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ECE606: Solid State Devices
Lecture 37: Nonideal Effects in MOSFET

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Topic Map

	Equilibrium	**DC**	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT					
MOS		◆			

Outline

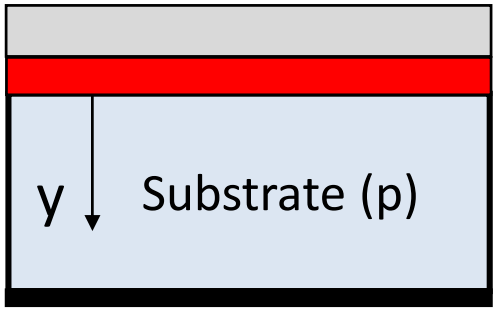
1. **Flat band voltage**
2. Threshold voltage shift due to trapped charges
3. Physics of interface traps
4. Conclusion

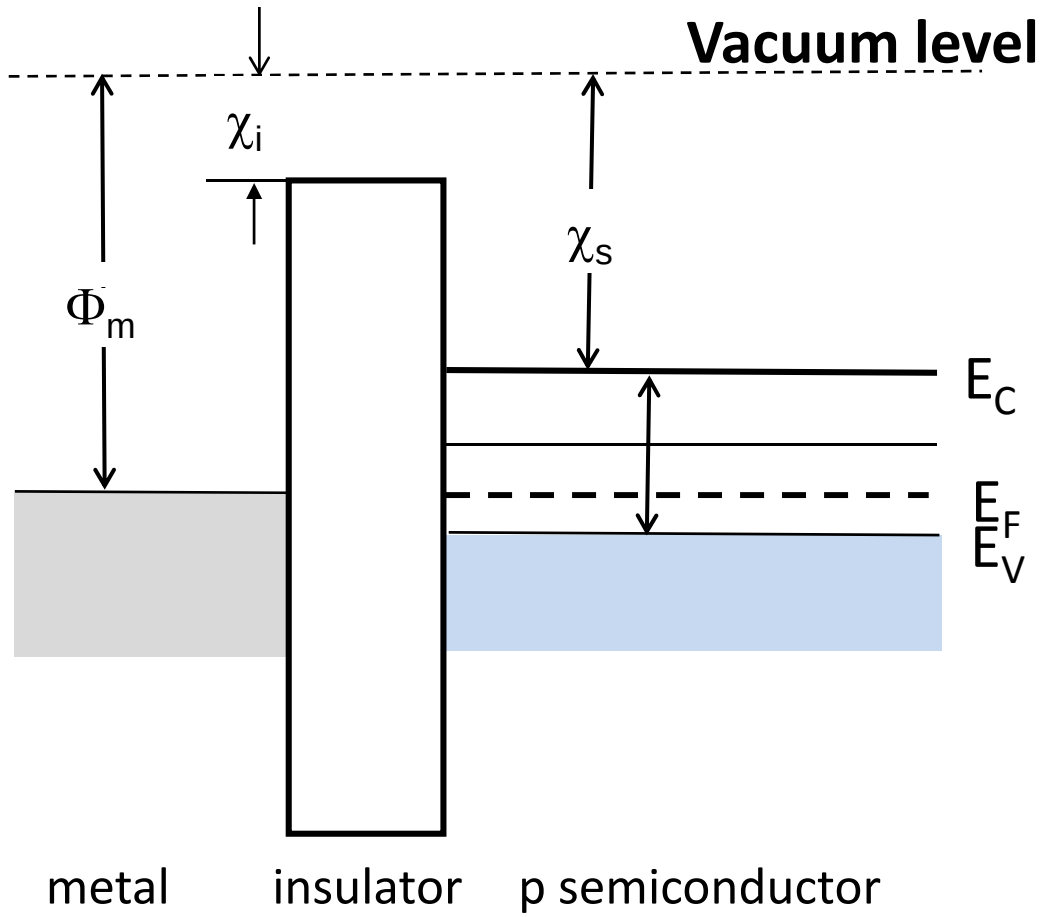
$$I_D = \frac{\mu_0 C_{ox}}{L_{ch}}(V_G - V_{th})^2$$

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

REF. Chapter 18, SDF

(1) Idealized MOS Capacitor



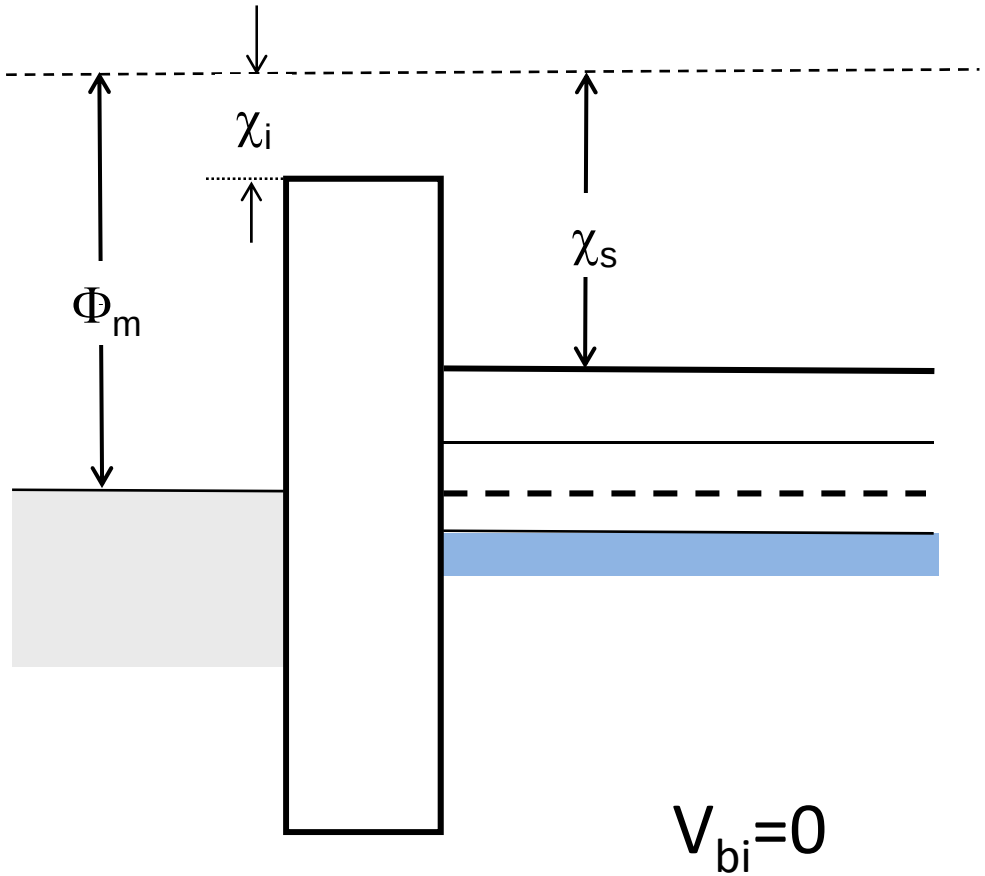


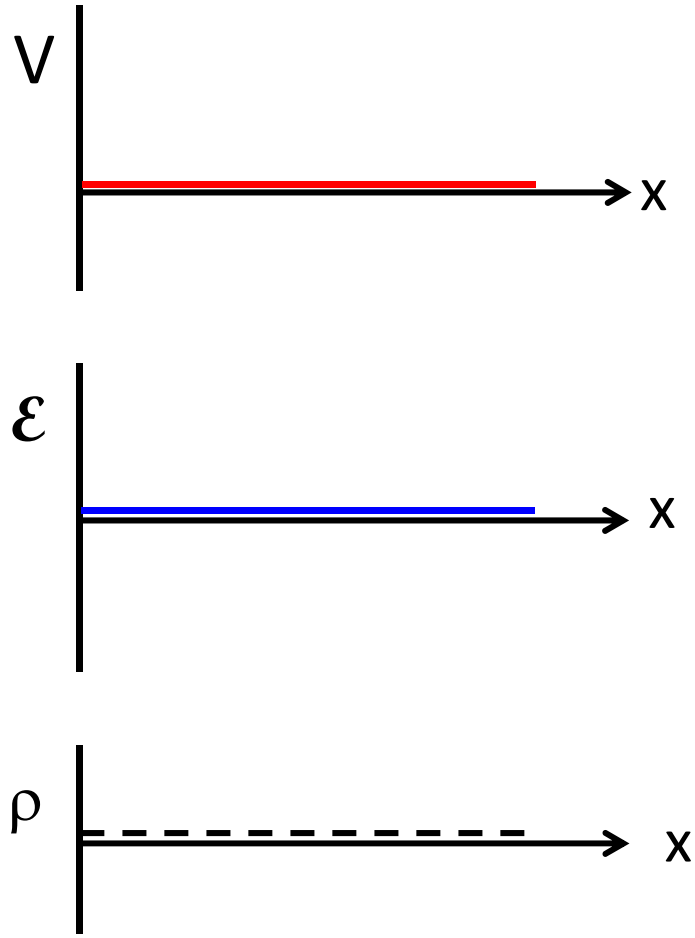
Recall that

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

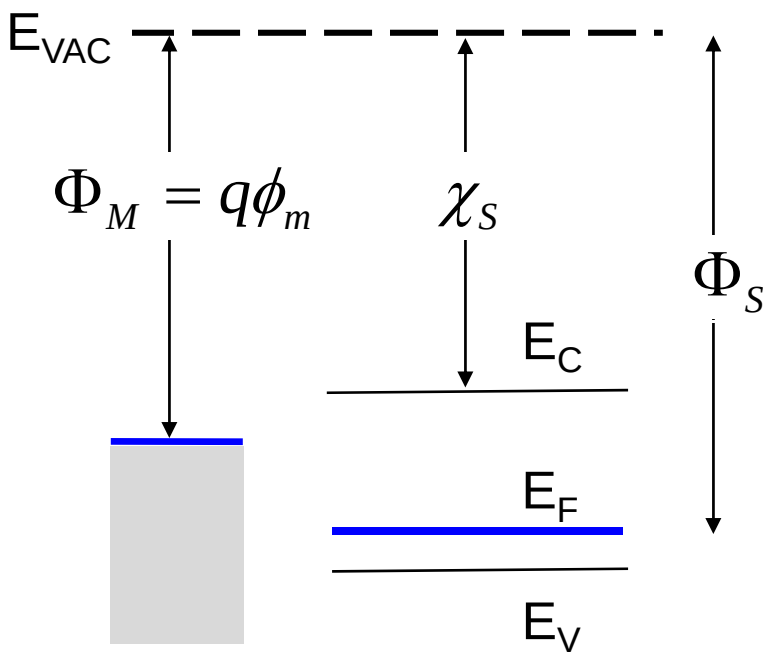
$$V_{th,ideal} = \psi_s - \left.\frac{Q_B}{C_{ox}}\right|_{\psi_s = 2\phi_F}$$

Potential, Field, Charges

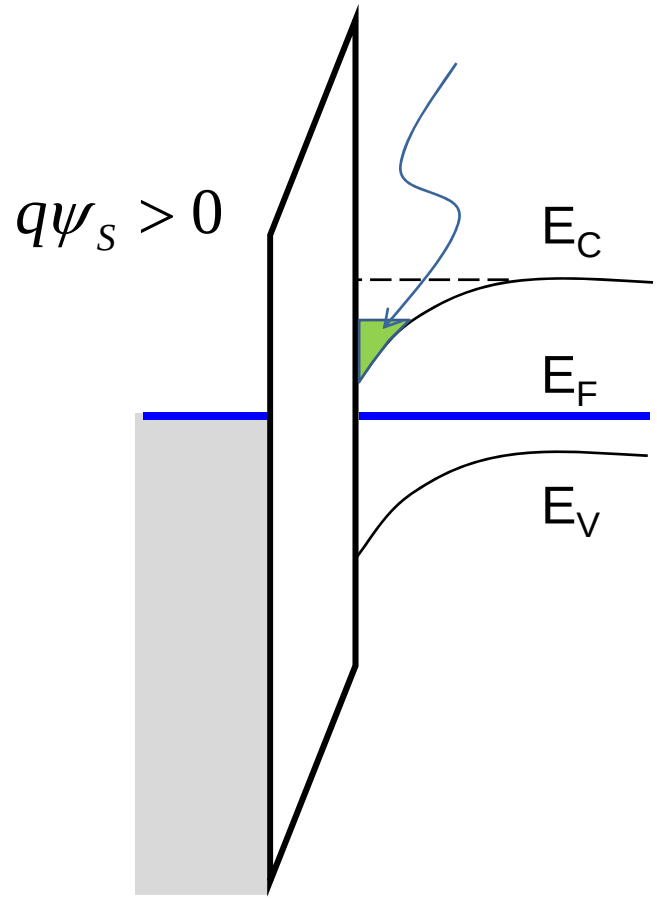




Real MOS Capacitor with $\Phi_M < \Phi_S$



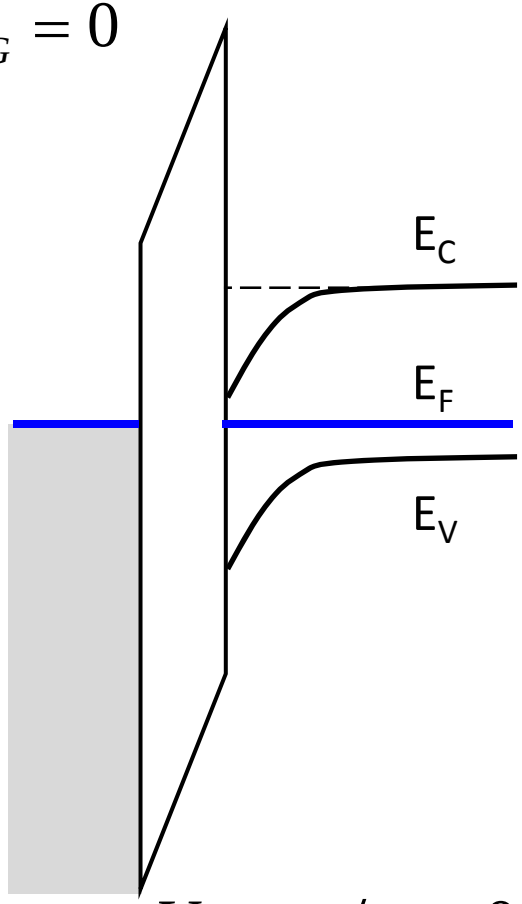
Note the difference



Do we need to apply less or more V_G to invert the channel ?

Physical Interpretation of Flatband Voltage

$V_G = 0$

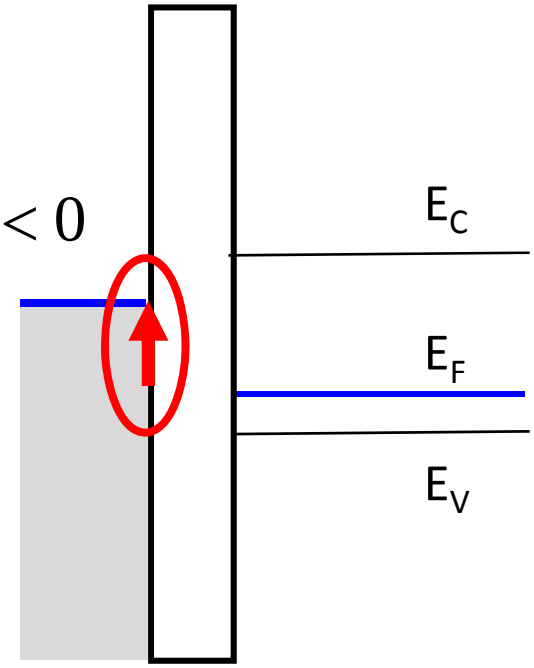


$V_{bi} = -\phi_{ms} > 0$

$+ \longleftarrow -$

$V_{FB} = \phi_{ms} = -V_{bi} < 0$

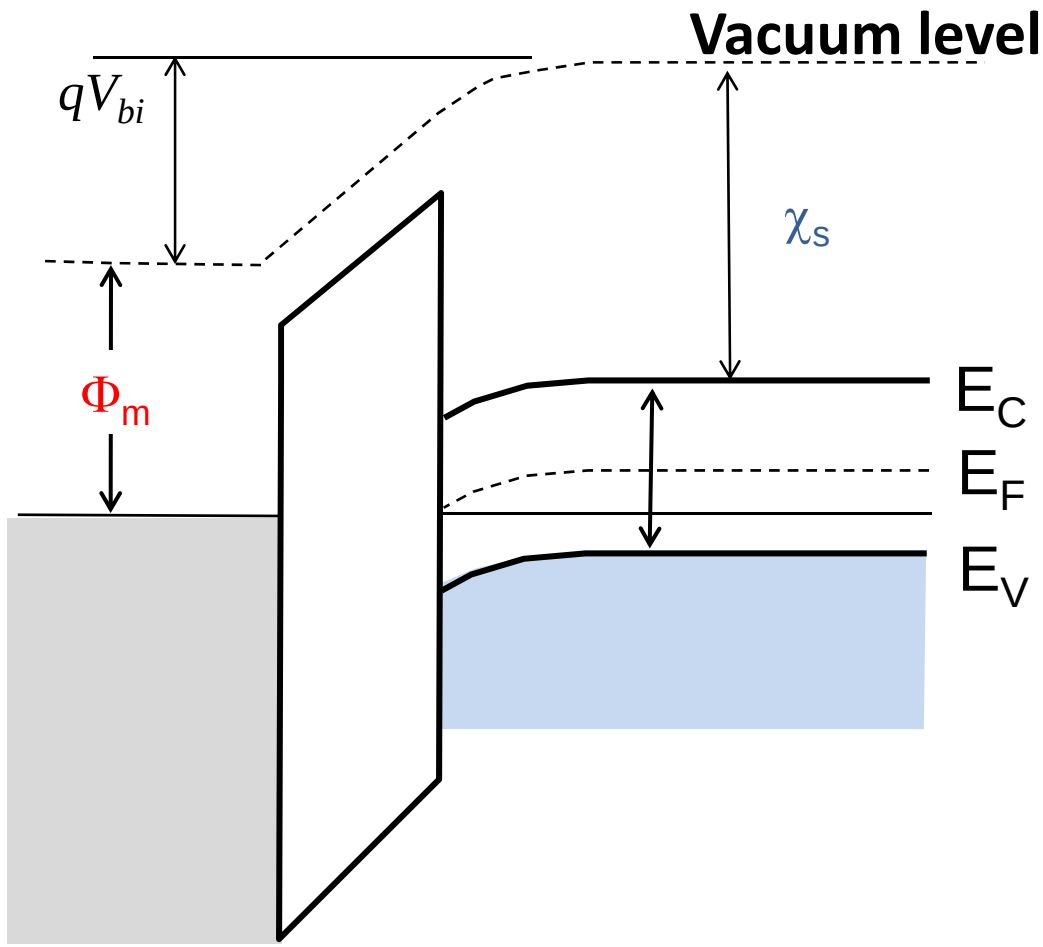
$V_G = V_{FB} < 0$



$\psi_S = 0$ flat band

How to Calculate Built-in or Flat-band Voltage

$$qV_{bi} = \left(\chi_s + E_g - \Delta_p\right) - \Phi_M$$
$$= qV_{FB} \equiv \phi_{MS}$$

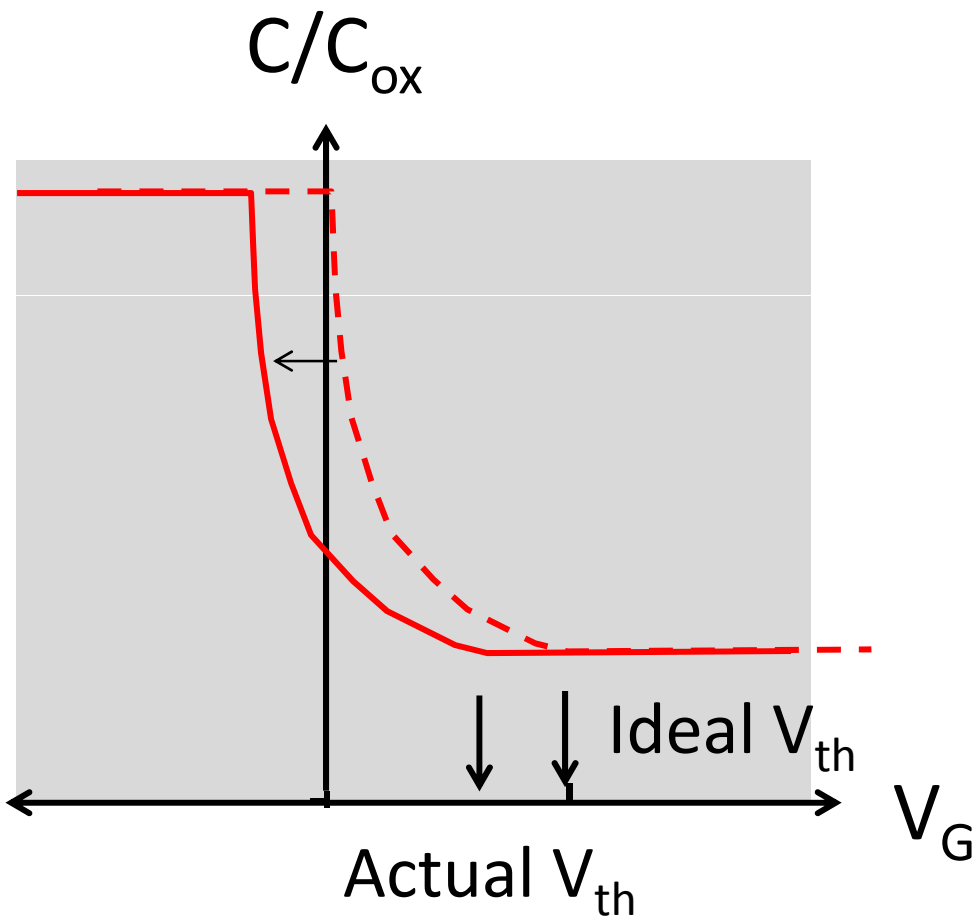


Therefore,

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

$$V_{th} = \left(2\phi_F - \frac{Q_B}{C_{ox}}\right) - V_{FB}$$

Measure of Flat-band shift from C-V Characteristics

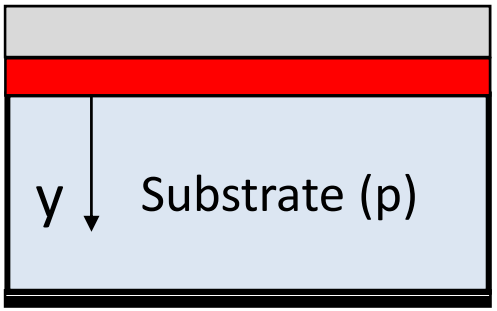


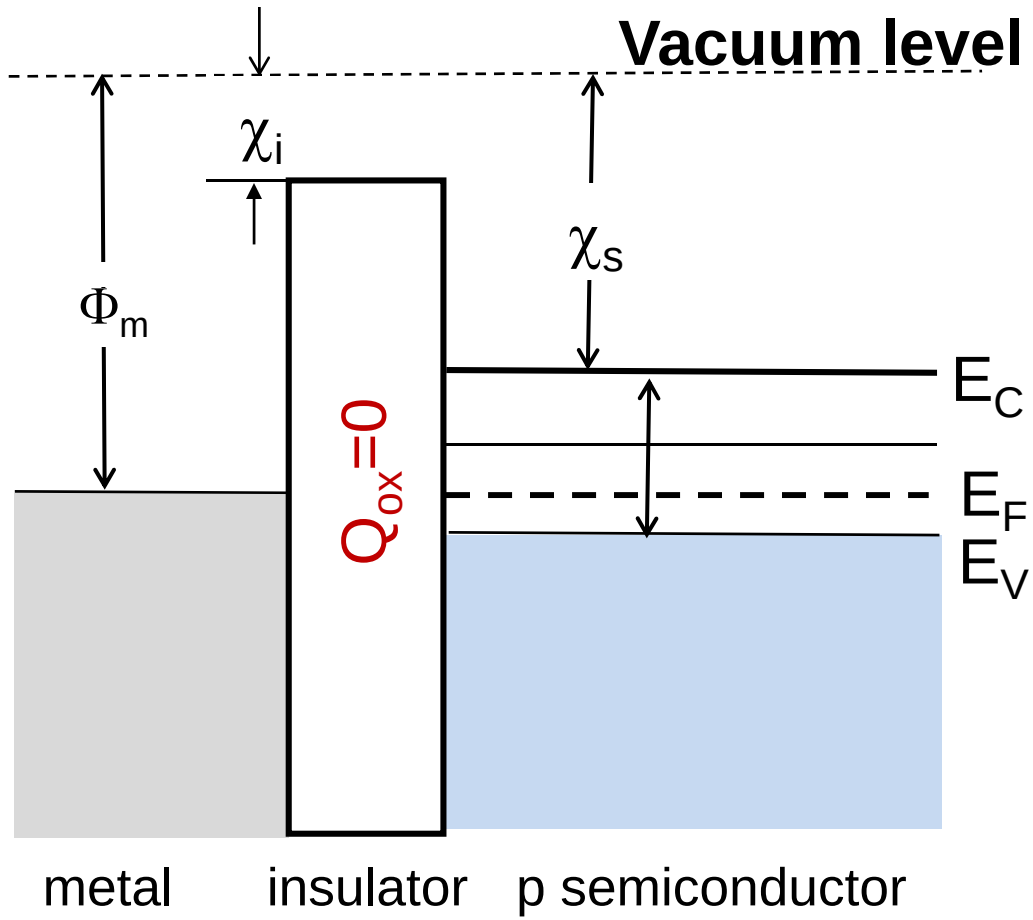
Outline

1. Flat band voltage
2. **VT-shift due to trapped charges**
3. Physics of interface traps
4. Conclusion

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

(2) Idealized MOS Capacitor



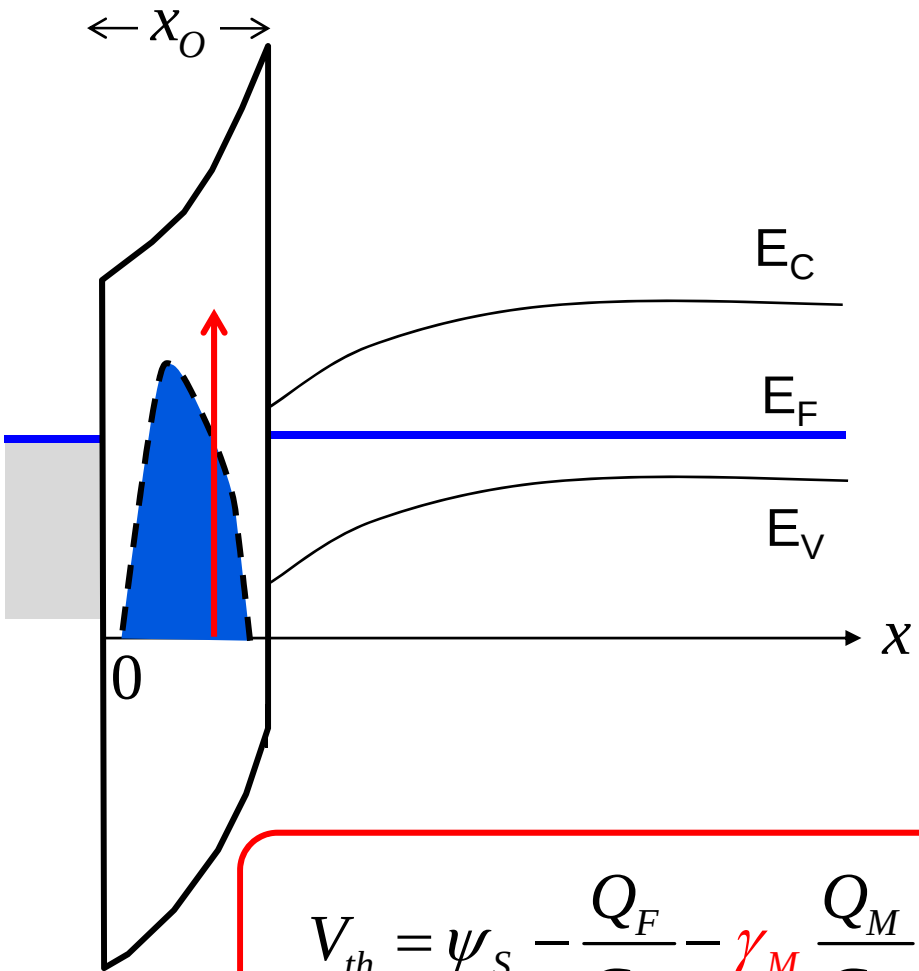


Recall that

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

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

Distributed Trapped charge in the Oxide



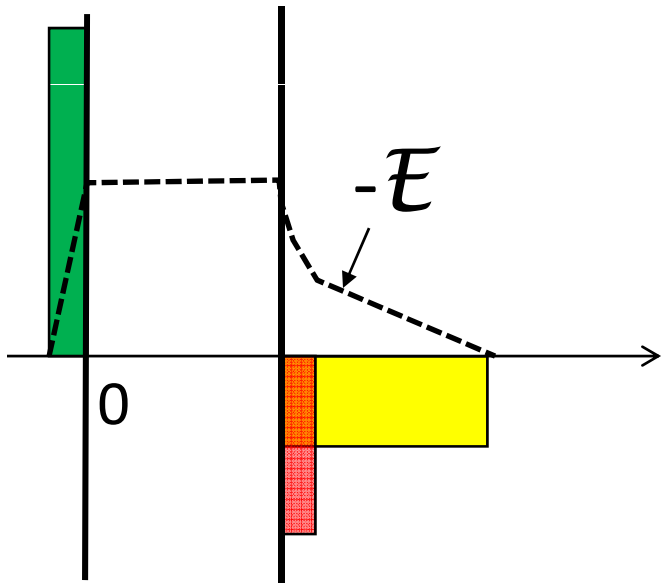
$$Q_M = \int_0^{X_O} \rho_{ox}(x)dx$$

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

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

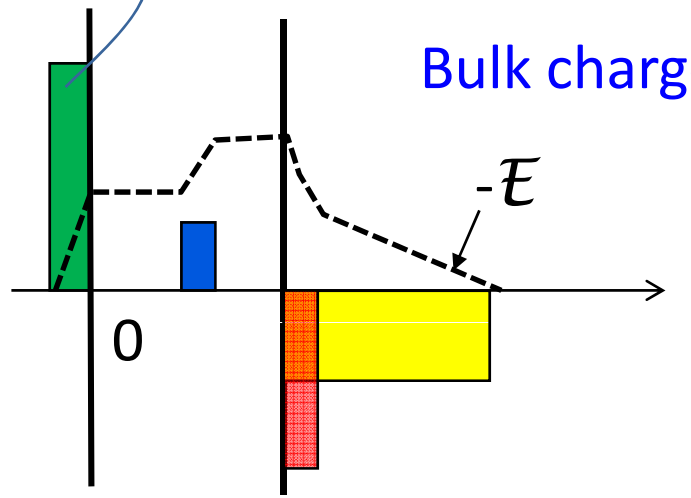
An Intuitive View

Ideal charge-free oxide

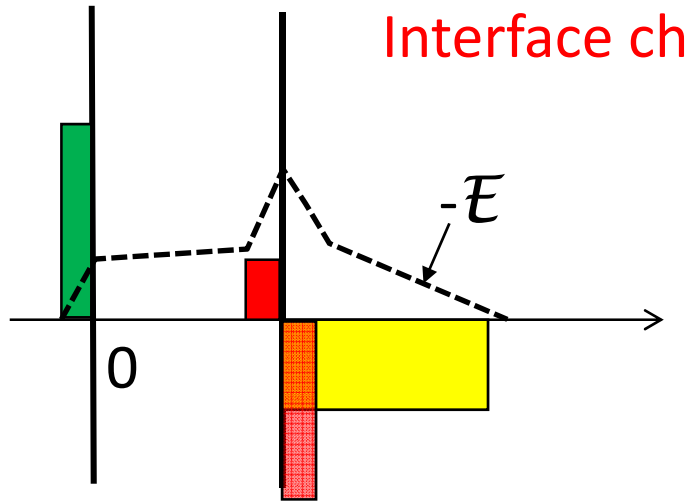


Reduced gate charge

Bulk charge



Interface charge



Gate Voltage and Oxide Charge

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

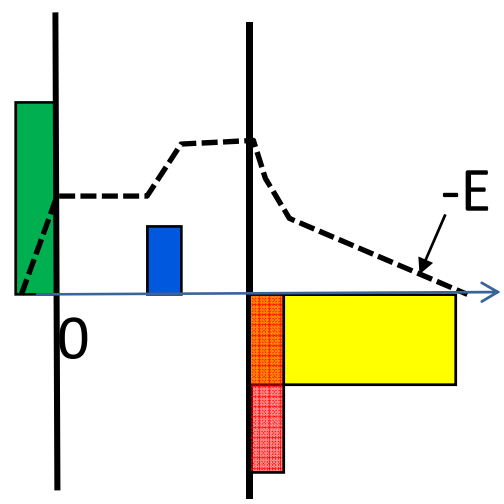
$$-\frac{d^2V_{ox}}{dx^2} = \frac{d\mathcal{E}_{ox}}{dx} = \frac{\rho_{ox}(x)}{\kappa_{ox}\varepsilon_0}$$

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

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

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

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



Gate Voltage and Oxide Charge

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

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

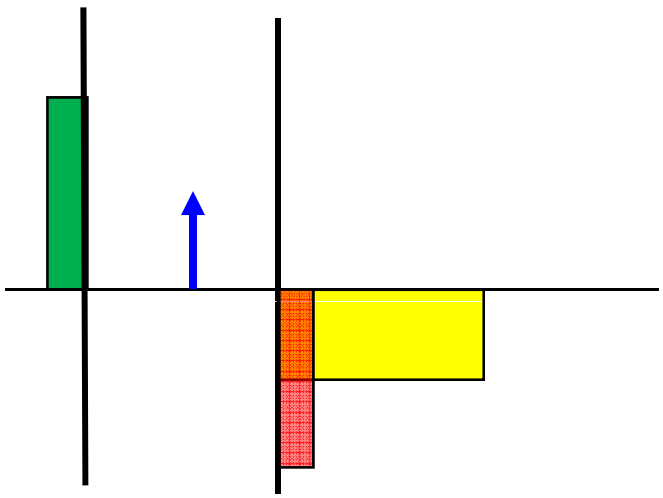
$$V_{th} = \psi_s (= 2\phi_F) + \Delta V_{ox}$$

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

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

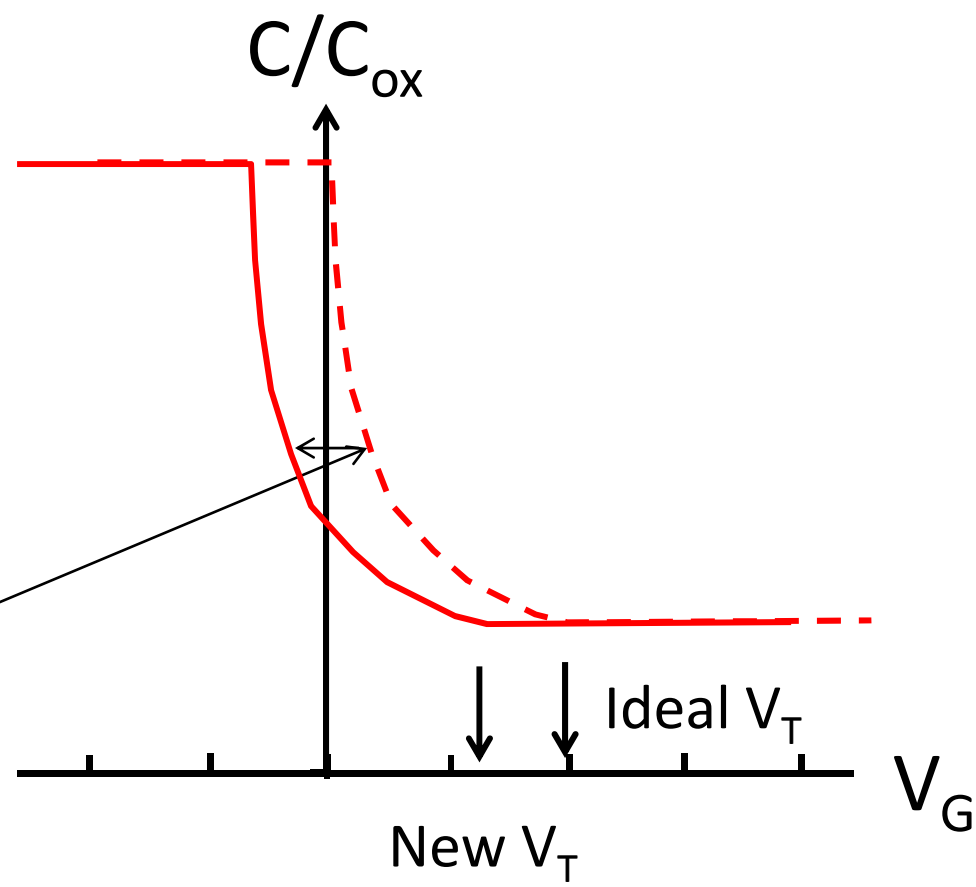
$$= V_{th,ideal} - \frac{Q_M}{C_{ox}} \gamma_M$$

Interpretation for Bulk Charge

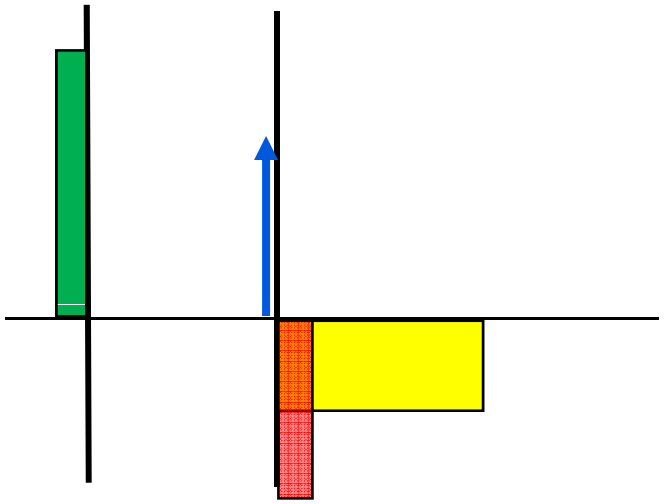


$$V_{th} = V_{th,ideal} - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x - x_1)dx$$

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

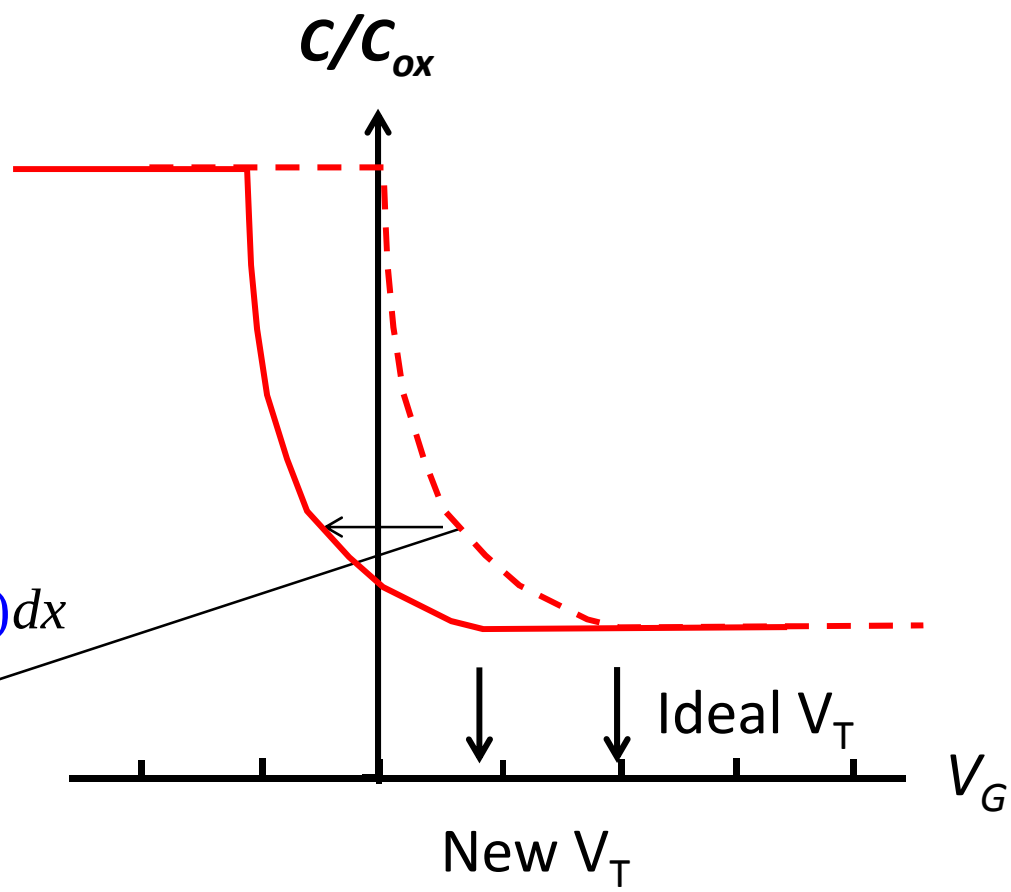


Interpretation for Interface Charge

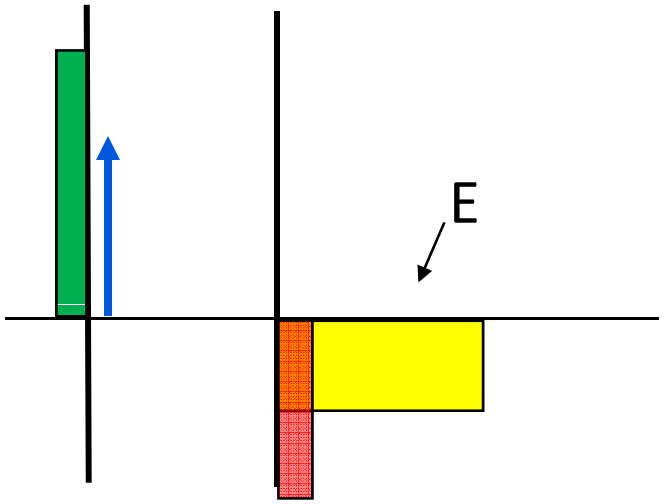


$$V_{th} = V_{th}^{*} - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x - x_o)dx$$

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

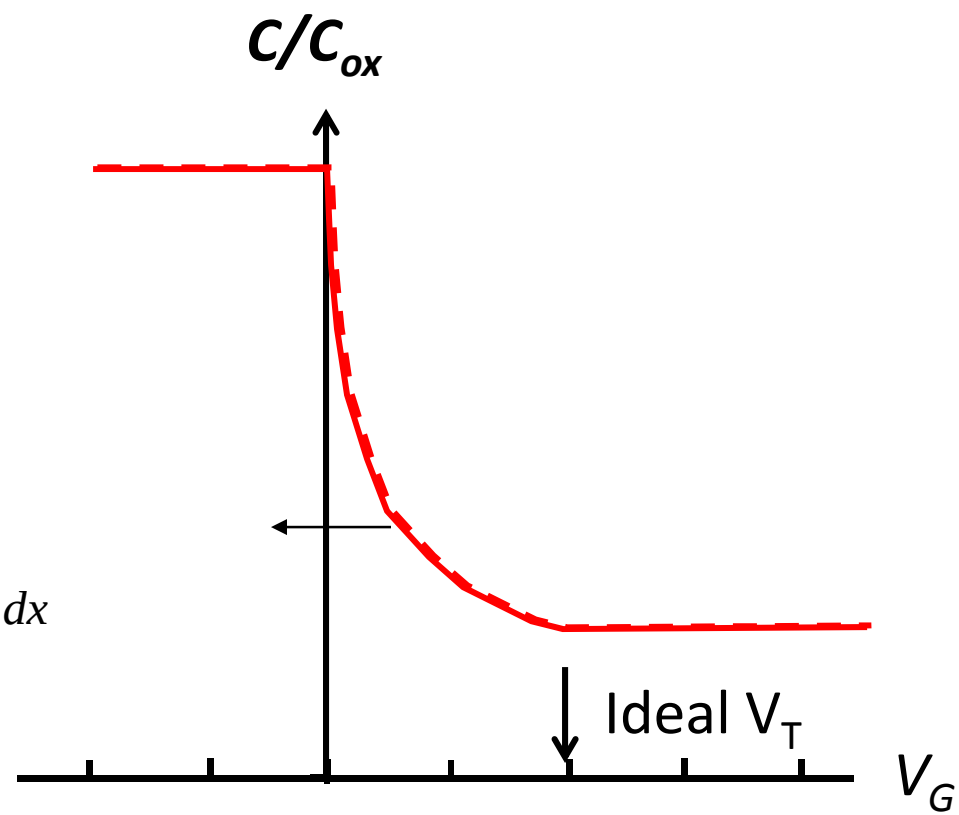


Time-dependent shift of Trapped Charge



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

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



Sodium related bias temperature instability (BTI) issue

Bias Temperature Instability (Experiment)