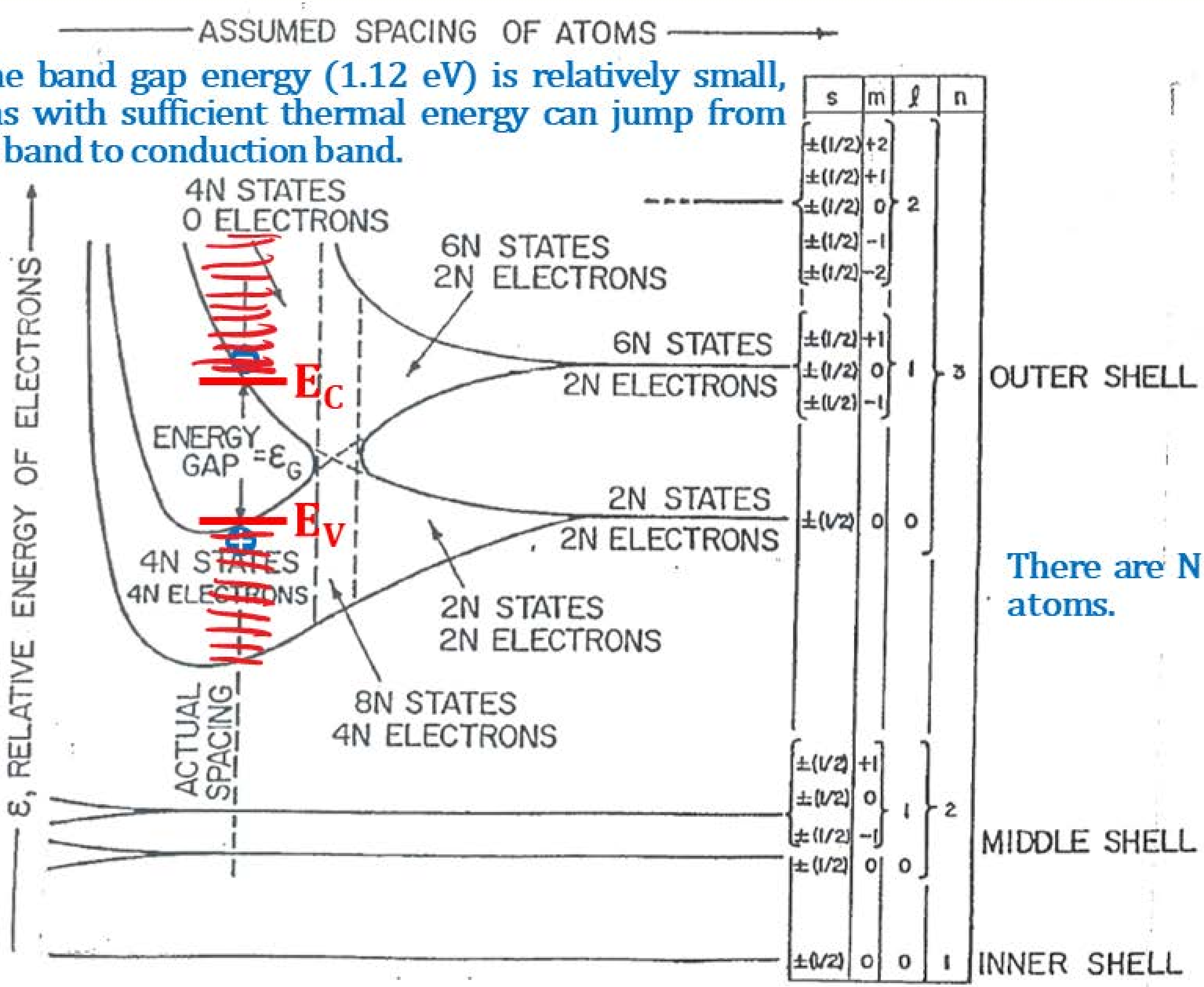
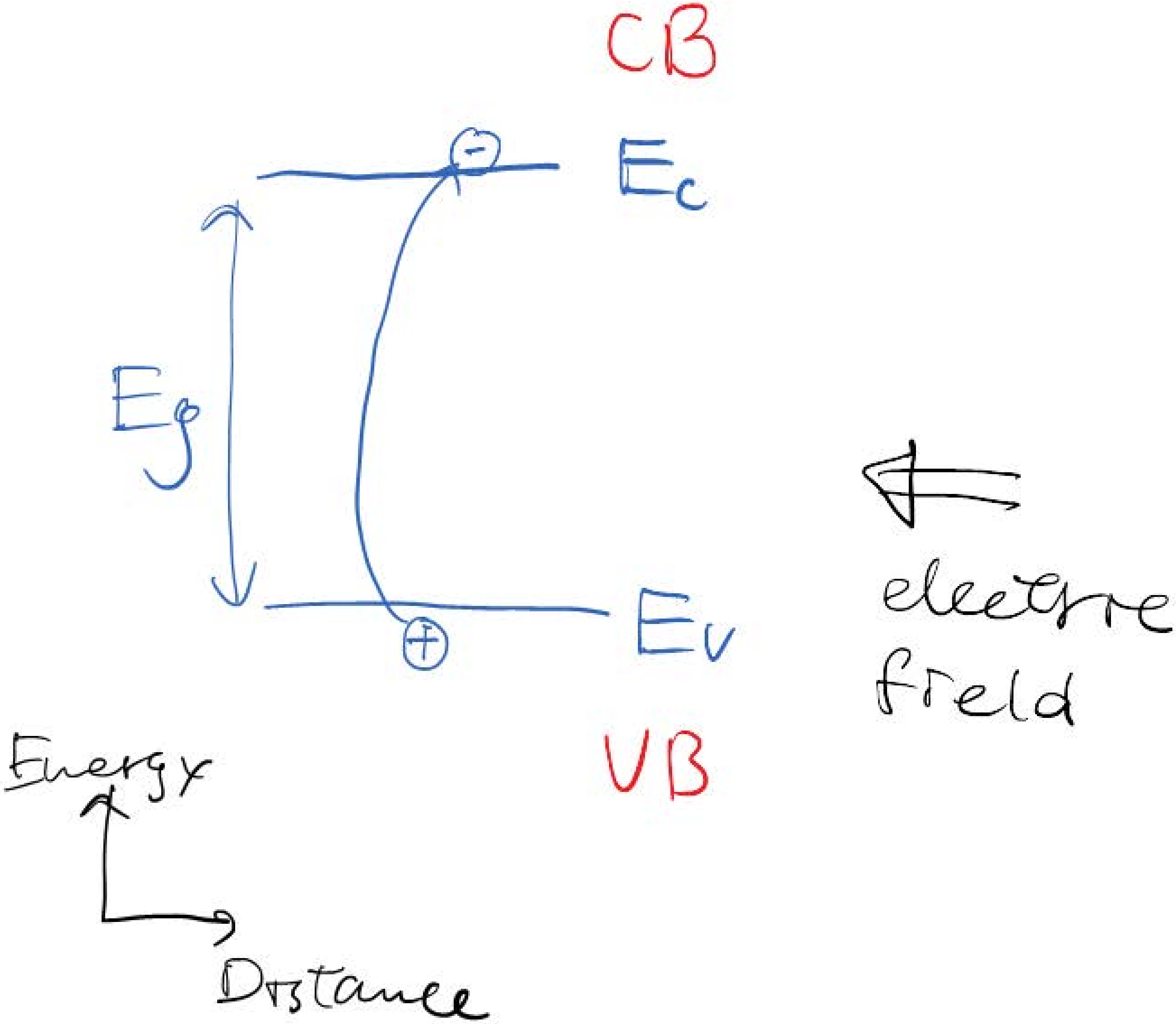
Band Formation for Si

Since the band gap energy (1.12 eV) is relatively small, electrons with sufficient thermal energy can jump from valence band to conduction band.

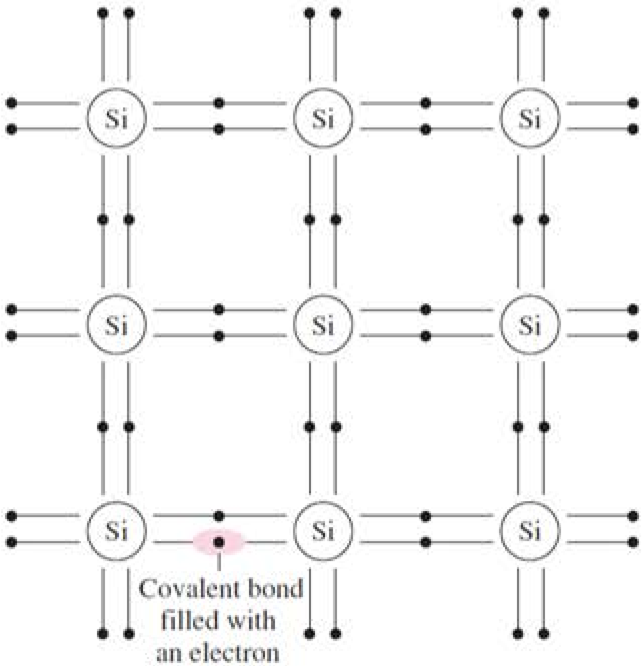


There are N silicon atoms.

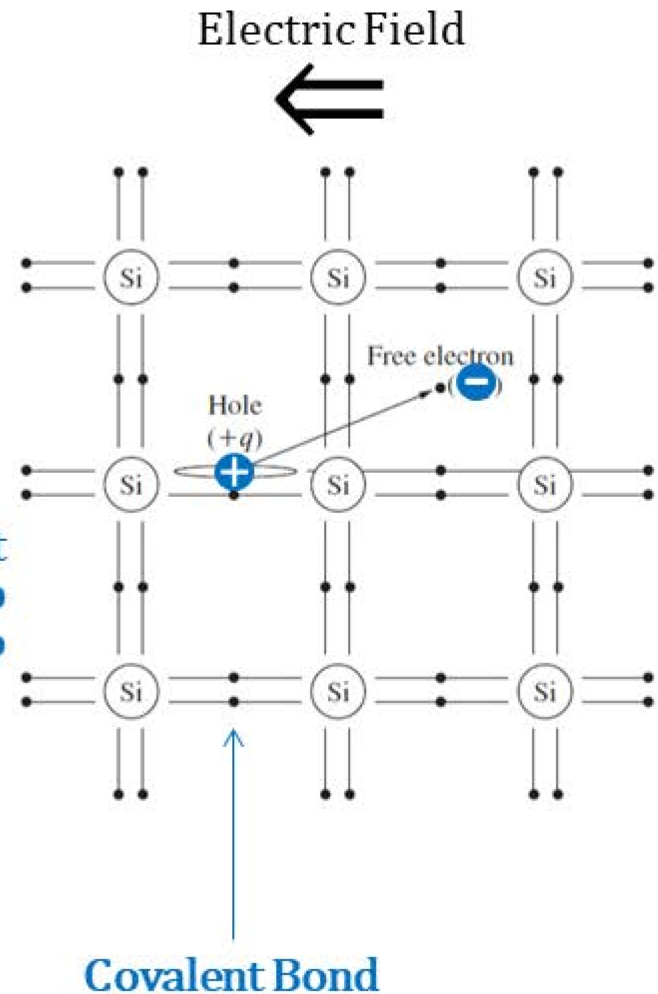
Energy band diagram



Intrinsic (i.e. no impurity) **Si** (I)



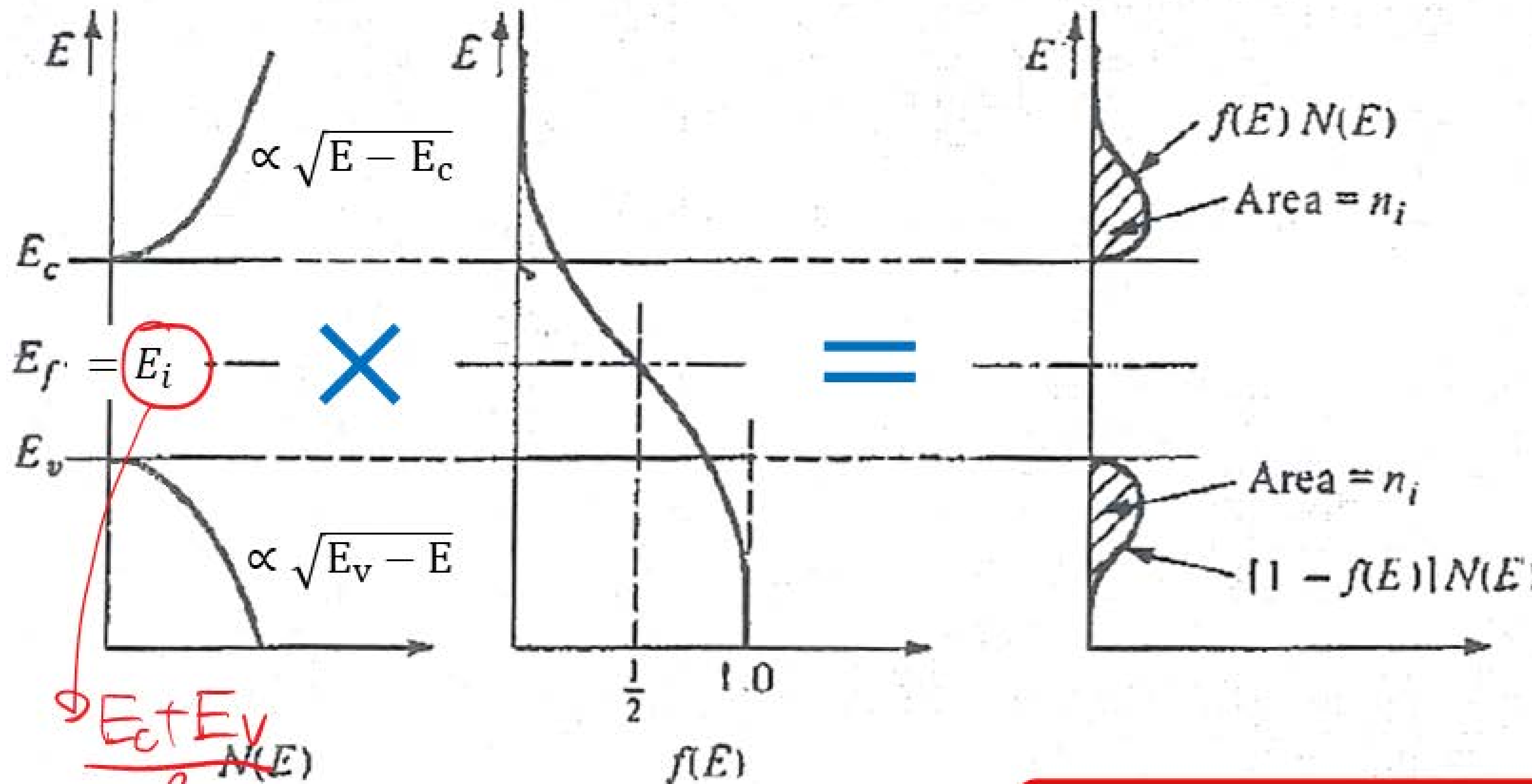
Electrons with sufficient thermal energy can jump from valence band to conduction band.



0 K

300 K

n and p for **Intrinsic Si** (II)



Density of States
\# of states/$(\mathrm{cm}^3 \cdot \mathrm{J})$

Fermi-Dirac Distribution
(the probability of the state occupied with an electron)

$$\mathbf{f(E) = \frac{1}{\exp\left(\frac{E - E_f}{kT}\right) + 1}}$$

$$\mathbf{n = \int_{E_C}^{\infty} f(E)N(E)dE = n_i}$$

$$\mathbf{p = \int_{-\infty}^{E_V} [1 - f(E)]N(E)dE = n_i}$$

$(1\ /\ \mathrm{cm}^3)$

n and p for **Intrinsic Si** (III)

$$\boxed{np = n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) = \text{constant}}$$

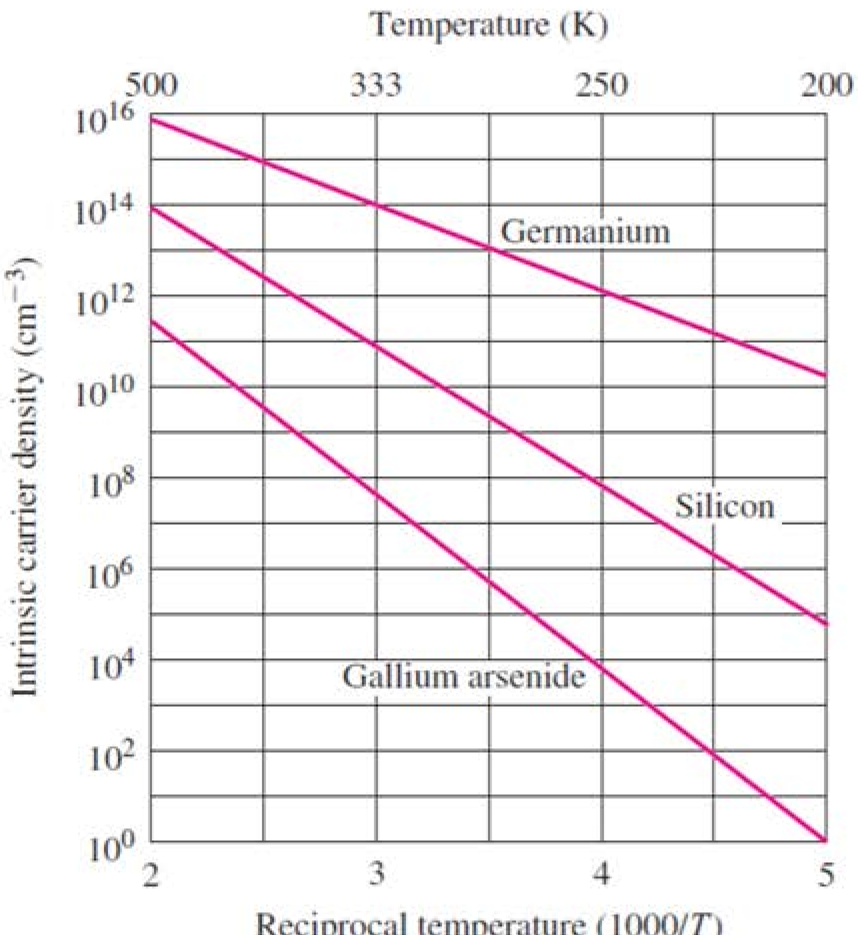
Source: Microelectronic Circuit Design, 4th Edition, by R. C. Jaeger and T. N. Blalock

k (Boltzmann's Constant)
$= 1.38 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K

At 300 K:

$$n_i^2 = (1.08 \times 10^{31}) 300^3 e^{\frac{-1.12}{(8.62\times10^{-5})\times300}}$$
$$= 4.52 \times 10^{19}\ (1/\text{cm}^6)$$

$$\boxed{n_i = 6.73 \times 10^9\ (1/\text{cm}^3) \cong 10^{10}\ (1/\text{cm}^3)}$$



	B ($K^{-3} \cdot cm^{-6}$)	E_G (eV)
Si	1.08×10^{31}	1.12
Ge	2.31×10^{30}	0.66
GaAs	1.27×10^{29}	1.42

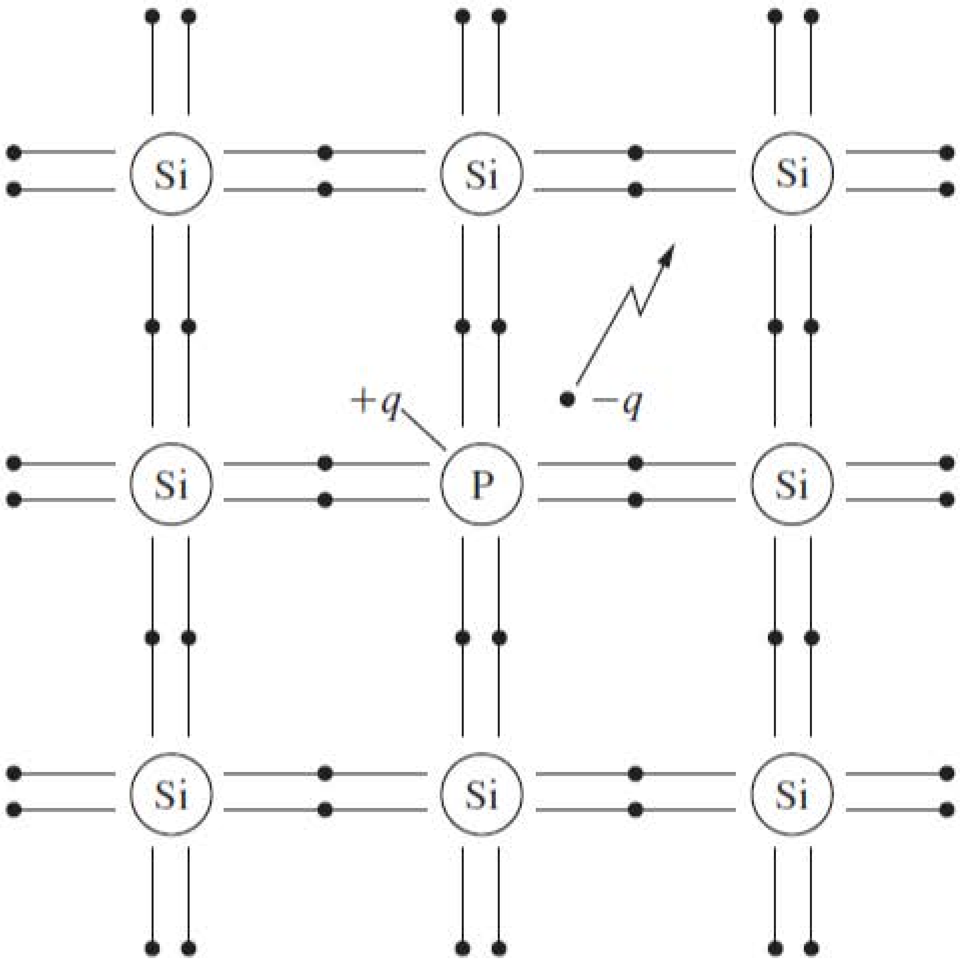
Figure 2.4 Intrinsic carrier density versus temperature from Eq. (2.1).

n and p for **n-type Si** (I)

300 K

At room temperature, nearly all phosphorus dopants are ionized.

Each dopant donates one electron away, which creates an electron in the conduction band.



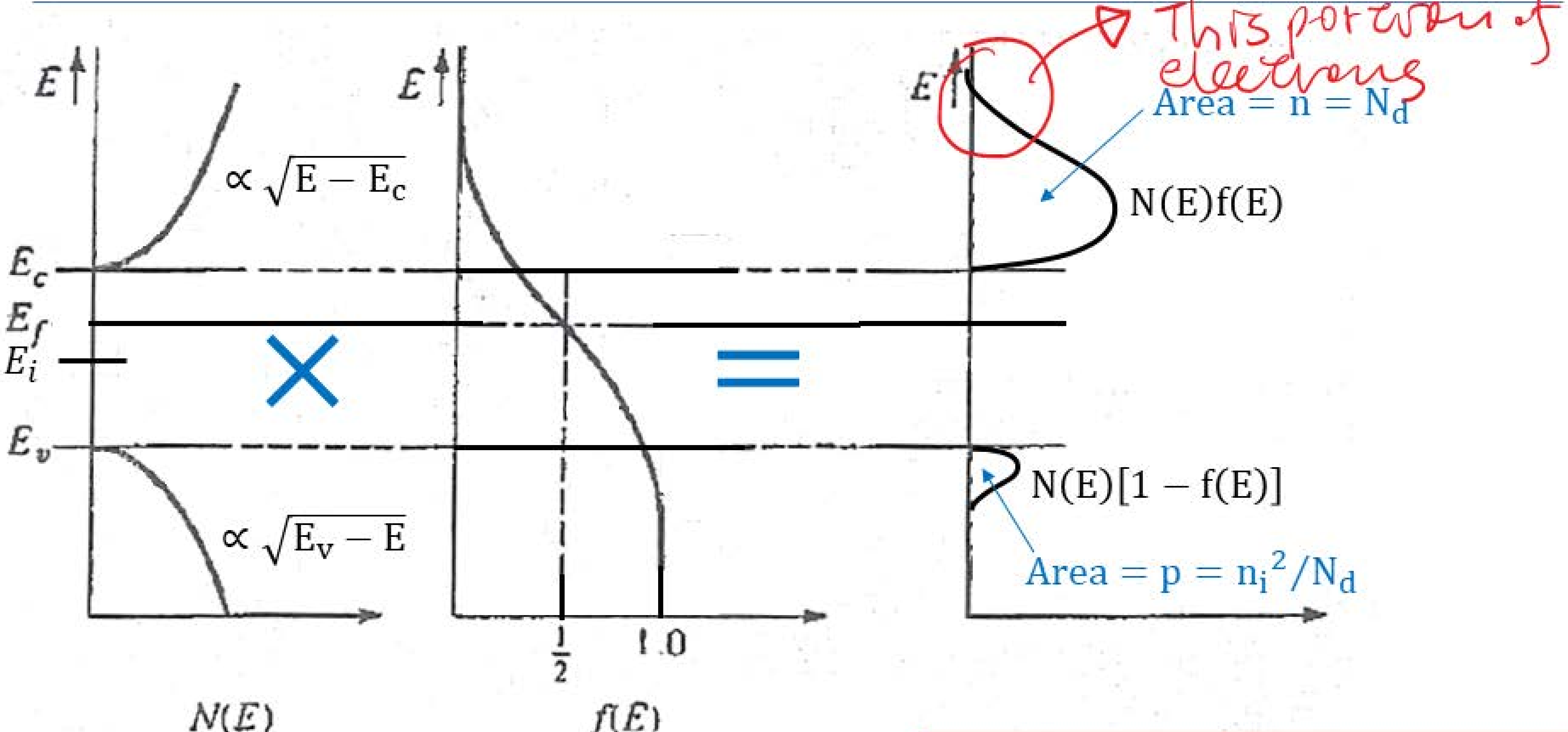
atom

ion

If the n-type dopant (e.g. 磷 **phosphorus**) concentration $N_d \gg n_i$,

$n = N_d$ and $p = n_i^2/N_d$ (1 / cm³)

n and p for **n-type Si** (II)



Density of States
\# of states/($cm^3 \cdot J$)

Fermi-Dirac Distribution
(the probability of the state occupied with an electron)

$$\mathbf{f(E) = \frac{1}{\exp\left(\frac{E - E_f}{kT}\right) + 1}}$$

$$\mathbf{n = \int_{E_C}^{\infty} f(E)N(E)dE = n_i\, e^{\frac{E_f - E_i}{kT}}}$$

$$\mathbf{p = \int_{-\infty}^{E_V} [1 - f(E)]N(E)dE = n_i\, e^{\frac{E_i - E_f}{kT}}}$$

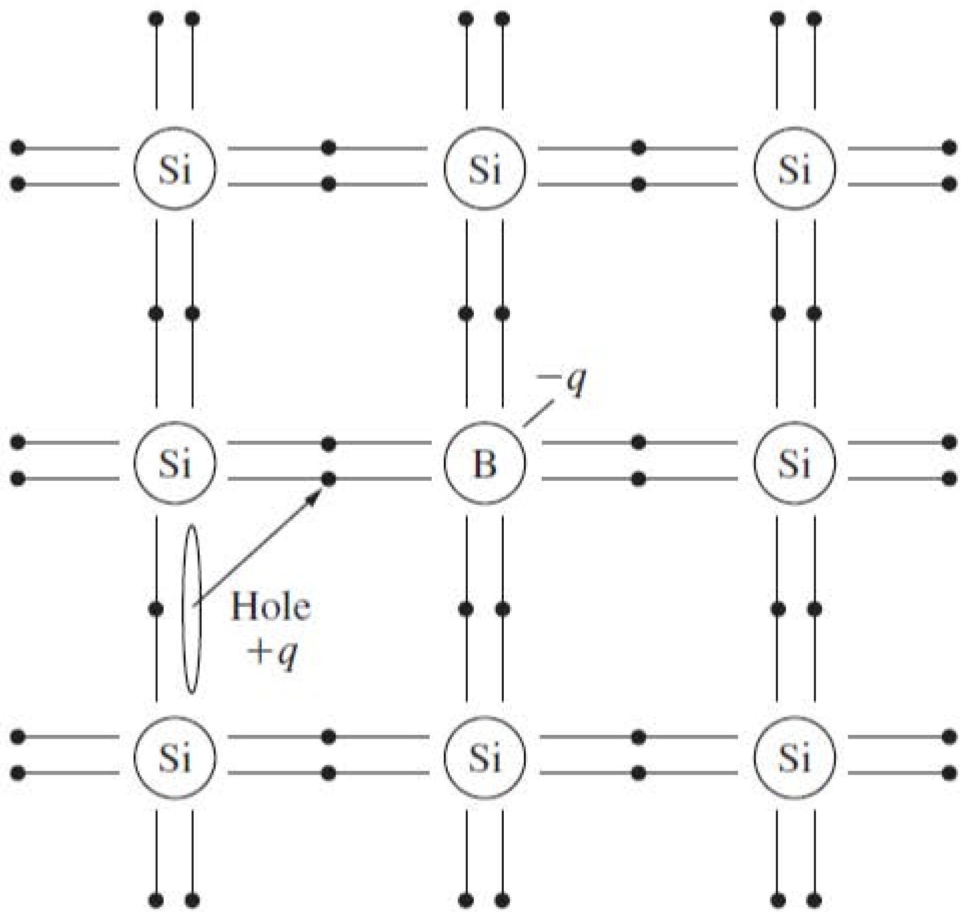
(1 / cm^3)

n and p for **p-type Si** (I)

300 K

At room temperature, nearly all boron dopants are ionized.

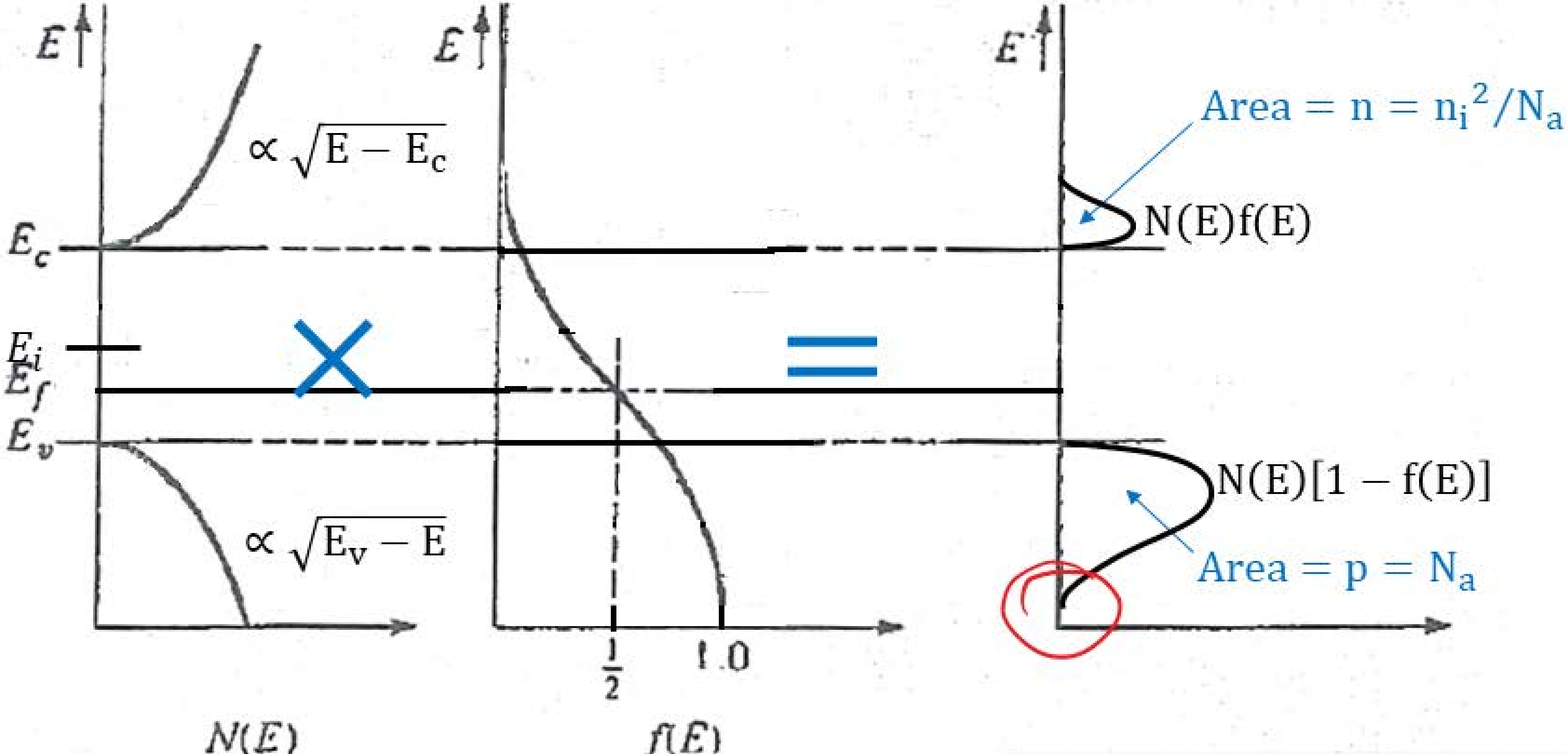
Each dopant takes one electron away from neighboring silicon, which creates a hole in the valence band.



If the p-type dopant (e.g. 硼 **boron**) concentration $N_a \gg n_i$,

$p = N_a$ and $n = n_i^2/N_a$ $(1 / cm^3)$

n and p for **p-type Si** (II)



Density of States
# of states/$(cm^3 \cdot J)$

Fermi-Dirac Distribution
(the probability of the state occupied with an electron)

$$f(E) = \frac{1}{\exp\left(\frac{E - E_f}{kT}\right) + 1}$$

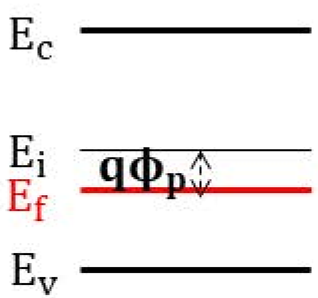
$$n = \int_{E_C}^{\infty} f(E)N(E)dE = n_i\, e^{\frac{E_f - E_i}{kT}}$$

$$p = \int_{-\infty}^{E_V} [1 - f(E)]N(E)dE = n_i\, e^{\frac{E_i - E_f}{kT}}$$

$(1\ /\ cm^3)$

Summary

p-type

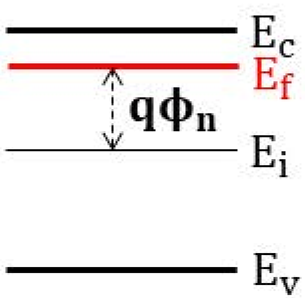


$$p = N_a = n_i e^{\frac{E_i - E_f}{kT}} = n_i e^{\frac{q\phi_p}{kT}}$$

$$n = \frac{{n_i}^2}{N_a} = n_i e^{\frac{E_f - E_i}{kT}} = n_i e^{\frac{-q\phi_p}{kT}}$$

$$np = {n_i}^2$$

n-type



$$n = N_d = n_i e^{\frac{E_f - E_i}{kT}} = n_i e^{\frac{q\phi_n}{kT}}$$

$$p = \frac{{n_i}^2}{N_d} = n_i e^{\frac{E_i - E_f}{kT}} = n_i e^{\frac{-q\phi_n}{kT}}$$

$$np = {n_i}^2$$

At 300K

#1

$n = p = n_i = 10^{10} \left(\frac{1}{cm^3}\right)$

Ion Implantation

$N_d = 10^{15}$

At 300K

#2

N-type

$n = N_d = 10^{15}$

$p = \frac{n_i^2}{n} = 10^5 \left(\frac{1}{cm^3}\right)$

Ion Implatation

$Na = 10^{12}$

At 300K

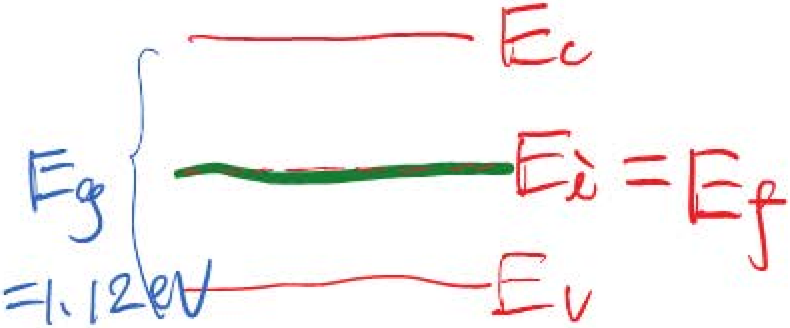
#3

P-type

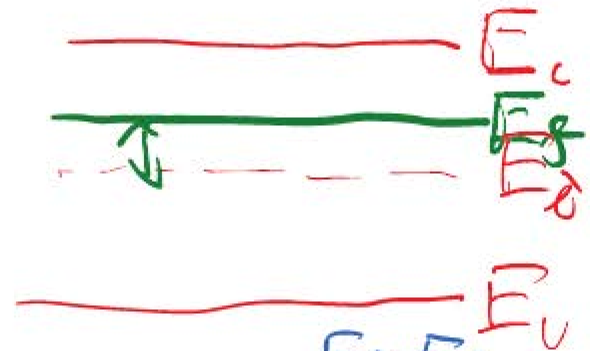
$p = N_a = 10^{12}$

$n = \frac{n_i^2}{p} = 10^8 \left(\frac{1}{cm^3}\right)$

#1



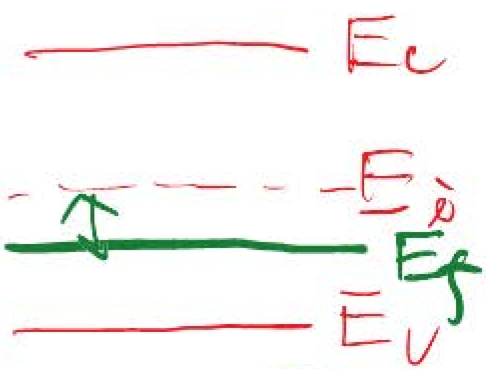
#2 N-type



$$10^{15} = 10^{10} e^{\frac{E_f - E_i}{kT}}$$

P-type

#3

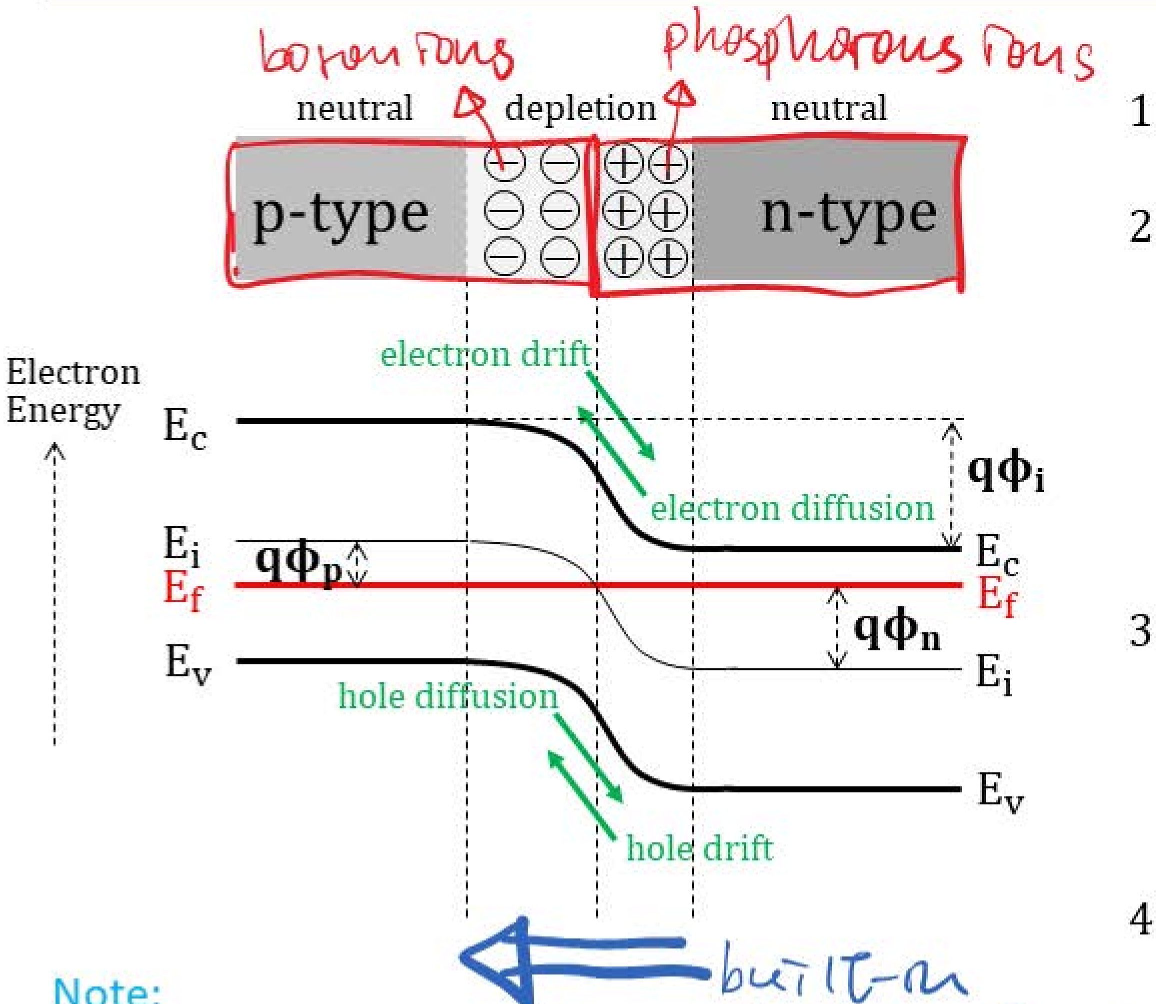


$$10^{12} = 10^{10} e^{\frac{E_i - E_f}{kT}}$$

Si PN Junction Diode

Qualitative Understanding

Si PN Junction in **Thermal Equilibrium**



Note:

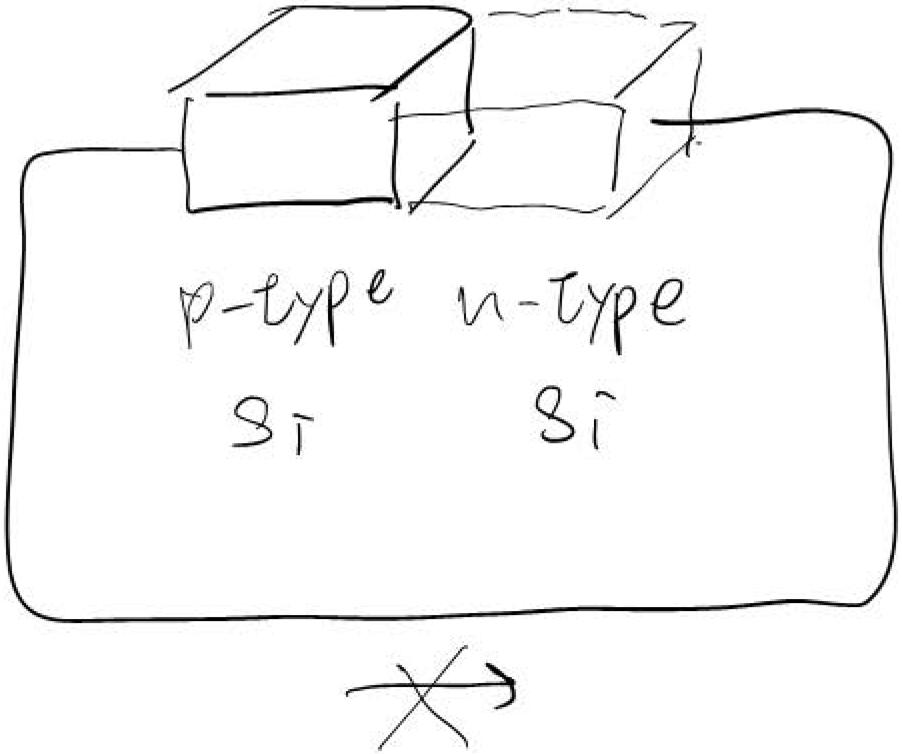
- E_C, E_i and E_V are parallel to each other.
- E_C, E_i and E_V bending means there is electric field.
- E_f bending means there is current.

At first

1. Electrons/holes near the junction diffuse to the opposite sides.
2. Ionized dopants, fixed in the lattice, are left behind. → Formation of **built-in electric field** and **energy barrier** ($\mathbf{q\phi_i}$) for diffusion.

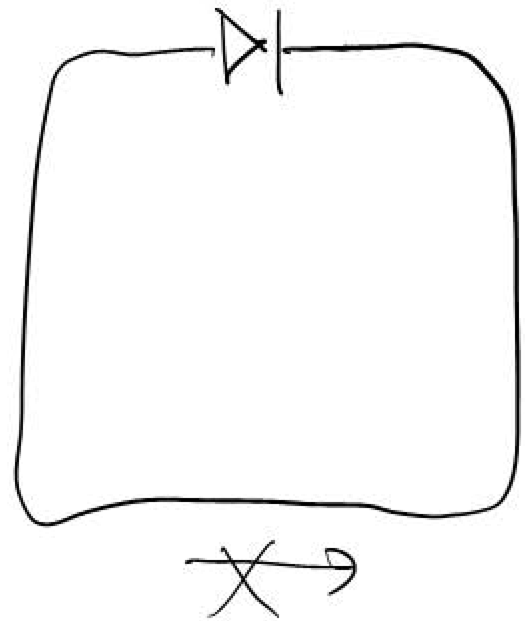
Then

3. Some electrons/holes in the neutral regions with sufficient energy continuously diffuse to the opposite sides. → Formation of **diffusion current.**
4. Some electrons/holes wandering into the in the depletion region get swept by the built-in electric field. → Formation of **drift current.**
5. Diffusion current cancels drift current. No net current flowing.



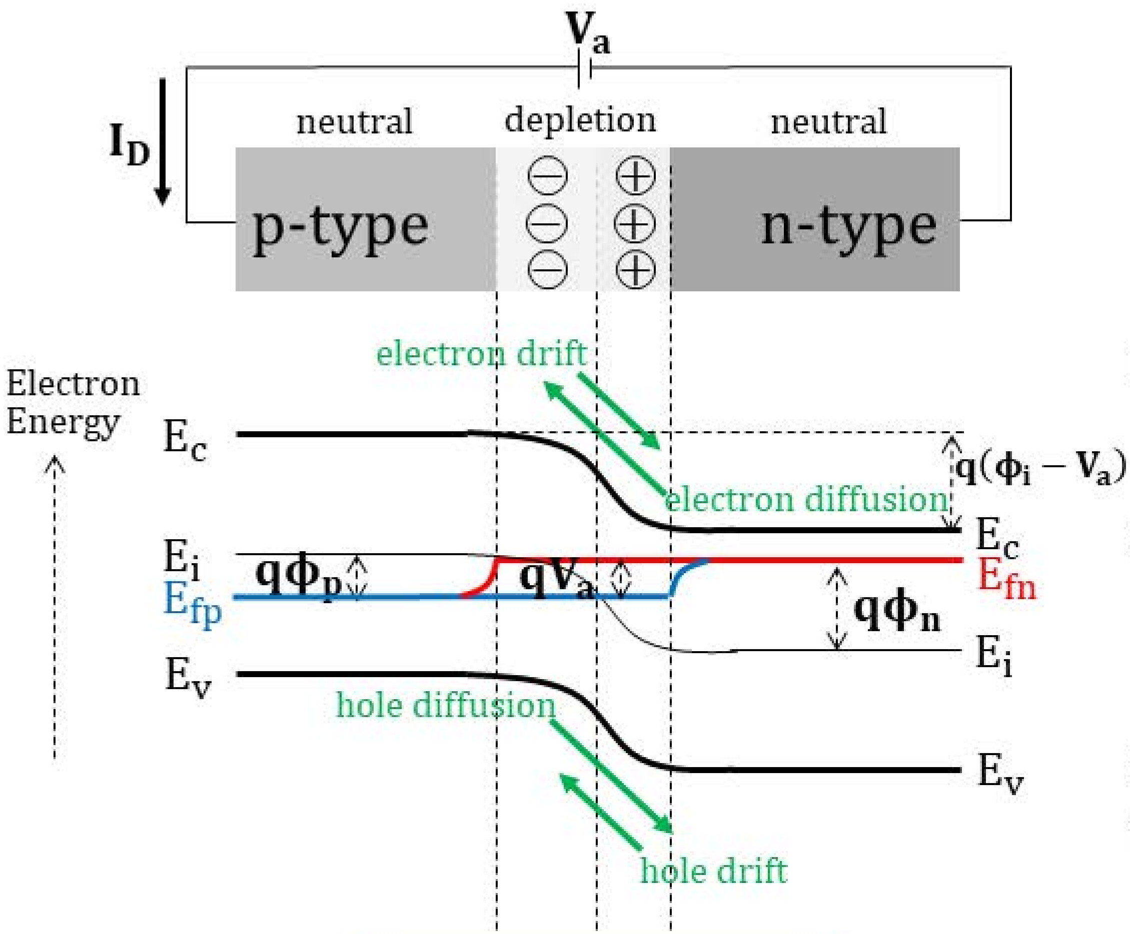
No net current

=



No net current

Si PN Junction in **Forward Bias**

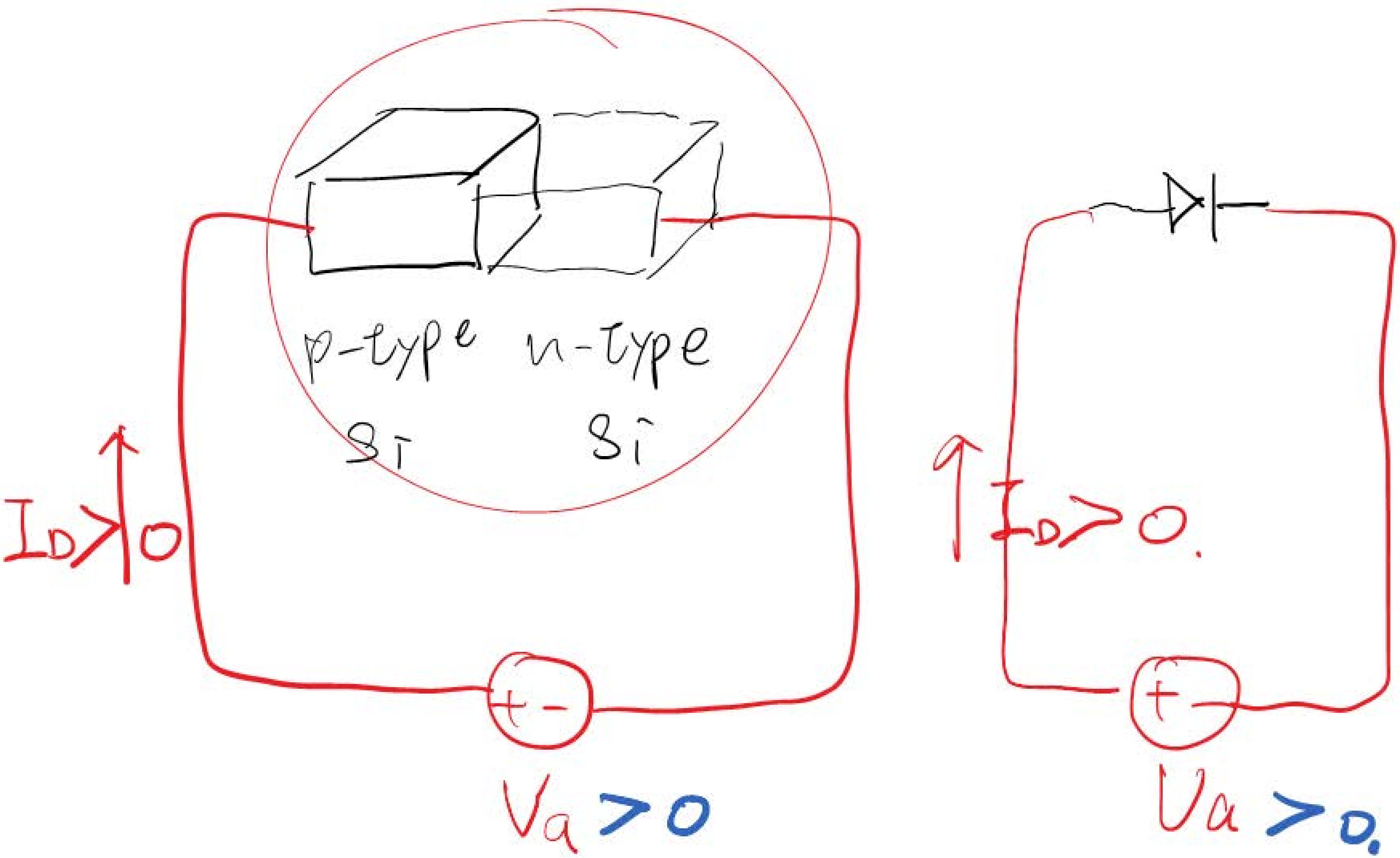


$$\boxed{I_D = I_S\left(e^{\frac{qV_a}{kT}} - 1\right)} > 0$$

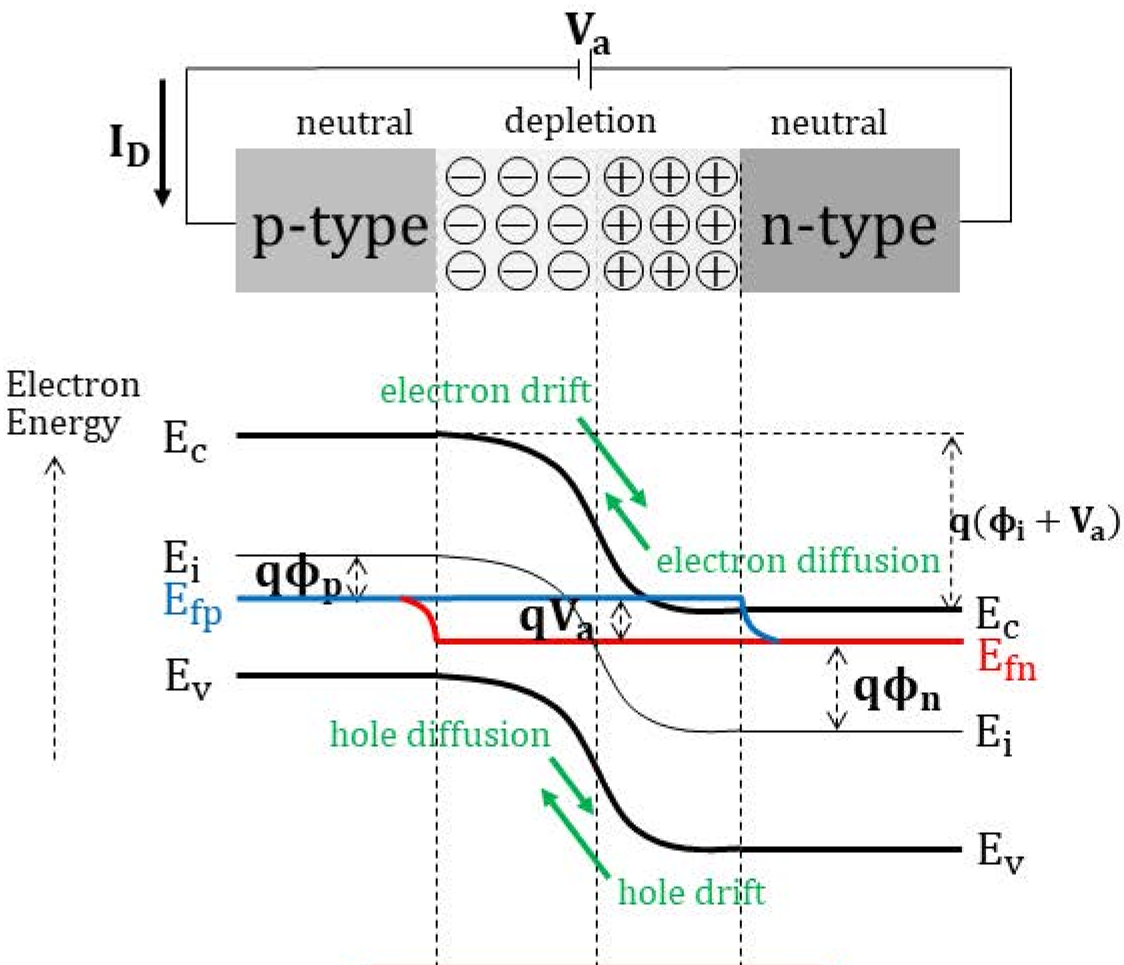
Constant Diffusion Drift

When $V_a > 0$ applied

1. The energy barrier formed by the built-in electric field becomes smaller, $\mathbf{q(\phi_i - V_a)}$.
2. More electrons/holes diffuse to the opposite sides. → **Diffusion current increases**, while **drift current remains the same.**
3. There is (+) net current flowing.
4. The depletion width becomes narrower.


p-type
n-type
Si
Si
I_D > 0
+ -
V_a > 0
I_D > 0.
+ -
V_a > 0.

Si PN Junction in **Reverse Bias**

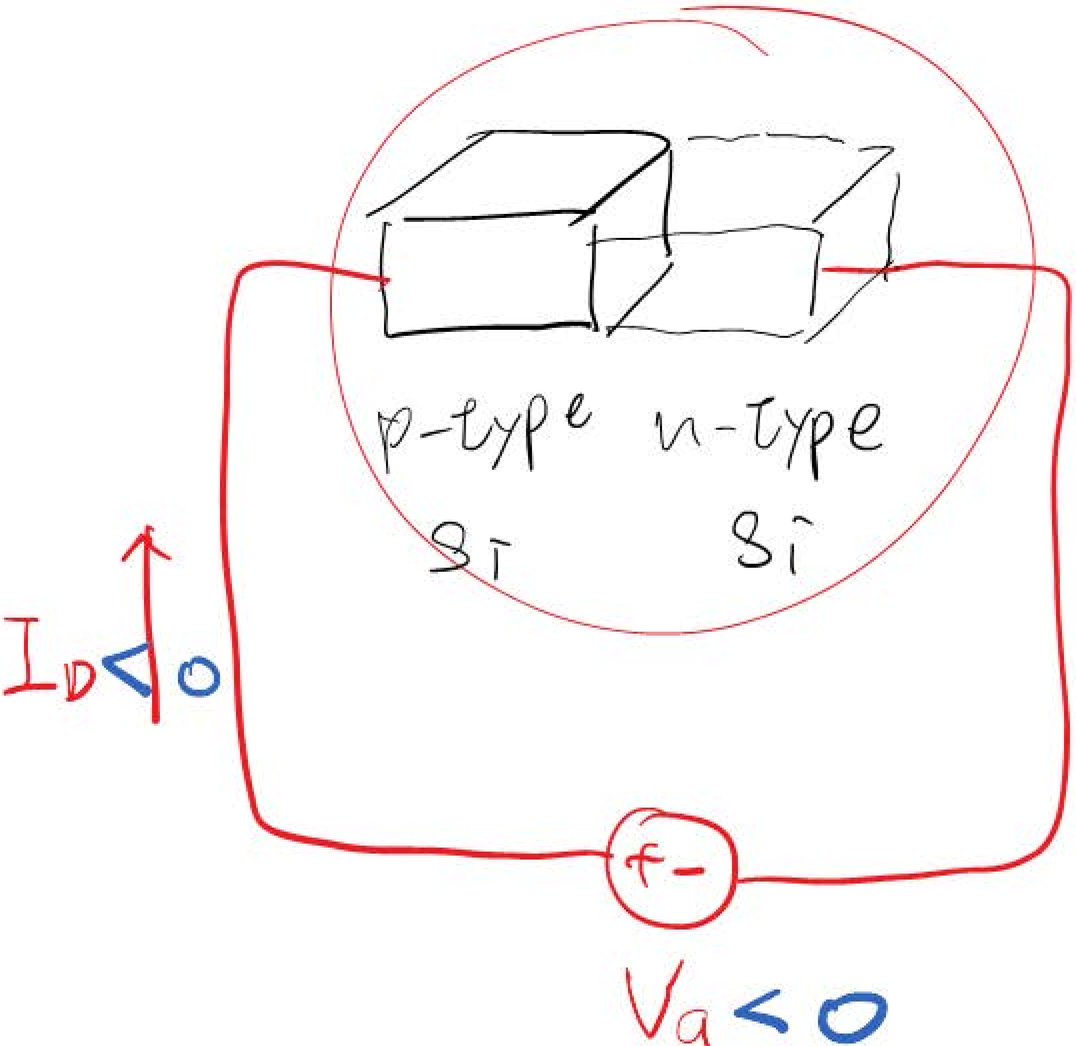


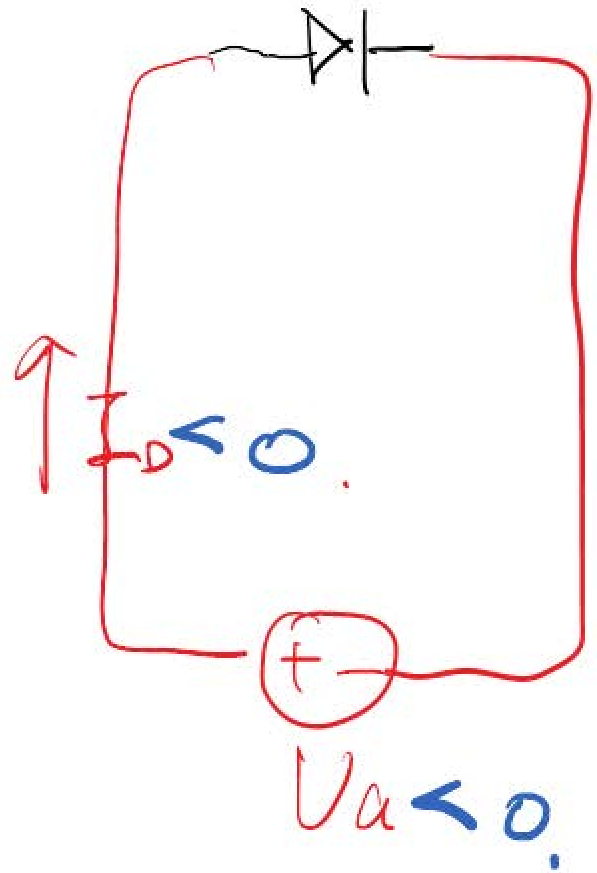
$$I_D = I_S\left(e^{\frac{-qV_a}{kT}} - 1\right) < 0$$

Constant Diffusion Drift

When $V_a < 0$ applied

1. The energy barrier formed by the built-in electric field becomes larger, $\mathbf{q(\phi_i + V_a)}$.
2. Less electrons/holes diffuse to the opposite sides. → **Diffusion current decreases**, while **drift current remains the same.**
3. There is (−) net current flowing.
4. The depletion width becomes wider.

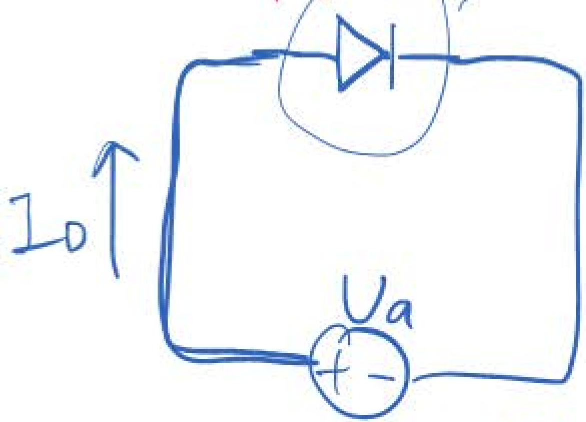

p-type
n-type
Si
Si
I_D < 0
+ -
V_a < 0

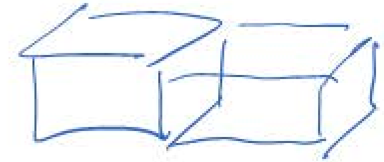

I_D < 0.
+ -
V_a < 0.

Diode I-V Characteristics

At 300 K

Diode.





p-type Si   n-type Si

$$I_D = I_s\left(e^{\frac{qV_a}{kT}} - 1\right) = I_s\left(e^{\frac{V_a}{(kT/q)}} - 1\right)$$

$$= I_s\left(e^{\frac{V_a}{0.026}} - 1\right)$$

DC sweep