Theory of Semiconductor Devices
(반도체 소자 이론)

Lecture 9. The PN diodes (1)

Young Min Song
Assistant Professor
School of Electrical Engineering and Computer Science
Gwangju Institute of Science and Technology
http://www.gist-foel.net
ymsong@gist.ac.kr, ymsong81@gmail.com
A207, ☎2655

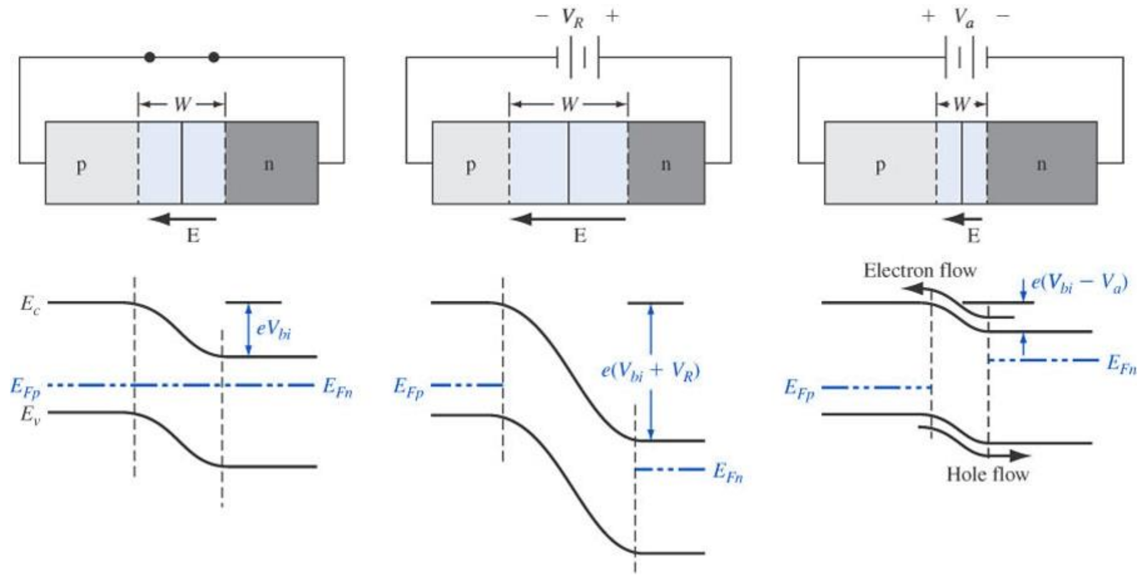
Qualitative Description of Charge Flow in a pn Junction

- Potential barrier for electrons and holes :

  Equilibrium: eV_{bi}

  Reverse biased: $e(V_{bi} + V_R)$

  Forward biased: $e(V_{bi} - V_a)$



The smaller potential barrier means that the electric field in the depletion region is also reduced.

The smaller electric field means that the electrons and holes are no longer held back in the n and p region, respectively.

→ There will be a diffusion of holes from the p region (and a diffusion of electrons from n region)

→ The flow of charge generates a current through the pn junction

The injected holes/electrons into the n/p region : acts as excess minority carriers.

→ The behavior of these minority carriers is described by the ambipolar transport equations.

→ There will be diffusion as well as recombination of excess carriers in these regions.

Qualitative Description of Charge Flow in a pn Junction

Ideal Current-Voltage Relationship

- ✓ Abrupt depletion layer approximation
- ✓ Maxwell-Boltzmann approximation
- ✓ Low injection
- ✓ Total current is a constant. Electron and hole currents are continuous functions through the pn structures and constant throughout the depletion region.

Table 8.1 | Commonly used terms and notation for this chapter

Term	Meaning
N_a	Acceptor concentration in the p region of the pn junction
N_d	Donor concentration in the n region of the pn junction
$n_{n0} = N_d$	Thermal-equilibrium majority carrier electron concentration in the n region
$p_{p0} = N_a$	Thermal-equilibrium majority carrier hole concentration in the p region
$n_{p0} = n_i^2/N_a$	Thermal-equilibrium minority carrier electron concentration in the p region
$p_{n0} = n_i^2/N_d$	Thermal-equilibrium minority carrier hole concentration in the n region
n_p	Total minority carrier electron concentration in the p region
p_n	Total minority carrier hole concentration in the n region
$n_p(-x_p)$	Minority carrier electron concentration in the p region at the space charge edge
$p_n(x_n)$	Minority carrier hole concentration in the n region at the space charge edge
$\delta n_p = n_p - n_{p0}$	Excess minority carrier electron concentration in the p region
$\delta p_n = p_n - p_{n0}$	Excess minority carrier hole concentration in the n region

Boundary Conditions

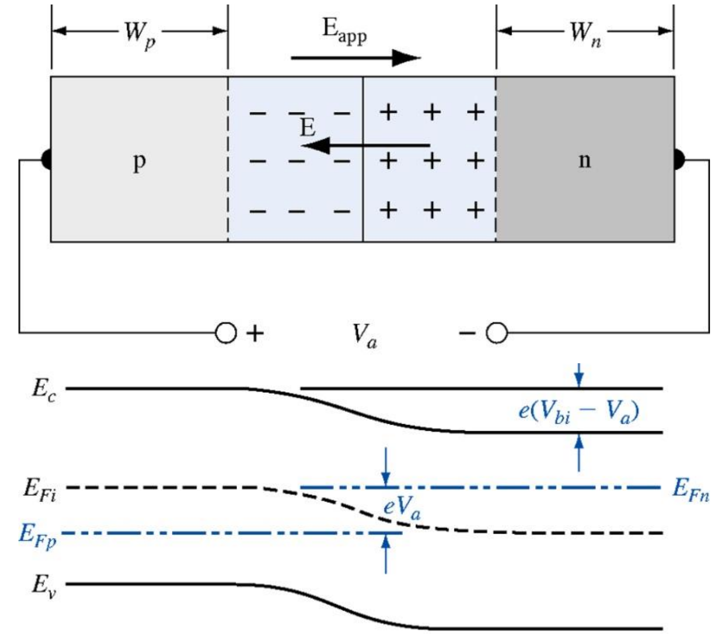
$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) \Rightarrow \frac{n_i^2}{N_a N_d} = \exp\left(\frac{-eV_{bi}}{kT}\right)$$

$$n_{n0} \approx N_d$$

$$n_{p0} \approx \frac{n_i^2}{N_a}$$

$$n_{p0} = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right)$$

: define the relation between the electrons in n-type and p-type regions

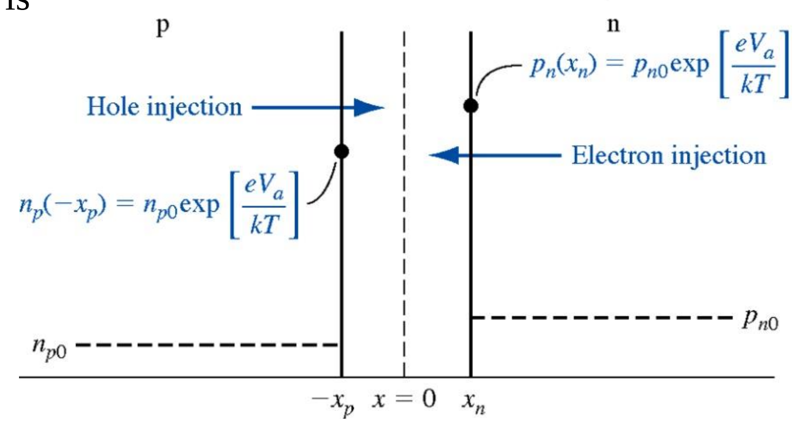


For a forward bias condition, $V_{bi} \rightarrow (V_{bi} - V_a)$:

$$n_p = n_{n0} \exp\left(\frac{-e(V_{bi} - V_a)}{kT}\right) = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right) \exp\left(\frac{+eV_a}{kT}\right)$$

$$\Rightarrow n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right)$$

: the minority electron concentration in p-type region edge is increased from its thermal equilibrium value.



Similarly, the minority hole concentration in n-type region edge is increased from its thermal equilibrium value :

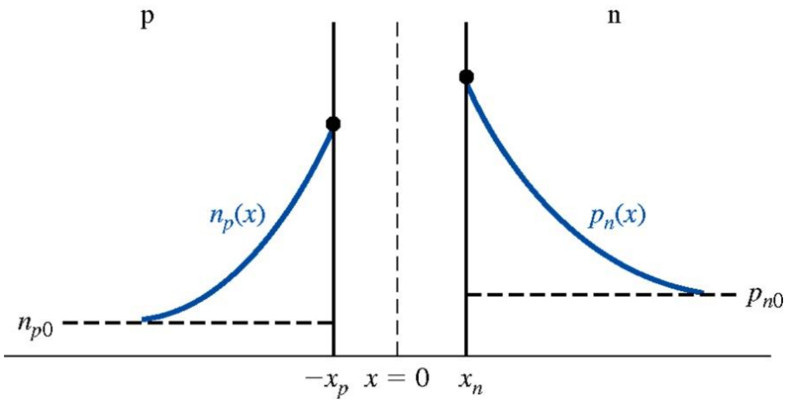
$$\Rightarrow p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right)$$

Example 8.1 : A silicon pn junction at T = 300K with $N_d = 10^{16}$ cm^{-3} and a forward bias of 0.6 V is applied to the junction. Calculate the minority carrier hole concentration at the edge of the space charge region.

$$p_{n0} = \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 \text{ cm}^{-3}$$

$$p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right) = 2.25 \times 10^4 \exp\left(\frac{0.60}{0.0259}\right) = 2.59 \times 10^{14} \text{ cm}^{-3}$$

Minority Carrier Distribution



Ambipolar transport equation for excess minority holes in n region :

$$\Rightarrow \quad D_p \frac{\partial^2(\delta p_n)}{\partial x^2} - \mu_p \mathrm{E} \frac{\partial(\delta p_n)}{\partial x} + g' - \frac{\delta p_n}{\tau_{p0}} = \frac{\partial(\delta p_n)}{\partial t}$$

In n region for $x > x_n$, $E = 0$ and $g' = 0$, also assume steady state :

$$\Rightarrow \quad \frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0 \qquad (x > x_n) \qquad\qquad \frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = 0 \qquad (x < x_p)$$

General solutions :

$$\left.\begin{aligned} \delta p_n(x) &= p_n(x) - p_{n0} = Ae^{x/L_p} + Be^{-x/L_p} && (x \geq x_n) \\ \delta n_p(x) &= n_p(x) - n_{p0} = Ce^{x/L_n} + De^{-x/L_n} && (x \leq -x_p) \end{aligned}\right\}$$

Boundary conditions :

$$p_n(x_n) = p_{n0} \exp\left(\frac{eV_a}{kT}\right)$$

$$n_p(-x_p) = n_{p0} \exp\left(\frac{eV_a}{kT}\right)$$

$$p_n(x \rightarrow +\infty) = p_{n0}$$

$$n_p(x \rightarrow -\infty) = n_{p0}$$

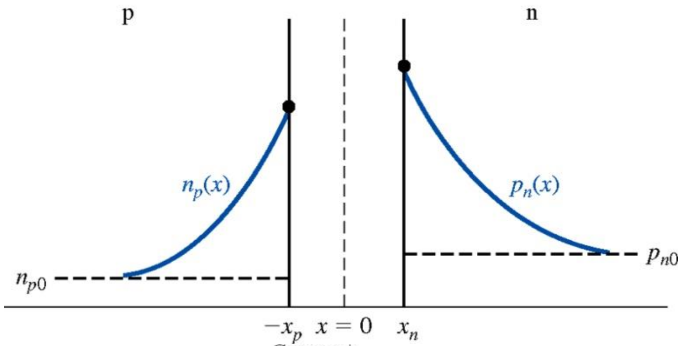
$$\Rightarrow \quad \begin{aligned} \delta p_n(x) &= p_n(x) - p_{n0} = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \exp\left(\frac{x_n - x}{L_p}\right) \\ \delta n_p(x) &= n_p(x) - n_{p0} = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \exp\left(\frac{x_p + x}{L_n}\right) \end{aligned}$$

Ideal pn Junction Current

Total current : the minority carrier hole diffusion current at $x = x_n$

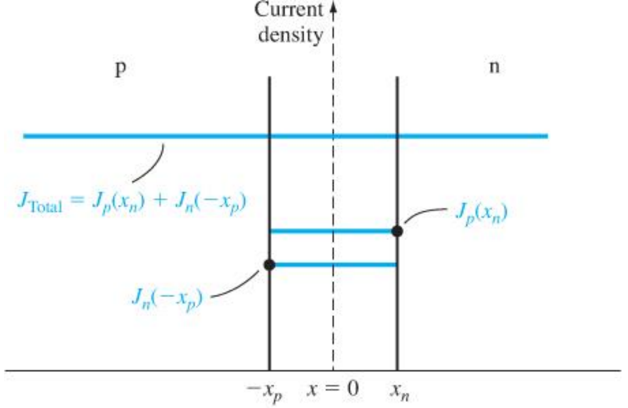
+ the minority carrier electron diffusion current at $x = -x_p$.

(neglect the minority carrier drift current at the neutral region)



$$J_p(x_n) = -eD_p \frac{dp_n(x)}{dx}\bigg|_{x=x_n} = -eD_p \frac{d(\delta p_n(x))}{dx}\bigg|_{x=x_n}$$

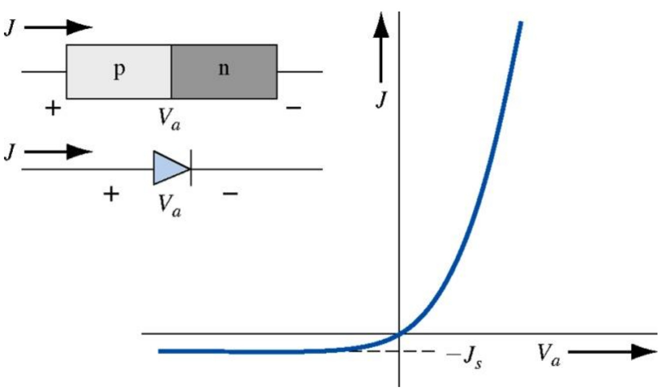
$$J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$



Similarly, electron diffusion current :

$$J_n(-x_p) = eD_n \frac{d(\delta n_p(x))}{dx}\bigg|_{x=-x_p} = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

Each electron and hole currents are continuous and constant through the depletion region.



$$J = J_p(x_n) + J_n(-x_p) = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

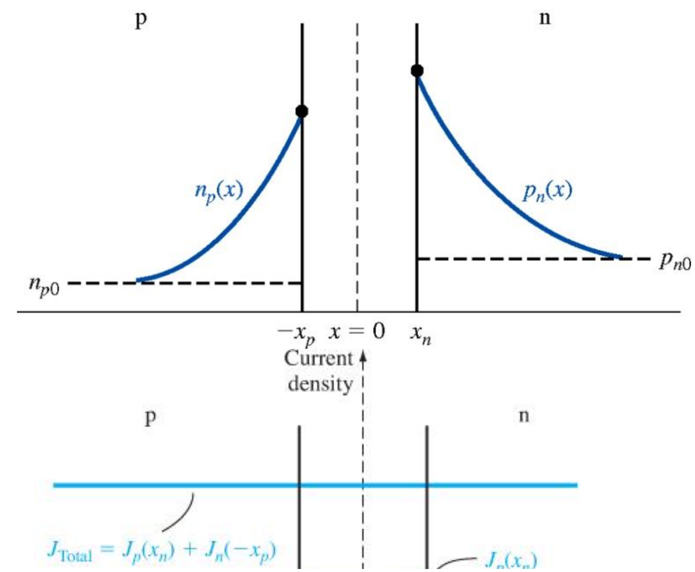
$$= J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \qquad \textit{where,} \quad J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]$$

Ideal pn Junction Current

Total current : the minority carrier hole diffusion current at $x = x_n$

+ the minority carrier electron diffusion current at $x = -x_p$.

(neglect the minority carrier drift current at the neutral region)



$$J_p(x_n) = -eD_p \frac{dp_n(x)}{dx}\bigg|_{x=x_n} = -eD_p \frac{d(\delta p_n(x))}{dx}\bigg|_{x=x_n}$$

$$J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

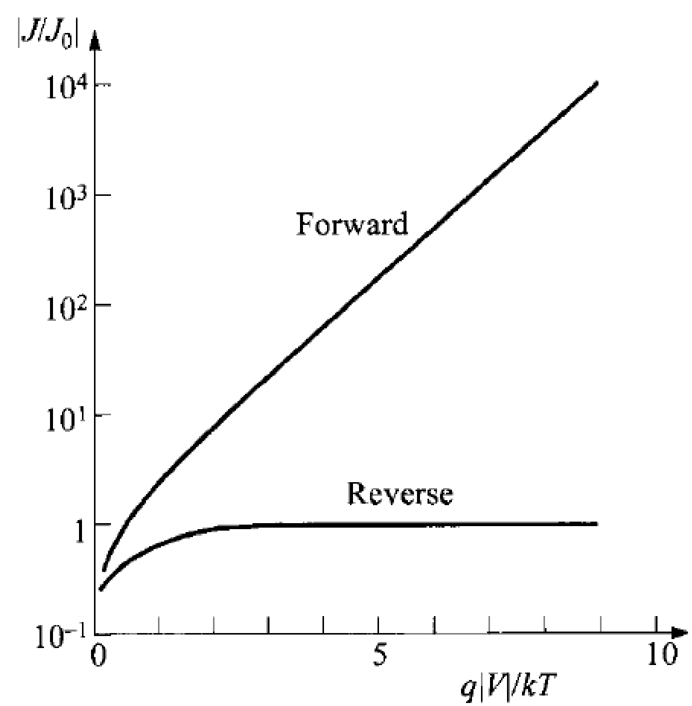
Similarly, electron diffusion current :

$$J_n(-x_p) = eD_n \frac{d(\delta n_p(x))}{dx}\bigg|_{x=-x_p} = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

Each electron and hole currents are continuous and constant through the depletion region.

$$J = J_p(x_n) + J_n(-x_p) = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

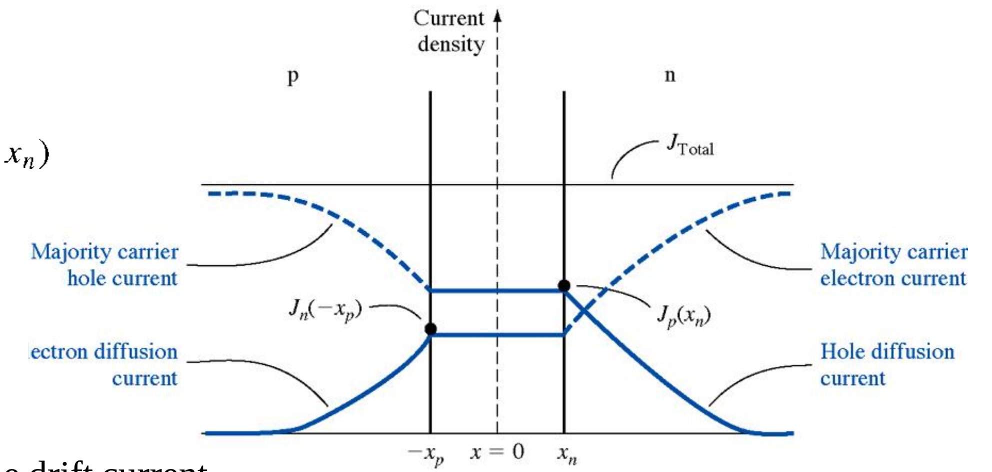
$$= J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \qquad where, \quad J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]$$



Minority carrier diffusion current densities :

$$J_p(x) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_p}\right) \qquad (x \geq x_n)$$

$$J_n(x) = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right) \qquad (x \leq -x_p)$$



Neutral *p* region (far away from junction) : mostly hole drift current
Neutral *p* region (near SCR) : minority electron diffusion current + majority hole drift current

Neutral *n* region (far away from junction) : mostly electron drift current
Neutral *n* region (near SCR) : minority hole diffusion current + majority electron drift current

Space Charge Region : electron and hole diffusion currents

Example 8.4 : A silicon pn junction at T = 300K with $J_s = 4.15\text{x}10^{-11}$ A/cm^2 , $N_d = 10^{16}$ cm^{-3} and V_a = 0.65 V. What is the electric field to produce a given majority carrier drift current ?

$$J = (4.15 \times 10^{-11})\left[\exp\left(\frac{0.65}{0.0259}\right) - 1\right] = 3.29 \text{ A/cm}^2$$

At neutral *n* region far away from SCR :

$$\mathrm{E} = \frac{J_n}{e\mu_n N_d} = \frac{3.29}{(1.6 \times 10^{-19})(1350)(10^{16})} = 1.52 \text{ V/cm}$$

$$J = J_n \approx e\mu_n N_d \mathrm{E}$$

Temperature effect

$$J_0 \equiv \frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n} \equiv \frac{qD_p n_i^2}{L_p N_D} + \frac{qD_n n_i^2}{L_n N_A}$$

We shall now briefly consider the temperature effect on the saturation current density J_0. We shall consider only the first term in Eq. 64, since the second term will behave similarly to the first one. For the one-sided p^+-n abrupt junction (with donor concentration N_D), $p_{no} \gg n_{po}$, the second term can also be neglected. The quantities n_i, D_p, p_{no}, and L_p ($\equiv \sqrt{D_p \tau_p}$) are all temperature-dependent. If D_p/τ_p is proportional to T^γ, where γ is a constant, then

$$J_0 \approx \frac{qD_p p_{no}}{L_p} \approx q\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} \propto T^{\gamma/2}\left[T^3 \exp\left(-\frac{E_g}{kT}\right)\right]$$
$$\propto T^{(3+\gamma/2)} \exp\left(-\frac{E_g}{kT}\right) \quad . \tag{65}$$

The temperature dependence of the term $T^{(3+\gamma/2)}$ is not important compared with the exponential term. The slope of a plot J_0 versus $1/T$ is determined mainly by the energy gap E_g. It is expected that in the reverse direction, where $|J_R| \approx J_0$, the current will increase approximately as $\exp(-E_g/kT)$ with temperature; and in the forward direction, where $J_F \approx J_0 \exp(qV/kT)$, the current will increase approximately as $\exp[-(E_g - qV)/kT]$.