Devices always involve interfaces:

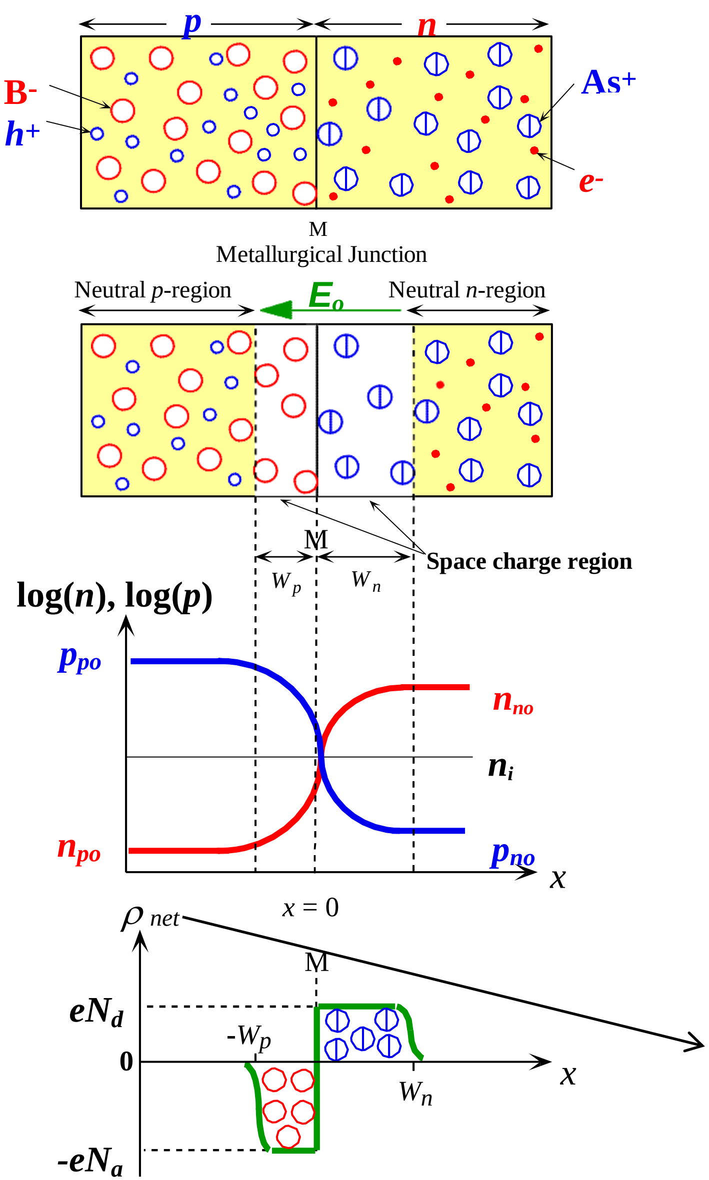
1. *metal-semiconductor*
   - *Schottky Junction*
   - *Ohmic Contact*

2. *semiconductor-semiconductor*
   - *pn Junction (1)*
   - *pn Junction (2)*
   - ***Tutorial***

     Metal-Oxide-Semiconductor Field-Effect Transistor

     (MOSFET, 金属氧化物半导体场效应晶体管)

pn Junction: Space Charge Layer



Each electron moves over the interface will combine with one hole.

The total number of negative charge on *p* side equals to that of positive charge on *n* side to remain charge neutrality

p_{p0}: majority carrier concentration

n_{p0}: minority carrier concentration

$$N_a W_p = N_d W_n$$

N: doping concentration, *W*: space charge layer width

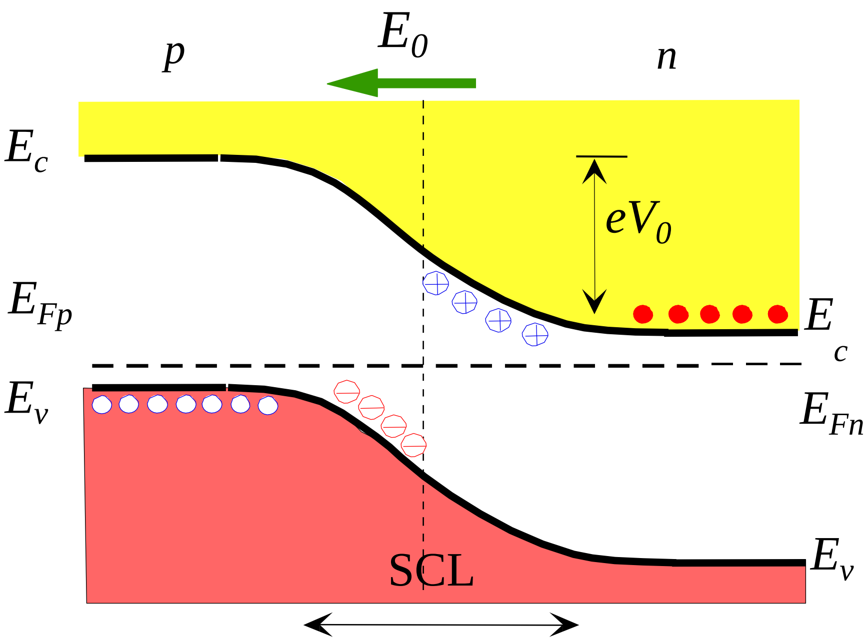
ρ_{net}: net space charge density (净空间电荷密度)

pn Junction: Space Charge Layer

Probability of electrons occupying energy E is determined by **Fermi-Dirac statistics**, which is reduced to **Boltzmann statistics** when $E-E_F \gg k_BT$

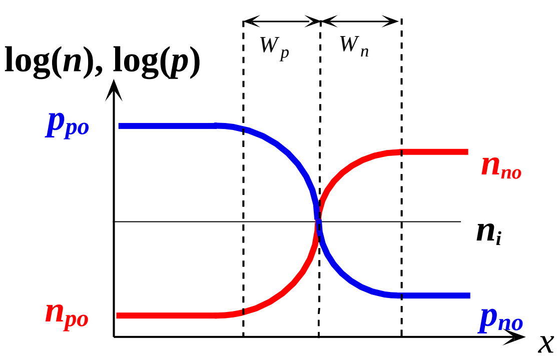
$$f(E) = A\exp[-(E-E_F)/k_BT]$$

$$\frac{n_2}{n_1} = \exp\left[-\frac{(E_2-E_1)}{kT}\right]$$



$$\frac{n_{po}}{n_{no}} = \exp(-\frac{eV_o}{k_BT}) \qquad \frac{p_{no}}{p_{po}} = \exp(-\frac{eV_o}{k_BT})$$

$$p_{po} = N_a \qquad p_{no} = \frac{n_i^{\,2}}{n_{no}} = \frac{n_i^{\,2}}{N_d}$$



$$\boxed{\begin{aligned} V_o &= \frac{k_BT}{e}\ln\left(\frac{N_aN_d}{n_i^{\,2}}\right) \\ W_o &= \sqrt{\frac{2\varepsilon_o\varepsilon_r(N_a+N_d)V_o}{eN_aN_d}} \end{aligned}}$$

Diffusion

Electron diffusion current density

$$J_{D,e} \propto -\frac{dn}{dx}$$
$$= eDe\frac{dn}{dx}$$

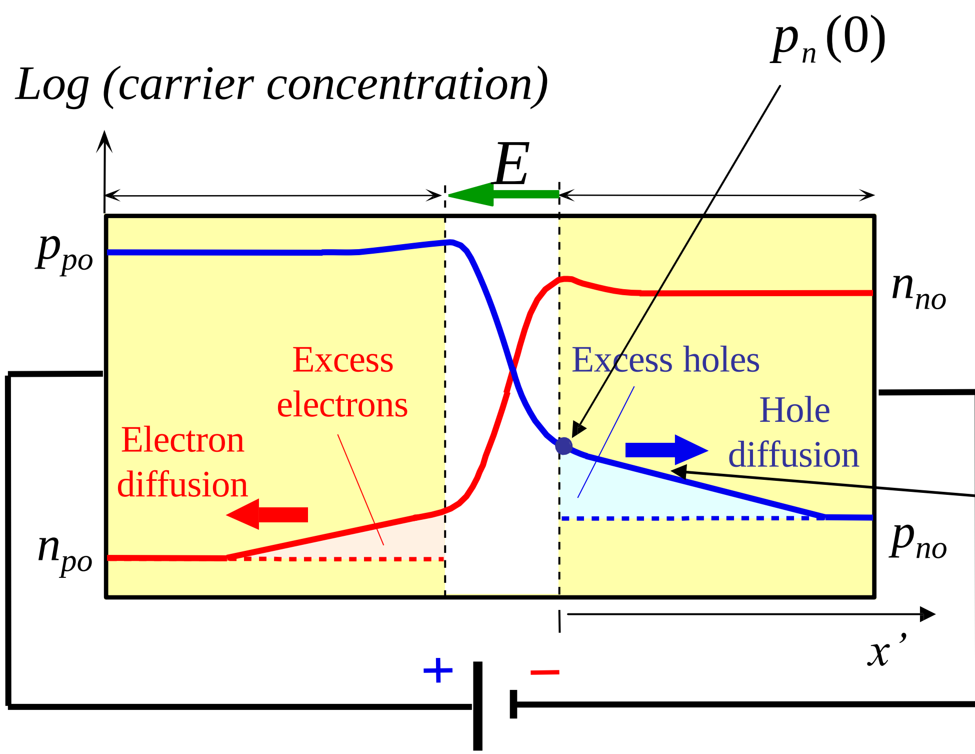
Hole diffusion current density

$$J_{D,h} \propto -\frac{dp}{dx}$$
$$= -eDh\frac{dp}{dx}$$

Diffusion coefficient, $\mathbf{D_e}$ or $\mathbf{D_h}$, is a measure of the ease of carrier diffusion motion in a medium. Mobility, μ_n or μ_p, is a measure of the ease of carrier drift motion in a medium. The two quantities are related by the **Einstein Relation.**

$$\frac{D_e}{\mu_e} = \frac{kT}{e} \quad \text{and} \quad \frac{D_h}{\mu_h} = \frac{kT}{e}$$

Current Across a **Forward Biased** *pn* Junction: **Diffusion**



Law of the junction

$$p_n(0) = p_{no} \exp\left[\frac{eV}{k_B T}\right]$$

$$J_{D,hole} = -eD_h \frac{dp_n(x')}{dx'}$$

$$\Delta p_n(x') = \Delta p_n(0) \exp\left(-\frac{x'}{L_h}\right)$$

$$\Delta p_n(x') = p_n(x') - p_{no}$$

$$J_{D,\text{hole}} = \left(\frac{eD_h}{L_h}\right) \Delta p_n(0) \exp\left(-\frac{x'}{L_h}\right)$$

At x'=0: $J_{D,\text{hole}} = \left(\frac{eD_h}{L_h}\right) \Delta p_n(0)$

$$J_{D,hole} = \left(\frac{eD_h p_{no}}{L_h}\right)\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

$$p_{no} = \frac{n_i^2}{n_{no}} = \frac{n_i^2}{N_d}$$

Minority Carrier **Diffusion Length**

$$L_h = \sqrt{D_h \tau_h}$$

τ_h is the mean hole **recombination lifetime** (minority carrier lifetime) in the n-region

Total Diffusion Current: Electron and Hole

$$J = J_{\text{elec}} + J_{\text{hole}}$$

$$J_{D,elec} = \left(\frac{eD_e n_i^2}{L_e N_a}\right)\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

$$J_{D,hole} = \left(\frac{eD_h n_i^2}{L_h N_d}\right)\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

$$J = \left(\frac{eD_e}{L_e N_a} + \frac{eD_h}{L_h N_d}\right) n_i^2 \left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

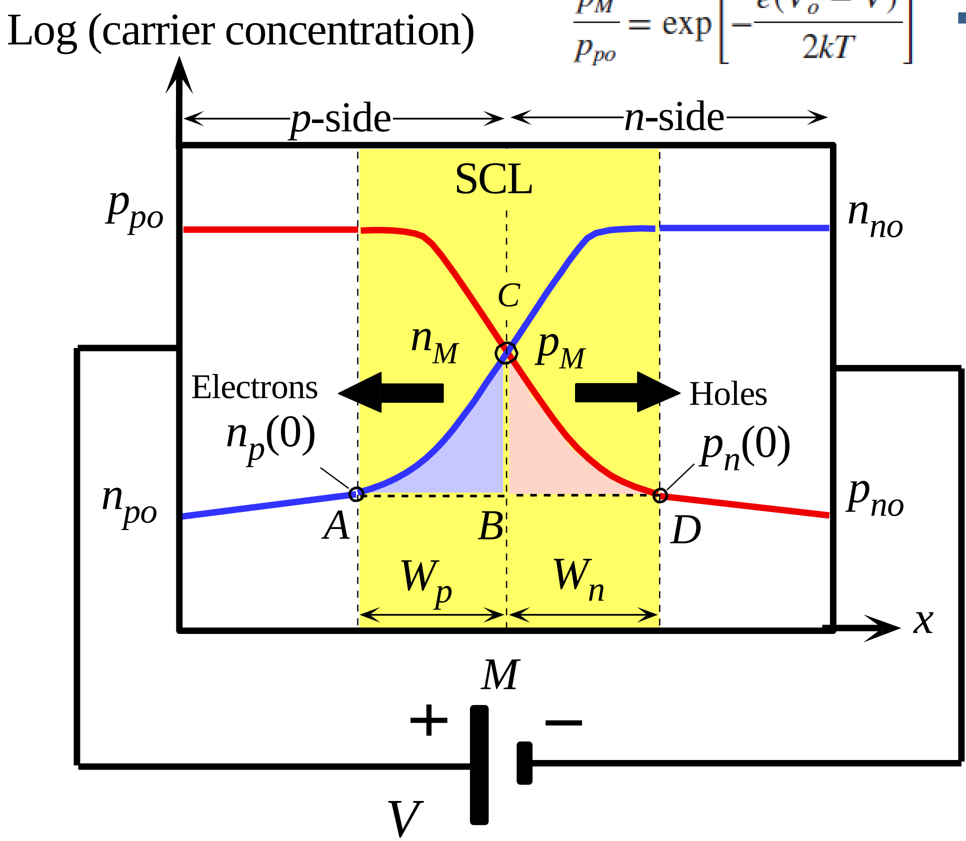
$$J = J_{so}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

Ideal diode (Shockley) equation

$$J_{so} = \left[\left(\frac{eD_h}{L_h N_d}\right) + \left(\frac{eD_e}{L_e N_a}\right)\right] n_i^2$$

reverse saturation current density

Current Across a Forward Biased pn Junction: **Recombination**



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

$$\frac{p_M}{p_{po}} = \exp\left[-\frac{e(V_o - V)}{2kT}\right] \Rightarrow p_M = n_i \exp\left(\frac{eV}{2kT}\right)$$

$$J_{recom} \approx \frac{e\frac{1}{2}W_p n_M}{\tau_e} + \frac{e\frac{1}{2}W_n p_M}{\tau_h}$$

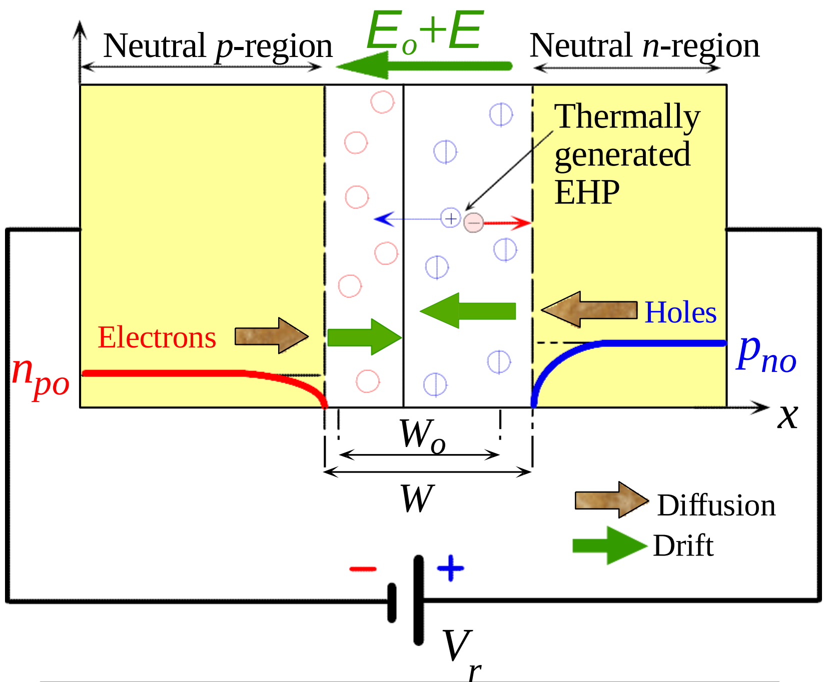
mean electron recombination time in W_p is $\boldsymbol{\tau_e}$.

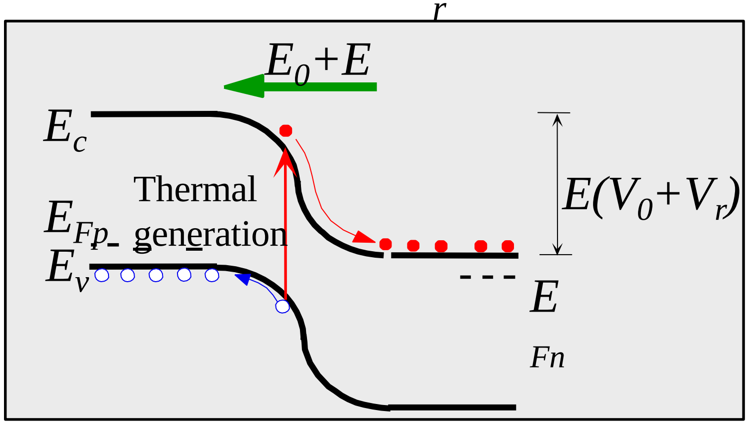
$$J_{recom} = J_{ro}[\exp(\frac{eV}{2k_BT}) - 1]$$

where $J_{ro} = \frac{en_i}{2}(\frac{W_p}{\tau_e} + \frac{W_n}{\tau_h})$

Current Across a pn Junction: **Reverse Bias**

Minority Carrier





(a) Minority carrier extracted and swept by the field across the SCL

Essentially **Shockley equation**:

$$J = \left(\frac{eD_e}{L_e N_a} + \frac{eD_h}{L_h N_d}\right) n_i^2 \left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

$$\approx -\left(\frac{eD_e}{L_e N_a} + \frac{eD_h}{L_h N_d}\right) n_i^2$$

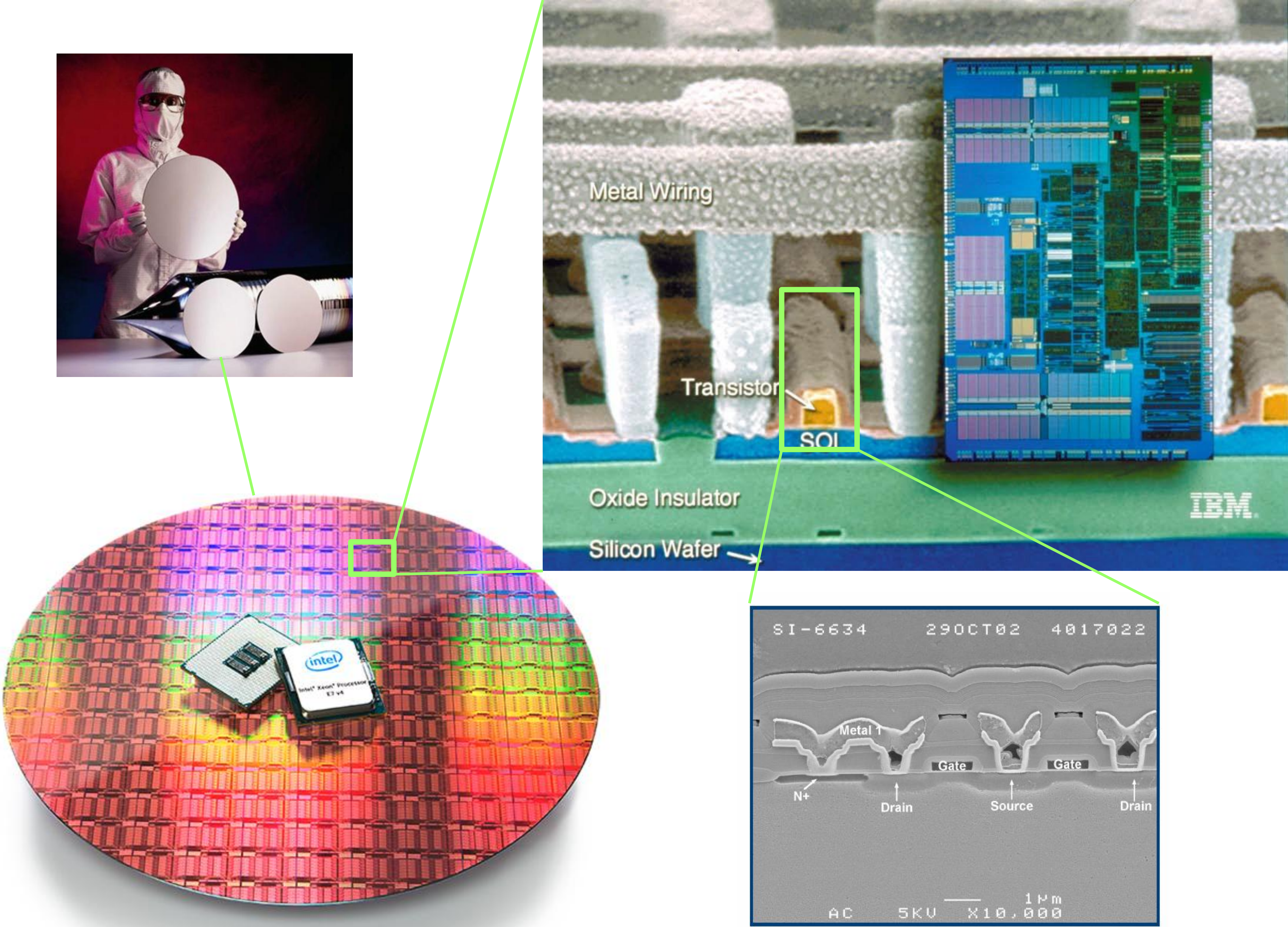
reverse saturation current density, $-J_0$

independent of voltage (V_r > kT/e)

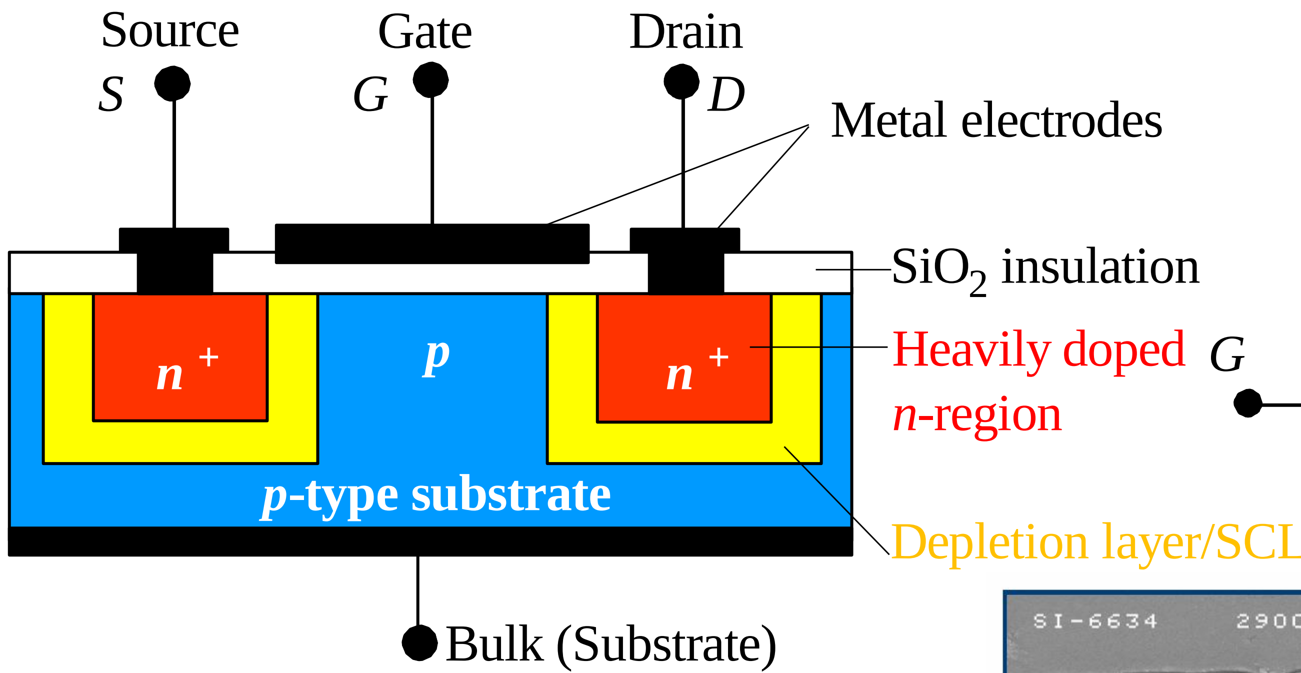
(b) Electron-hole pair generated within the SCL.

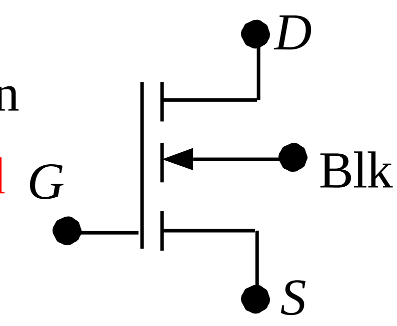
$$J_{gen} = \frac{eWn_i}{\tau_g}$$

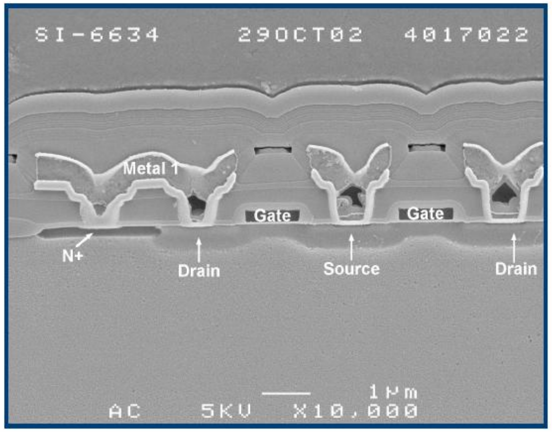
τ_g is the mean time to generate an EHP


Metal Wiring
Transistor
SOI
Oxide Insulator
Silicon Wafer
SI-6634 29OCT02 4017022
Metal 1
Gate
Gate
N+
Drain
Source
Drain
1μm
AC 5KV X10,000

Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)





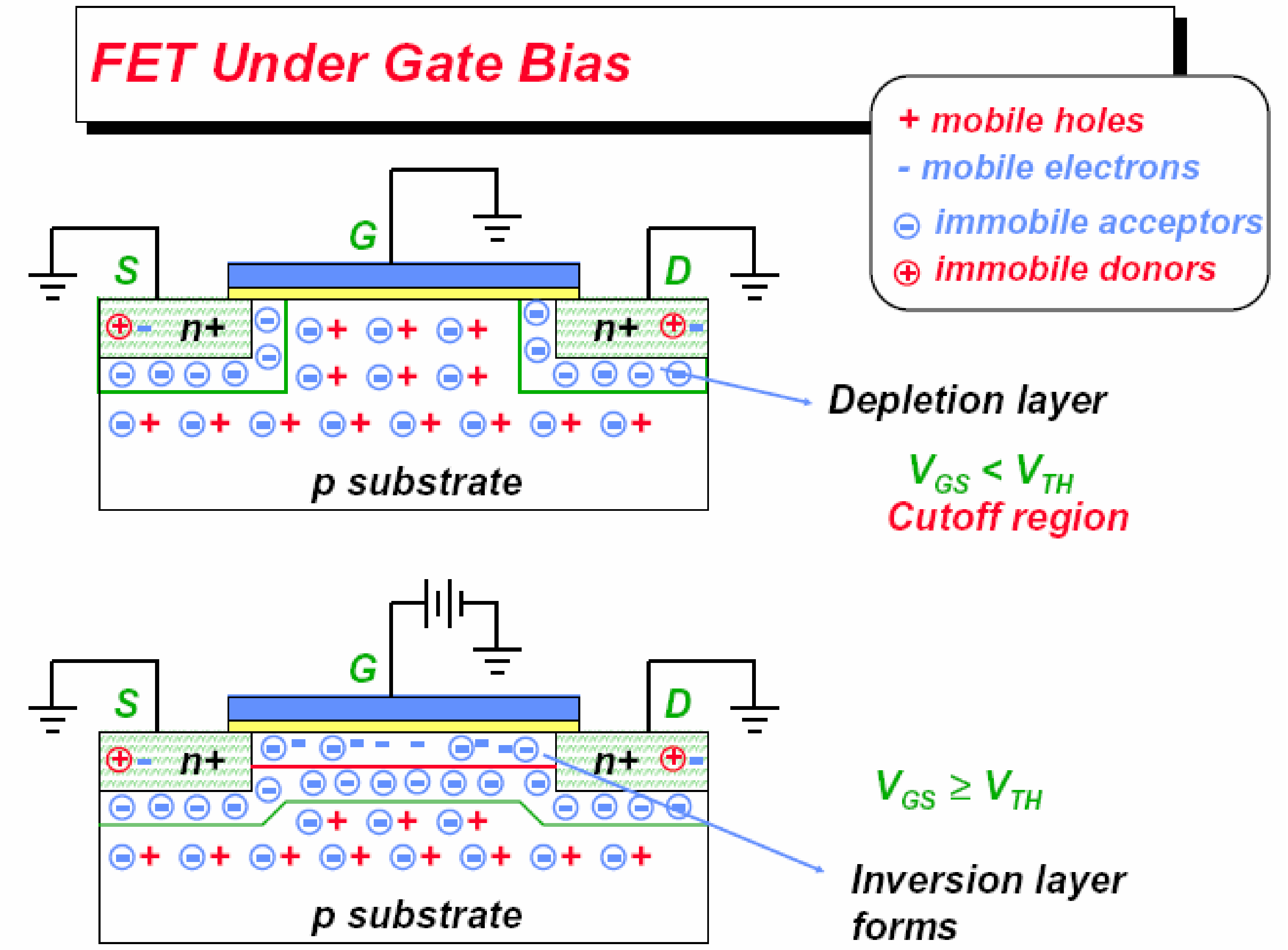


SEM cross section of a MOS Transistor

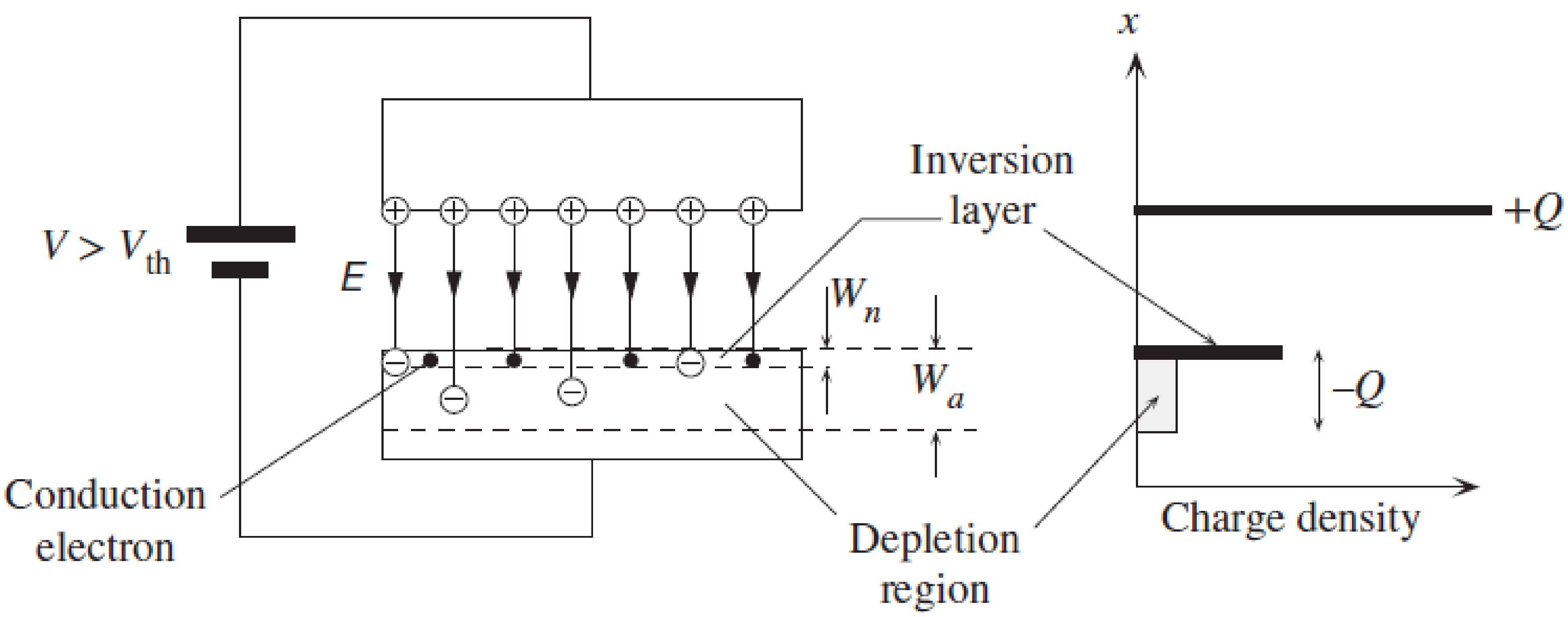
|SOURCE: Courtesy of Don Scansen, Semicondutcor Insights, Kanata, Ontario, Canada

The basic structure of MOSFET and its circuit symbol

Operation of Field Effect Transistor

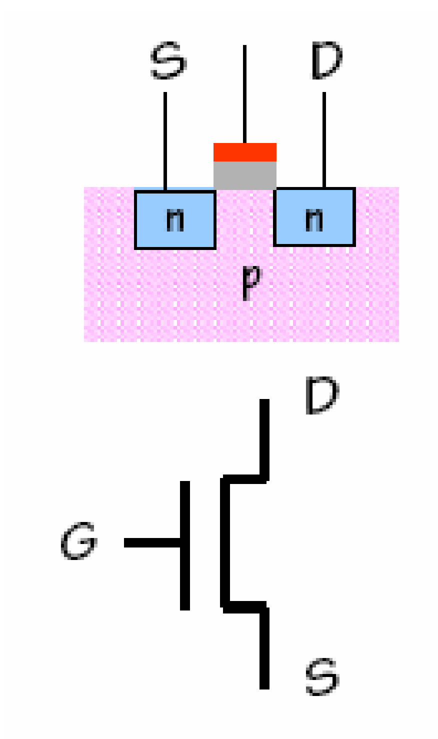


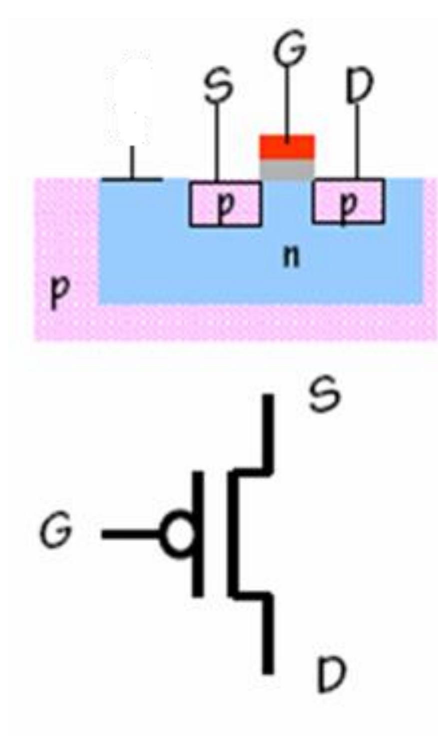
Field Effect and Inversion

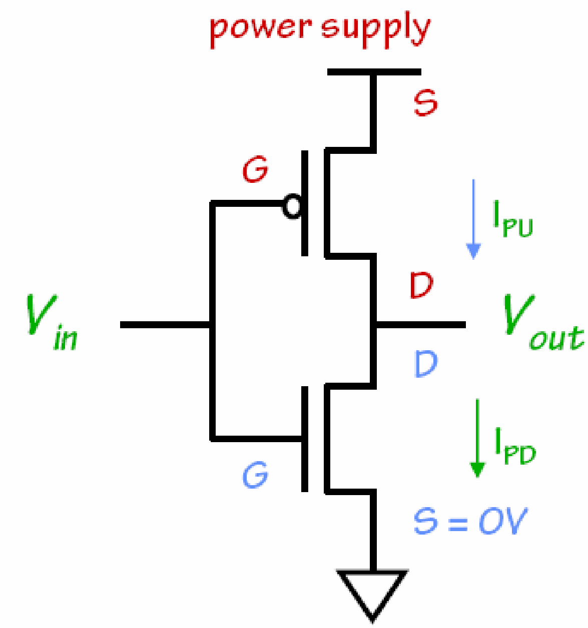


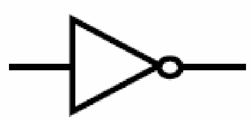
CMOS: The Heart of Modern Computer

By embedding p-type source and drain in a n-type substrate, we can fabricate a complement to the n-FET







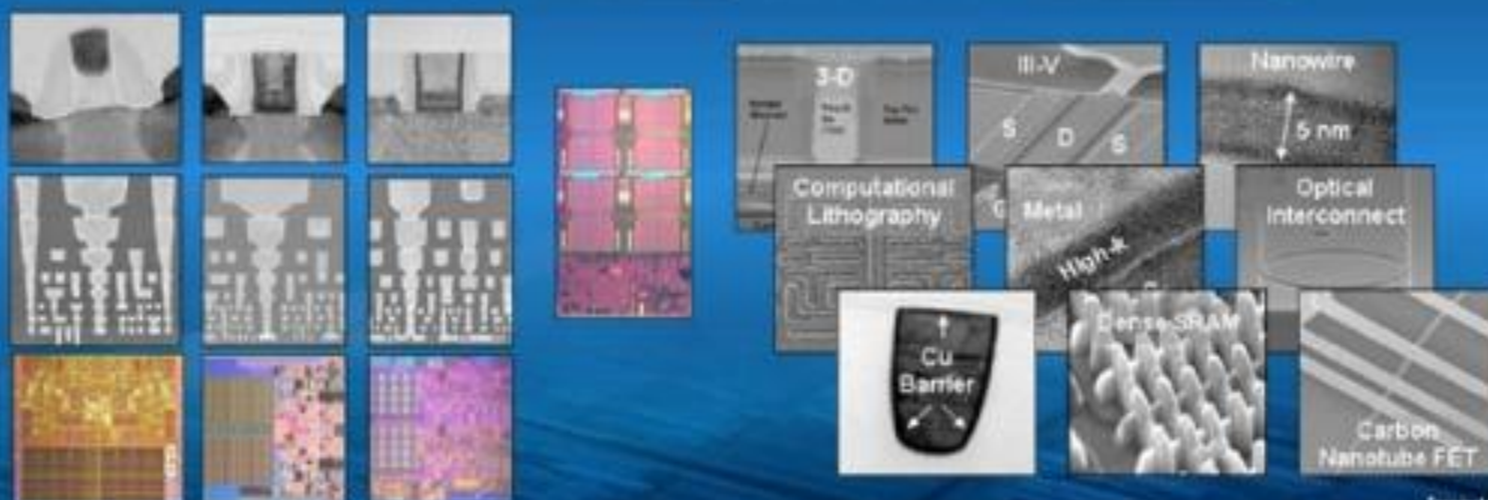


The use of both n-FET and p-FET is a key to **CMOS (complementary Metal Oxide Semiconductor)** logic function.   只有需要切换启动与关闭时才需消耗能量

Innovation-Enabled Technology Pipeline is Full

65nm	45nm	32nm	22nm	15nm	11nm	8nm	
2005	2007	2009	2011*	2013*	2015*	2017*	2019+

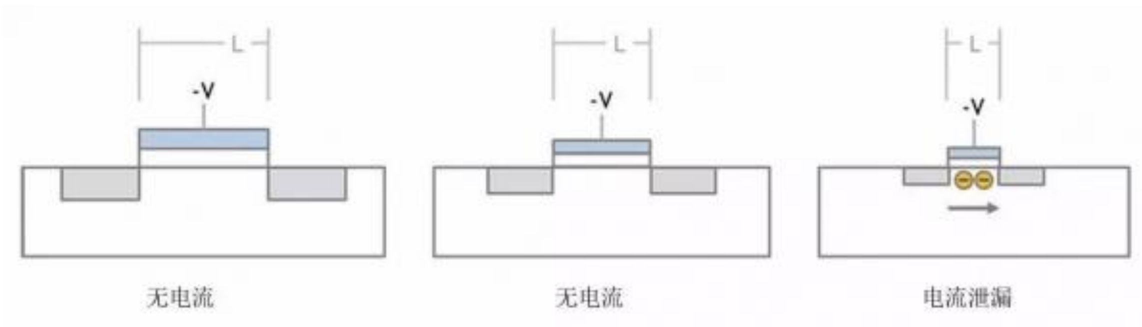
MANUFACTURING → DEVELOPMENT → RESEARCH

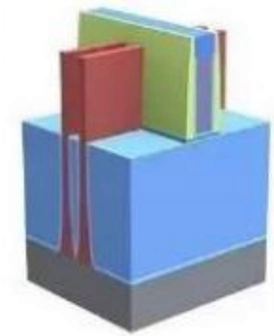


*projected

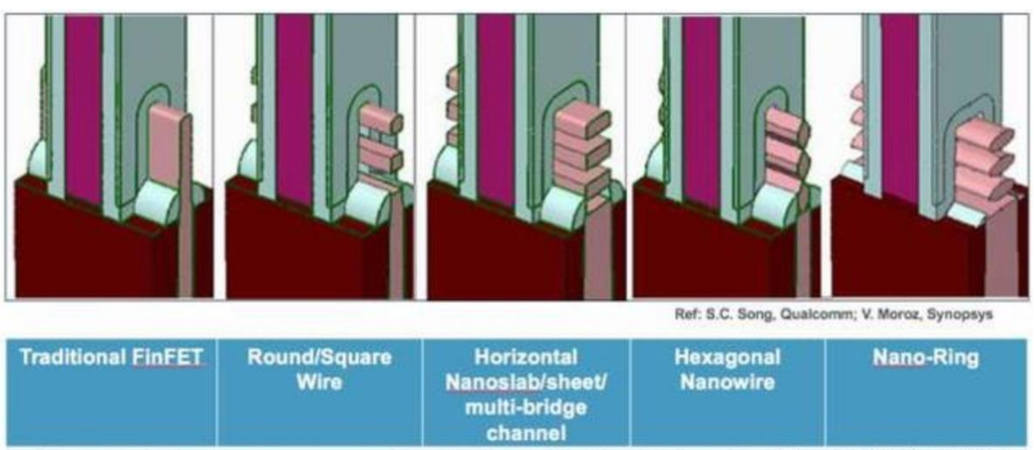
Our limit to visibility goes out ~10 years

FinFET(鳍式场效应晶体管)





变种FinFET：环绕栅极



发展趋势：
形状、材料、界面

Assignment 6.3

Question 1:

Sketch the energy diagrams of a *pn* junction, indicating the Fermi energy (E_F), the bottom of the conduction band (E_C), the top of the valence band (E_V), built-in potential (V_o), and the direction of the internal field.

Question 2:

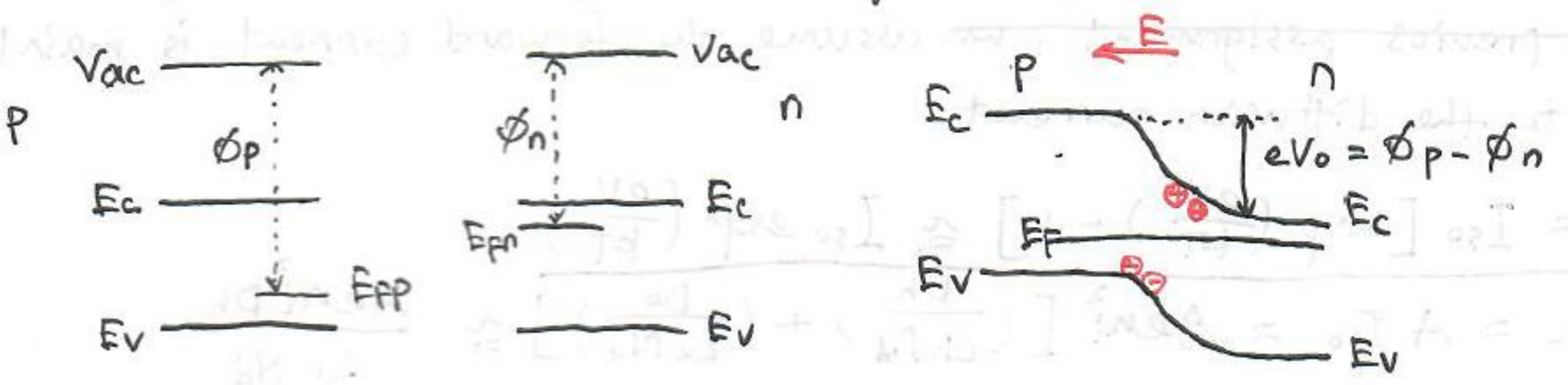
In the lecture, we used Boltzmann statistics to derive the built-in potential, V_o, of a *pn* junction. The energy band treatment allows a simple way to calculate V_o. When the junction is formed, E_{Fp} and E_{Fn} must shift and line up. The shift in E_{Fp} and E_{Fn} to line up is clearly $\Phi_p - \Phi_n$, the work function difference.

Using the energy band diagrams and semiconductor equations, derive an expression for the built-in potential V_o in terms of N_d, N_a, and n_i.

Question 3:

Consider a p^+n junction, which has a heavily doped p-side relative to the n-side, that is, $N_a \gg N_d$. What is your comment on the depletion width on the n-side and the p-side? What is the total depletion width (W_0) for the p^+n junction Si diode that has been doped with 10^{18} acceptor atoms cm^{-3} on the p-side and 10^{16} donor atoms cm^{-3} on the n-side?

∵ The shift in E_{Fp} and E_{Fn} to line up is $\phi_p - \phi_n$.



$$\therefore \quad eV_0 = \phi_p - \phi_n = (E_c - E_{Fp}) - (E_c - E_{Fn})$$

$$\because \quad n = N_c \exp\left(-\frac{E_c - E_F}{kT}\right) \Rightarrow n_{no} = N_c \exp\left(-\frac{E_c - E_{Fn}}{kT}\right)$$

$$\Rightarrow n_{po} = N_c \exp\left(-\frac{E_c - E_{Fp}}{kT}\right)$$

$$\Rightarrow \ln\left(\frac{n_{no}}{n_{po}}\right) = \frac{1}{kT}\cdot\left[(E_c - E_{Fp}) - (E_c - E_{Fn})\right] = \frac{eV_0}{kT}$$

$$\because \quad n_{po} = n_i^2 / N_a, \quad n_{no} = N_d$$

$$\therefore \quad V_0 = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right)$$

THE p^+n JUNCTION Consider a p^+n junction, which has a heavily doped p-side relative to the n-side, that is, $N_a \gg N_d$. Since the amount of charge Q on both sides of the metallurgical junction must be the same (so that the junction is overall neutral)

$$Q = eN_aW_p = eN_dW_n$$

it is clear that the depletion region essentially extends into the n-side. According to Equation 6.7, when $N_d \ll N_a$, the width is

$$W_o = \left[\frac{2\varepsilon V_o}{eN_d}\right]^{1/2}$$

What is the depletion width for a pn junction Si diode that has been doped with 10^{18} acceptor atoms cm^{-3} on the p-side and 10^{16} donor atoms cm^{-3} on the n-side?

SOLUTION

To apply the above equation for W_o, we need the built-in potential, which is

$$V_o = \left(\frac{kT}{e}\right)\ln\left(\frac{N_dN_a}{n_i^2}\right) = (0.0259\text{ V})\ln\left[\frac{(10^{16})(10^{18})}{(1.0\times10^{10})^2}\right] = 0.835\text{ V}$$

Then with $N_d = 10^{16}$ cm^{-3}, that is, 10^{22} m^{-3}, $V_o = 0.835$ V, and $\varepsilon_r = 11.9$ in the equation for W_o

$$W_o = \left[\frac{2\varepsilon V_o}{eN_d}\right]^{1/2} = \left[\frac{2(11.9)(8.85\times10^{-12})(0.835)}{(1.6\times10^{-19})(10^{22})}\right]^{1/2}$$

$$= 3.32\times10^{-7}\text{ m} \qquad \text{or} \qquad 0.33\ \mu\text{m}$$

Nearly all of this region (99 percent of it) is on the n-side.

Assignment 6.3 (2)

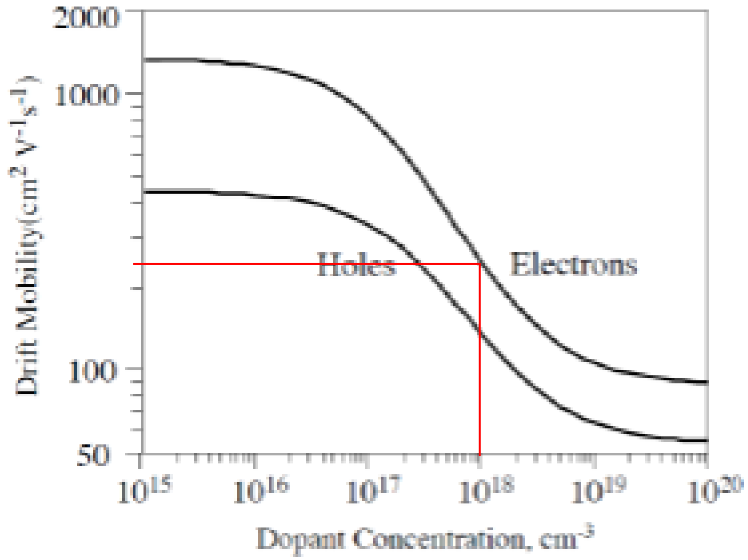


Figure 1. The variation of the drift mobility with dopant concentration in Si for electrons and holes at 300 K

Question 1:

Consider a Si ($n_i = 1.45\times10^{10}$ cm^3, ε_r is 11.9) *pn* junction diode, with an acceptor concentration N_a of 10^{18} cm^{-3} on the p-side and donor concentration N_d of 10^{15} cm^{-3} on the n-side. The drift mobility refers to Figure 1. The diode is forward biased and has a voltage of 0.6 V across it. The diode cross-sectional area is 1 mm^2. The minority carrier recombination time, τ, depends on the dopant concentration, N_{dopant} (cm^{-3}), through the following approximate relation

$$\tau = \frac{5\times10^{-7}}{\left(1+2\times10^{-17}N_{dopant}\right)}$$

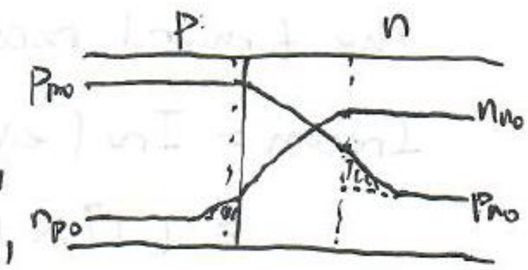
Calculate the diffusion current and the recombination current. What is your conclusion on the contributions to the total diode current?

Q1. This is a p^+n diode : $N_d = 10^{15}\,cm^{-3}$. Hole recombination lifetime τ_h :

$$\tau_h = \frac{5\times10^{-7}}{(1+2\times10^{-17}N_{dopant})} = \frac{5\times10^{-7}}{1+2\times10^{-17}\times10^{15}cm^{-3}} = 490.2\,ns$$

similarly : $\tau_e = 23.81\,ns$

1) Diffusion diode current :



From Figure 1, $N_a = 10^{18}\,cm^{-3} \Rightarrow \mu_e \cong 250\,cm^2V^{-1}s^{-1}$

$N_d = 10^{15}\,cm^{-3} \Rightarrow \mu_h \cong 450\,cm^2V^{-1}s^{-1}$

Einstein Relation : $D_e = \frac{kT}{e}\cdot\mu_e = (0.02586\,V)(250\,cm^2V^{-1}s^{-1}) = 6.465\,cm^2s^{-1}$

$D_h = \frac{kT}{e}\cdot\mu_h = (0.02586\,V)(450\,cm^2V^{-1}s^{-1}) = 11.64\,cm^2s^{-1}$

Thus diffusion length : $L_e = \sqrt{D_e\tau_e} = \sqrt{(6.465\,cm^2s^{-1})(23.81\times10^{-9}s)}$

$= 3.923\times10^{-4}\,cm$

$L_h = \sqrt{D_h\tau_h} = \sqrt{(11.64\,cm^2s^{-1})(490.2\times10^{-9})}$

$= 2.389\times10^{-3}\,cm$

Diffusion current : $I_{diff} = A \cdot J_{diff} = A \cdot J_{so} [\exp(eV/kT - 1]$

$\cong A \cdot J_{so} \exp(eV/kT)$ $\because V >> kT/e = 0.02586\,V$

where $I_{so} = A \cdot J_{so} = Aen_i^2 [D_h/(L_h N_d) + D_e/(L_e N_a)] \cong Aen_i^2 D_h/(L_h N_d)$

$\because N_a >> N_d$. In other words, the current is mainly due to the diffusion of the holes in n-region.

$$\therefore I_{so} = \frac{(1\times10^{-2}\,cm^2)(1.602\times10^{-19}\,C)(\overset{1.0}{\cancel{1.45}}\times10^{10}\,cm^{-3})^2(11.64\,cm^2s^{-1})}{(2.389\times10^{-3}\,cm)(1\times10^{15}\,cm^{-3})}$$

$= 1.641\times10^{-12}\,A$

$\therefore$ Forward current due to diffusion :

$I_{diff} = I_{so}\exp(eV/kT) = (1.641\times10^{-12}A)\exp(0.6V/0.02586V)$

$= 0.0196\,A$ or $19.6\,mA$

2) Recombination current.

Buit-in potential : $V_o = (kT/e)\ln(N_a N_d/n_i^2) = (0.02586\,V)\ln(10^{18}\,cm^{-3} \times 10^{15}\,cm^{-3})/(\underset{1.0}{\cancel{1.45}}\times10^{10}\,cm^{-3})^2] = 0.7549\,V$

depletion region width W is mainly on the n-side :

$$W = \left[\frac{2\varepsilon(N_a+N_d)(V_o - V)}{eN_aN_d}\right]^{1/2} \cong \left[\frac{2\varepsilon(V_o - V)}{eN_d}\right]^{1/2} (= W_n)$$

$$= \left[\frac{2(11.9)(8.854\times10^{-12}\,Fm^{-1})(0.7549\,V - 0.6\,V)}{(1.602\times10^{-19}\,C)(10^{21}\,m^{-3})}\right]^{1/2} = 0.4514\times10^{-4}\,cm$$

$$J_{recom} = J_{ro}\left[\exp\left(\frac{eV}{2kT}\right) - 1\right] \quad \text{where } J_{ro} = \frac{en_i}{2}\left(\frac{W_p}{\tau_e} + \frac{W_n}{\tau_h}\right)$$

$$I_{ro} = A \cdot \frac{en_i}{2} \cdot W_n/\tau_h = \frac{(1\times10^{-2}\,cm^2)(1.602\times10^{-19}\,C)(0.4514\times10^{-4}\,cm)}{2(490\times10^{-9}\,s)} \cdot (1.45\times10^{10}\,cm^{-3})$$

$$= 1.070\times10^{-9}\,A$$

$\therefore$ The forward recombination current is:

$$I_{recom} = I_{ro}(eV/2kT) = (1.070\times10^{-9}A)\exp[(0.6V)/2(0.02586V)]$$

$$= 1.17\times10^{-4}\,A \quad \text{or} \quad 0.117\,mA$$

Conclusion: the diffusion current dominates the total diode current in this diode.

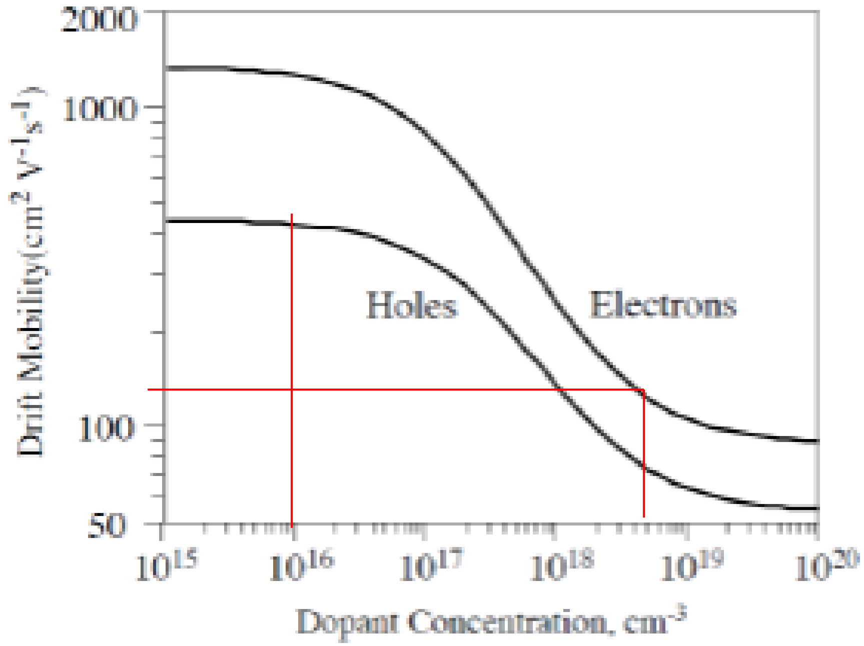


Figure 1. The variation of the drift mobility with dopant concentration in Si for electrons and holes at 300 K

Question 2:

An Si $p^{+}n$ junction diode has a cross-sectional area of 1 mm^2, an acceptor concentration of 5×10^{18} cm^{-3} on the p-side, and a donor concentration of 10^{16} cm^{-3} on the n-side. The recombination lifetime of holes in the n-region is 420 ns, whereas that of electrons in the p-region is 5 ns due to a greater concentration of impurities (recombination centers) on that side. Mean thermal generation lifetime (τ_g) is about 1 μs.

(a) Calculate the minority carrier diffusion lengths.

(b) What is the built-in potential across the junction?

(c) What is the current when there is a forward bias of 0.6 V across the diode at 27 °C?

Assume that the current is by minority carrier diffusion.

(d) What is the reverse current when the diode is reverse biased by a voltage $V_r = 5$ V?

a) From Figure 1. $N_a = 5\times10^{18}\,cm^{-3} \Rightarrow \mu_e \approx 150\,cm^2V^{-1}s^{-1}$

$N_d = 10^{16}\,cm^{-3} \Rightarrow \mu_h \approx 430\,cm^2V^{-1}s^{-1}$

Einstein relation: $D_e = \frac{kT}{e}\cdot\mu_e = (0.02586V)(150\,cm^2V^{-1}s^{-1}) = 3.88\,cm^2s^{-1}$

$D_h = \frac{kT}{e}\cdot\mu_h = (0.02586V)(430\,cm^2V^{-1}s^{-1}) = 11.12\,cm^2s^{-1}$

Diffusion lengths: $L_e = \sqrt{D_e\tau_e} = \sqrt{(3.88\,cm^2s^{-1})(5\times10^{-9}s)} = 1.39\times10^{-4}cm$

$L_h = \sqrt{D_h\tau_h} = \sqrt{(11.12cm^2s^{-1})(420\times10^{-9}s)} = 21.6\times10^{-4}cm$

(b) Built-in potential:

$$V_o = \left(\frac{kT}{e}\right)\ln\left(\frac{N_dN_a}{n_i^2}\right) = (0.02586V)\ln\left[\frac{10^{16}\times5\times10^{18}}{(1.45\times10^{10})^2}\right] = 0.875V$$

(c) ~~From previos assignment~~, we assume the forward current is mainly due to the diffusion current.

$$I = I_{s0}\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \cong I_{s0}\exp\left(\frac{eV}{kT}\right)$$

where $I_{s0} = A\,J_{s0} = Aen_i^2\left[\left(\frac{D_h}{L_h N_d}\right) + \left(\frac{D_e}{L_e N_a}\right)\right] \cong \frac{Aen_i^2 D_h}{L_h N_d}$

as $N_a >> N_d$, the diffusion current mainly due to holes diffusing in n-region.

$$I_{s0} = \frac{(0.01\,cm^2)(1.602\times10^{-19}C)(1.45\times10^{10}\,cm^{-3})^2(11.12\,cm^2s^{-1})}{(21.6\times10^{-4}\,cm)(10^{16}\,cm^{-3})}$$

$$= 8.24\times10^{-14}A$$

$$I \cong I_{s0}\exp\left(\frac{eV}{kT}\right) = (8.24\times10^{-14}A)\exp\left(\frac{0.6V}{0.02586V}\right)$$

$$= 0.99\times10^{-3}A = 1.0\,mA$$

(d) Reverse saturation current: $I = I_{s0} = 8.24\times10^{-14}A$

Thermal generation current:

$$I_{gen} = A\cdot J_{gen} = A\cdot\frac{eWn_i}{\tau_g}$$

$$W = \left[\frac{2\varepsilon(V_0+V_r)}{eN_d}\right]^{1/2} = \left[\frac{2(11.9)(8.85\times10^{-12})(0.875+5)}{(1.6\times10^{-19})(10^{22})}\right]^{1/2}$$

$$= 0.88\times10^{-4}cm$$

$$\therefore I_{gen} = (0.01\,cm^2)\frac{(1.602\times10^{-19}c)(0.88\times10^{-4}cm)(1.45\times10^{10}cm^{-3})}{(10^{-6}s)}$$

$$= 1.41\times10^{-9}A$$

$I_{gen} >> I_{s0} \Rightarrow$ The reverse current is dominated by thermal generation current.