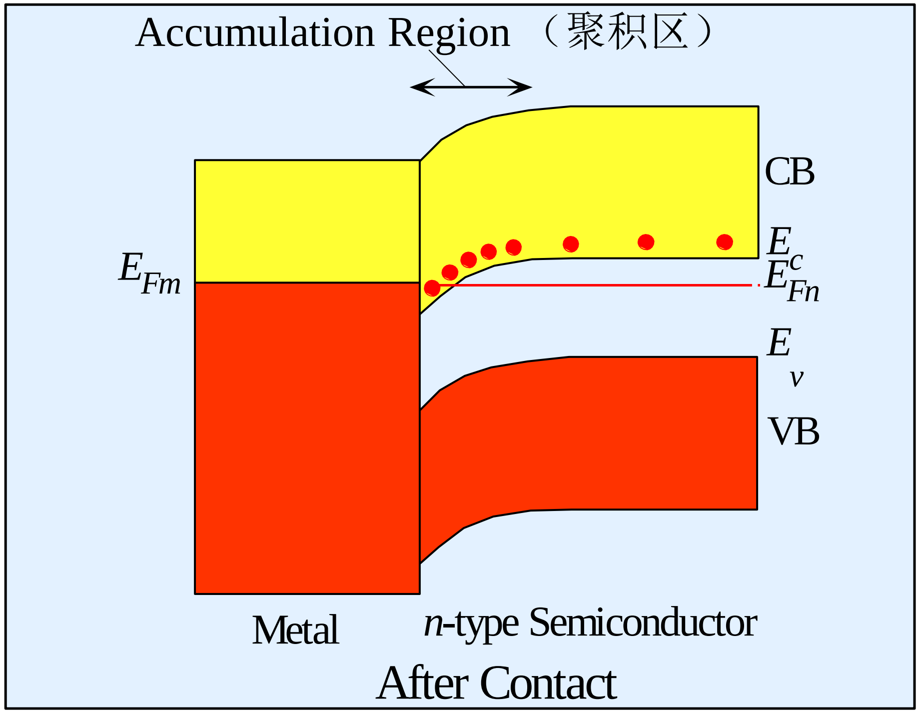
J_0, reverse saturation current

Ohmic contact（欧姆接触）

An ohmic contact is a junction between a metal and a semiconductor, that does not limit the current flow.

The work function of the metal $\mathbf{\Phi_m}$ is **smaller** than the work function $\mathbf{\Phi_n}$ of the semiconductor.





When a metal with a smaller work function than an n-type semiconductor are put into contact, the excess electrons in the accumulation region *increase* the conductivity of the semiconductor in this region, the resulting junction is an Ohmic contact in the sense that it does not limit the current flow.

Assignment 6.1

Table 5.1 Selected typical properties of Ge, Si, and GaAs at 300 K

	E_g (eV)	χ (eV)	N_c (cm^{-3})	N_v (cm^{-3})	n_i (cm^{-3})	μ_e ($cm^2\ V^{-1}\ s^{-1}$)	μ_h ($cm^2\ V^{-1}\ s^{-1}$)	m_e^*/m_e	m_h^*/m_e	ε_r
Ge	0.66	4.13	1.04×10^{19}	6.0×10^{18}	2.3×10^{13}	3900	1900	0.12*a* 0.56*b*	0.23*a* 0.40*b*	16
Si	1.10	4.01	2.8×10^{19}	1.2×10^{19}	1.0×10^{10}	1350	450	0.26*a* 1.08*b*	0.38*a* 0.60*b*	11.9
GaAs	1.42	4.07	4.7×10^{17}	7×10^{18}	2.1×10^{6}	8500	400	0.067*a,b*	0.40*a* 0.50*b*	13.1

NOTE: Effective mass related to conductivity (labeled *a*) is different than that for density of states (labeled *b*). In numerous textbooks, n_i is taken as 1.45×10^{10} cm^{-3} and is therefore the most widely used value of n_i for Si, though the correct value is actually 1.0×10^{10} cm^{-3}. (M. A. Green, *J. Appl. Phys.*, **67**, 2944, 1990.)

Question 1: Using the values of the density of states effective masses m_e^* and m_h^* in Table 5.1, calculate the intrinsic concentration in Ge at *400K*.

What is n_i if you use N_c and N_v from Table 5.1 at 300K?

Calculate the intrinsic resistivity of Ge at 300 K.

Assignment 6.1

Q1:

(a)

$$N_C = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} = 2\left[\frac{2\pi(0.56\times9.1\times10^{-31})(1.38\times10^{-23})400}{(6.626\times10^{-34})^2}\right]^{3/2}$$

$$= 1.62\times10^{25}\,m^{-3}$$

$$N_V = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} = 2\left[\frac{2\pi(0.4\times9.1\times10^{-31})(1.38\times10^{-23})400}{(6.626\times10^{-34})^2}\right]^{3/2}$$

$$= 9.75\times10^{24}\,m^{-3}$$

$$n_i = (N_c N_v)^{1/2}\exp\left(-\frac{E_g}{2kT}\right) = \left[(1.62\times10^{25})(9.75\times10^{24})\right]^{1/2}\cdot\exp\left(-\frac{0.66\times1.6\times10^{-19}}{2(1.38\times10^{-23})400}\right)$$

$$= 8.81\times10^{20}\,m^{-3} = \underline{8.81\times10^{14}\,cm^{-3}}$$

(b)

$$n_i = (N_c N_v)^{1/2}\exp\left(-\frac{E_g}{2kT}\right) = \left[(1.04\times10^{19})(6.0\times10^{18})\right]^{1/2}\cdot\exp\left(-\frac{0.66\times1.6\times10^{-19}}{2(1.38\times10^{-23})300}\right)$$

$$= 2.28\times10^{19}\,m^{-3} = \underline{2.28\times10^{13}\,cm^{-3}}$$

(c)

$$\rho = \frac{1}{\sigma} = \frac{1}{en_i(\mu_h+\mu_e)} = \frac{1}{(1.6\times10^{-19})(2.28\times10^{13})(3900+1900)}$$

$$= \underline{46.85\,\Omega cm}$$

Question 2: Using the values of the density of states effective masses m_e^* and m_h^* in Table 5.1, find the position of the Fermi energy in intrinsic GaAs with respect to the middle of the bandgap ($E_g/2$).

Question 3: A Si crystal has been doped with P. The donor concentration is 10^{15} cm^{-3}. Find the conductivity, and resistivity of the crystal at room temperature (300 K).

Q2:

$$E_{Fi} = E_v + \frac{1}{2}E_g - \frac{3}{4}kT\ln\left(\frac{m_e^*}{m_h^*}\right)$$

$$= E_v + \frac{1}{2}E_g - \frac{3}{4}(8.62\times10^{-5}\,eVK^{-1})(300K)\ln\left(\frac{0.067m_e}{0.5\,m_e}\right)$$

$$= E_v + \frac{1}{2}E_g + \underline{0.039\,eV}$$

(assumption of E_{Fi} at middle of E_g is valid !)

Q3:

$$\sigma = en\mu_e + ep\mu_h$$

$$\approx e\underline{N_d\mu_e}$$

$$= (1.6\times10^{-19}\,c)(10^{15}\,cm^{-3})(1350\,cm^2V^{-1}s^{-1})$$

$$= 0.216\,\Omega^{-1}cm^{-1}$$

$$\rho = \frac{1}{\sigma} = \underline{4.63\,\Omega cm}$$

Question 4:

a) From Table 5.1, calculate the expected doping concentration of a p-type Si semiconductor with a resistivity of 1 Ω·cm at room temperature, assuming the electron and hole drift mobility remain unchanged.

b) What is the change in the Fermi energy of the p-type Si compared to intrinsic Si?

Question 5:

Schematically draw the energy diagram, density of states, Fermi-Dirac probability, and carrier distributions of a *p-type* semiconductor.

Q4:

(a) $\sigma = \frac{1}{\rho} = 1\ \Omega^{-1}\mathrm{cm}^{-1}$

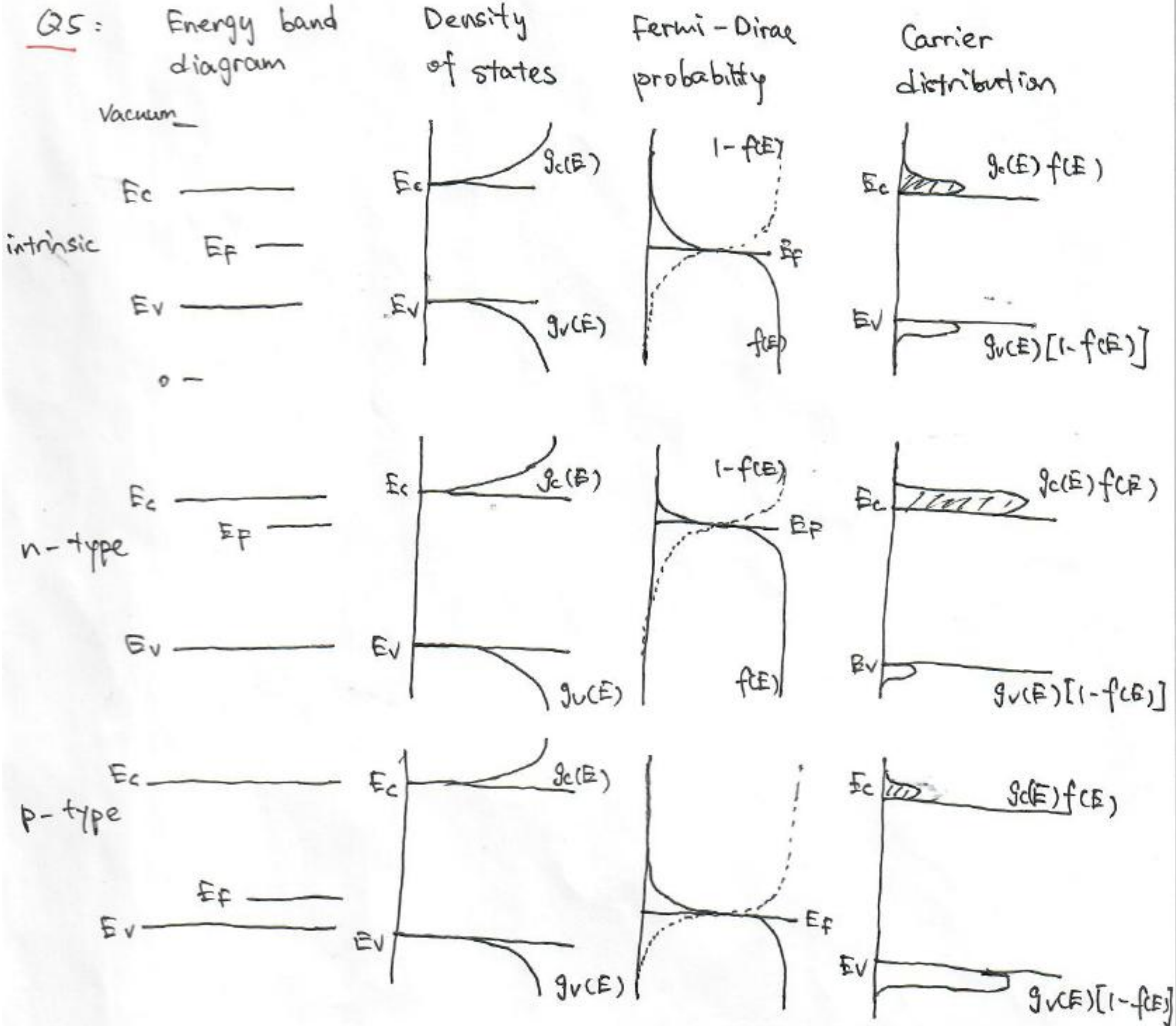
For p-type Si: $\sigma = en\mu_e + ep\mu_h = eN_a\mu_h$

$$N_a = \frac{\sigma}{e\mu_h} = \frac{1}{1.6\times10^{-19}\times 450} = 1.39\times10^{16}\ \mathrm{cm}^{-3}$$

(b) $$E_{Fp} - E_{Fi} = -kT\ln\left(\frac{N_a}{n_i}\right) = -(8.62\times10^{-5}\,\mathrm{eV\,K^{-1}})(300\,\mathrm{K})\cdot\ln\left[\frac{1.39\times10^{16}\,\mathrm{cm}^{-3}}{10^{10}\,\mathrm{cm}^{-3}}\right] = -0.37\,\mathrm{eV}$$

$$\frac{N_a}{n_i} = \exp\left[-\frac{E_{Fp}-E_{Fi}}{kT}\right]$$

Q5:


Energy band diagram
Density of states
Fermi-Dirac probability
Carrier distribution
Vacuum
intrinsic
Ec
EF
Ev
0
Ec
gc(E)
Ev
gv(E)
1-f(E)
EF
f(E)
Ec
gc(E) f(E)
Ev
gv(E)[1-f(E)]
n-type
Ec
EF
Ev
Ec
gc(E)
Ev
gv(E)
1-f(E)
EF
f(E)
Ec
gc(E) f(E)
Ev
gv(E)[1-f(E)]
p-type
Ec
EF
Ev
Ec
gc(E)
Ev
gv(E)
Ef
Ec
gc(E) f(E)
Ev
gv(E)[1-f(E)]

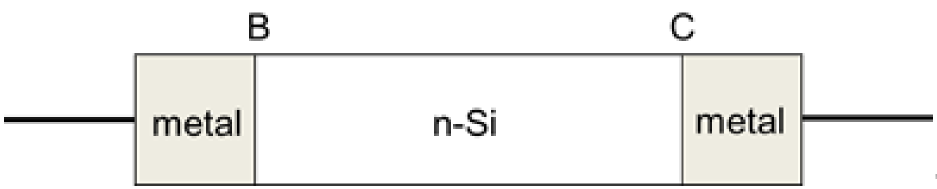
Assignment 6.2

Question 1: Consider an *n*-type Si sample doped with 10^{16} donors per cm^3. The length L is 100 μm; the cross-sectional area A is 10 μm × 10 μm. The two ends of the sample are labeled as B and C. The electron affinity (χ) of Si is 4.01 eV and the work functions of four potential metals (Φ_m) for contacts at *B* and *C* are listed in the table below:

Table 5.5 Work functions in eV

Cs	Li	Al	Au
1.8	2.5	4.25	5.0

a) Which metals will result in a Schottky contact? Draw the energy band diagram **after** contact.



b) Sketch the I-V characteristics when both B and C are Ohmic contacts. What is the relationship (gradient) between I and V? (Hint: conductivity of n-type Si)

c) Sketch the I-V characteristics when both B and C are Schottky contacts. What is the relationship between I and V?

d) Sketch the I-V characteristics when B is Ohmic and C is a Schottky junction. What is the relationship between I and V?

Assignment 6.2

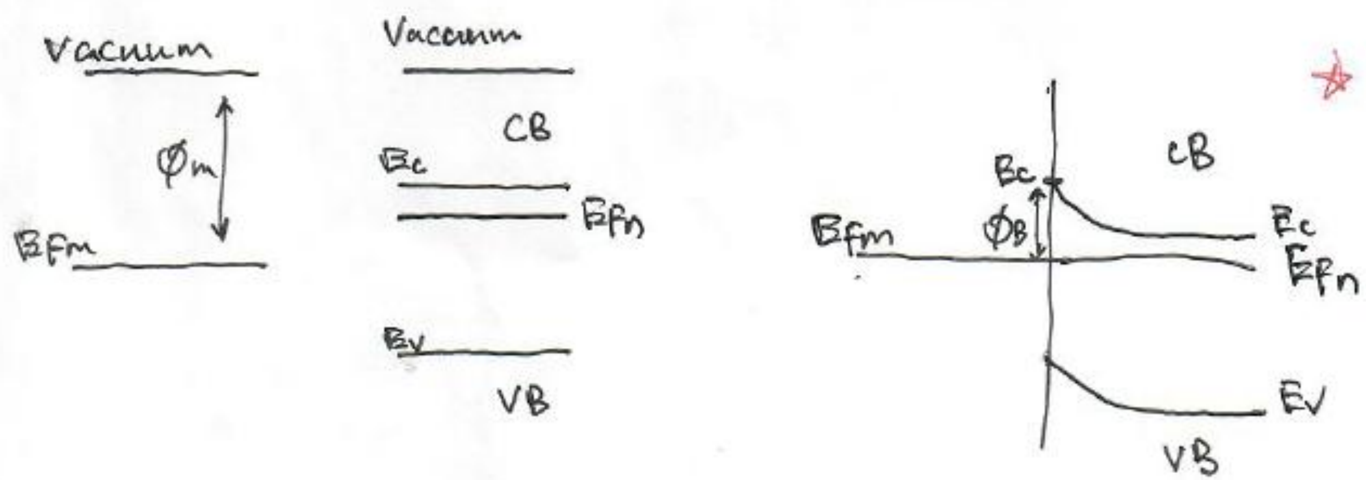
Q1: For n-type Si:

$$\phi_n = \chi + (E_c - E_{Fn}) = 4.01 + 0.21 = \underline{4.22\,eV}$$

$$n = N_c \exp\left[-\frac{E_c - E_{Fn}}{kT}\right] = N_d$$

$$\Rightarrow E_c - E_{Fn} = -kT\ln\left(\frac{N_d}{N_c}\right) = -(8.62\times10^{-5})(300)\ln\left(\frac{10^{16}}{2.8\times10^{19}}\right) = 0.21\,eV$$

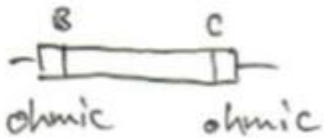
$\phi_m > \phi_n$, Schottky contact $\begin{cases} \phi_m = 5.0\,eV \text{ for Au} \\ \phi_m = 4.25\,eV \text{ for Al} \end{cases}$

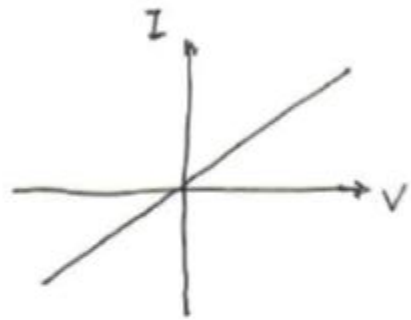


(b) Relationship between I and V: a straight line with slope equal to the conductance. (or inverse of the resistance)

$$R = \frac{L}{\sigma A} = \frac{L}{e N_d \mu_e A} = \frac{100\times10^{-4}\,\text{cm}}{(1.602\times10^{-19}\text{C})(10^{16}\,\text{cm}^{-3})(1350\,\text{cm}^2\text{V}^{-1}\text{s}^{-1})(10^{-6}\text{cm}^2)}$$

$$= 4620\ \Omega$$





(c)

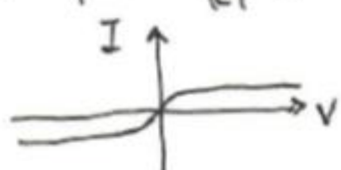
There is maximum saturation current in both directions (reverse bias).

$$J = -J_0\left[1-\exp\left(-\frac{eV}{kT}\right)\right]$$

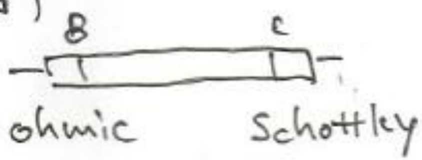
∴ the saturation current is the thermionic emission current over ϕ_B.

$$\phi_B = \phi_{Au} - \chi = 5.1\text{eV} - 4.01\text{eV} = 1.09\text{eV}$$

$$I_0 = A\cdot J_0 = A\cdot C_1 \exp\left(-\frac{\phi_B}{kT}\right)$$



(d)



when C is reverse biased, current is limited by I_o (themionic saturation current). when C is forward biased, current is limited by resistance of the semiconductor.