Section 31
MOSFET Non-Idealities

31.2 Threshold voltage shift due to trapped charges

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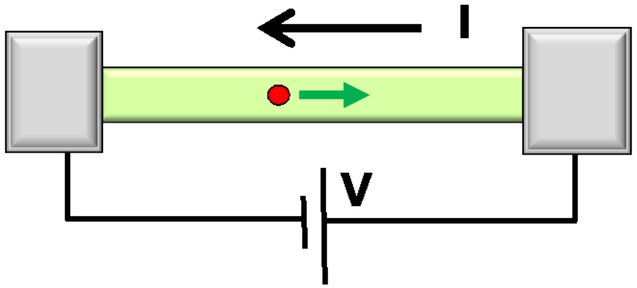
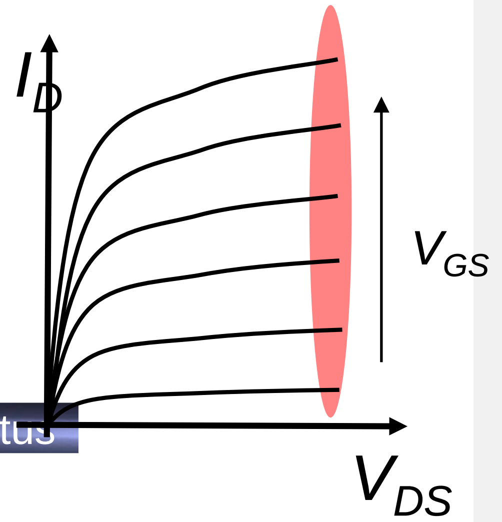
MOSFET Non-Idealities



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



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- 31.1 Flat band voltage - What is it and how to measure it?
- 31.2 Threshold voltage shift due to trapped charges
- 31.3 Physics of interface traps

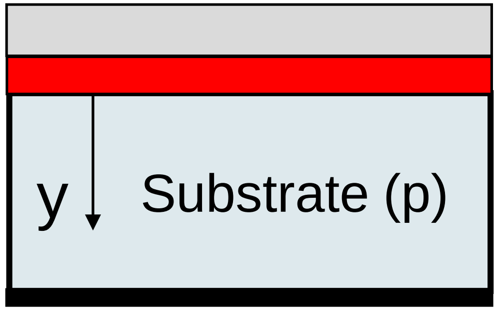
$$I_D(V_D = V_{DD}) \sim (V_G - V_{th})^{\alpha}$$
$$1 < \alpha < 2$$

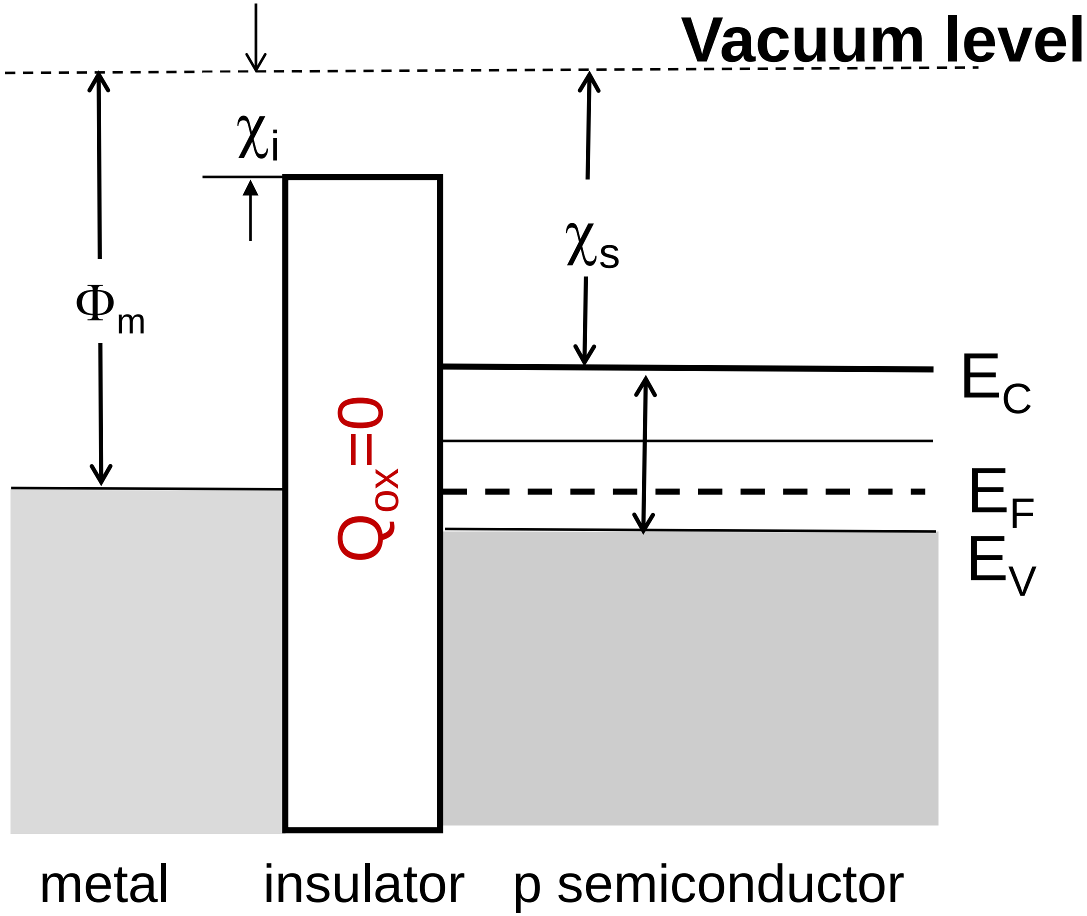
$$V_{th} = V_{th,ideal} + \phi_{MS} - \frac{\gamma_M Q_M}{C_O} - \frac{Q_F}{C_O} - \frac{Q_{IT}(\phi_s)}{C_O}$$

Metal contact | Charge in oxide | Fixed charge | interface traps

Ref: Sec. 16.4 of SDF Chapter 18, SDF

(2) Idealized MOS Capacitor



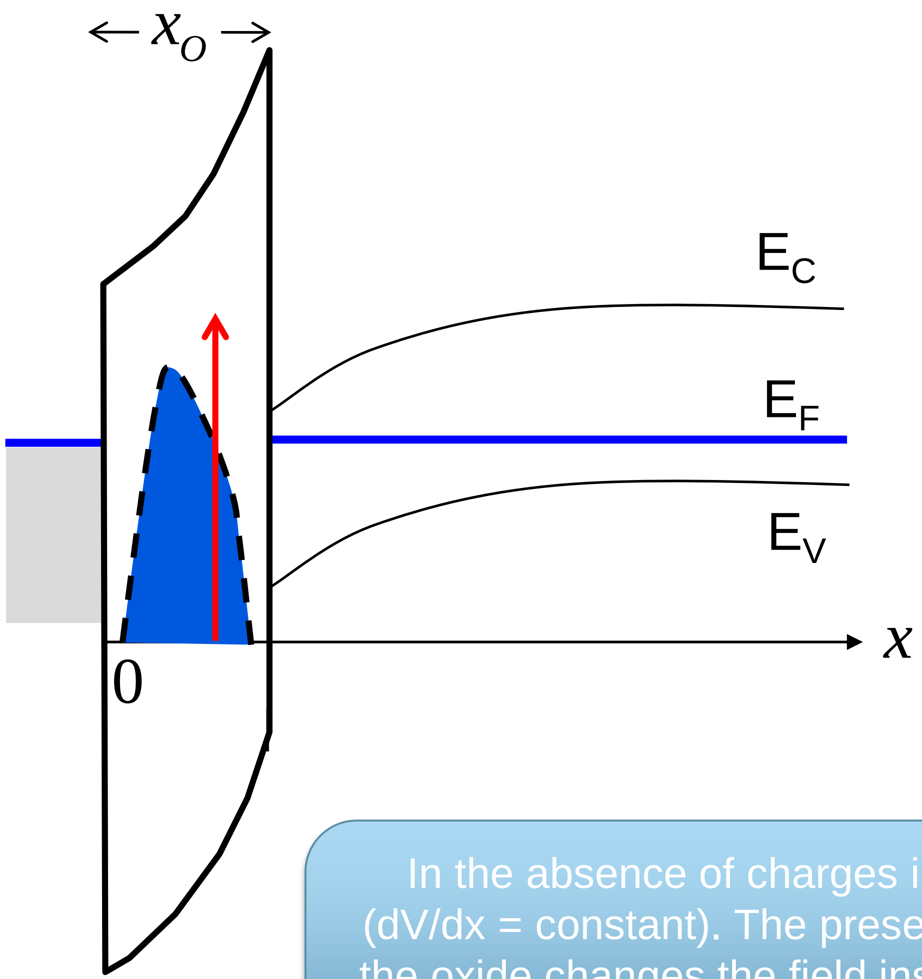


Recall that

$$Q_i = C_{ox}(V_G - V_{th,ideal})$$

$$V_{th,ideal} = \psi_s - \left.\frac{Q_B}{C_{ox}}\right|_{\psi_s = 2\phi_F}$$

Distributed Trapped charge in the Oxide

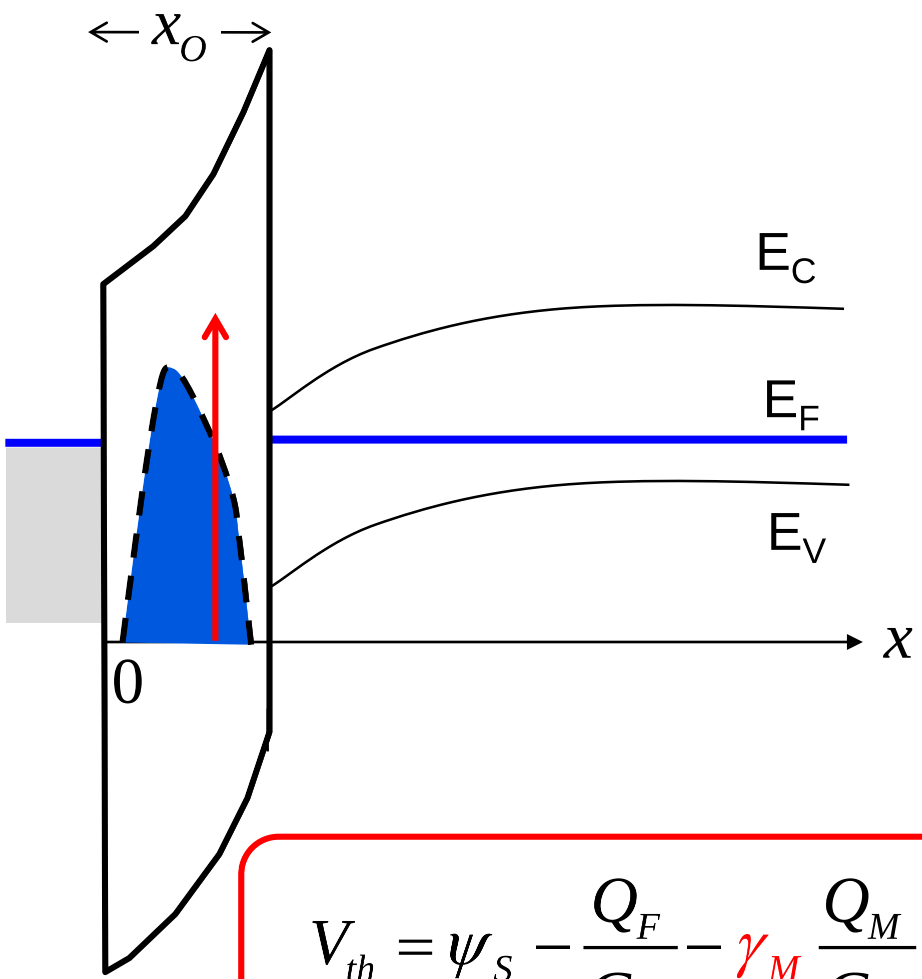


$$Q_M = \int_0^{X_O} \rho_{ox}(x)dx$$

$$\gamma_M \equiv \frac{x_M}{x_0} = \frac{\int_0^{x_0} x\rho_{ox}(x)dx}{x_0\int_0^{x_0} \rho_{ox}(x)dx}$$

In the absence of charges in the oxide, the field is constant (dV/dx = constant). The presence of a charge distribution inside the oxide changes the field inside the oxide and effectively traps field lines coming from the gate. As a result, depending on the polarity of charges in the oxide, the threshold voltage is modified.

Distributed Trapped charge in the Oxide



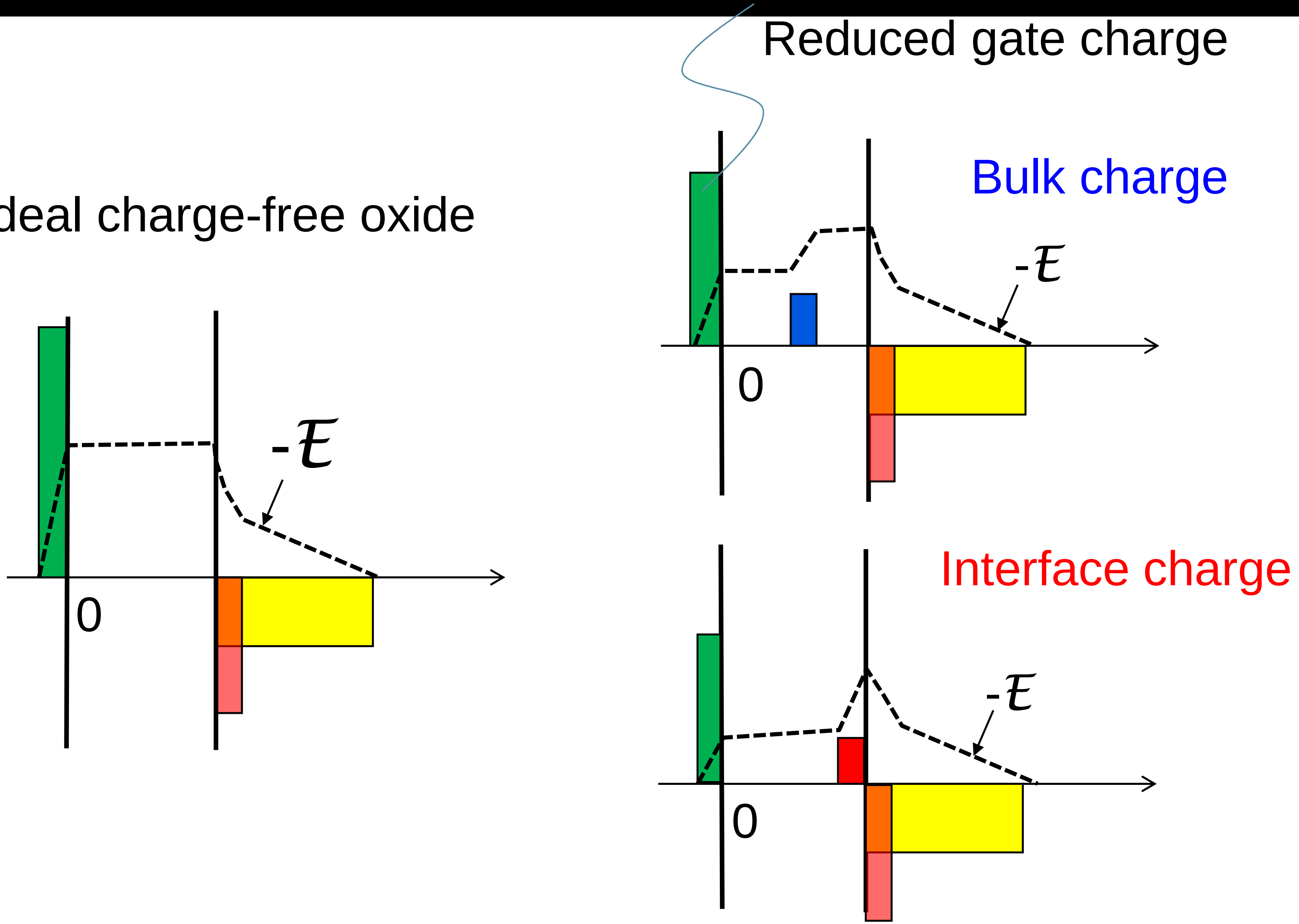
$$Q_M = \int_0^{x_O} \rho_{ox}(x)dx$$

$$\gamma_M \equiv \frac{x_M}{x_0} = \frac{\int_0^{x_0} x\rho_{ox}(x)dx}{x_0\int_0^{x_0} \rho_{ox}(x)dx}$$

$$V_{th} = \psi_S - \frac{Q_F}{C_{ox}} - \gamma_M \frac{Q_M}{C_{ox}}$$

x_m represents the centroid of the charge distribution – one can think of this as replacing the entire distribution with a delta charge at this point

An Intuitive View



Gate Voltage and Oxide Charge

$$V_G = V_{ox} + \psi_s$$

Kirchoff’s Law – balancing voltages

$$-\frac{d^2V_{ox}}{dx^2} = \frac{d\mathcal{E}_{ox}}{dx} = \frac{\rho_{ox}(x)}{\kappa_{ox}\varepsilon_0}$$

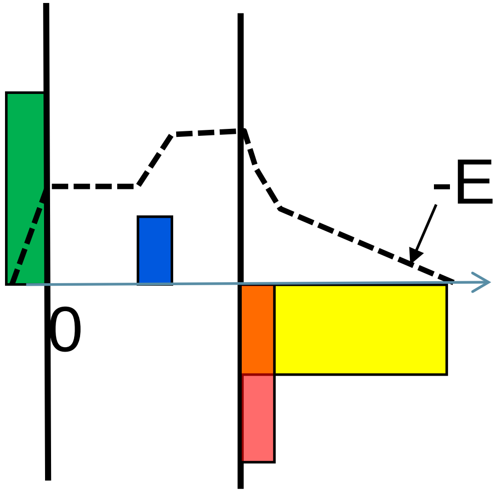
$$\int_{\mathcal{E}(x)}^{\mathcal{E}(x_0)} d\mathcal{E}_{ox} = \int_{x}^{x_0} \frac{\rho_{ox}(x')dx'}{\kappa_{ox}\varepsilon_0}$$

$$-\frac{dV_{ox}}{dx} = \mathcal{E}_{ox}(x_0) - \mathcal{E}_{ox}(x) = \mathcal{E}_{ox}(x_0) - \int_0^{x} \frac{\rho_{ox}(x')dx'}{\kappa_{ox}\varepsilon_0}$$

Known from boundary conditions in semiconductor and continuity of E

$$V_{ox} = \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \int_0^{x_0} dx \int_0^{x} \frac{\rho_{ox}(x')dx'}{\kappa_{ox}\varepsilon_0}$$

$$= \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \int_0^{x_0} \frac{x\rho_{ox}(x)dx}{\kappa_{ox}\varepsilon_0}$$



Gate Voltage and Oxide Charge

$$\Delta V_{ox} = \frac{\kappa_S}{\kappa_o} x_0 \mathcal{E}_S(x_0) - \int_0^{x_0} \frac{x\rho_{ox}(x)dx}{\left(\frac{\kappa_{ox}\varepsilon_0}{x_0}\right) x_0}$$

$$= \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \frac{1}{C_{ox} x_0} \int_0^{x_0} x\rho_{ox}(x)dx$$

$$V_{th} = \psi_s(=2\phi_F) + \Delta V_{ox}$$

$$= \psi_s(=2\phi_F) + \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \frac{1}{C_o x_0} \int_0^{x_0} x\rho_{ox}(x)dx$$

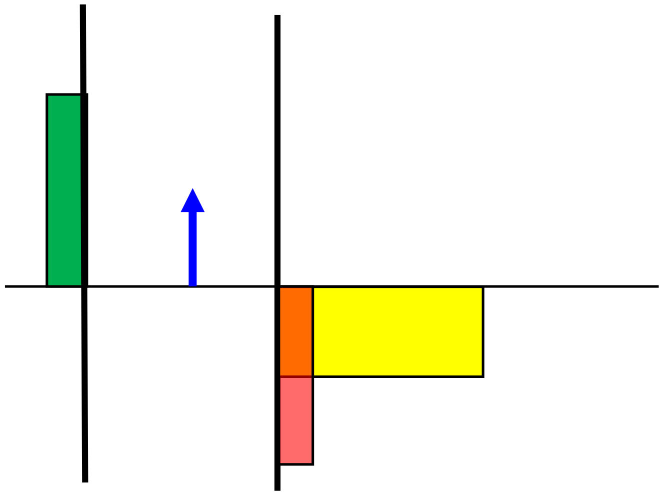
$$Q_M = \int_0^{X_O} \rho_{ox}(x)dx$$

$$= V_{th,ideal} - \frac{1}{C_{ox} x_0} \int_0^{x_0} x\rho_{ox}(x)dx$$

$$= V_{th,ideal} - \frac{Q_M}{C_{ox}} \gamma_M$$

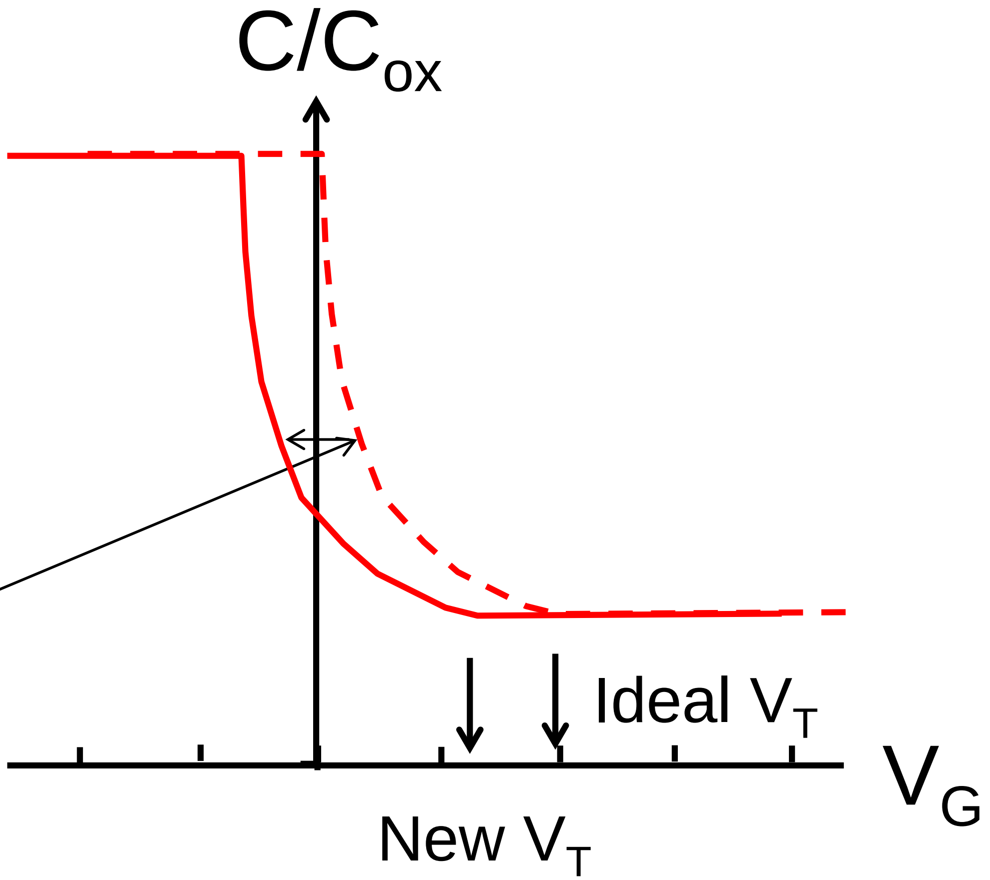
$$\gamma_M \equiv \frac{x_M}{x_0} = \frac{\int_0^{x_0} x\rho_{ox}(x)dx}{x_0 \int_0^{x_0} \rho_{ox}(x)dx}$$

Interpretation for Bulk Charge

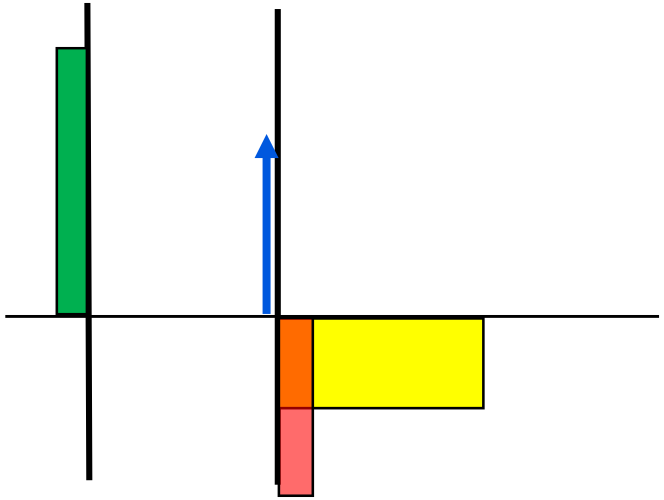


$$V_{th} = V_{th,ideal} - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x-x_1)dx$$

$$= V_{th,ideal} - \frac{x_1}{x_0}\frac{Q_M(x_1)}{C_o}$$

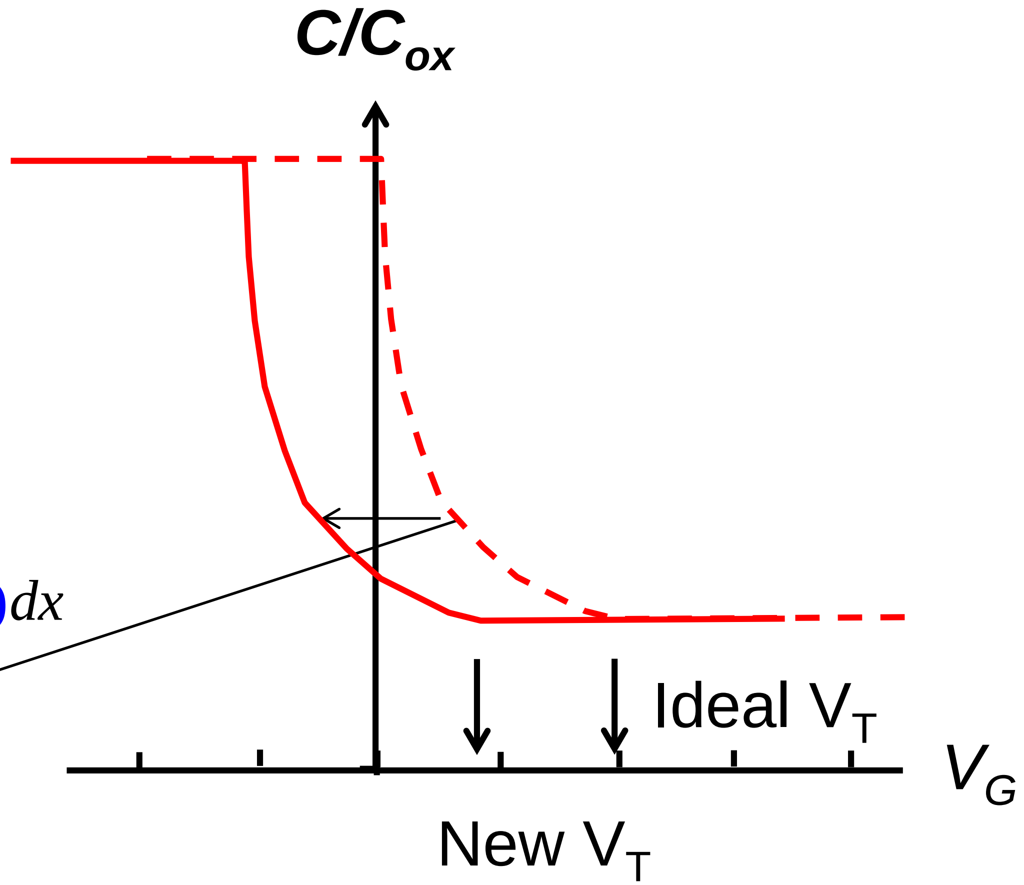


Interpretation for Interface Charge

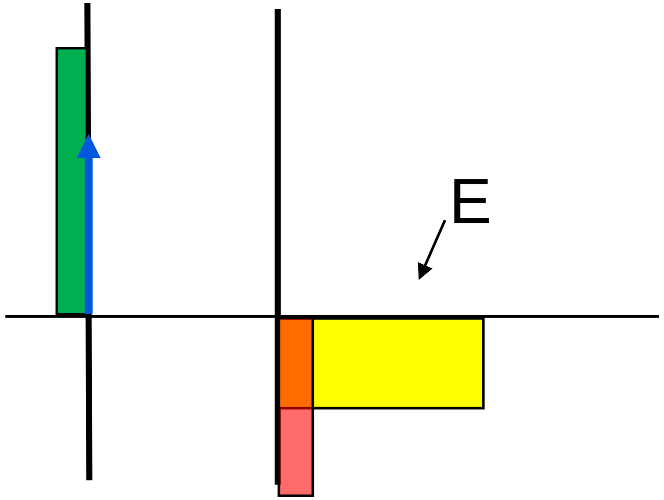


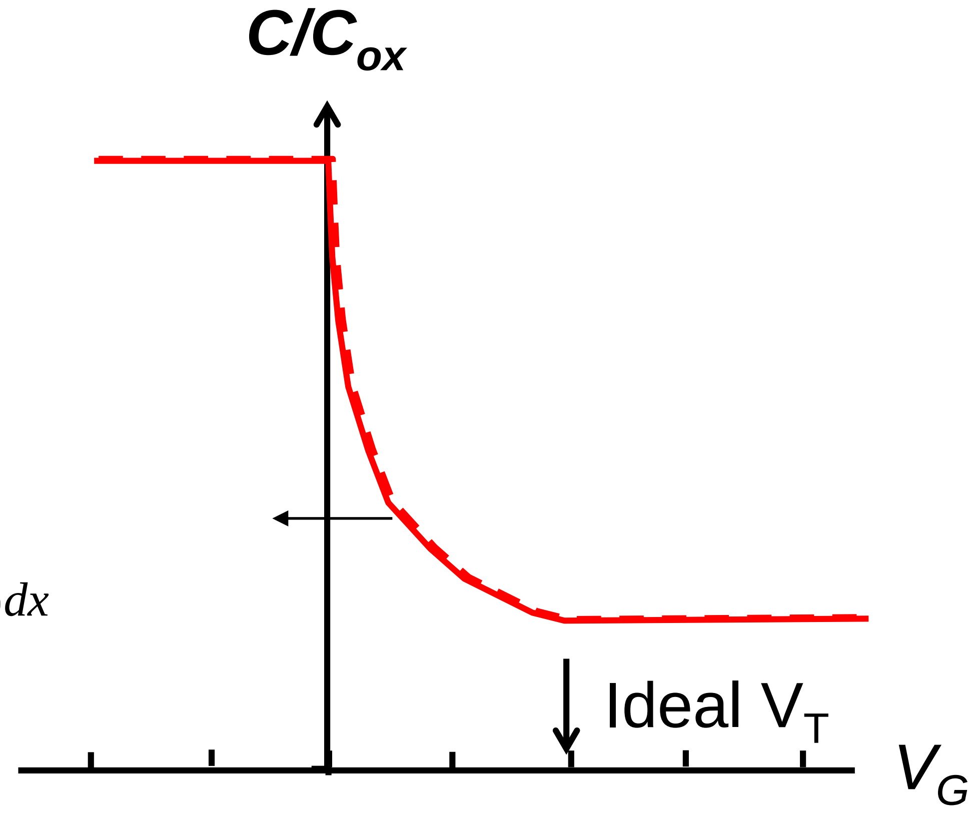
$$V_{th} = V_{th}^* - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x - x_o)dx$$

$$= V_{th}^* - \frac{Q_F}{C_o}$$



Time-dependent shift of Trapped Charge



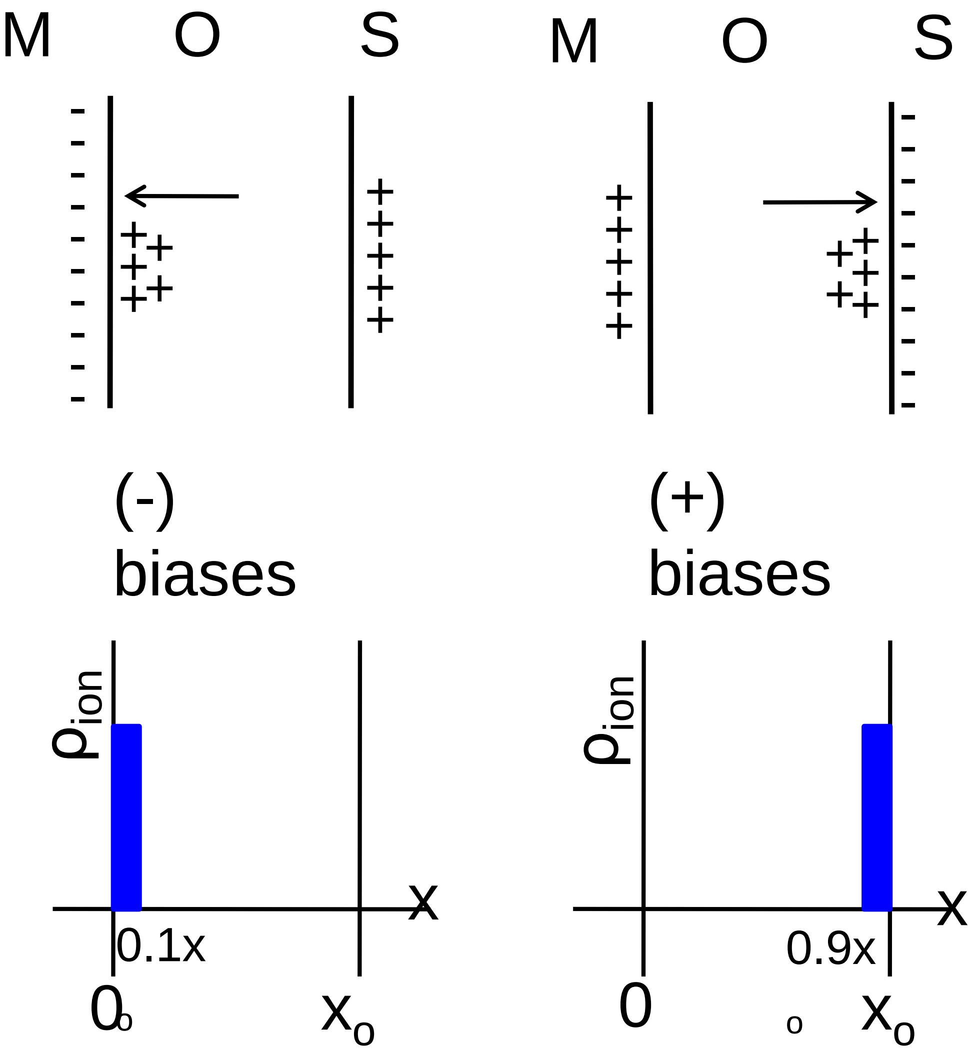


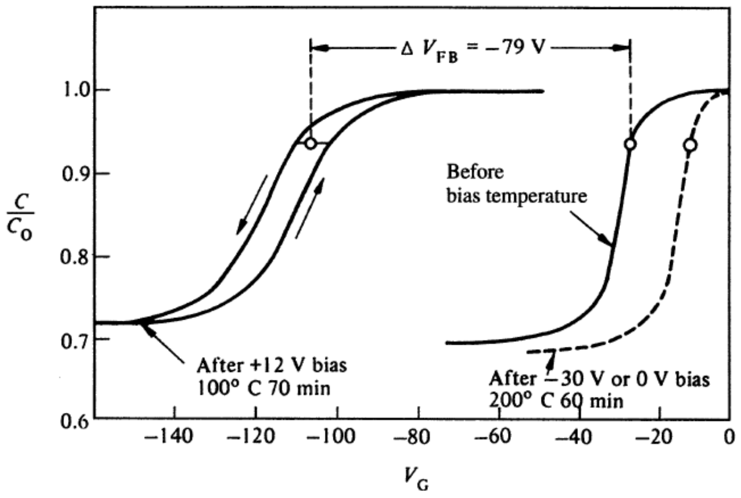
$$V_{th} = V_{th,ideal} - \frac{1}{C_{ox}x_0}\int_0^{x_0} xQ_{ox}(x)\times\delta(x - x_1(t))dx$$

$$= V_{th,ideal} - \frac{x_1(t)}{x_0}\times\frac{Q_{ox}(x)}{C_{ox}}$$

Sodium related bias temperature instability (BTI) issue

Bias Temperature Instability (Experiment)





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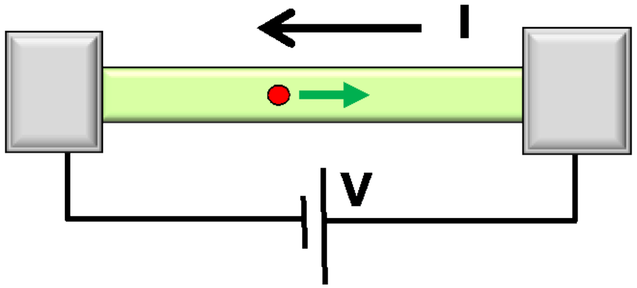

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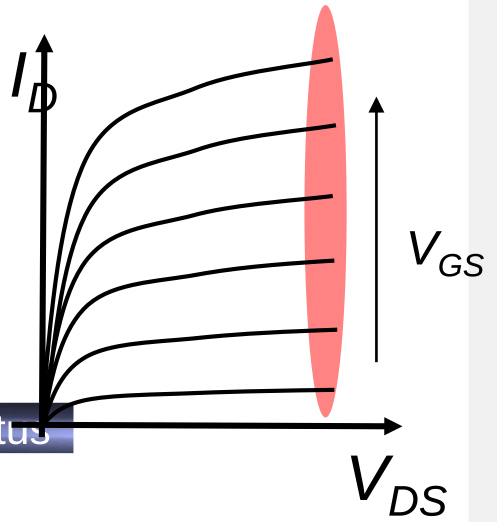

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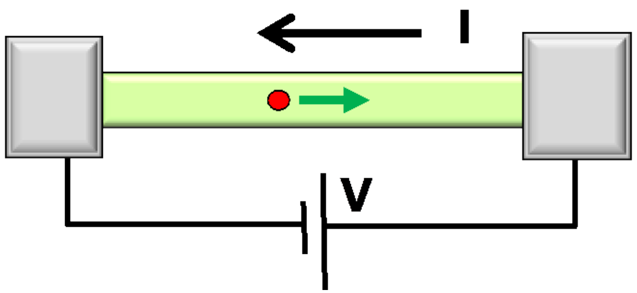

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