

# **Lecture 7 - PN Junction and MOS Electrostatics (IV)**

## **ELECTROSTATICS OF METAL-OXIDE-SEMICONDUCTOR STRUCTURE**

February 27, 2003

### **Contents:**

1. Introduction to MOS structure
2. Electrostatics of MOS at zero bias
3. Electrostatics of MOS under bias

### **Reading assignment:**

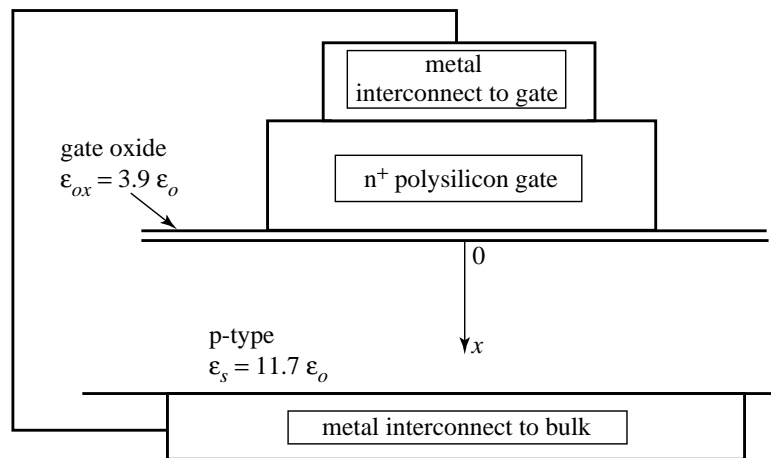
Howe and Sodini, Ch. 3, §§3.7-3.8

## Key questions

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

# 1. Introduction

Metal-Oxide-Semiconductor structure:

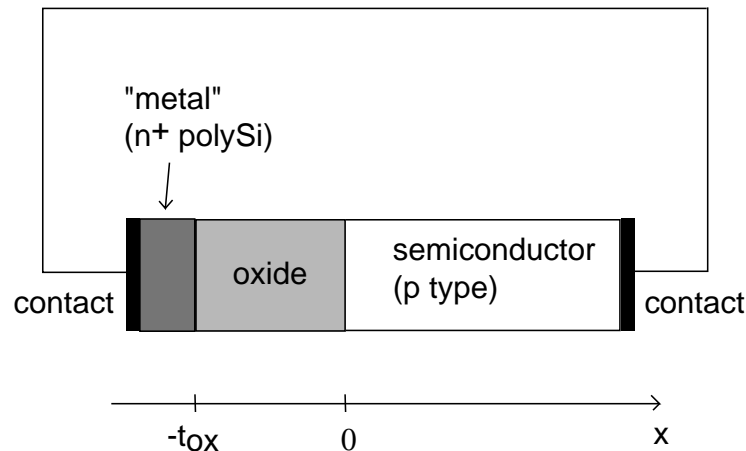


MOS at the heart of the electronics revolution:

- *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 at zero bias

Idealized 1D structure:

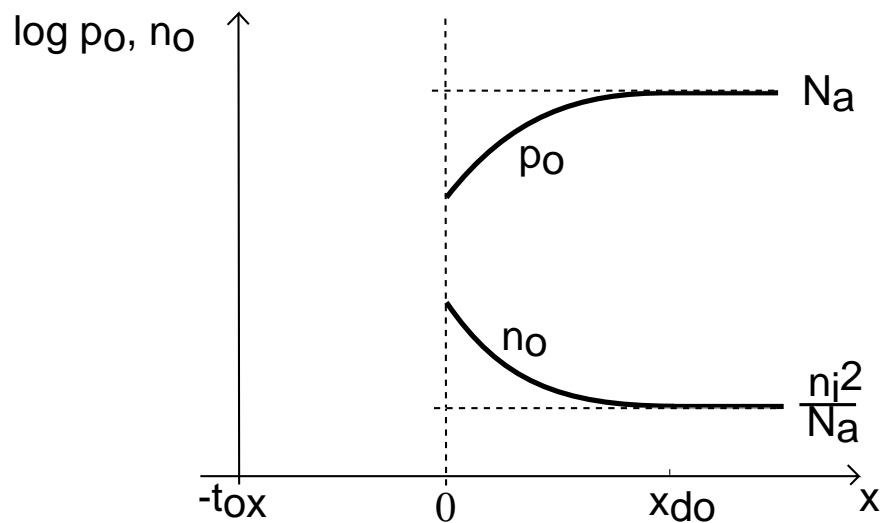


- Metal: does not tolerate volume charge  $\Rightarrow$  charge can only exist at its surface
- Oxide: insulator  $\Rightarrow$  no volume charge (no free carriers, no dopants)
- Semiconductor: can have volume charge (SCR)

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 at zero bias  $\Rightarrow$  built-in potential

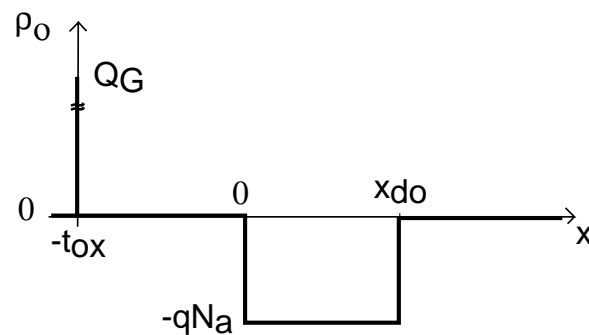
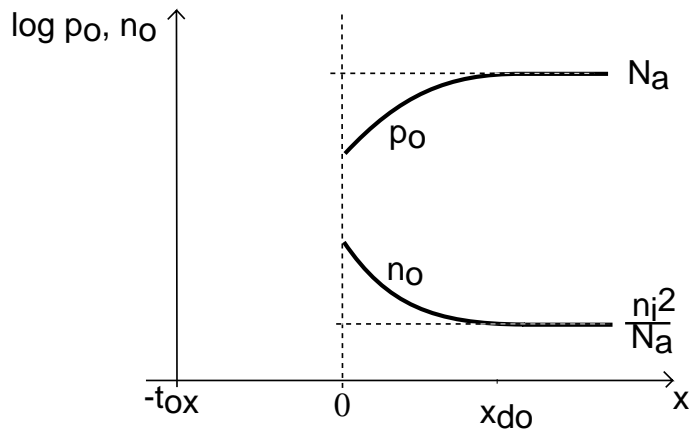
For most metals on p-Si, equilibrium achieved by electrons diffusing from metal to semiconductor and holes from semiconductor to metal:



Remember:  $n_o p_o = n_i^2$

Fewer holes near Si/SiO<sub>2</sub> interface  $\Rightarrow$  ionized acceptors exposed (volume space charge)

## □ SPACE CHARGE DENSITY



- In semiconductor: space-charge region close to Si/SiO<sub>2</sub> interface  $\Rightarrow$  can do *depletion approximation*
- In metal: sheet of charge at metal/SiO<sub>2</sub> interface
- Overall charge neutrality

$x \leq -t_{ox}$	$\rho_o(x) = Q_G \delta(-t_{ox})$
$-t_{ox} < x < 0$	$\rho_o(x) = 0$
$0 < x < x_{do}$	$\rho_o(x) = -qN_a$
$x_{do} < x$	$\rho_o(x) = 0$

## □ ELECTRIC FIELD

Integrate Gauss' equation:

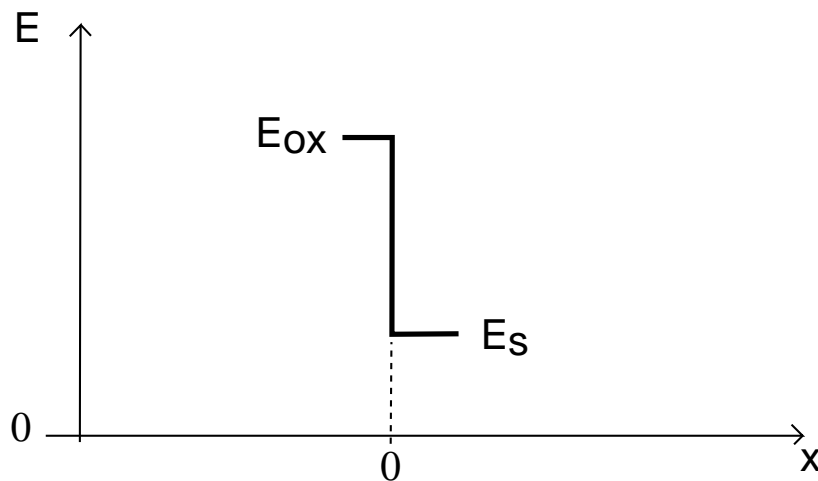
$$E_o(x_2) - E_o(x_1) = \frac{1}{\epsilon} \int_{x_1}^{x_2} \rho_o(x) dx$$

At interface between oxide and semiconductor:

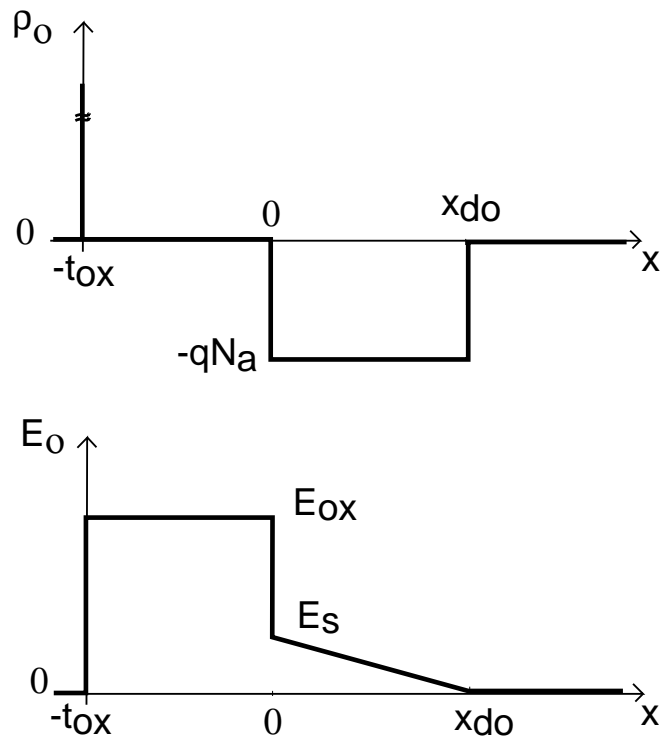
change in permittivity  $\Rightarrow$  change in electric field

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

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



Start integrating from deep inside semiconductor:



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

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

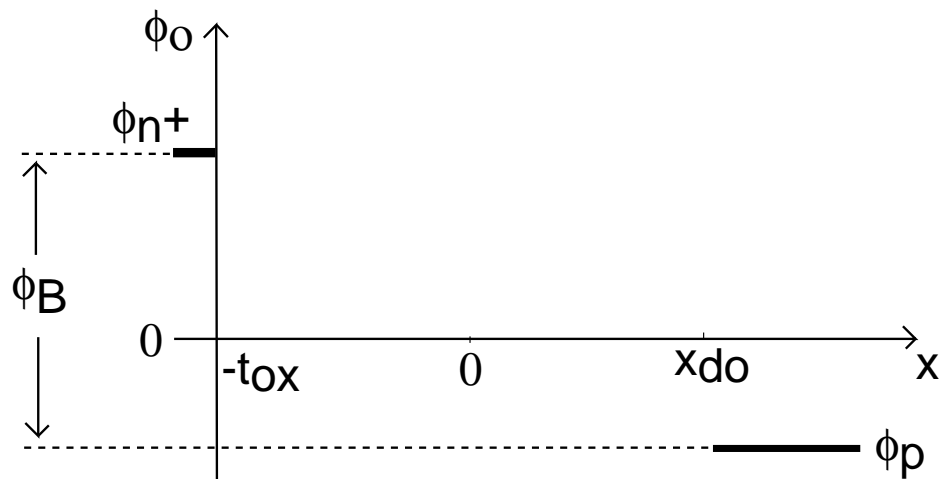
$$-t_{ox} < x < 0 \quad E_o(x) = \frac{\epsilon_s}{\epsilon_{ox}} E_o(x = 0^+) = \frac{qN_a x_{do}}{\epsilon_{ox}}$$

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

## □ ELECTROSTATIC POTENTIAL

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

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

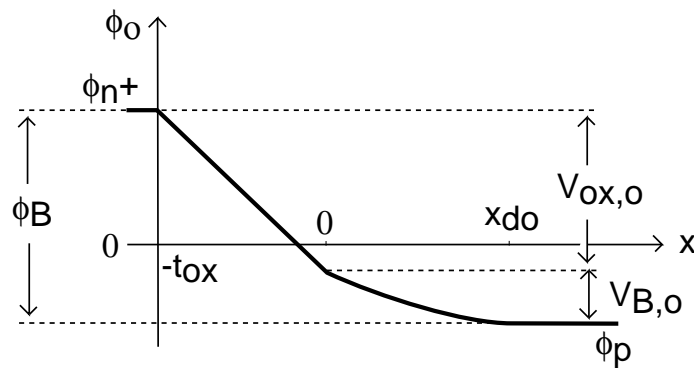
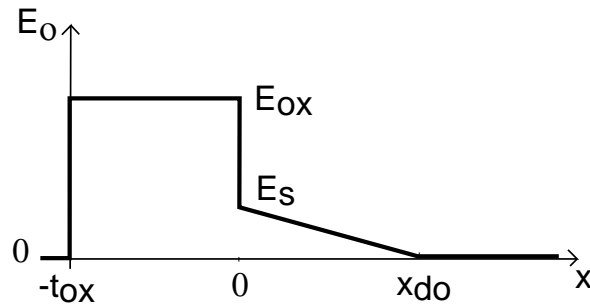
In QNR's,  $n_o$  and  $p_o$  known  $\Rightarrow$  can determine  $\phi$ :in  $n^+$  gate:  $n_o = N_d^+ \Rightarrow \phi_g = \phi_{n^+}$ in p-QNR:  $p_o = N_a \Rightarrow \phi_p = -\frac{kT}{q} \ln \frac{N_a}{n_i}$ 

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:

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



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

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

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

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

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

Potential difference across structure has to add up to  $\phi_B$ :

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

Solve quadratic equation:

$$x_{do} = \frac{\epsilon_s}{\epsilon_{ox}} t_{ox} \left[ \sqrt{1 + \frac{2\epsilon_{ox}^2 \phi_B}{\epsilon_s q N_a t_{ox}^2}} - 1 \right] = \frac{\epsilon_s}{C_{ox}} \left[ \sqrt{1 + \frac{4\phi_B}{\gamma^2}} - 1 \right]$$

where  $C_{ox}$  is *capacitance per unit area of oxide* [units:  $F/cm^2$ ]:

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

and  $\gamma$  is *body factor coefficient* [units:  $V^{-1/2}$ ]:

$$\gamma = \frac{1}{C_{ox}} \sqrt{2\epsilon_s q N_a}$$

□ Numerical example:

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

$$\phi_B = 550 \text{ mV} + 420 \text{ mV} = 970 \text{ mV}$$

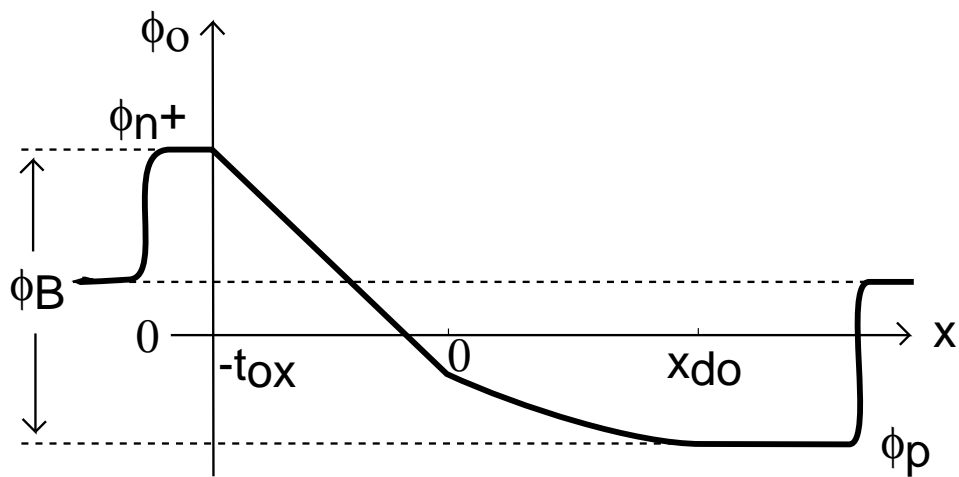
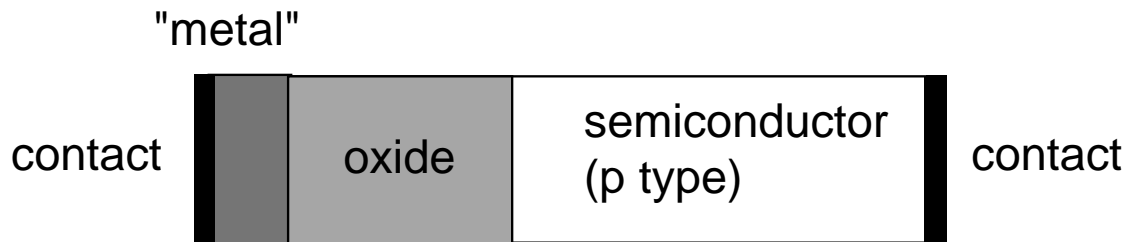
$$C_{ox} = 4.3 \times 10^{-7} \text{ F/cm}^2$$

$$\gamma = 0.43 \text{ V}^{-1/2}$$

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

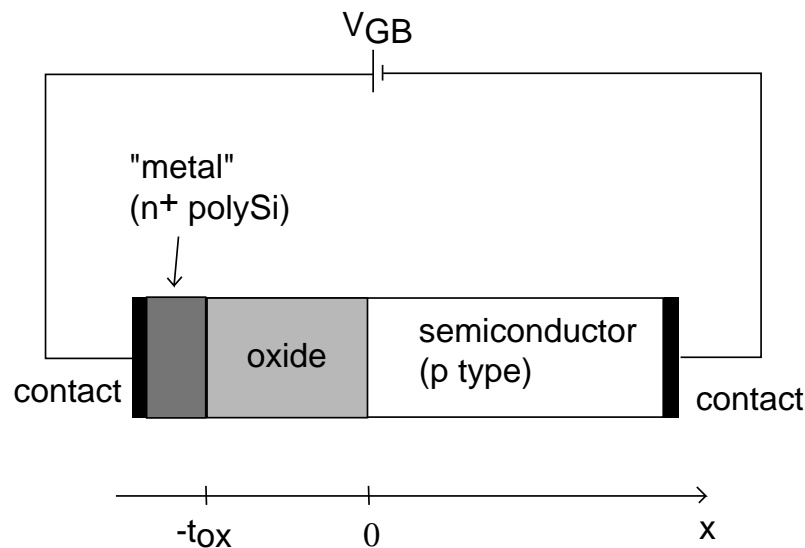
There are also *contact potentials*

$\Rightarrow$  total contact-to-contact potential difference is zero!



### 3. MOS electrostatics under bias

Apply voltage to gate with respect to semiconductor:



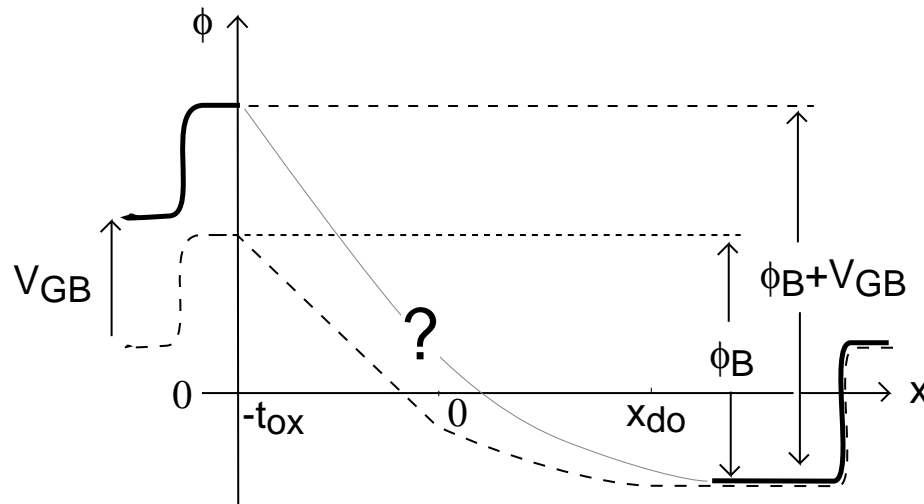
Electrostatics of MOS structure affected  $\Rightarrow$  potential difference across entire structure now  $\neq 0$ .

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:



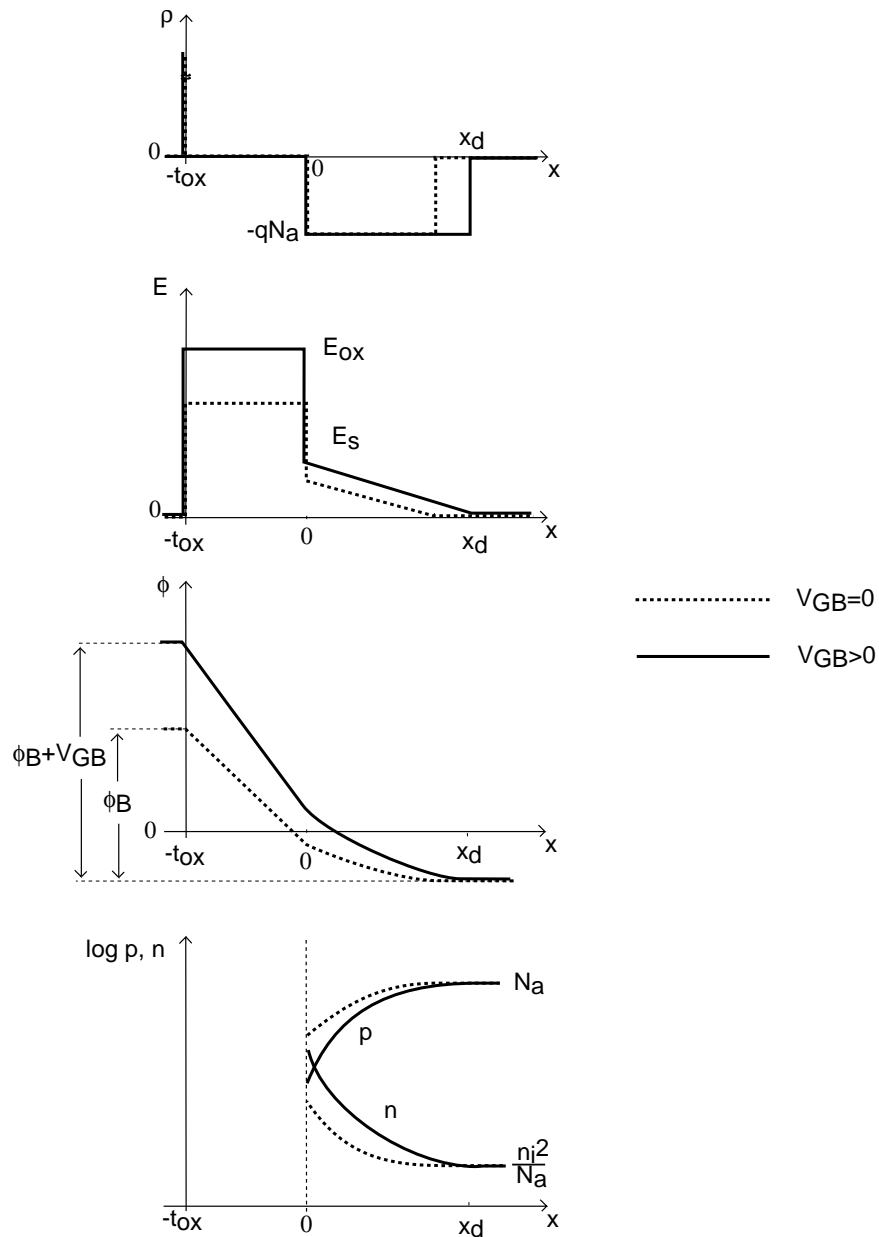
Oxide is insulator  $\Rightarrow$  no current anywhere in structure

In SCR, quasi-equilibrium situation prevails

$\Rightarrow$  new balance between drift and diffusion

- electrostatics qualitatively identical to zero bias (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 of zero bias, but:

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

For example,

$$x_d(V_{GB}) = \frac{\epsilon_s}{C_{ox}} \left[ \sqrt{1 + \frac{4(\phi_B + V_{GB})}{\gamma^2}} - 1 \right]$$

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

## Key conclusions

- Charge redistribution in MOS structure at zero bias:
  - 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.