Semiconductor Materials and Devices
(반도체 재료 및 소자)

Chapter 7. The PN junction

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

PN Junction

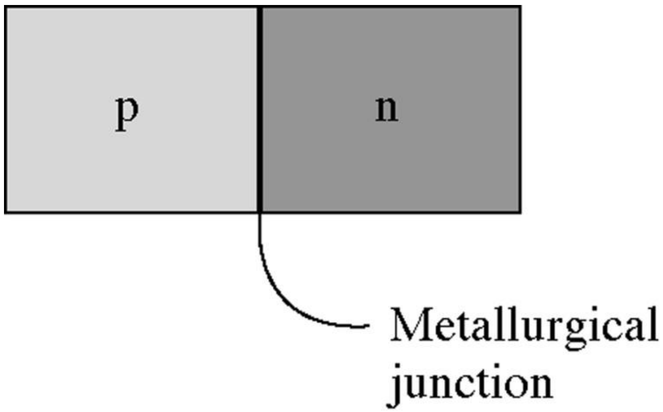
Basic structure in most semiconductors

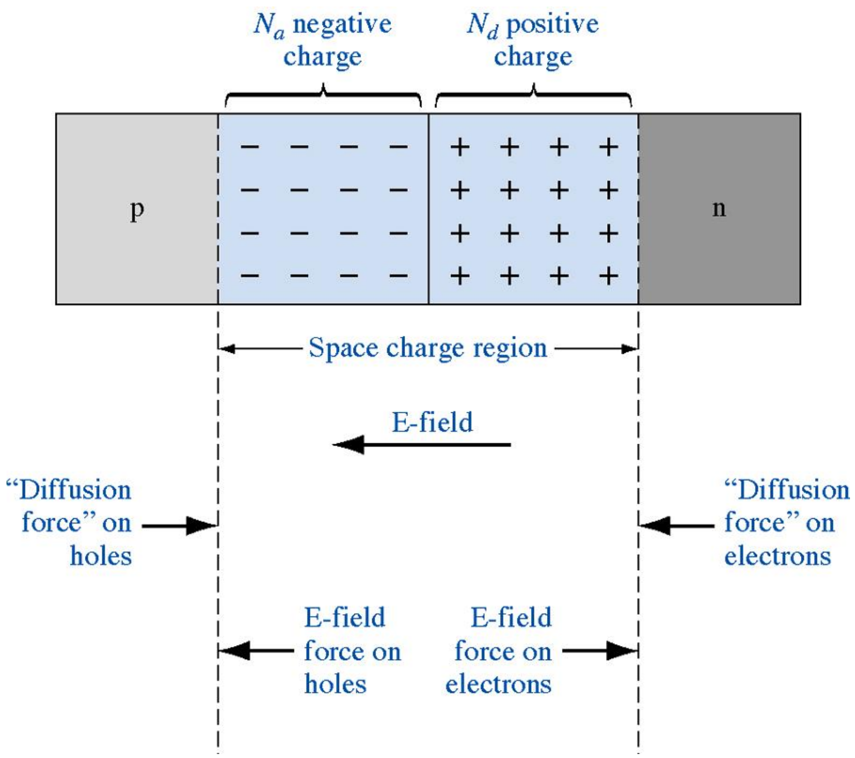
Metallurgical junction

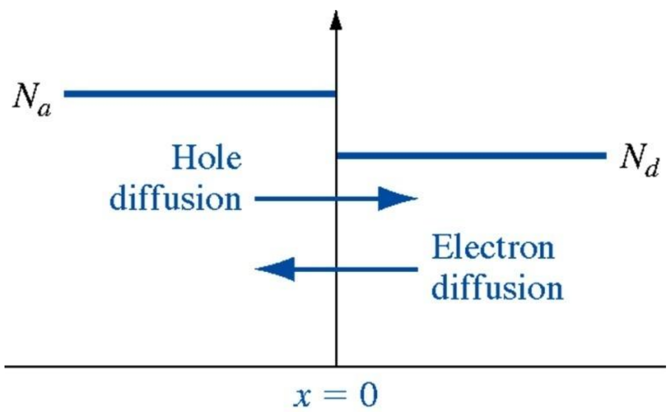
Step junction (abrupt junction)

Space charge region (depletion region)

Diffusion force vs. Electric field

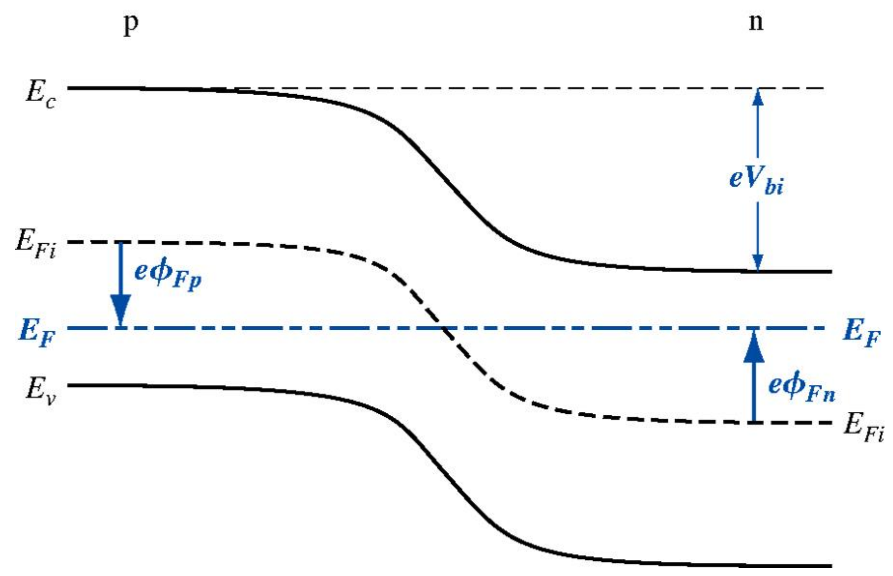






Built-in Potential Barrier

: prevent diffusion flow



$$V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|$$

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$= n_i \exp\left[\frac{-(e\phi_{Fn})}{kT}\right] \qquad e\phi_{Fn} = E_{Fi} - E_F$$

$$\Longrightarrow \quad \phi_{Fn} = \frac{-kT}{e} \ln\left(\frac{N_d}{n_i}\right)$$

$$p_0 = N_a = n_i \exp\left[\frac{E_{Fi} - E_F}{kT}\right]$$

$$\Longrightarrow \quad \phi_{Fp} = +\frac{kT}{e} \ln\left(\frac{N_a}{n_i}\right)$$

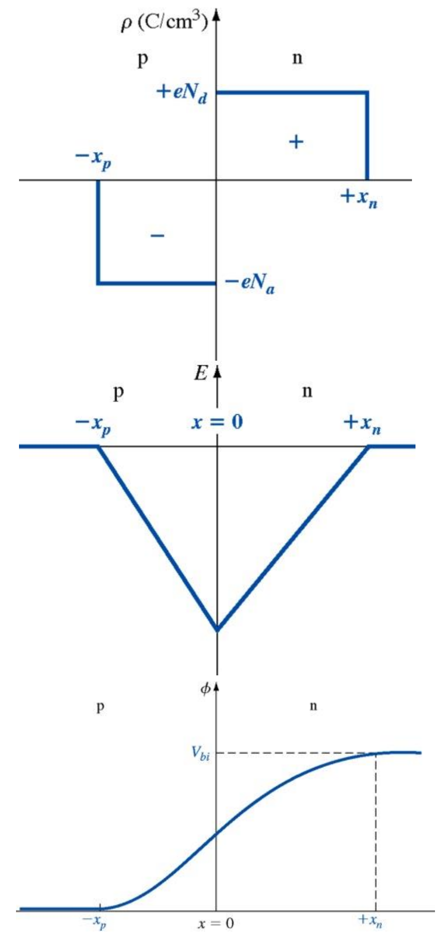
$$e\phi_{Fp} = E_{Fi} - E_F$$

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

Calculation of E-field

Poisson's equation: $$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\epsilon_s} = -\frac{d\mathrm{E}(x)}{dx}$$

ϕ(x) : electric potential
E(x) : electric field *ρ(x)* : charge density



$$\rho(x) = -eN_a \qquad -x_p < x < 0$$
$$\rho(x) = eN_d \qquad 0 < x < x_n$$

$$\mathrm{E} = \int \frac{\rho(x)}{\epsilon_s}\,dx = -\int \frac{eN_a}{\epsilon_s}\,dx = \frac{-eN_a}{\epsilon_s}x + C_1$$
$$\mathrm{E} = \int \frac{(eN_d)}{\epsilon_s}\,dx = \frac{eN_d}{\epsilon_s}x + C_2$$

$$\mathrm{E} = \frac{-eN_a}{\epsilon_s}(x + x_p) \qquad -x_p \le x \le 0$$
$$\mathrm{E} = \frac{-eN_d}{\epsilon_s}(x_n - x) \qquad 0 \le x \le x_n$$

$$N_a x_p = N_d x_n$$

$$\phi(x) = -\int \mathrm{E}(x)\,dx = \int \frac{eN_a}{\epsilon_s}(x + x_p)\,dx$$
$$\phi(x) = \int \frac{eN_d}{\epsilon_s}(x_n - x)\,dx$$

$$\phi(x) = \frac{eN_a}{\epsilon_s}\left(\frac{x^2}{2} + x_p \cdot x\right) + C_1'$$
$$\phi(x) = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + C_2'$$

$$C_1' = \frac{eN_a}{2\epsilon_s}x_p^2$$
$$C_2' = \frac{eN_a}{2\epsilon_s}x_p^2$$

$$\phi(x) = \frac{eN_a}{2\epsilon_s}(x + x_p)^2 \qquad (-x_p \le x \le 0)$$
$$\phi(x) = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + \frac{eN_a}{2\epsilon_s}x_p^2 \qquad (0 \le x \le x_n)$$

$$V_{bi} = |\phi(x = x_n)| = \frac{e}{2\epsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)$$

Space Charge Width

Distance that the space charge region extends from the metallurgical junction

$$N_a x_p = N_d x_n \Rightarrow x_p = \frac{N_d x_n}{N_a}$$

$$V_{bi} = |\phi(x = x_n)| = \frac{e}{2\epsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)$$

$$x_n = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}$$

$$x_p = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_d}{N_a}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}$$

$$W = x_n + x_p \qquad W = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

Example 7.2 : Consider silicon pn junction at T = 300K with $N_a = 10^{16}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}

$$W = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

$$= \left\{\frac{2(11.7)(8.85 \times 10^{-14})(0.635)}{1.6 \times 10^{-19}}\left[\frac{10^{16} + 10^{15}}{(10^{16})(10^{15})}\right]\right\}^{1/2}$$

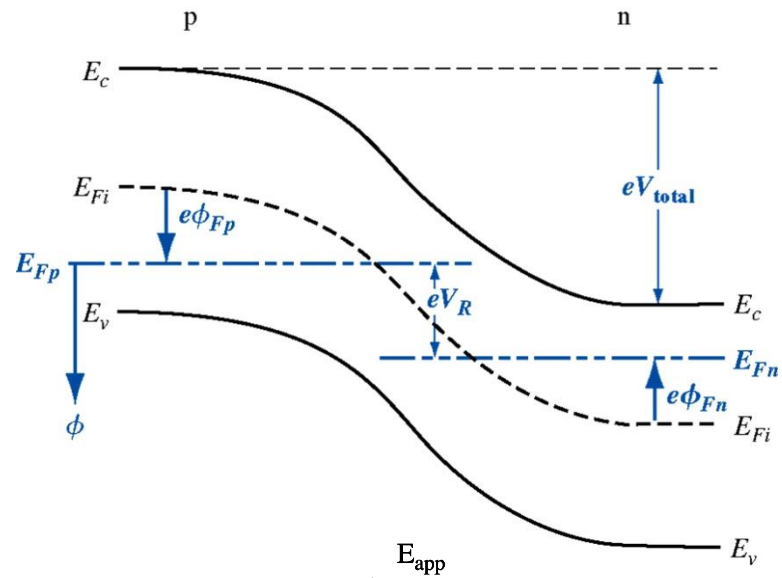
$$= 0.951 \times 10^{-4} \text{ cm} = 0.951\ \mu\text{m}$$

$$\mathrm{E}_{max} = \frac{-eN_d x_n}{\epsilon_s} = \frac{-(1.6 \times 10^{-19})(10^{15})(0.864 \times 10^{-4})}{(11.7)(8.85 \times 10^{-14})} = -1.34 \times 10^4 \text{ V/cm}$$

Reverse Bias : a positive voltage is applied to the *n* region with respect to the *p* region.

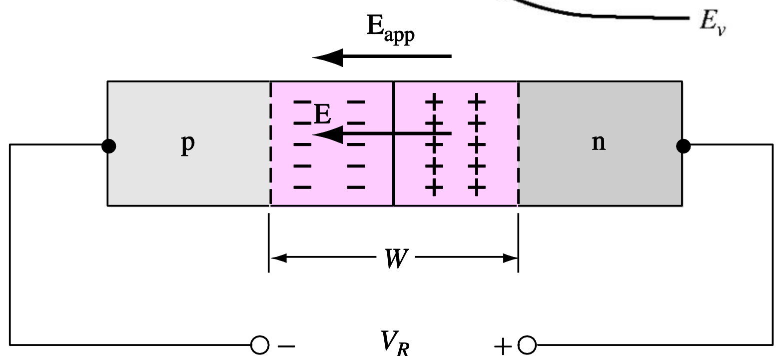
→ Fermi level is no longer constant through the system. (quasi-Fermi level !)

$$V_{\text{total}} = |\phi_{Fn}| + |\phi_{Fp}| + V_R \qquad V_{\text{total}} = V_{bi} + V_R$$



The electric fields in the neutral *p* and *n* regions are essentially zero, or at least very small !!

$$W = \left\{ \frac{2\epsilon_s (V_{bi} + V_R)}{e} \left[\frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$$



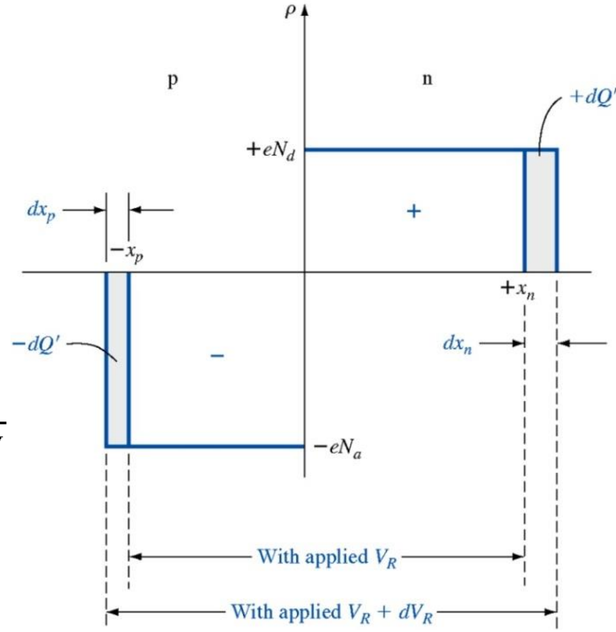
Example 7.2 : A silicon pn junction at T = 300K with $N_a = 10^{16}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}. Let V_R = 5V.

$$W = \left\{ \frac{2(11.7)(8.85 \times 10^{-14})(0.635 + 5)}{1.6 \times 10^{-19}} \left[\frac{10^{16} + 10^{15}}{(10^{16})(10^{15})} \right] \right\}^{1/2}$$

$$W = 2.83 \times 10^{-4} \text{ cm} = 2.83\ \mu\text{m}$$

Junction Capacitance

Separated positive and negative charges across the depletion region. → Capacitance !!



$$C' = \frac{dQ'}{dV_R}$$ where $$dQ' = eN_d\,dx_n = eN_a\,dx_p$$

Q' : C/cm², C' : F/cm²

$$C' = \frac{dQ'}{dV_R} = eN_d \frac{dx_n}{dV_R} \Rightarrow C' = \left\{\frac{e\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}\right\}^{1/2} = \frac{\epsilon_s}{W}$$

$$x_n = \left\{\frac{2\epsilon_s(V_{bi}+V_R)}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a+N_d}\right]\right\}^{1/2}$$

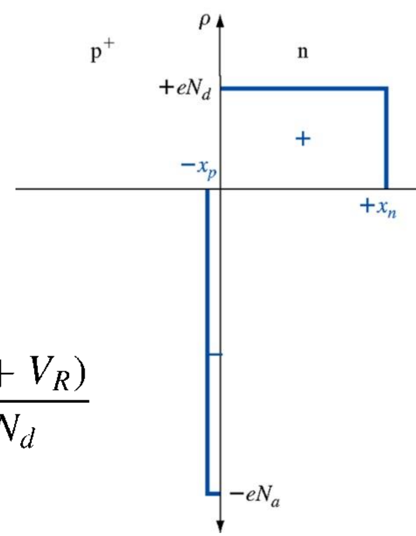
⇑ same as using x_p

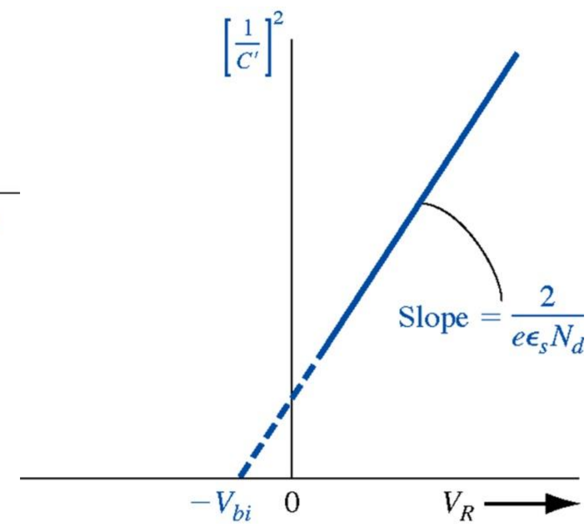
One-sided Junction (p^+n junction for $N_a \gg N_d$)

$$W \approx \left\{\frac{2\epsilon_s(V_{bi}+V_R)}{eN_d}\right\}^{1/2}$$

$$x_p \ll x_n \quad W \approx x_n$$

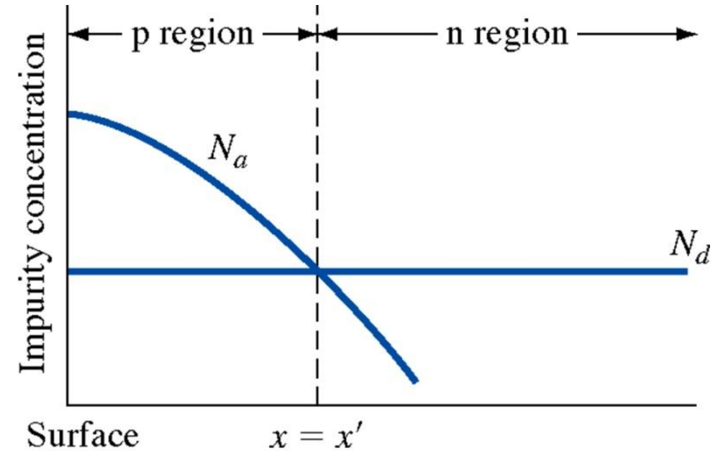
$$C' \approx \left\{\frac{e\epsilon_s N_d}{2(V_{bi}+V_R)}\right\}^{1/2} \Rightarrow \left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi}+V_R)}{e\epsilon_s N_d}$$





Linearly Graded Junctions

Junction made by diffusion can be regarded as linearly graded junction in the metallurgical point.

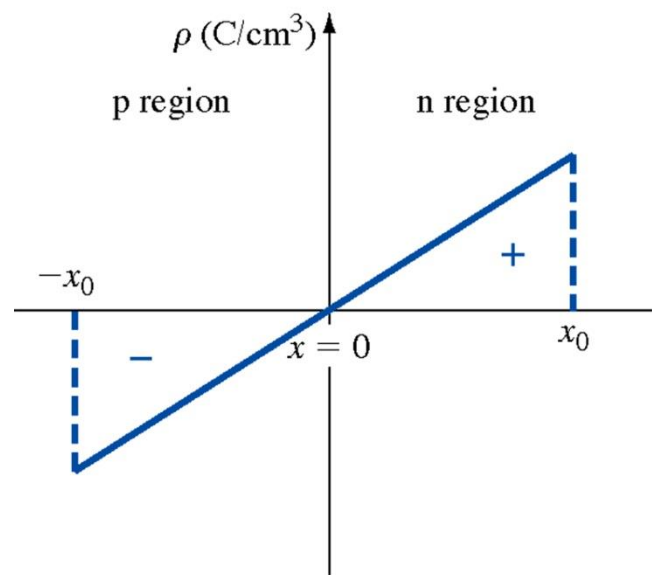


$$\rho(x) = eax \qquad \frac{dE}{dx} = \frac{\rho(x)}{\epsilon_s} = \frac{eax}{\epsilon_s}$$

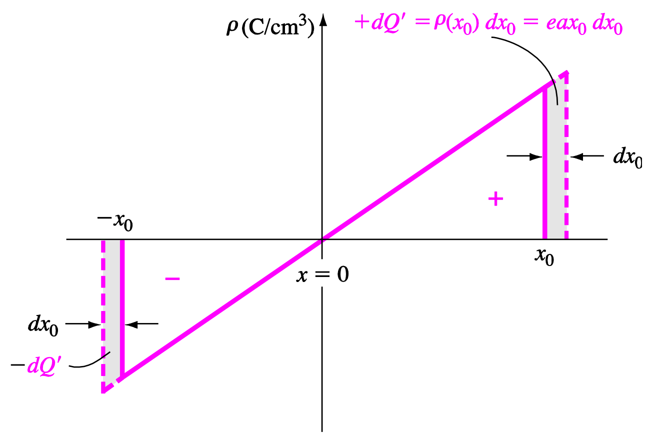
$$E = \int \frac{eax}{\epsilon_s} dx = \frac{ea}{2\epsilon_s}\left(x^2 - x_0^2\right) \quad \leftarrow E(-x_0) = E(+x_0) = 0$$

$$\phi(x) = -\int E\, dx = \frac{-ea}{2\epsilon_s}\left(\frac{x^3}{3} - x_0^2 x\right) + \frac{ea}{3\epsilon_s} x_0^3 \quad \leftarrow \phi(-x_0) = 0$$

$$\phi(x_0) = \frac{2}{3} \cdot \frac{eax_0^3}{\epsilon_s} = V_{bi}$$



For reverse biased junction,



$$x_0 = \left\{\frac{3}{2} \cdot \frac{\epsilon_s}{ea}(V_{bi} + V_R)\right\}^{1/3}$$

$$C' = \frac{dQ'}{dV_R} = (eax_0)\frac{dx_0}{dV_R} = \left\{\frac{ea\epsilon_s^2}{12(V_{bi} + V_R)}\right\}^{1/3}$$