Lecture 7 - PN Junction and MOS Electrostatics (IV)

Electrostatics of Metal-Oxide-Semiconductor Structure

March 1, 2001

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1. Introduction to MOS structure
2. Electrostatics of MOS in thermal equilibrium
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Reading assignment:

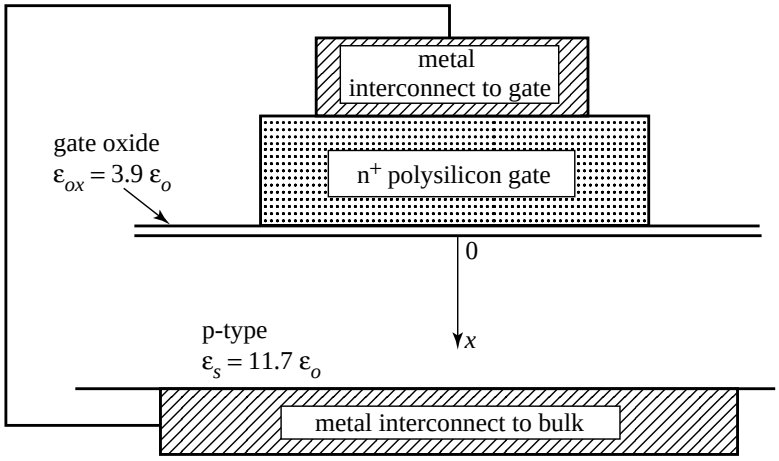
Howe and Sodini, Ch. 3, §§3.7-3.8

Key questions

- What is the big deal about the metal-oxide-semiconductor structure?
- What do the electrostatics of the MOS structure look like in thermal equilibrium?
- How do the electrostatics of the MOS structure get modified if a voltage is applied across its terminals?

1. Introduction

Metal-Oxide-Semiconductor structure:

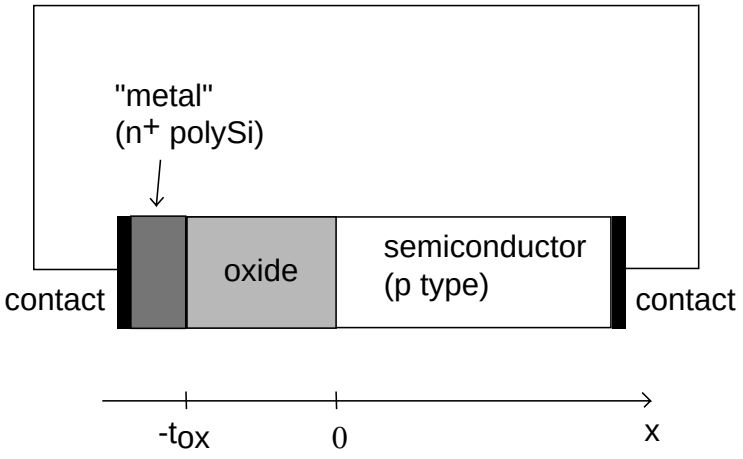


MOS at the heart of the electronics revolution:

- *Digital and analog functions*: Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is key element of Complementary Metal-Oxide-Semiconductor (CMOS) circuit family
- *Memory function*: Dynamic Random Access Memory (DRAM) and Flash Erasable Programmable Memory (EPROM)
- *Imaging*: Charge-Couple Device (CCD) camera
- *Displays*: Active-Matrix Liquid-Crystal Displays
- ...

2. MOS Electrostatics in equilibrium

Idealized 1D structure:

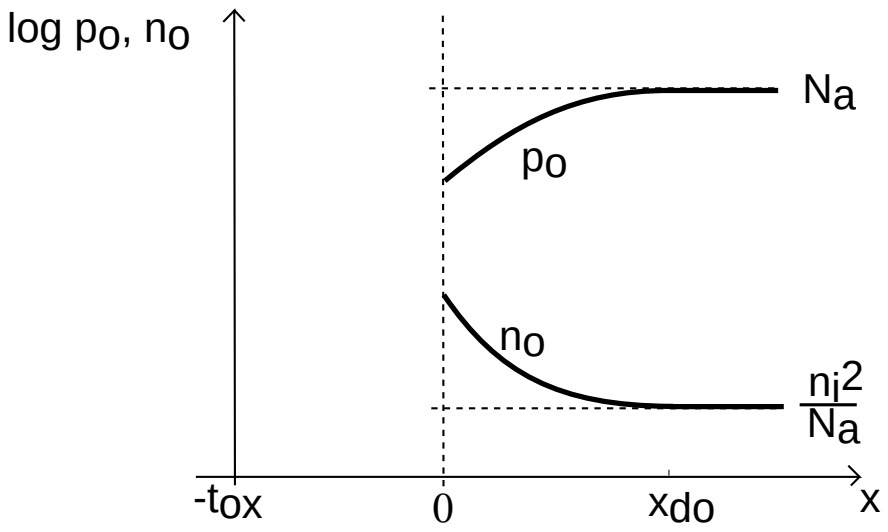


- Metal: does not tolerate volume charge $\Rightarrow$ charge can only exist at its surface
- Oxide: insulator $\Rightarrow$ no volume charge (no free carriers, no dopants)
- Semiconductor: can have volume charge (SCR)

Thermal equilibrium can't be established through oxide; need wire to allow transfer of charge between metal and semiconductor.

MOS structure: sandwich of dissimilar materials $\Rightarrow$ carrier transfer $\Rightarrow$ space-charge region in equilibrium $\Rightarrow$ built-in potential

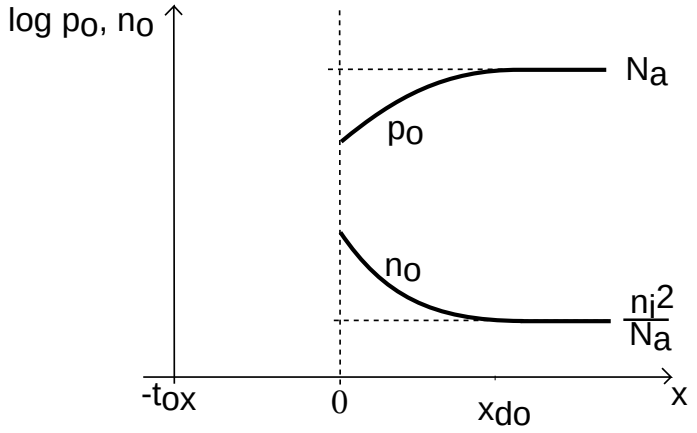
For most metals on p-Si, equilibrium achieved by electrons diffusing from metal to semiconductor and holes from semiconductor to metal:

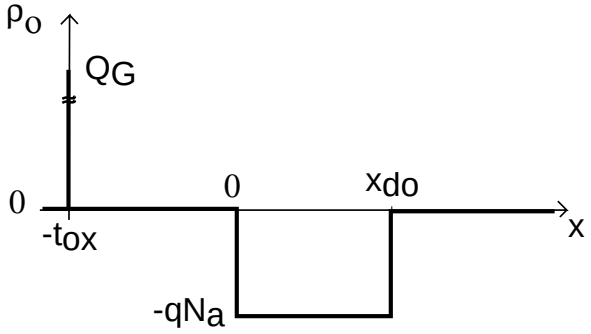


Remember: $n_o p_o = n_i^2$

Fewer holes near Si/SiO_2 interface $\Rightarrow$ ionized acceptors exposed (volume space charge)

□ Space charge density





- In semiconductor: space-charge region close to Si/SiO_2 interface $\Rightarrow$ can do *depletion approximation*
- In metal: sheet of charge at metal/SiO_2 interface
- Overall charge neutrality

$$\begin{aligned} x &= -t_{ox} & \sigma &= Q_G \\ -t_{ox} &< x < 0 & \rho_o(x) &= 0 \\ 0 &< x < x_{do} & \rho_o(x) &= -qN_a \\ x_{do} &< x & \rho_o(x) &= 0 \end{aligned}$$

□ Electric field

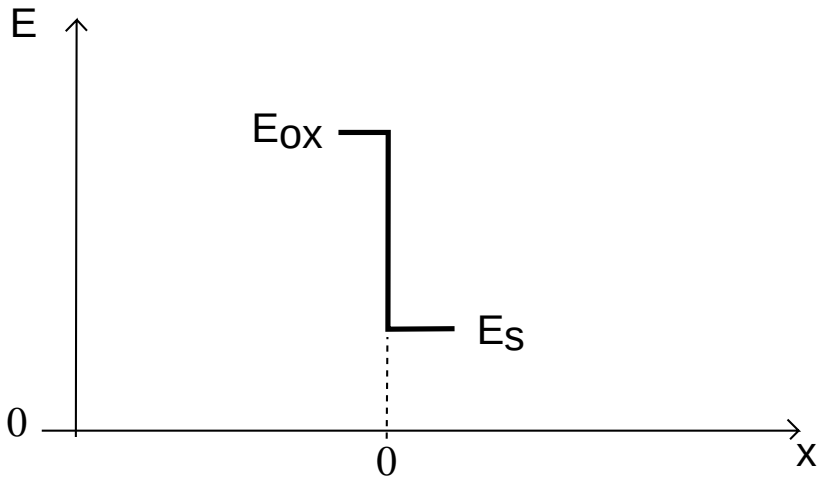
Integrate Gauss' equation:

$$E_o(x_1) - E_o(x_2) = \frac{1}{\epsilon}\int_{x_1}^{x_2} \rho_o(x)dx$$

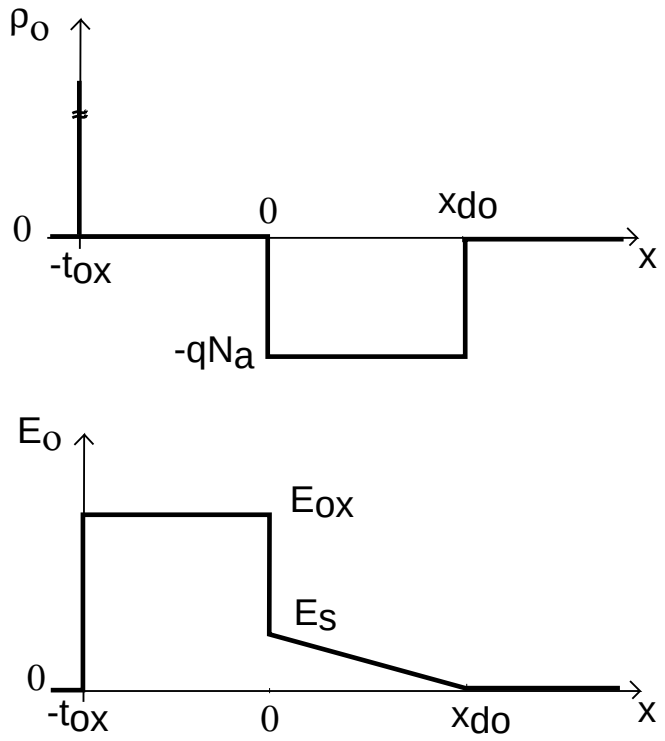
At interface between oxide and semiconductor, change in permittivity ⇒ change in electric field

$$\epsilon_{ox} E_{ox} = \epsilon_s E_s$$

$$\frac{E_{ox}}{E_s} = \frac{\epsilon_s}{\epsilon_{ox}} \simeq 3$$



Start integrating from deep inside semiconductor:



$$x_{do} < x \qquad E_o(x) = 0$$

$$0 < x < x_{do} \qquad E_o(x) = -\frac{qN_a}{\epsilon_s}(x - x_{do})$$

$$-t_{ox} < x < 0 \qquad E_o(x) = \frac{\epsilon_s}{\epsilon_{ox}} E_o(x = 0^+) = \frac{qN_a x_{do}}{\epsilon_{ox}}$$

$$x < -t_{ox} \qquad E_o(x) = 0$$

□ Electrostatic potential

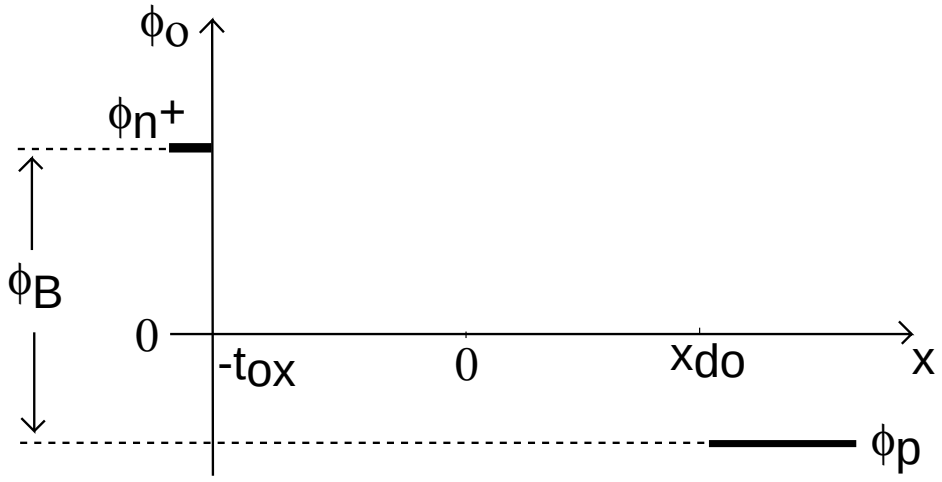
(with $\phi = 0$ @ $n_o = p_o = n_i$)

$$\phi = \frac{kT}{q} \ln \frac{n_o}{n_i} \qquad \phi = -\frac{kT}{q} \ln \frac{p_o}{n_i}$$

In QNR's, n_o and p_o known $\Rightarrow$ can determine ϕ:

in n^+ gate: $n_o = N_d^+ \;\Rightarrow\; \phi_g = \phi_{n^+}$

in p-QNR: $p_o = N_a \;\Rightarrow\; \phi_p = -\frac{kT}{q} \ln \frac{N_a}{n_i}$

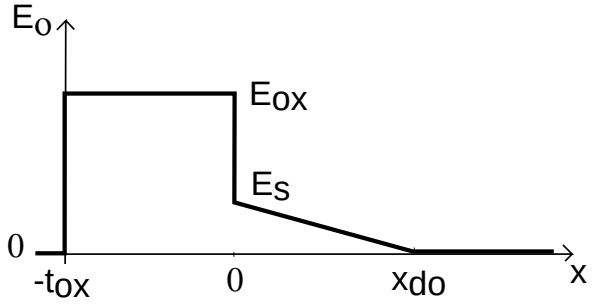


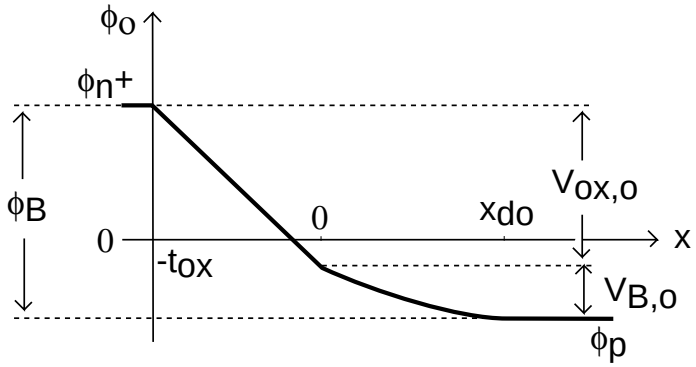
Built-in potential:

$$\phi_B = \phi_g - \phi_p = \phi_{n^+} + \frac{kT}{q} \ln \frac{N_a}{n_i}$$

To get $\phi_o(x)$, integrate $E_o(x)$; start from deep inside semiconductor bulk:

$$\phi_o(x_1) - \phi_o(x_2) = -\int_{x_1}^{x_2} E_o(x)dx$$





$$x_{do} < x \qquad \phi_o(x) = \phi_p$$

$$0 < x < x_d \qquad \phi_o(x) = \phi_p + \frac{qN_a}{2\epsilon_s}(x - x_{do})^2$$

$$-t_{ox} < x < 0 \qquad \phi_o(x) = \phi_p + \frac{qN_a x_{do}^2}{2\epsilon_s} + \frac{qN_a x_{do}}{\epsilon_{ox}}(-x)$$

$$x < -t_{ox} \qquad \phi_o(x) = \phi_{n^+}$$

□ Still don't know $x_{do} \Rightarrow$ need one more equation:

Potential difference across structure has to add up to ϕ_B:

$$\phi_B = V_{B,o} + V_{ox,o} = \frac{qN_a x_{do}^2}{2\epsilon_s} + \frac{qN_a x_{do} t_{ox}}{\epsilon_{ox}}$$

Solve quadratic equation:

$$x_{do} = \frac{\epsilon_s}{\epsilon_{ox}} t_{ox} [\sqrt{1 + \frac{2\epsilon_{ox}^2 \phi_B}{\epsilon_s q N_a t_{ox}^2}} - 1] = \frac{\epsilon_s}{C_{ox}} [\sqrt{1 + \frac{2C_{ox}^2 \phi_B}{\epsilon_s q N_a}} - 1]$$

where C_{ox} is capacitance per unit area of oxide:

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

□ Numerical example:

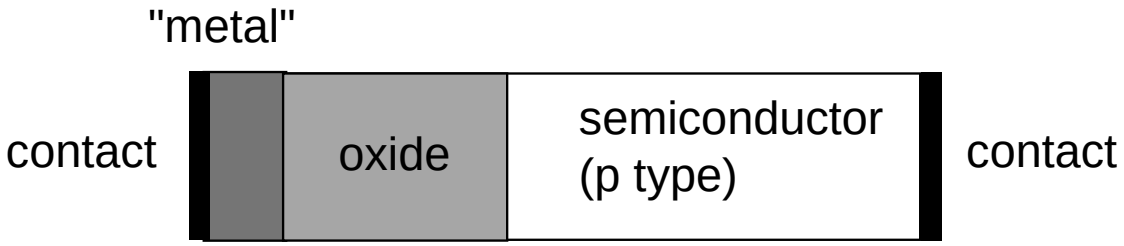
$$N_d = 10^{20}\ cm^{-3},\ N_d = 10^{17}\ cm^{-3},\ t_{ox} = 8\ nm$$

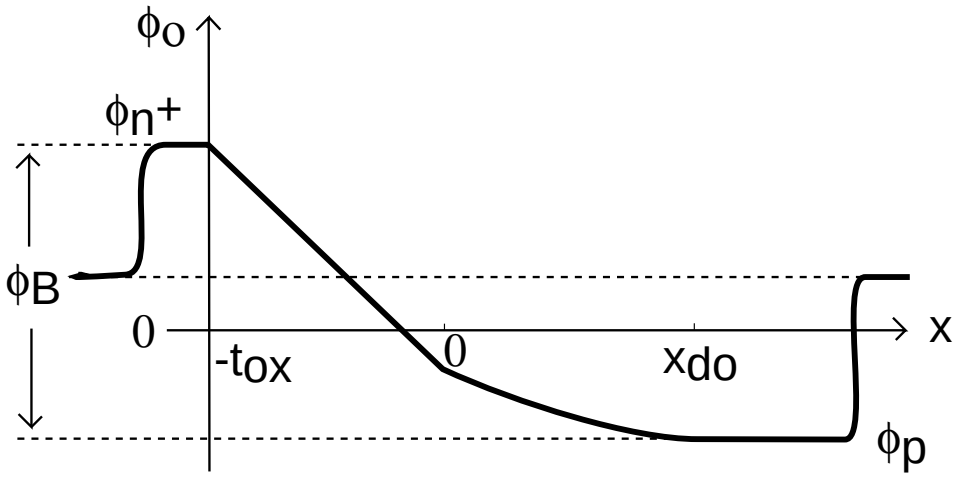
$$\phi_B = 550\ mV + 420\ mV = 970\ mV$$

$$C_{ox} = 4.3 \times 10^{-7}\ F/cm^2$$

$$x_{do} = 91\ nm$$

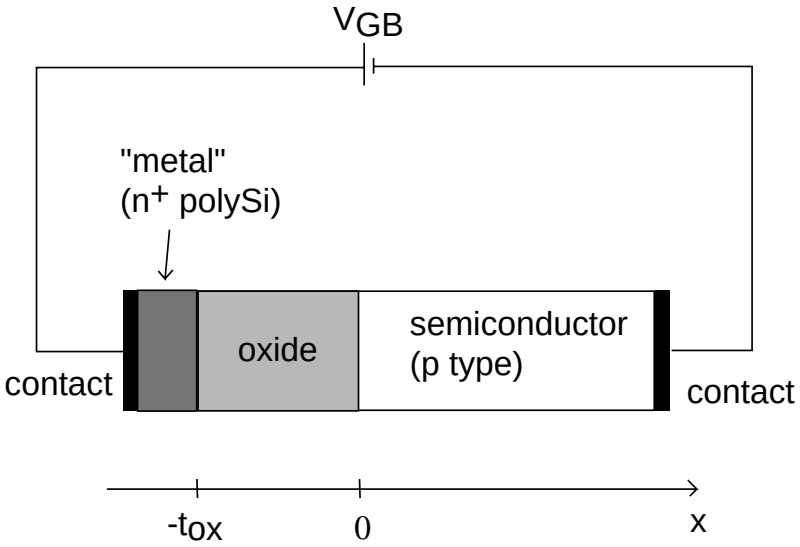
There are also *contact potentials*
$\Rightarrow$ total contact-to-contact potential difference is zero!





3. MOS out of equilibrium

Apply voltage to gate with respect to semiconductor:



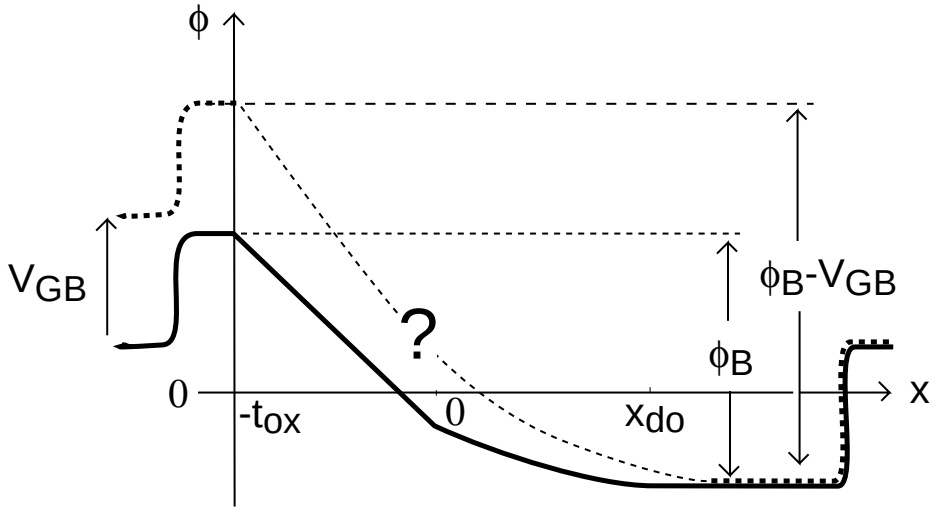
Electrostatics of MOS structure affected $\Rightarrow$ potential difference across entire structure now $\neq 0$.

How is potential difference accommodated?

Potential can drop in:

- gate contact
- n^+-polysilicon gate
- oxide
- semiconductor SCR
- semiconductor QNR
- semiconductor contact

Potential difference shows up across oxide and SCR in semiconductor:

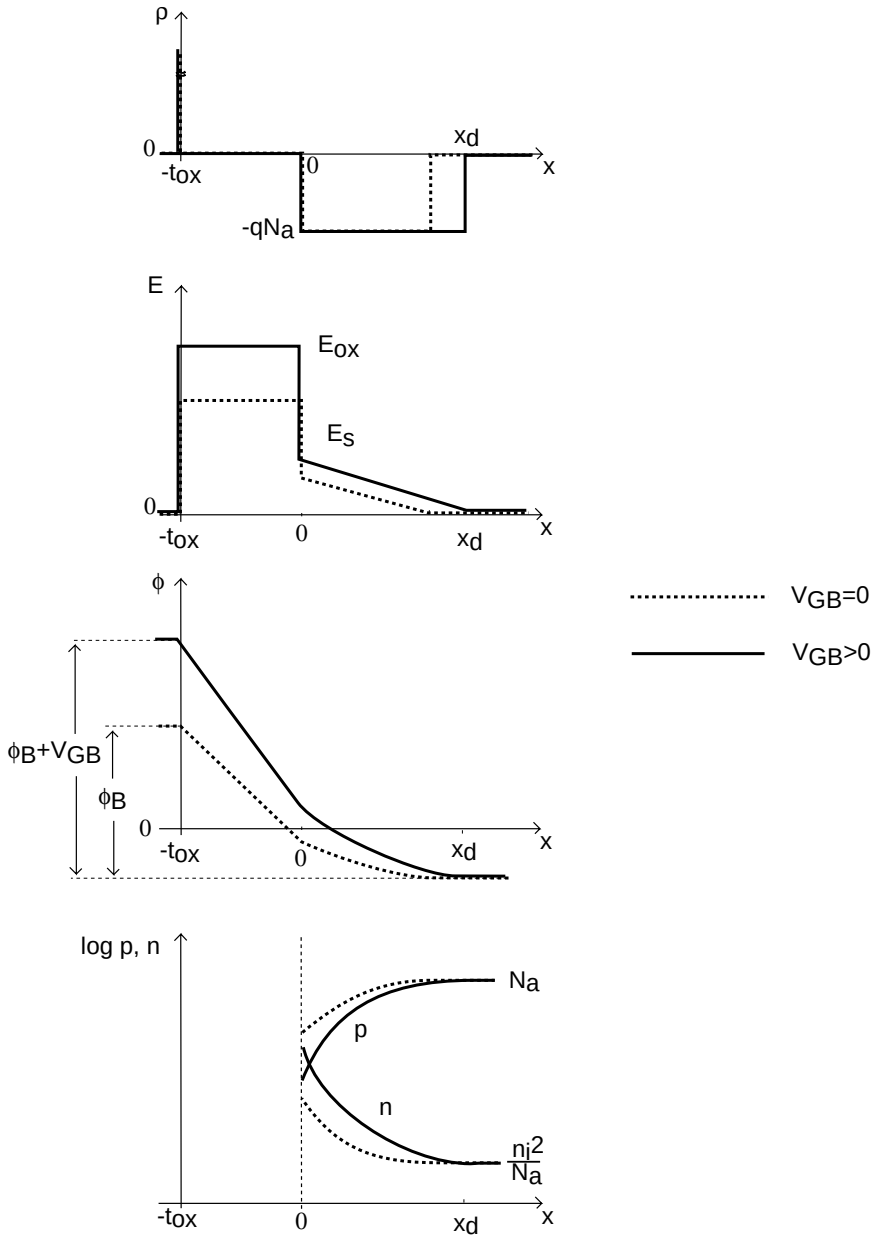


Oxide is insulator ⇒ no current anywhere in structure

In SCR, quasi-equilibrium situation prevails
⇒ new balance between drift and diffusion

- electrostatics qualitatively identical to thermal equilibrium (but *amount of charge redistribution is different*)
- $np = n_i^2$

Apply $V_{GB} > 0$: potential difference across structure increases $\Rightarrow$ need larger charge dipole $\Rightarrow$ SCR expands into semiconductor substrate:



Simple way to remember:

with $V_{GB} > 0$, gate attracts electrons and repels holes.

Qualitatively, physics unchanged by applying $V_{GB} > 0$.

Use mathematical formulation in thermal equilibrium, but:

$$\phi_B \rightarrow \phi_B + V_{GB}$$

For example,

$$x_d(V_{GB}) = \frac{\epsilon_s}{C_{ox}}[\sqrt{1 + \frac{2C_{ox}^2(\phi_B + V_{GB})}{\epsilon_s q N_a}} - 1]$$

$$V_{GB} \uparrow \rightarrow \ x_d \uparrow$$

Key conclusions

- Charge redistribution in MOS structure in thermal equilibrium:
  - SCR in semiconductor
  - built-in potential across MOS structure.
- In most cases, can do depletion approximation in semiconductor SCR.
- Application of voltage modulates depletion region width in semiconductor. No current flows.