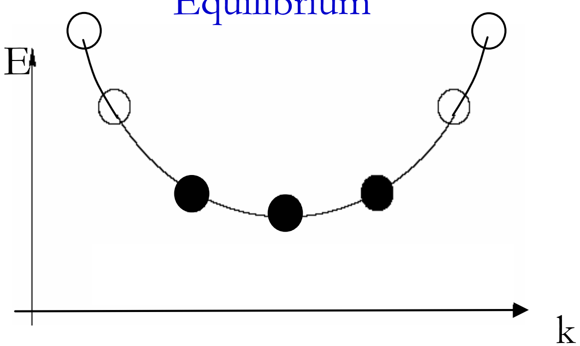
The np junction diode

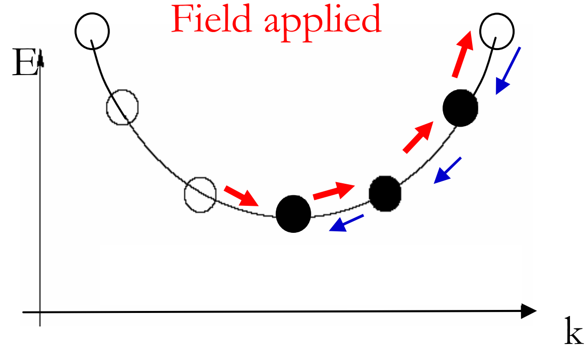
LECTURE 7

- Current balancing in an *np*-junction at equilibrium
- Drift velocity and mobility
- Drift-Diffusion Equation
- Built-in voltage
- Carrier concentrations and potential
- Depletion Approximation

Secs. 5.5.1-2

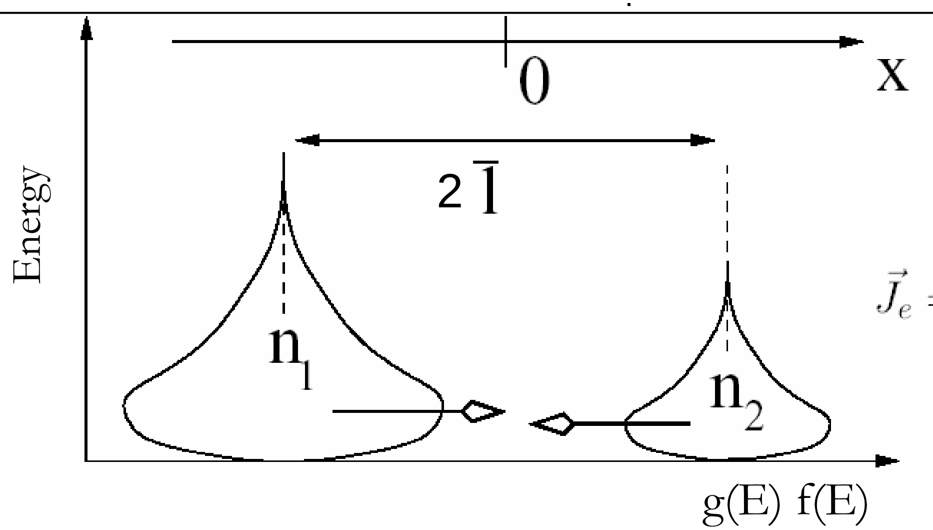
Diffusion and drift currents





Drift current density:

$$
\begin{aligned}
\vec{J}_{e,\text{drift}} &= \vec{J}_{e,\text{drift}\rightarrow} + \vec{J}_{e,\text{drift}\leftarrow} \\
&= -q\frac{n}{2}\left(2\vec{v}_R + \vec{v}_{de}\right) + \left(-q\frac{n}{2}\left(-2\vec{v}_R + \vec{v}_{de}\right)\right) \\
&= -qn\vec{v}_{de}\,,
\end{aligned}
$$



The diffusion current density is

$$\vec{J}_e = -q\frac{n_1}{2}2\vec{v}_R + (-q)\frac{n_2}{2}(-2\vec{v}_R) = -q\left(\frac{n_1}{2} - \frac{n_2}{2}\right)2\vec{v}_R$$

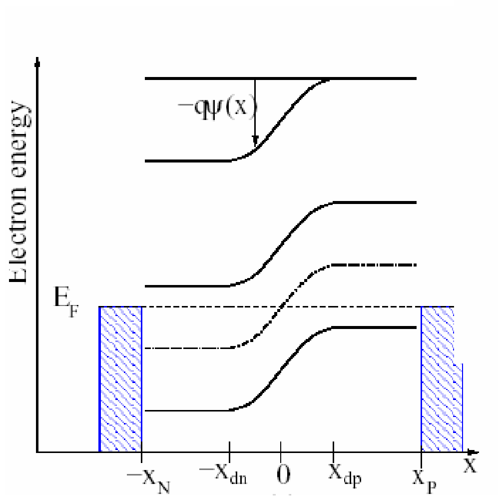
Do Taylor

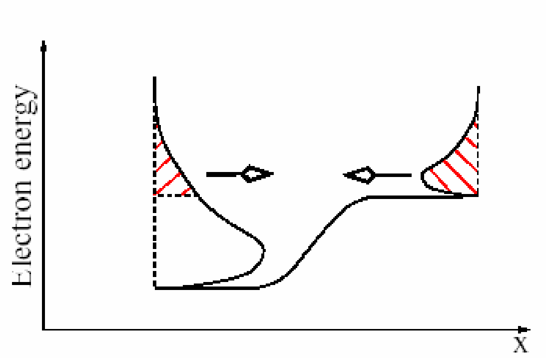
$$q\bar{l}2v_R\frac{d\vec{n}}{dx} \equiv qD_e\frac{d\vec{n}}{dx}$$

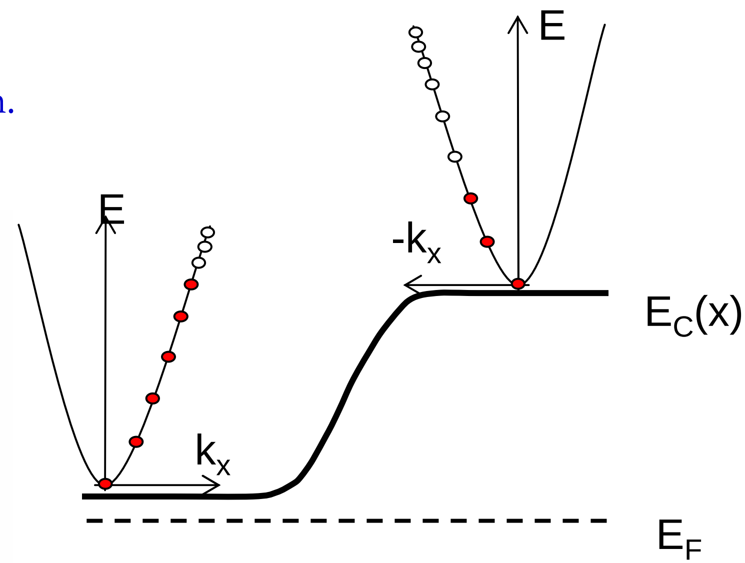
Sec. 6.1

Current balancing at equilibrium

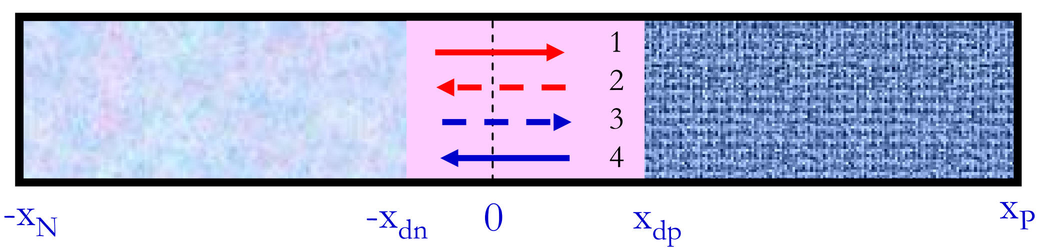
We've already seen how to view this on an energy band diagram.







In real space we have:



What are the 3 different regions?

Match the arrows to the current components:

a $qp\vec{v}_{dh}$

b $-qn\vec{v}_{de}$

c $qD_e\nabla n$

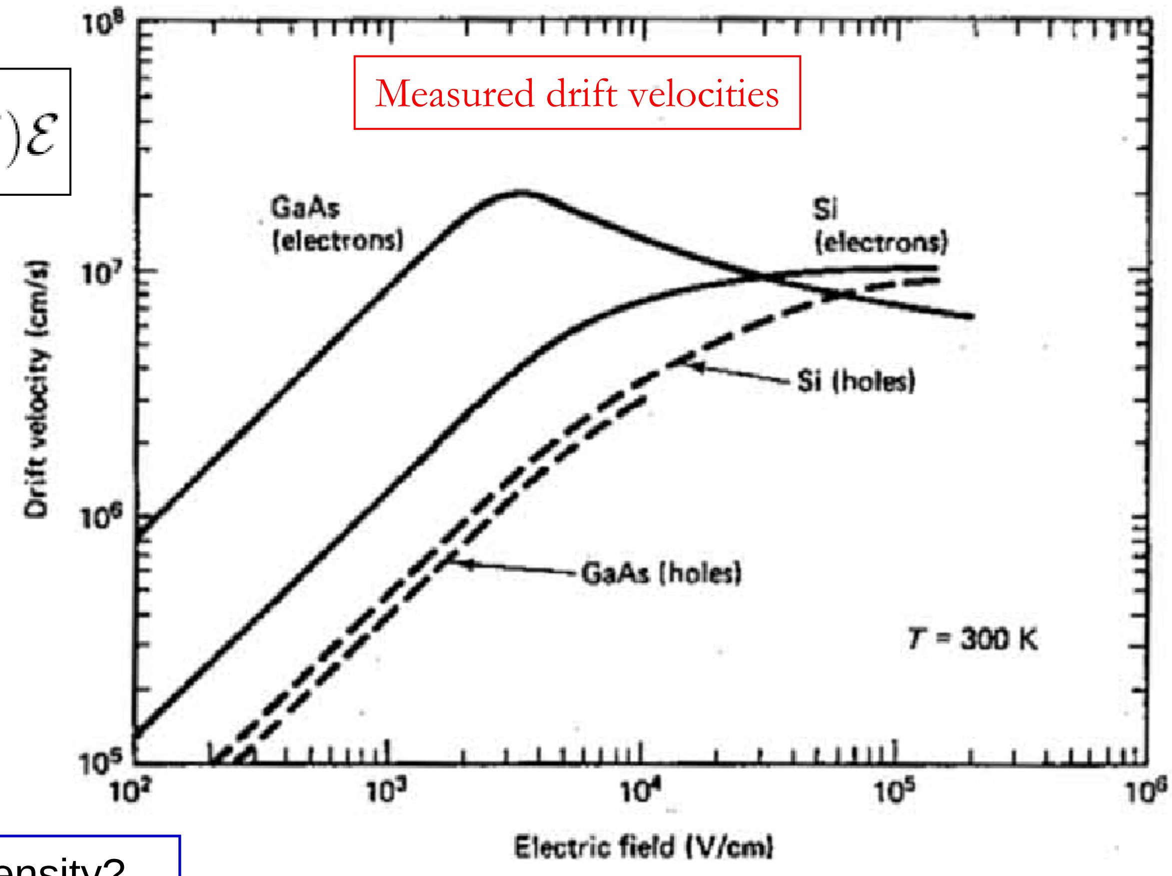
d $-qD_h\nabla p$

Secs. 5.4, 5.4.1

Mobility

$$v_{de}(\mathcal{E}) = |\vec{v_{de}}(\mathcal{E})| \equiv \mu_e(\mathcal{E})\mathcal{E}$$

- At low fields, the relationship is linear:
- Low-field mobility is
- Why does v_d saturate at high fields?



Does mobility depend on doping density?

μ_{e0}

μ_{h0}

Empirical equations

Secs. 5.2.2, 5.5.1, 5.5.2

DDE

For electrons

$$J_{e,x} = qn\mu_e\mathcal{E} + qD_e\frac{dn}{dx}$$

Mobility is a macroscopic parameter.

It is related to the microscopic properties of band structure and scattering.

$$\mu_e \equiv \frac{q}{m^*} << \tau_M >>$$

Mobility and diffusivity are related via the Einstein Relation.

$$D_e \equiv \frac{2\mu_e}{q} < u_x >$$

At moderate doping densities and moderate fields, what is the mean value of the x-directed KE of a carrier?

Sec. 6.1.1

Built-in voltage

At equilibrium

$$\vec{J}_e = -qn\mu_e \nabla\psi + k_B T_L \mu_e \nabla n = 0$$

Integrate

$$\int_{\psi(p-side)}^{\psi(n-side)} d\psi = \frac{k_B T_L}{q} \int_{n_{0p}}^{n_{0n}} \frac{1}{n} dn$$

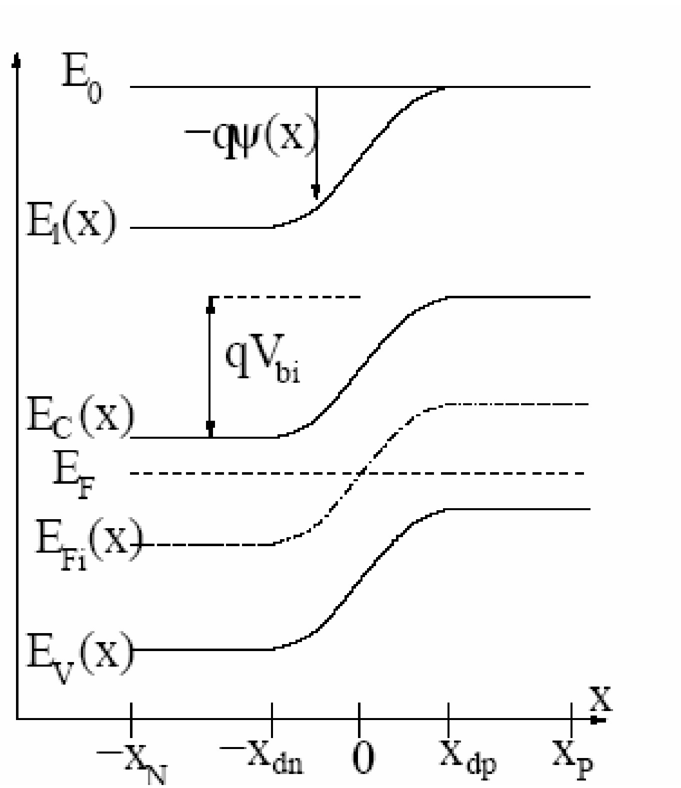
The difference in potential is the

$$V_{bi} = \frac{k_B T_L}{q} \ln \frac{n_{0n}}{n_{0p}} \equiv V_{\rm th} ln \left[\frac{N_D N_A}{n_i^2}\right]$$

where, we've related $n_0 p_0$ to n_i^2 (see next slide), and

$$V_{\rm th} \equiv \frac{k_B T}{q}$$

What is the name for this voltage?



Sec. 4.4

Intrinsic carrier concentration

MB statistics apply.

$$\begin{cases} n_i = N_C \exp\left(\dfrac{E_{Fi} - E_C}{k_B T}\right) \\ p_i = N_V \exp\left(\dfrac{E_V - E_{Fi}}{k_B T}\right) \end{cases}$$

Equate:

$$E_{Fi} - E_V = \frac{E_g}{2} + \frac{3k_B T}{4} \ln\left(\frac{m^*_{h,\text{DOS}}}{m^*_{e,\text{DOS}}}\right)$$

Multiply:

$$n_i = \sqrt{(N_C N_V)} \exp\left(\frac{-E_g}{2k_B T}\right)$$

Amalgamate with previous expressions for n_0 and p_0

$$\begin{cases} n_0 = n_i \exp\left(\dfrac{E_F - E_{Fi}}{k_B T}\right) \\ p_0 = n_i \exp\left(\dfrac{E_{Fi} - E_F}{k_B T}\right) \end{cases}$$

Multiply:

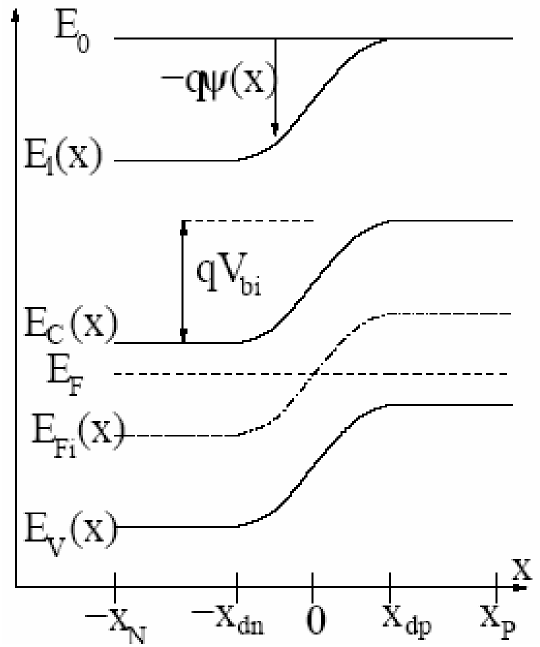
$$n_0 p_0 = n_i p_i = n_i^2$$

Sec. 6.1.3

Carrier concentrations and potential

$$-q\psi(x) = E_l(x) - E_0$$

$$\left\{ \begin{array}{l} -q\psi(x) \equiv E_C(x) - E_C(x_P) \\ \qquad\qquad\qquad \text{system} \end{array} \right\}$$



Leads to concentrations in terms of potential

$$n_0(x) = n_0(x_P)e^{\psi(x)/V_{\text{th}}}$$

$$p_0(x) = p_0(x_P)$$

Sec. 6.1.3

The potential profile

Use Poisson's Equation:

$$-\frac{d^2\psi}{dx^2} =$$

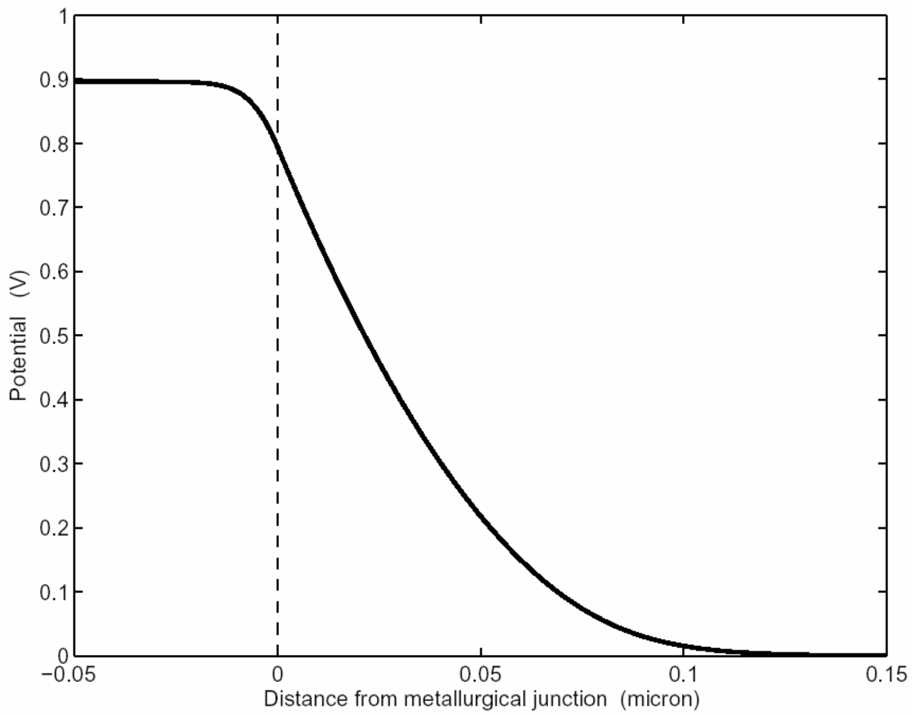
$$-\frac{d^2\psi}{dx^2} = \frac{q}{\epsilon}\left[p_0(x_P)e^{-\psi(x)/V_{\rm th}} - n_0(x_P)e^{\psi(x)/V_{\rm th}} + N_D - N_A\right]$$

Results for an

np-diode

N_D=1E18/cc

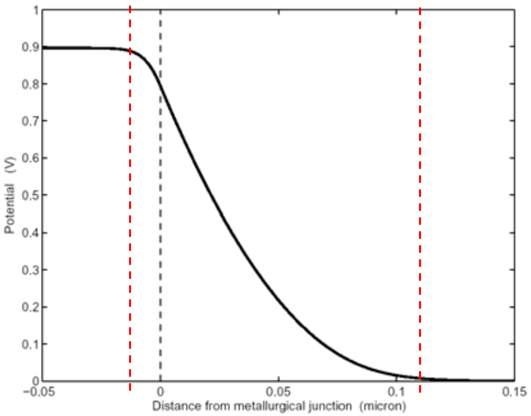
N_A=1E17/cc



The Depletion Approximation

Sec. 6.2

- Approximate the [blank] boundaries



- Approximate the carrier concentrations within the SCR

$$n(x), p(x) \ll N_D \qquad -x_{dn} \leq x \leq 0$$
$$n(x), p(x) \ll N_A \qquad 0 \leq x \leq x_{dp}\,,$$

- Split the non-linear DE into two, [blank]

$$\frac{d^2\psi}{dx^2} = \frac{-qN_D}{\epsilon} \qquad -x_{dn} \leq x \leq 0$$
$$\frac{d^2\psi}{dx^2} = \frac{qN_A}{\epsilon} \qquad 0 \leq x \leq x_{dp}\,.$$

- Impose BC's

$$-\frac{d\psi}{dx} = 0 \qquad x = -x_{dn}$$
$$-\frac{d\psi}{dx} = 0 \qquad x = x_{dp}$$
$$\psi = 0 \qquad x = x_{dp}\,.$$

- Solution is

$$\psi(-x_{dn}) - \psi(x_{dp}) \equiv V_J = \frac{q}{2\epsilon}\left[N_D x_{dn}^2 + N_A x_{dp}^2\right]$$

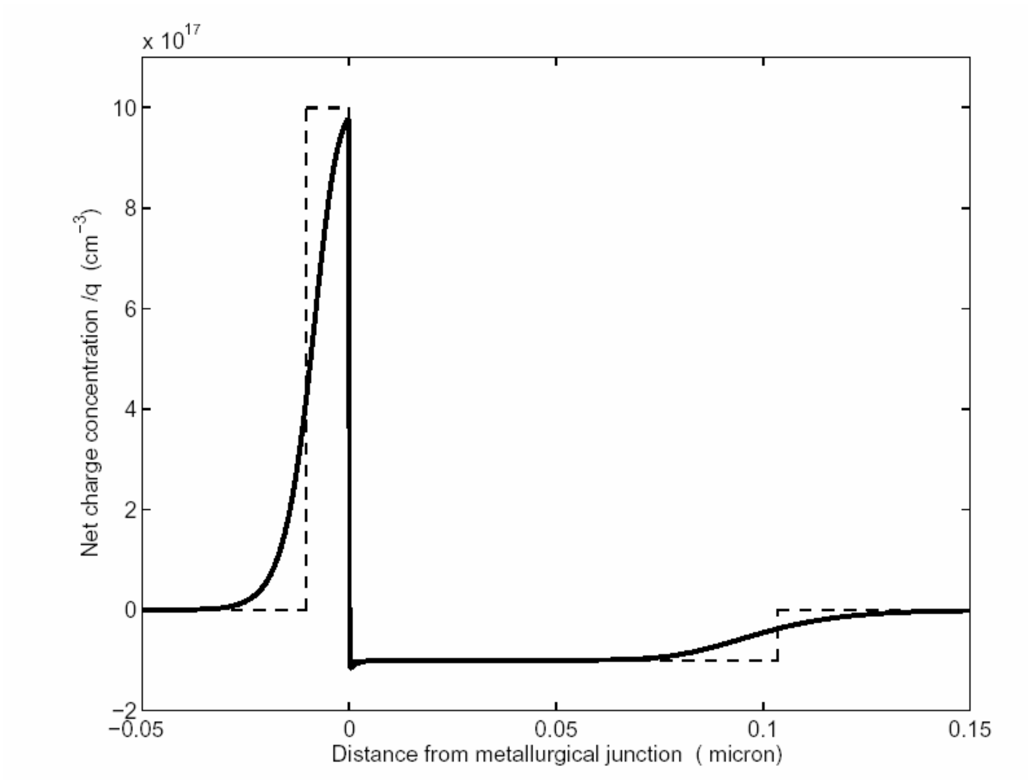
Sec. 6.2

How good is the DA?

Results for an np-diode

N_D=1E18/cc

N_A=1E17/cc



Overall charge neutrality → $$qN_D x_{dn} A = qN_A x_{dp} A$$

Values for x_{dn} and x_{dp} ?

Depletion approximation for the SCR width

$$W = \sqrt{\frac{2\epsilon}{q} V_J \left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

Value for W ?