ECE-305: Spring 2018
Metal Oxide Semiconductor Devices

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapters 15+16 (pp. 525-530, 563-599)

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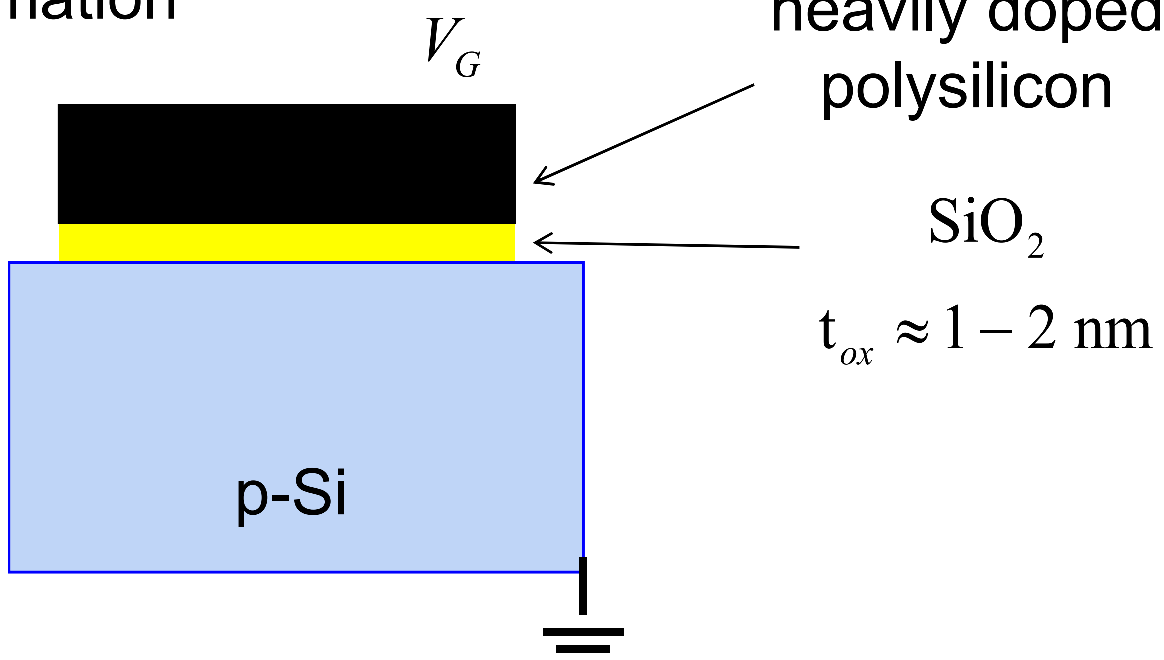
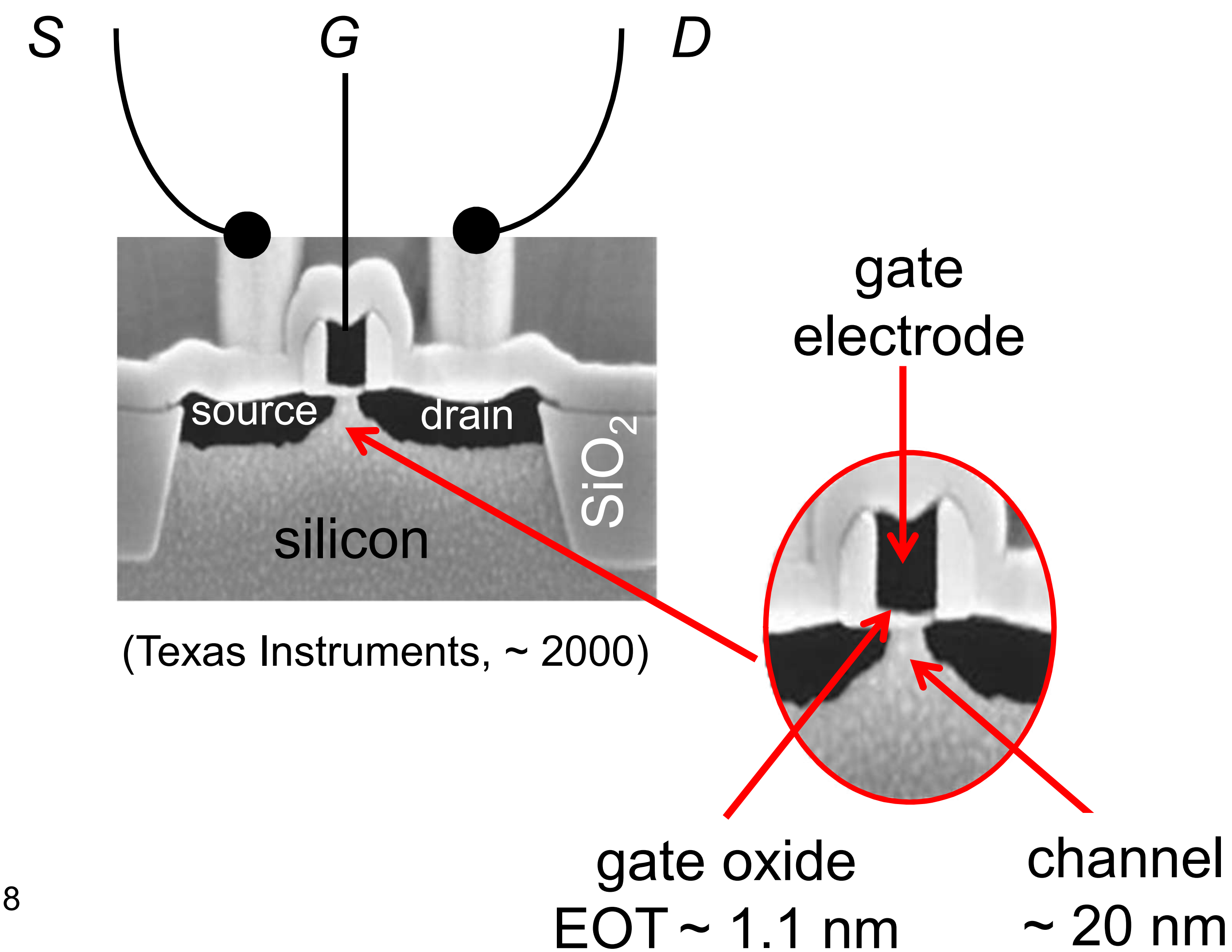
MOS capacitor

1) **MOSFET and MOS capacitors**
2) E-bands and work functions
3) Band-bending in ideal MOS-C's
4) Accumulation, depletion, inversion
5) Depletion approximation

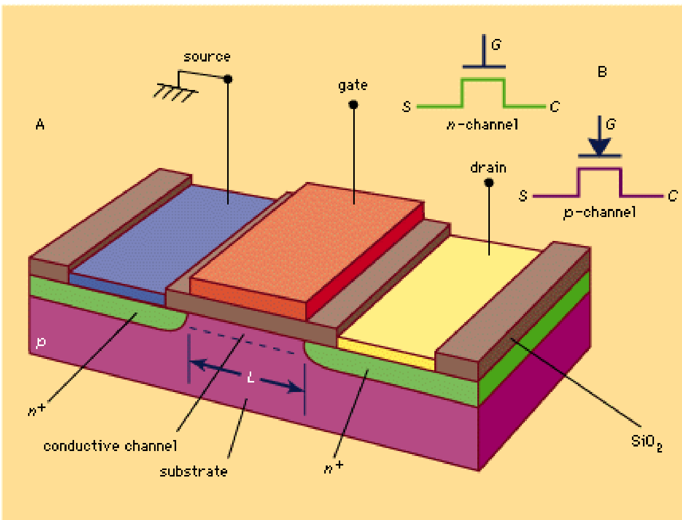


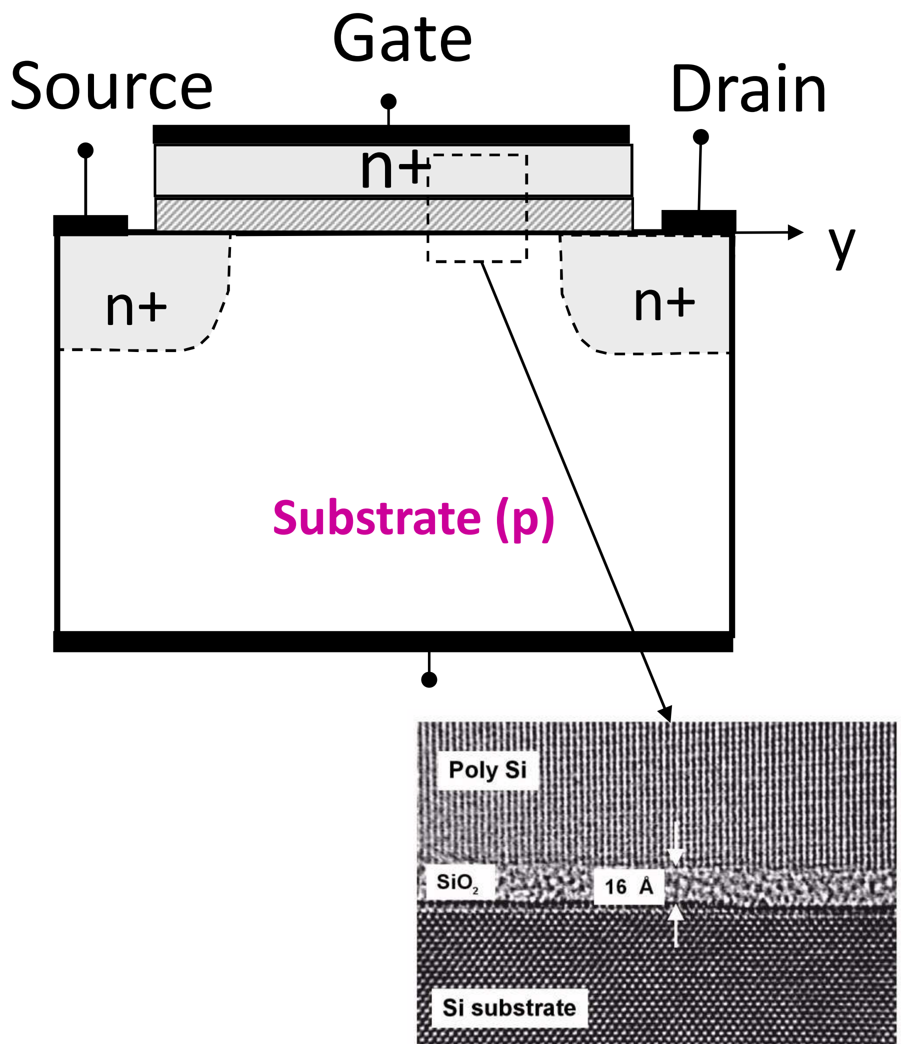
MOSFETs



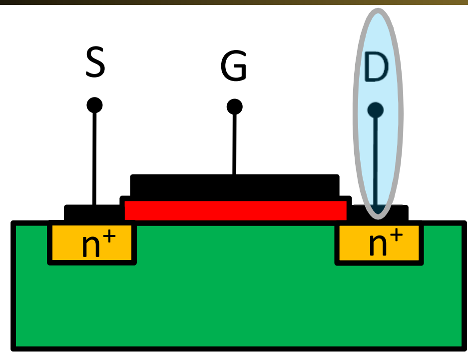
(Texas Instruments, ~ 2000)

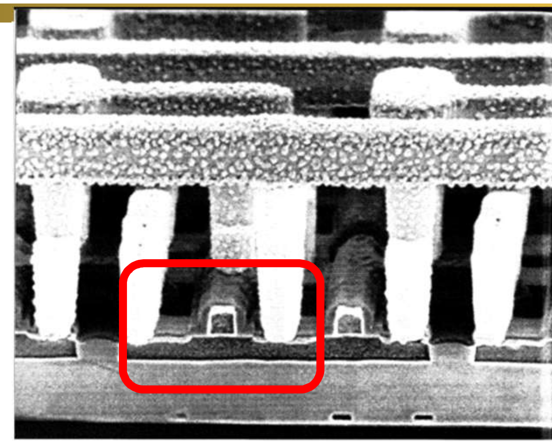
Basic Configuration of a MOSFET



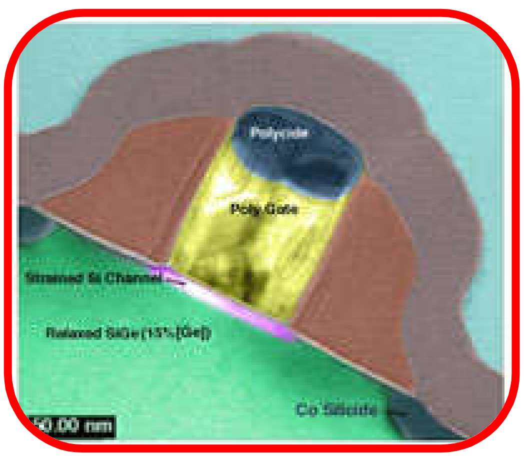


Background

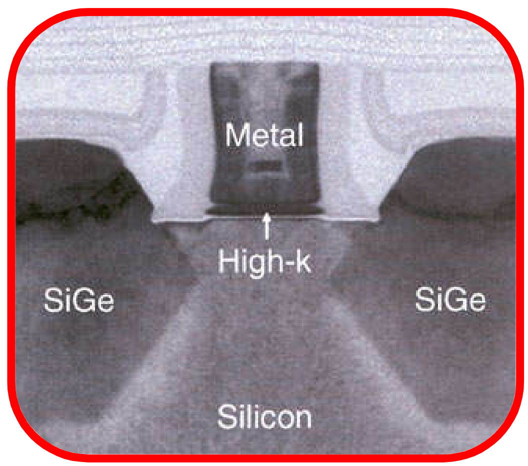




Strained MOSFET

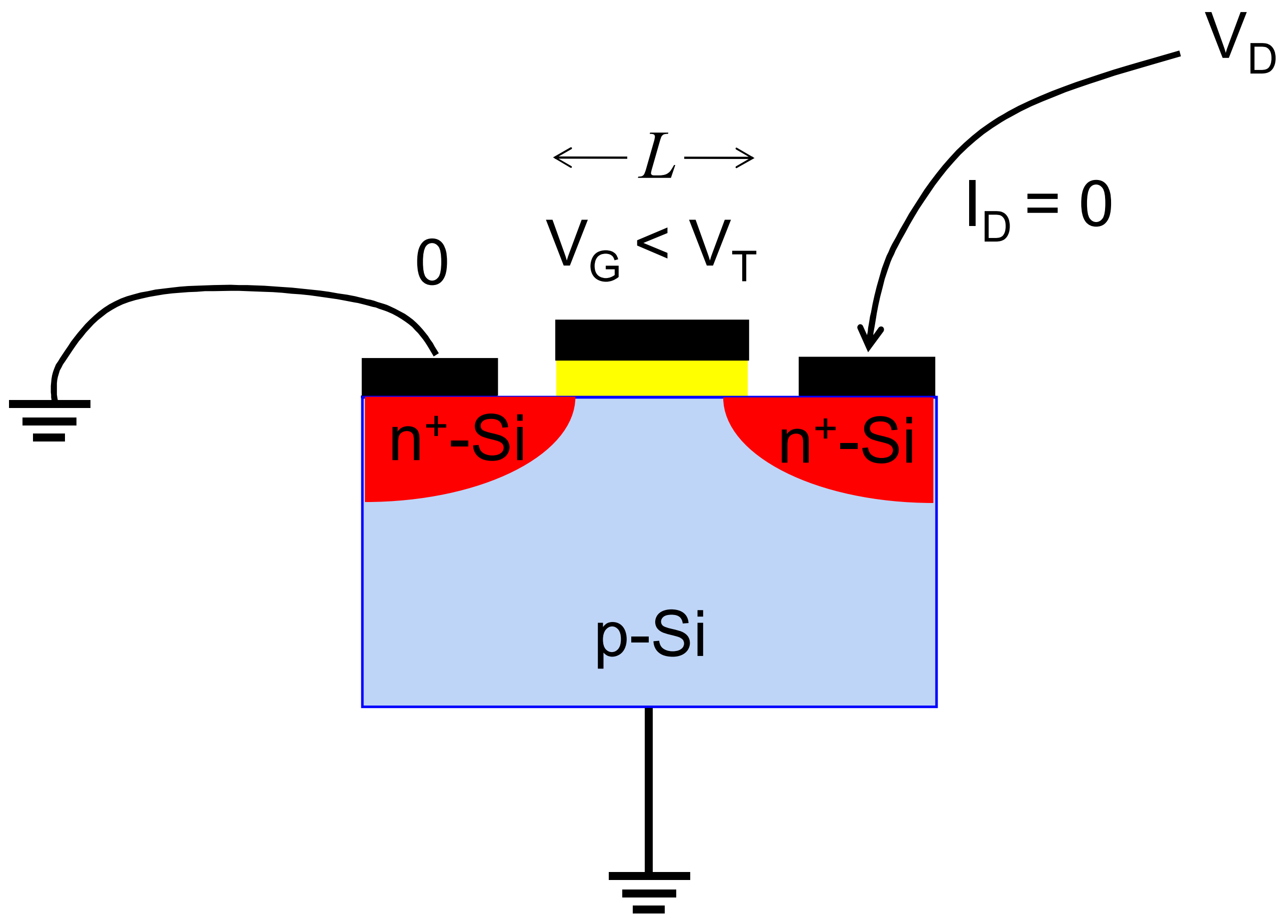


High-k/metal gate MOSFET

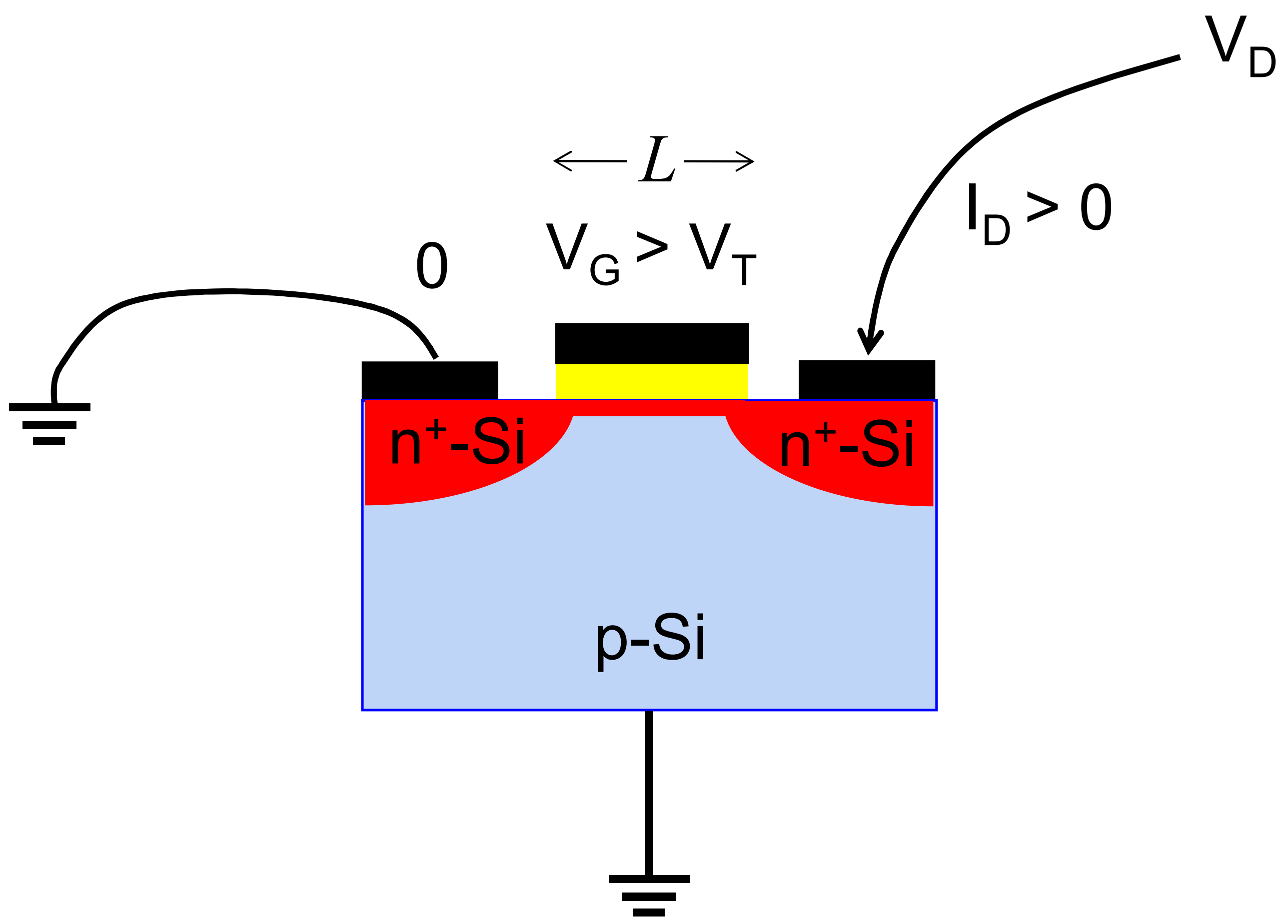


Sources:
IBM J. Res. Dev.
Google Images
Intel website

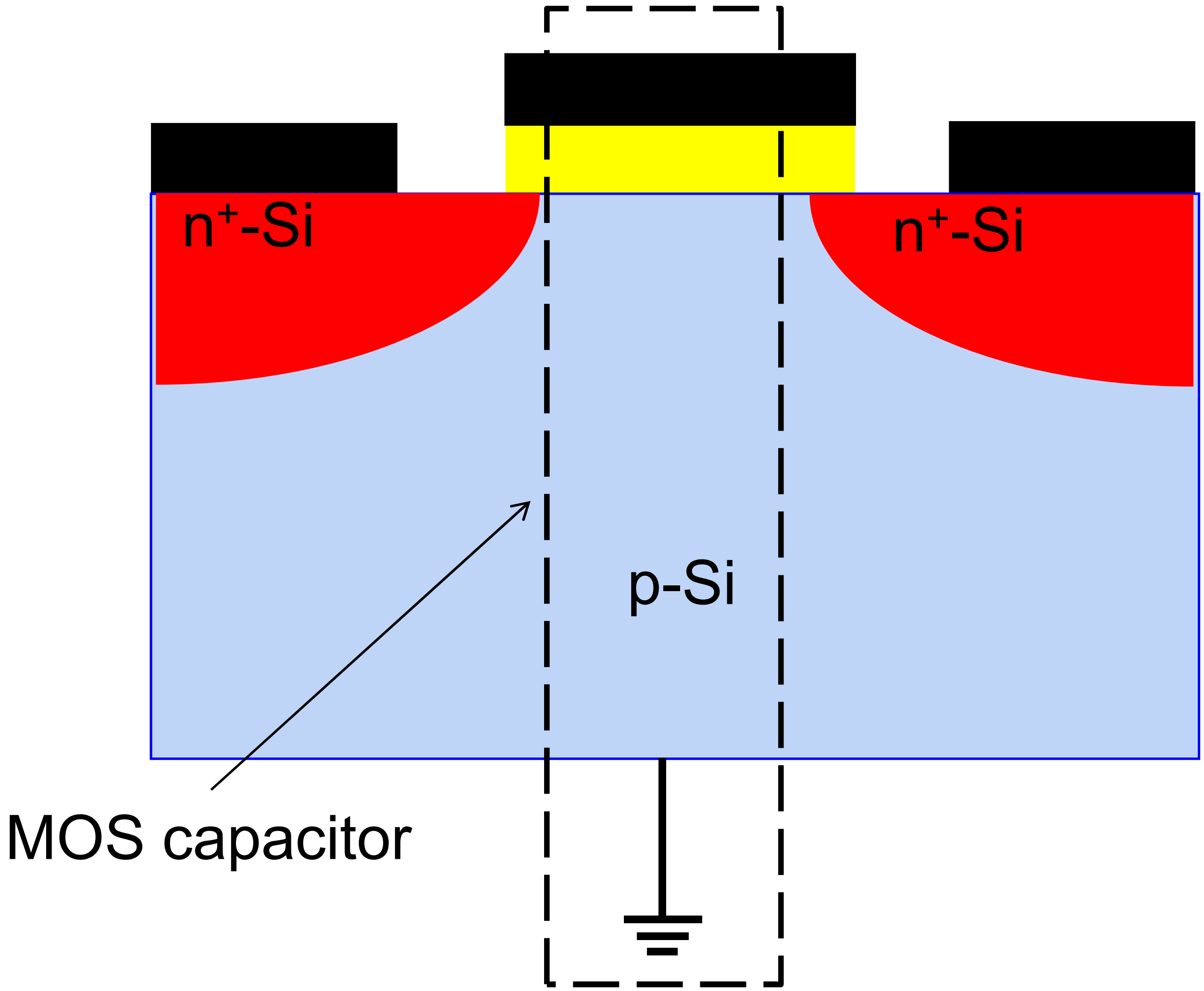
MOSFET (off)



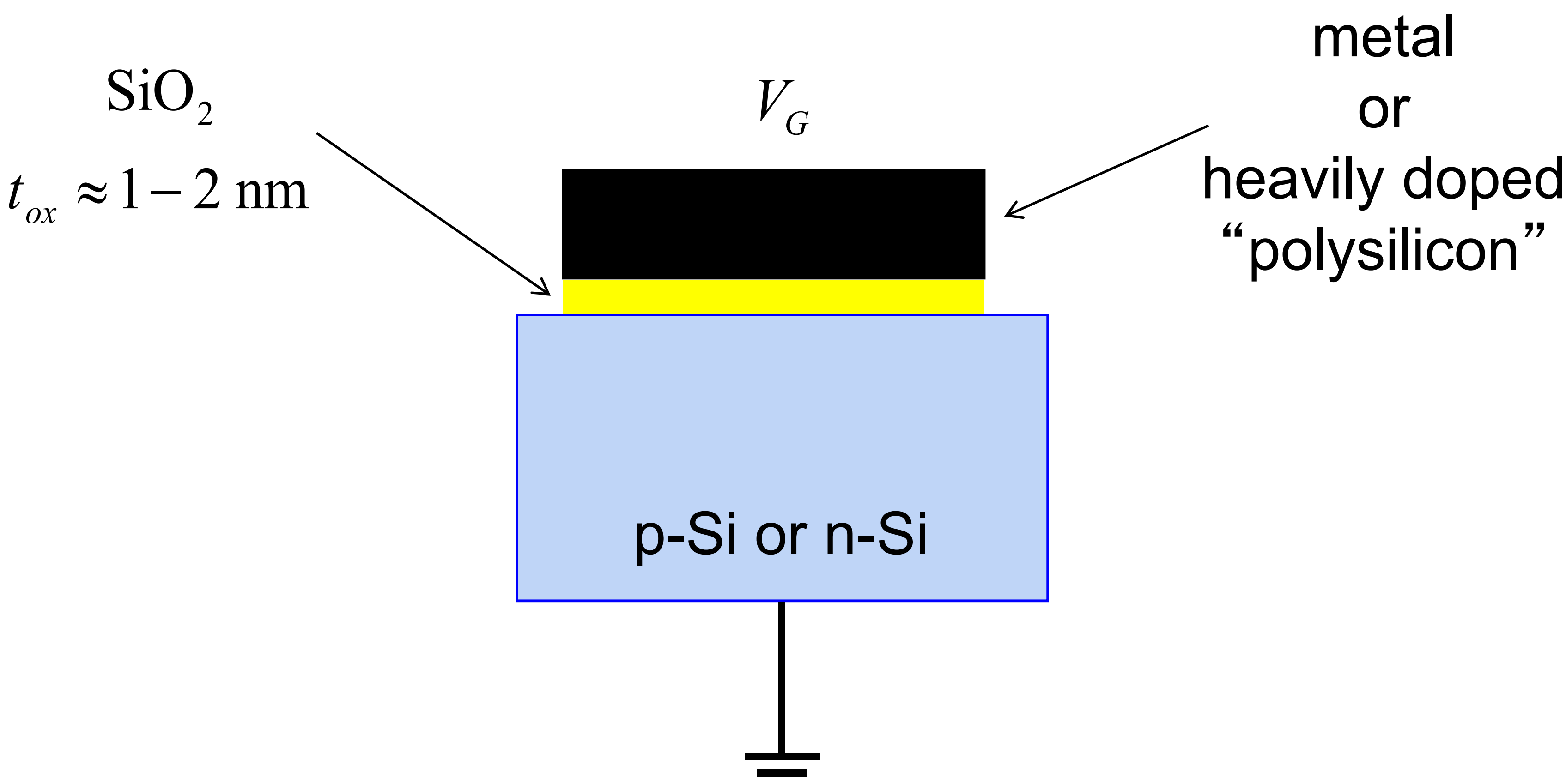
MOSFET (on)



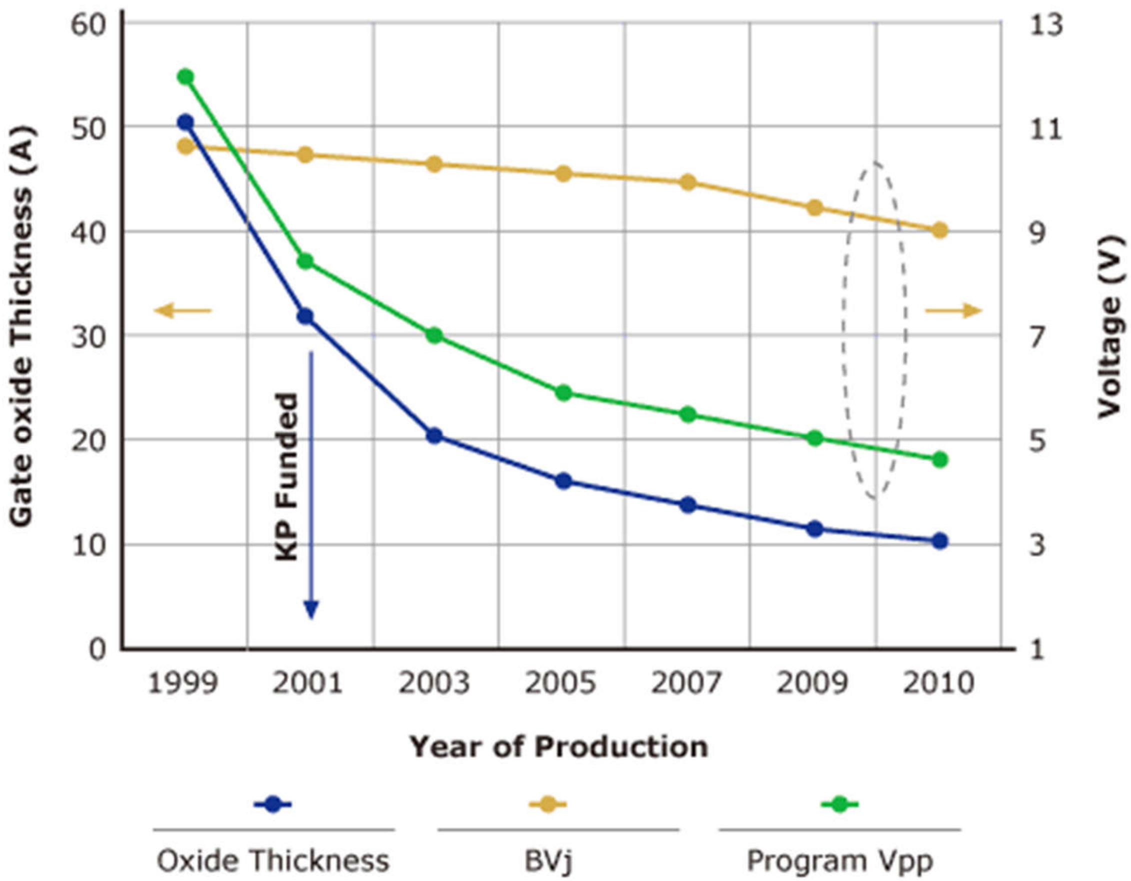
MOSFET and MOS C

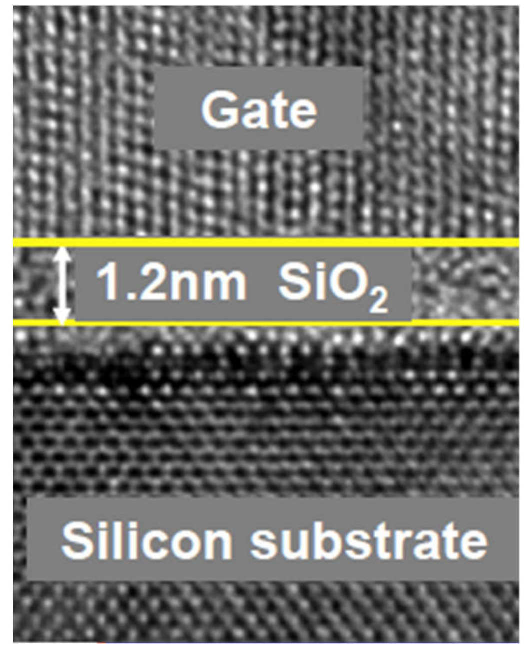


MOS capacitor



oxide scaling: reaching its limits



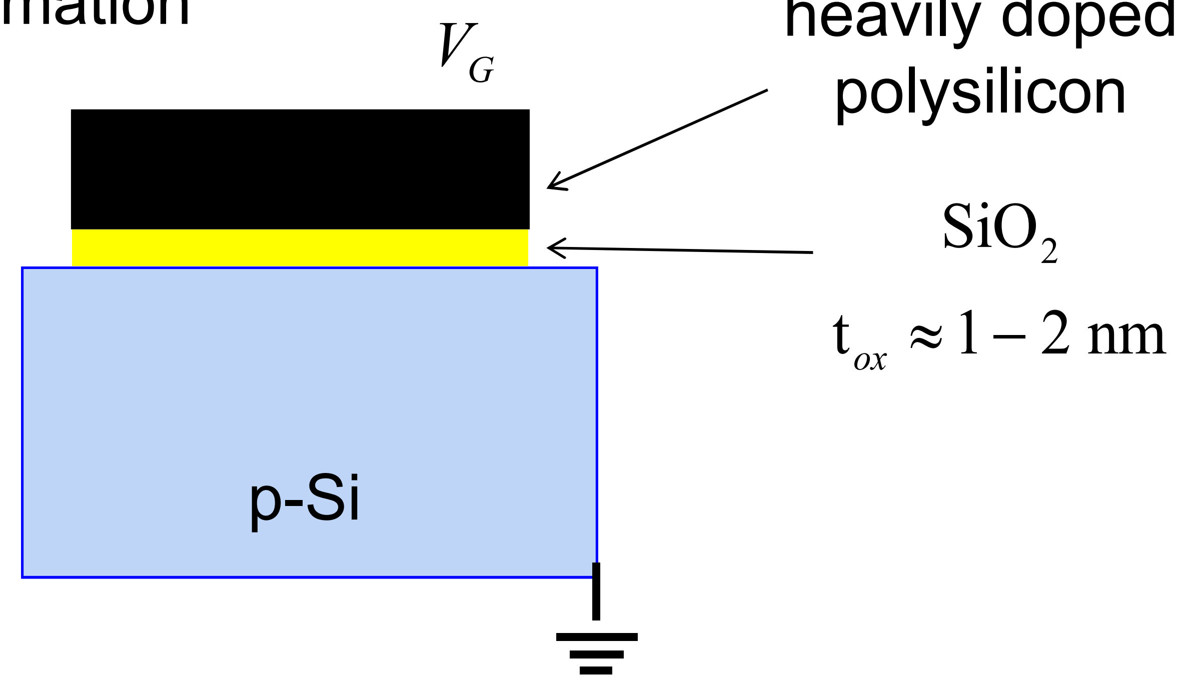


how can we understand MOSFET performance?

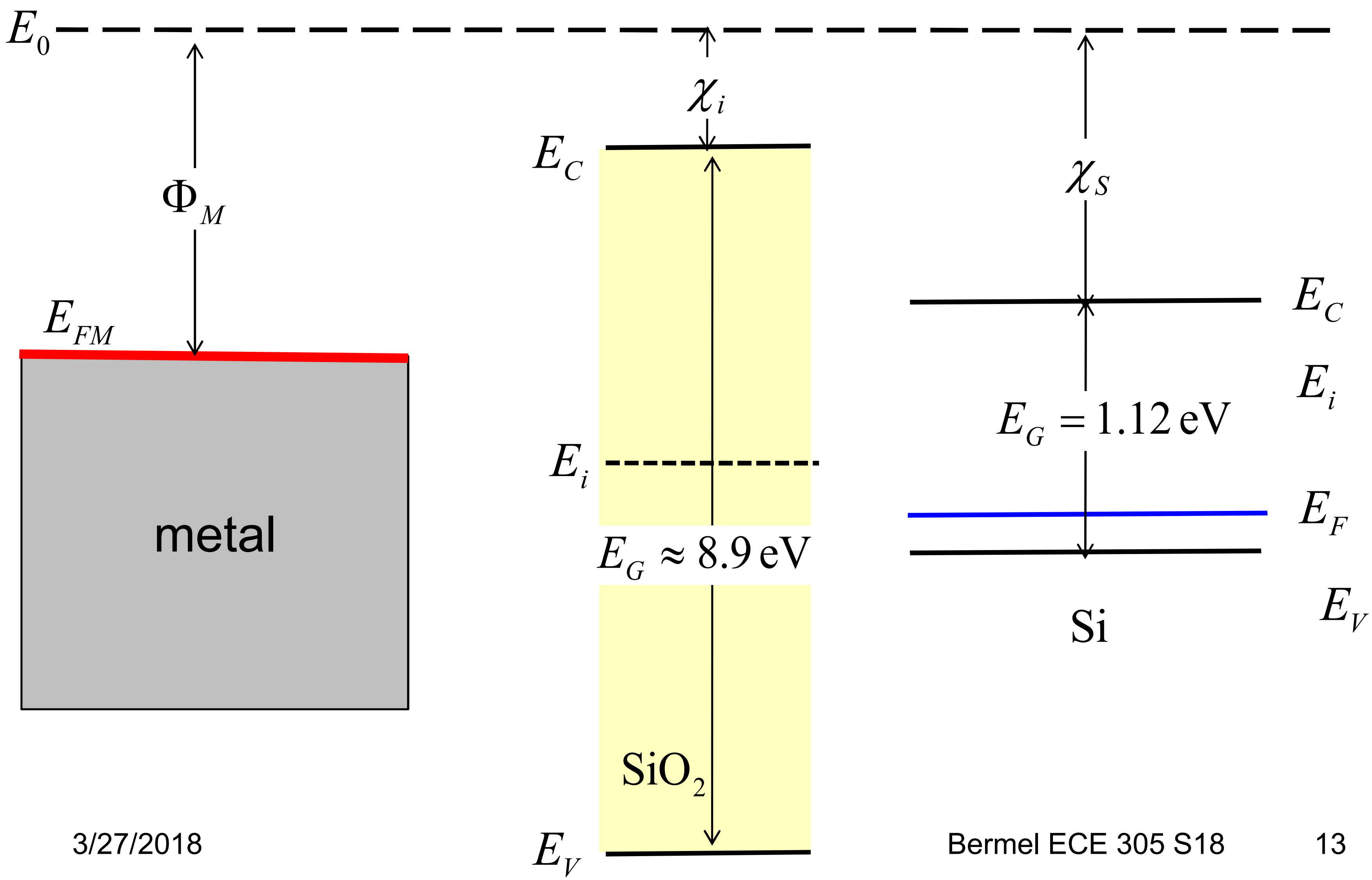
- What characterizes its performance?
- How can we calculate it?
- What is the closest analogue that we’ve already seen?

MOS capacitor

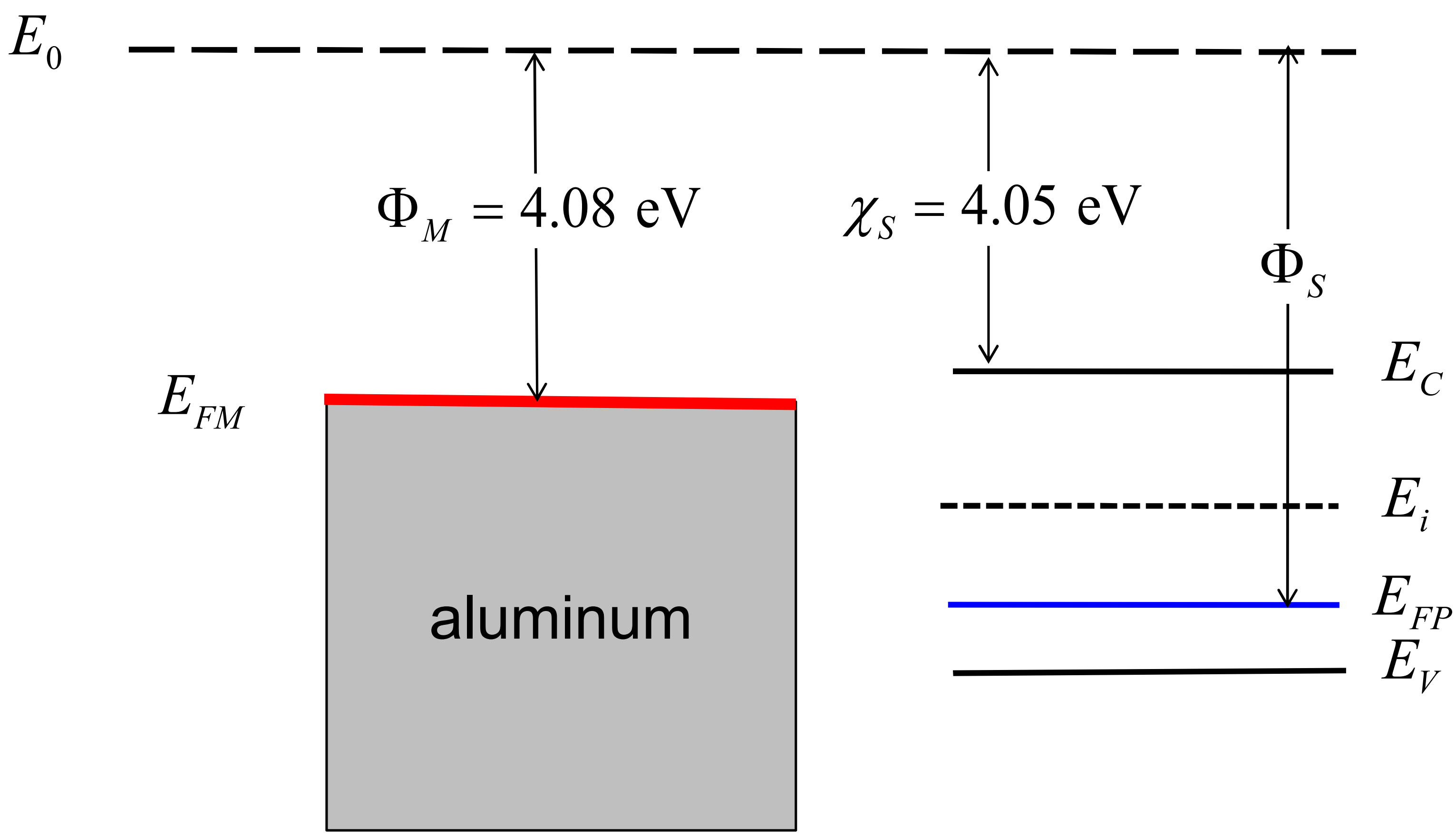
1) MOSFET and MOS capacitors
2) **E-bands and work functions**
3) Band-bending in ideal MOS-C's
4) Accumulation, depletion, inversion
5) Depletion approximation



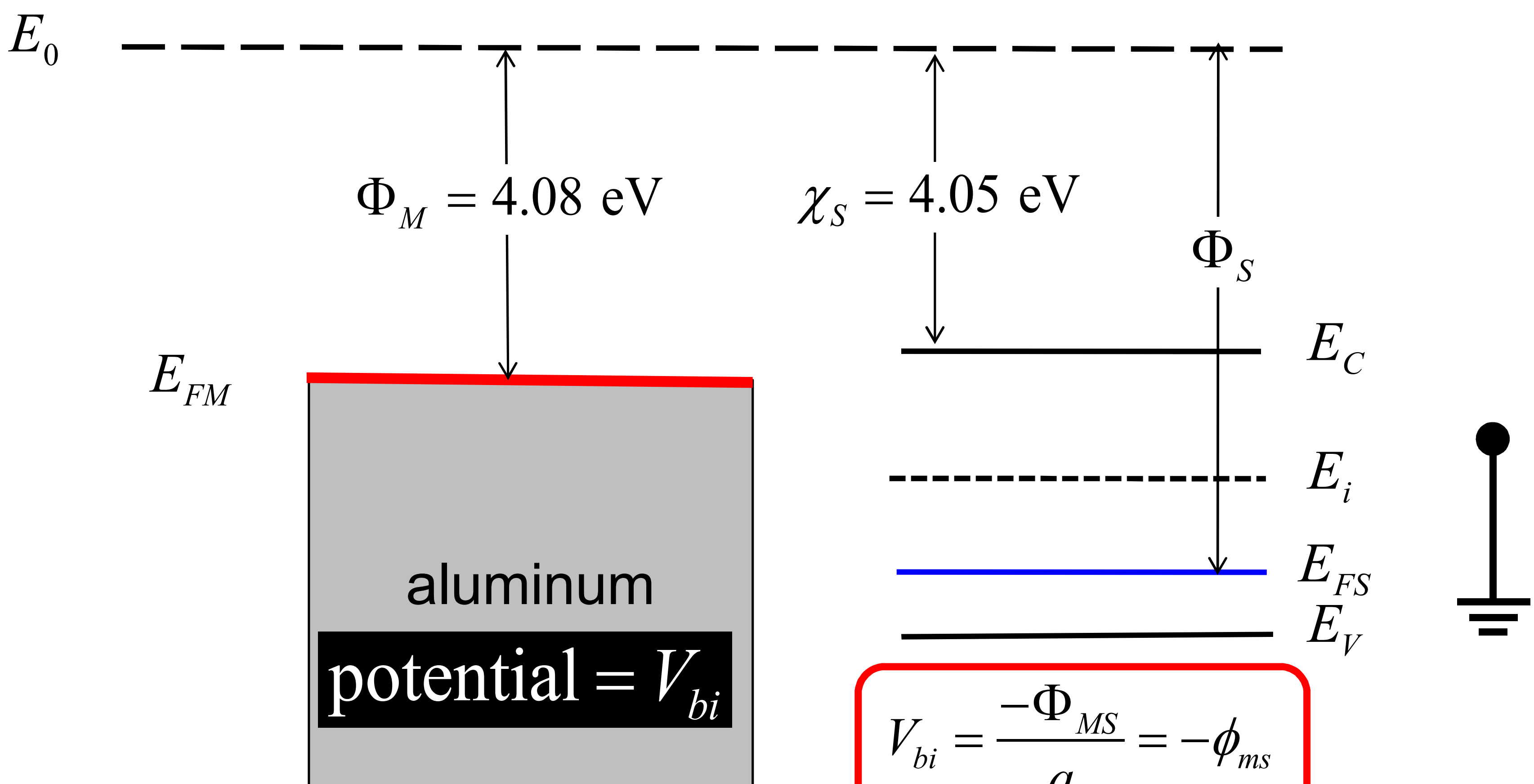
What we need to do: draw e-band diagram



Recall the MS junction



built-in potential



$$V_{bi} = \frac{-\Phi_{MS}}{q} = -\phi_{ms}$$

$$qV_{bi} = \left(E_{FM} - E_{FS}\right) = \left(\Phi_S - \Phi_M\right) = -\left(\Phi_M - \Phi_S\right) = -\Phi_{MS}$$

example:

Aluminum metal and p-type Si

$$N_A = 10^{16} \text{ cm}^{-3}$$

$$p_0 = N_V e^{(E_V - E_{FS})/k_B T} \text{ cm}^{-3}$$

$$E_{FS} - E_V = k_B T \ln\left(\frac{N_V}{N_A}\right)$$

$$N_V = 2\left[\frac{\left(m_p^* k_B T\right)}{2\pi\hbar^2}\right]^{3/2} = 1.83\times 10^{19} \text{ cm}^{-3}$$

$$\frac{E_{FS} - E_V}{q} = 0.2$$

$$\Phi_M = 4.08 \text{ eV}$$

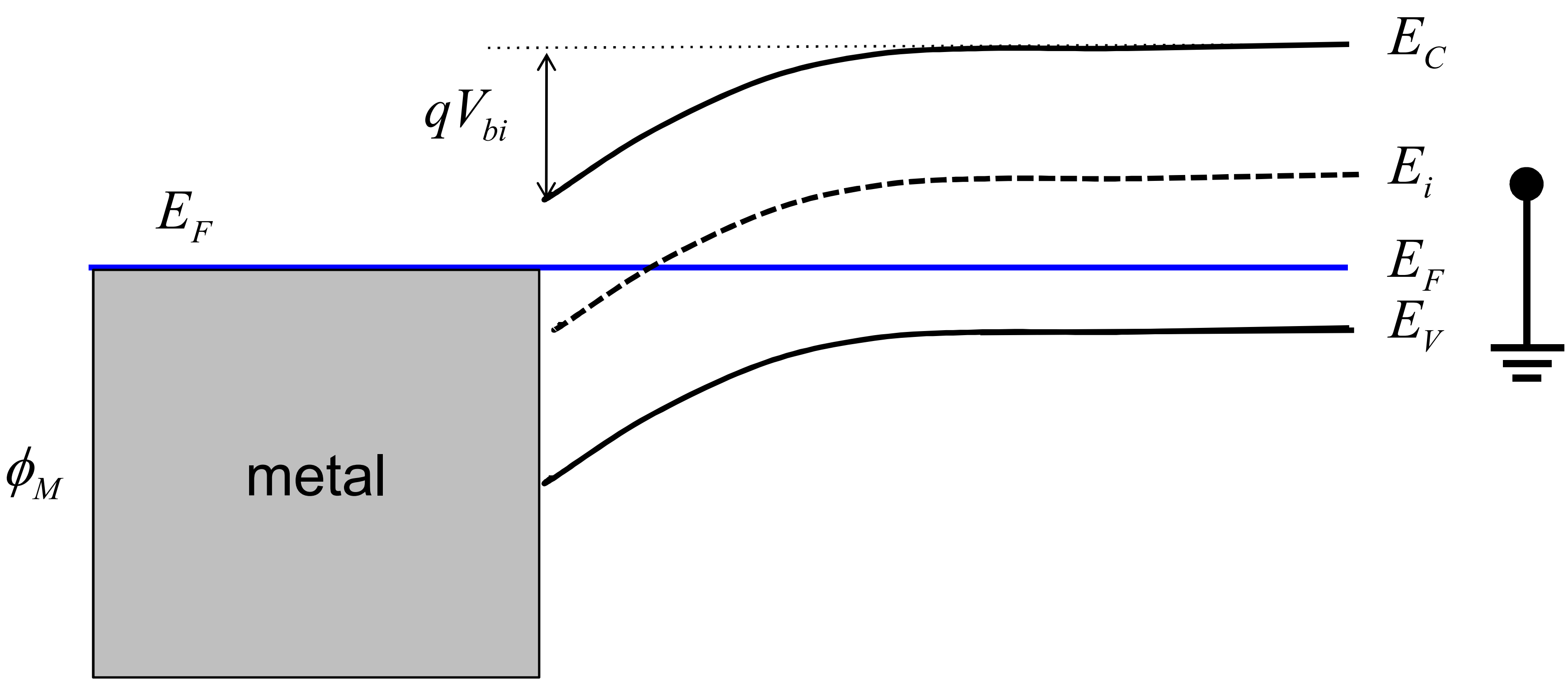
$$\Phi_S = \chi_S + E_G - \left(E_{FS} - E_V\right)/q$$

$$\Phi_S = 4.97 \text{ eV}$$

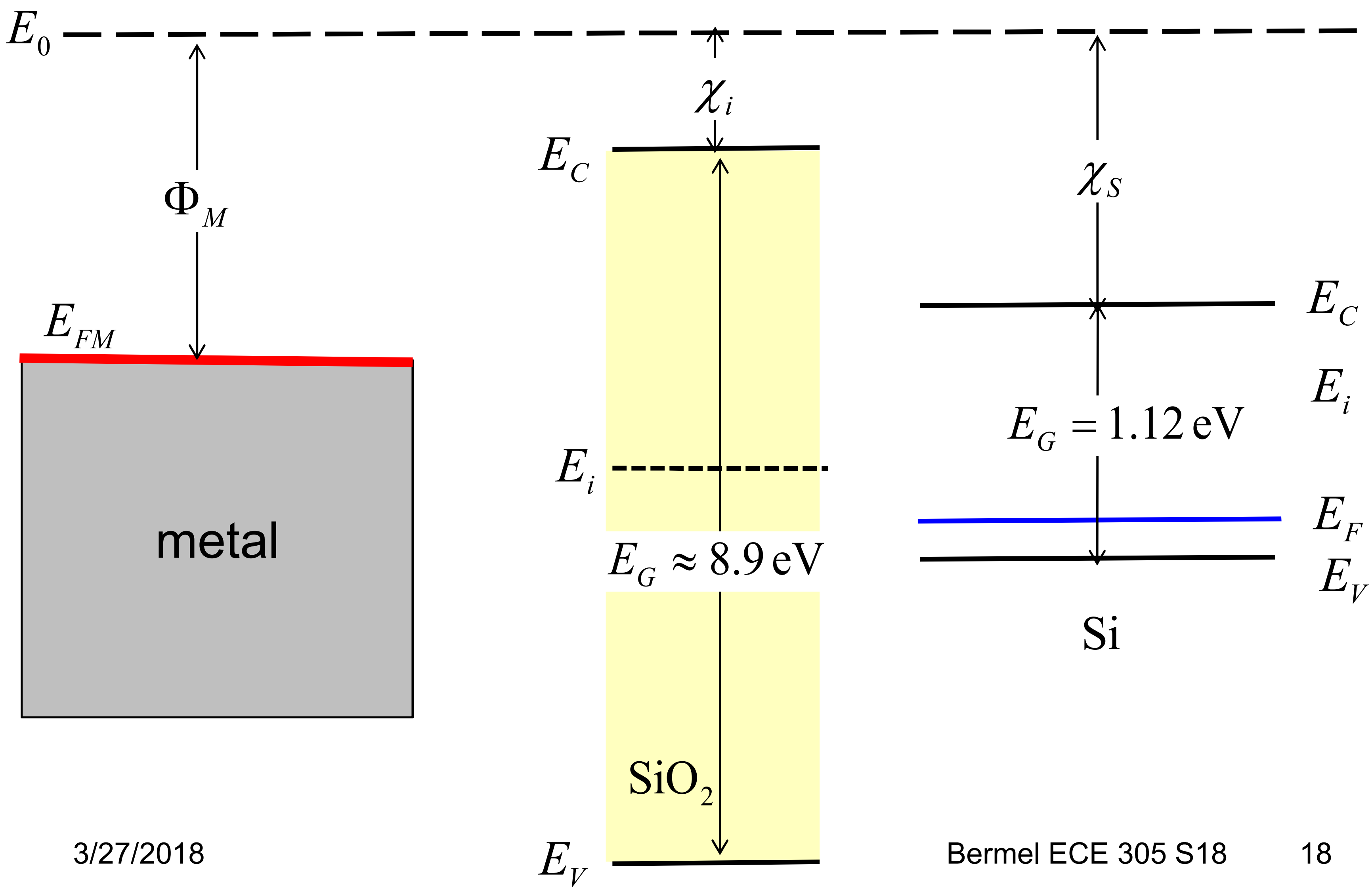
$$\phi_{ms} = \frac{\left(\Phi_M - \Phi_S\right)}{q} = -0.9 \text{ V}$$

$$V_{bi} = -\phi_{ms} = +0.9 \text{ V}$$

the band diagram



MOS e-band diagram



MOS e-band diagram

1) Built-in potential is exactly the same.

2) **But** part of the voltage drop occurs across the semiconductor and part across the oxide.

MOS capacitor

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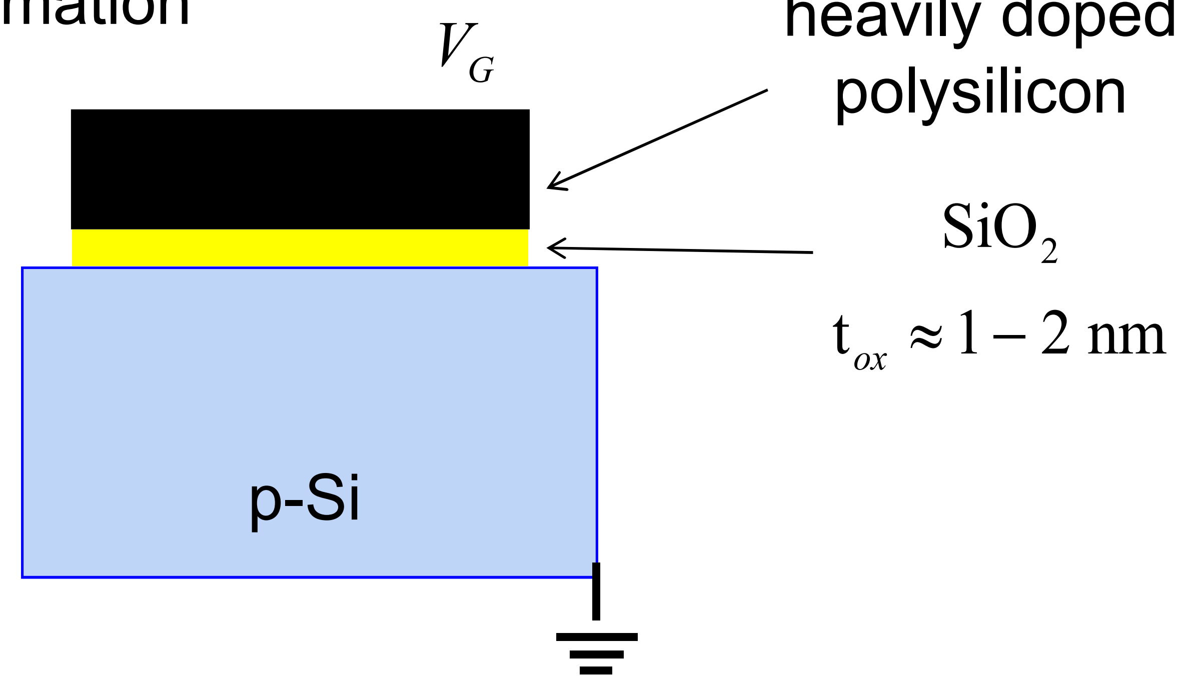
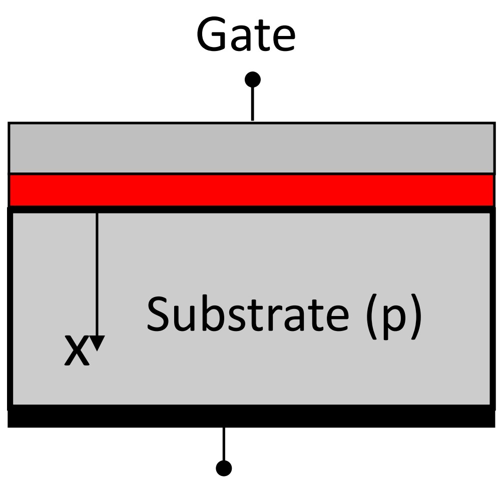
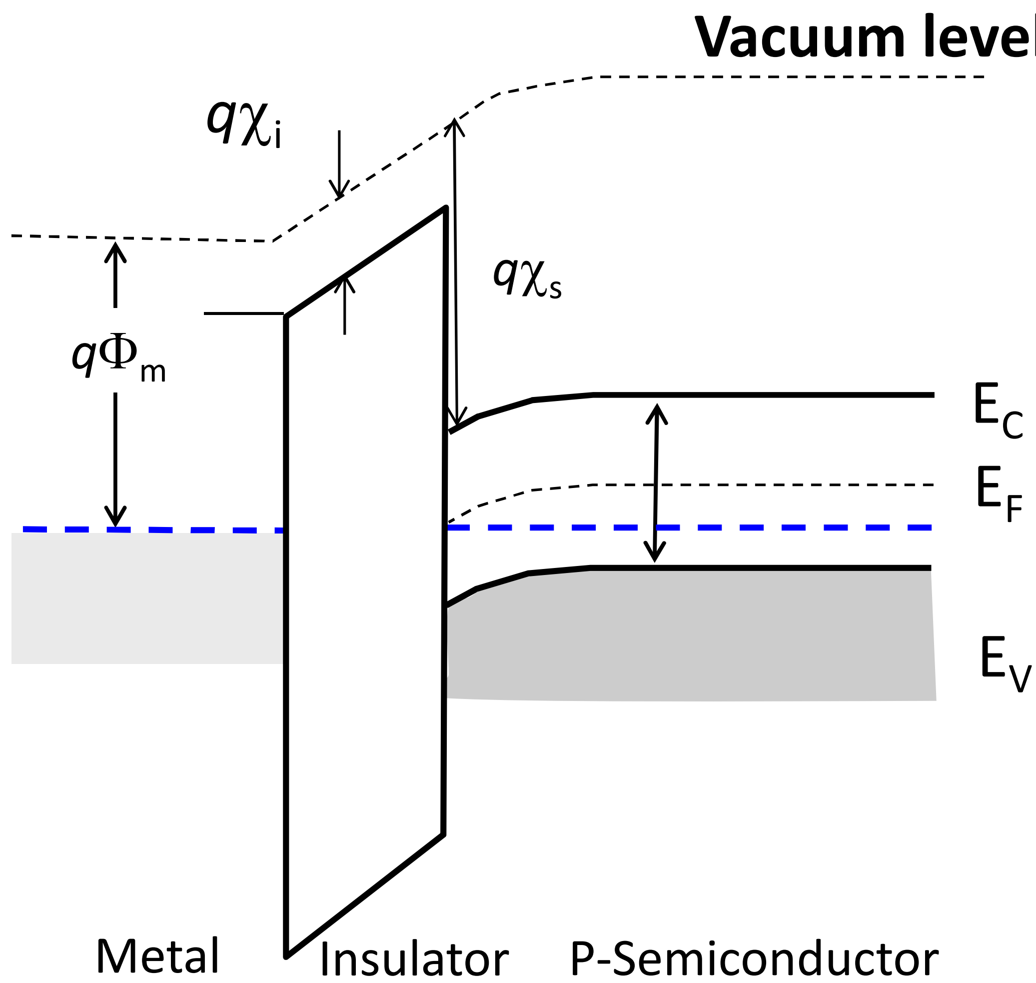
5) Depletion approximation



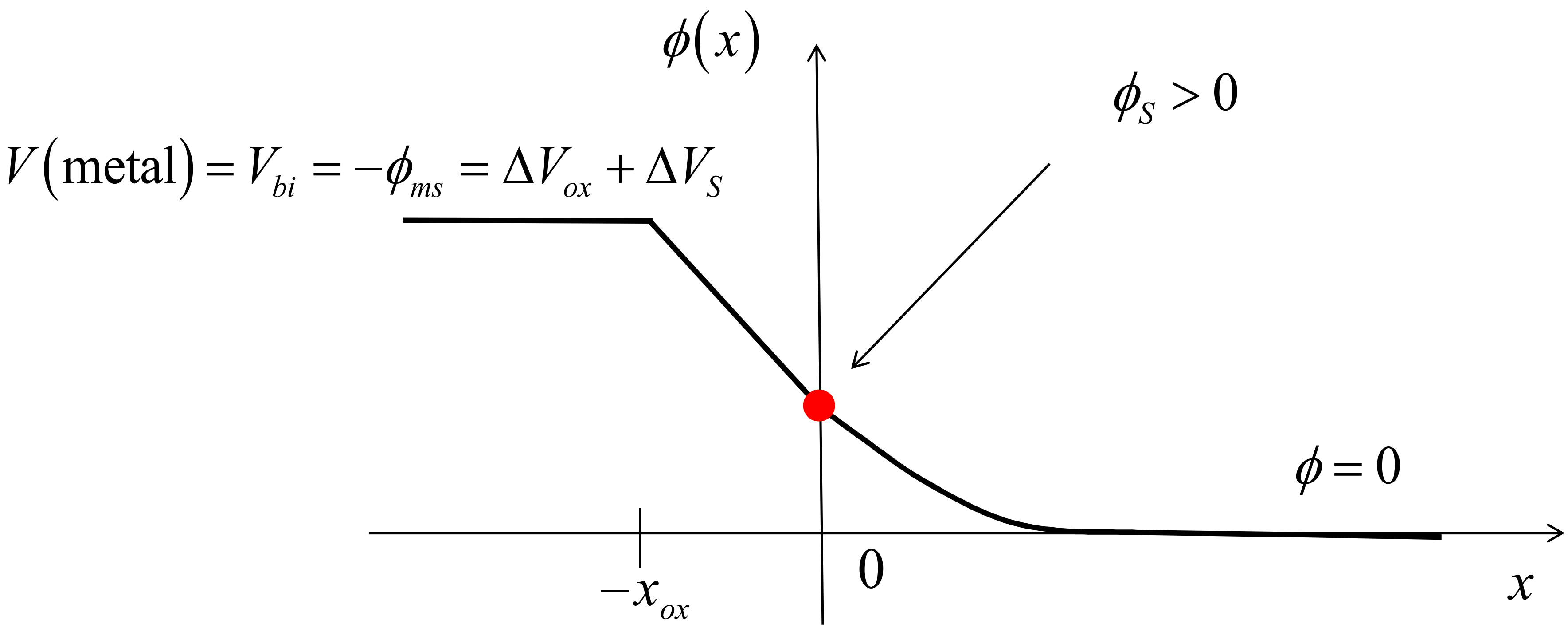
Electrostatics of MOS Capacitor in Equilibrium



Schottky barrier with an interposed dielectric



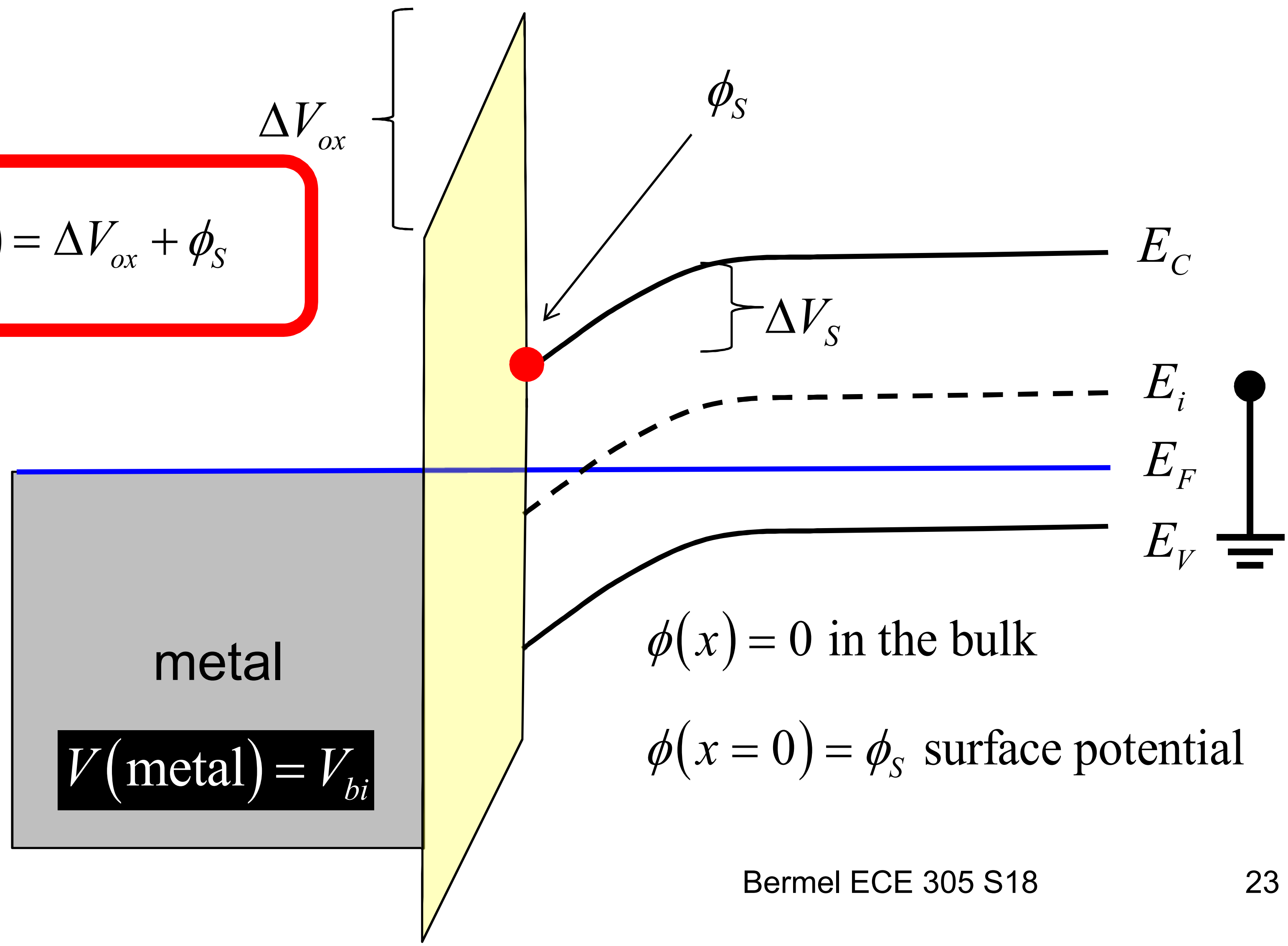
potential vs. position



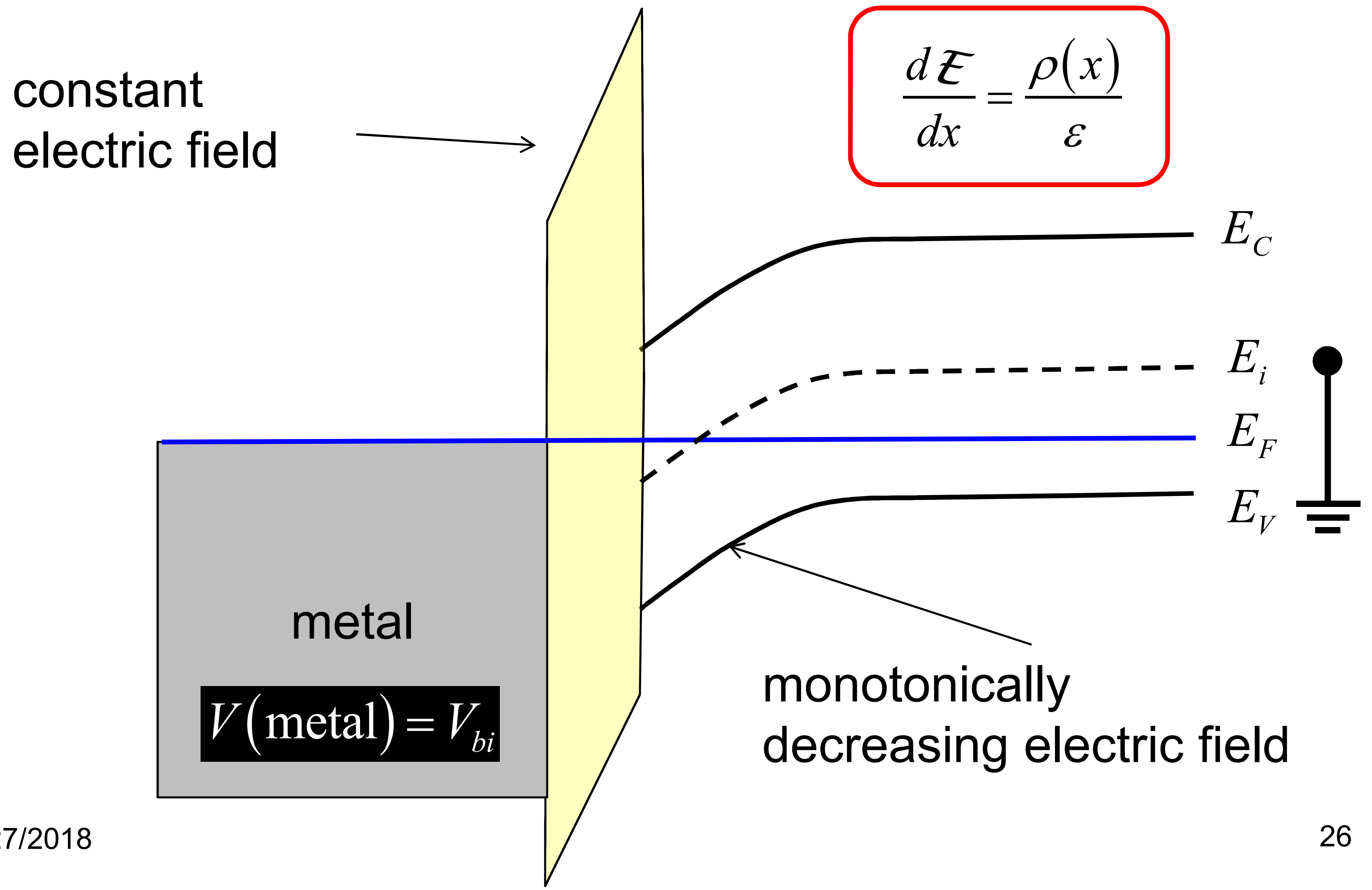
equilibrium e-band diagram

$$V(\text{metal}) = \Delta V_{ox} + \phi_S$$

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



equilibrium e-band diagram



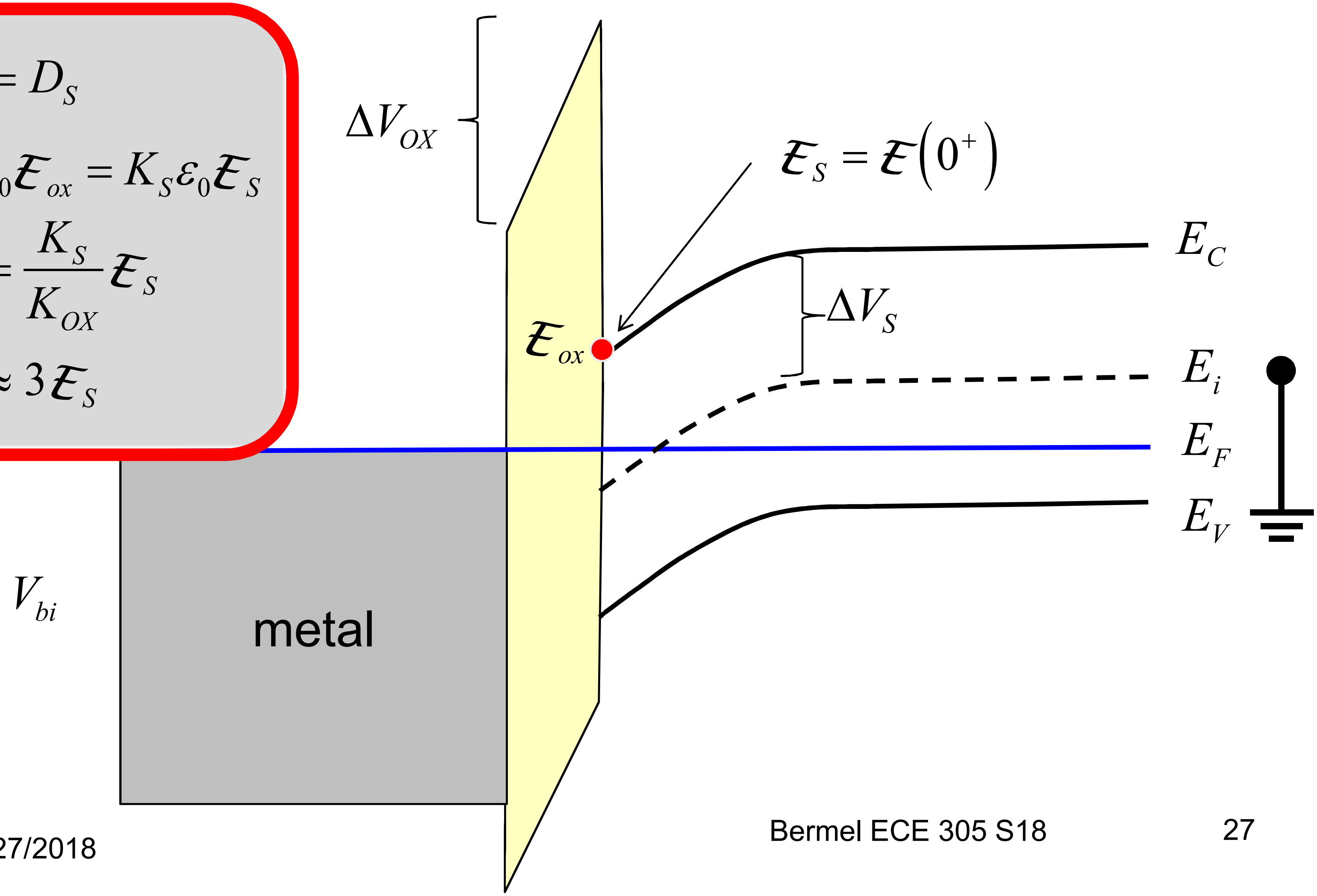
equilibrium e-band diagram

$$D_{ox} = D_S$$

$$K_{ox}\varepsilon_0\mathcal{E}_{ox} = K_S\varepsilon_0\mathcal{E}_S$$

$$\mathcal{E}_{ox} = \frac{K_S}{K_{OX}}\mathcal{E}_S$$

$$\mathcal{E}_{ox} \approx 3\mathcal{E}_S$$



MOS capacitor

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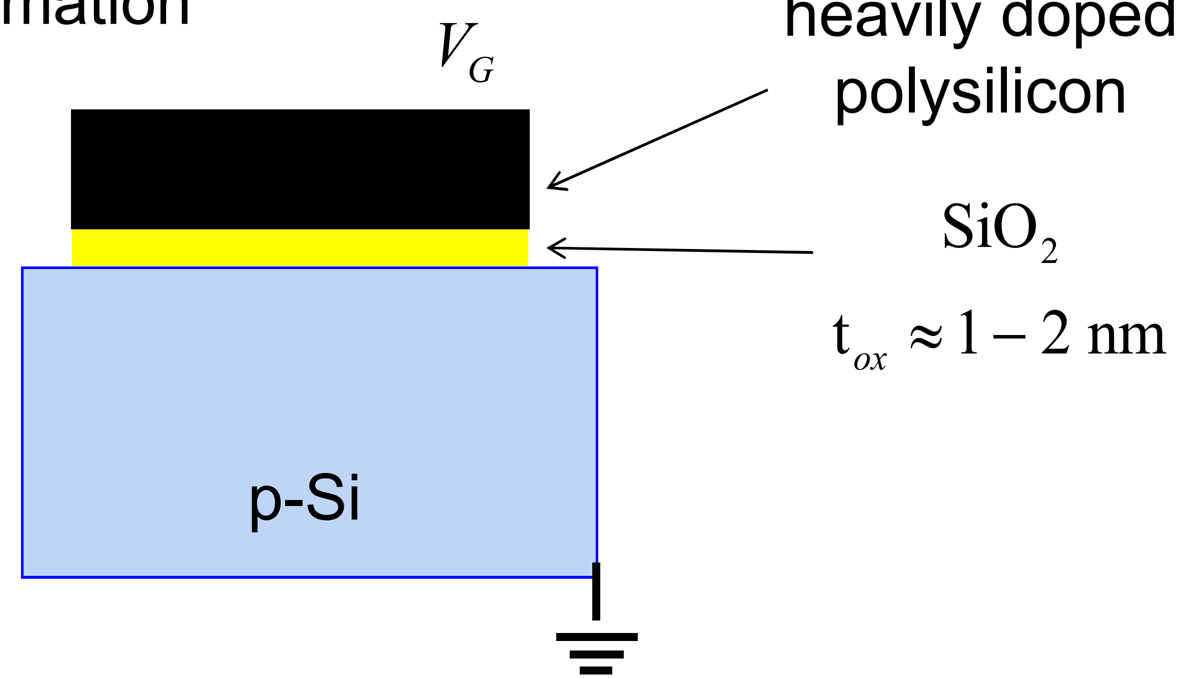
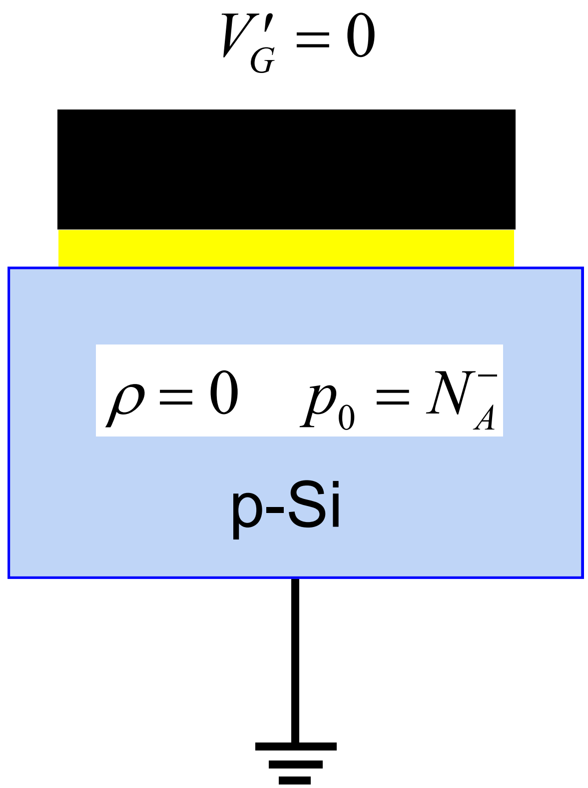
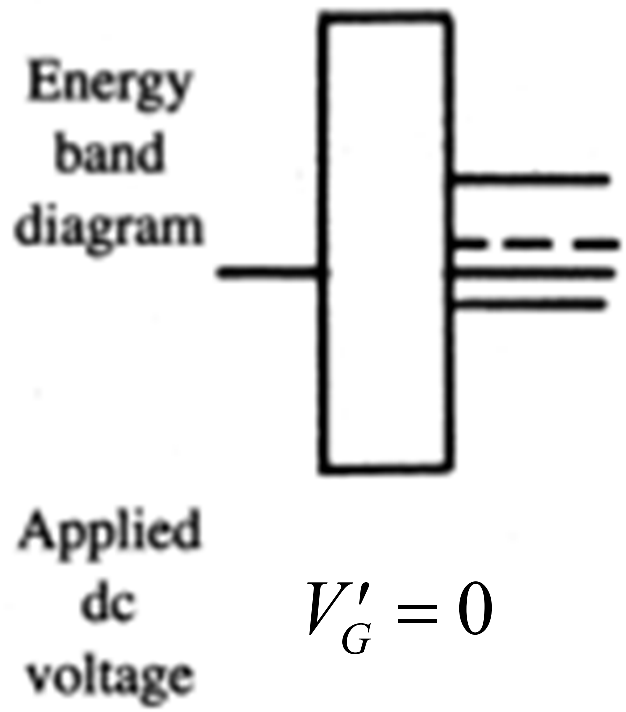
4) **Accumulation, depletion, inversion**
5) Depletion approximation



MOS capacitor (flat band)

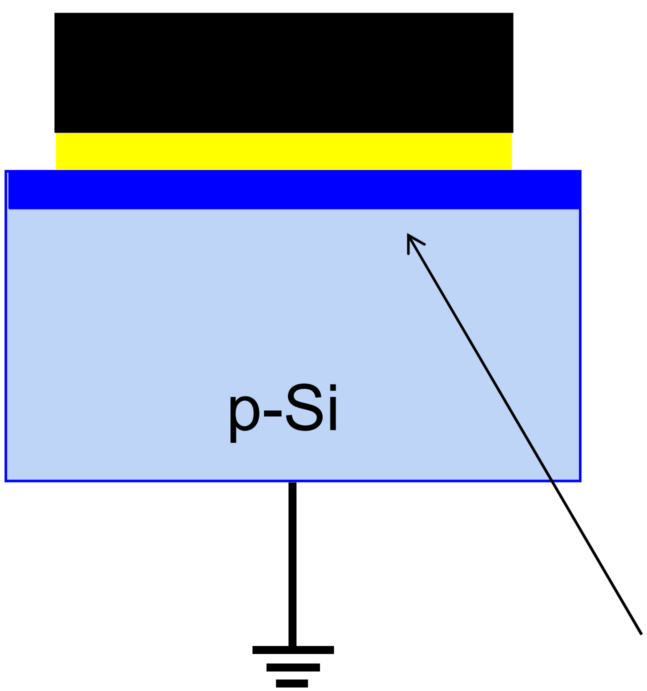


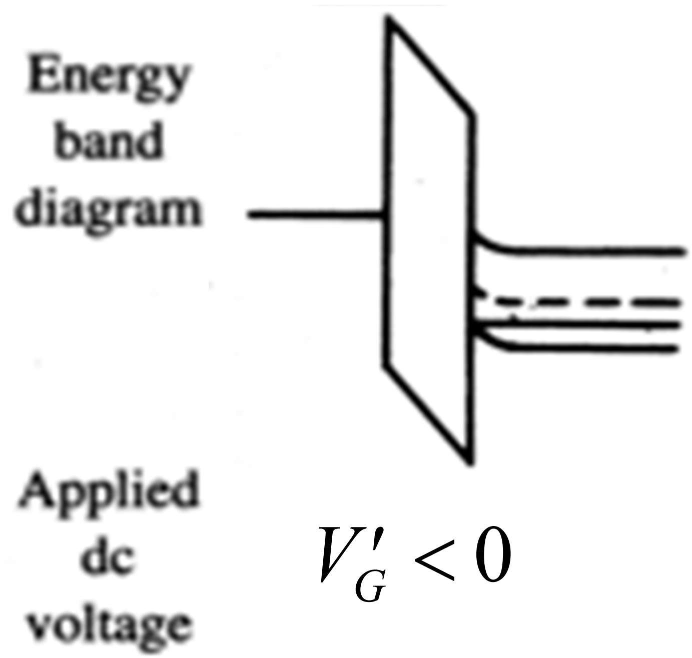


No metal-semiconductor work function difference

MOS capacitor (accumulation)

$V_G' < 0$

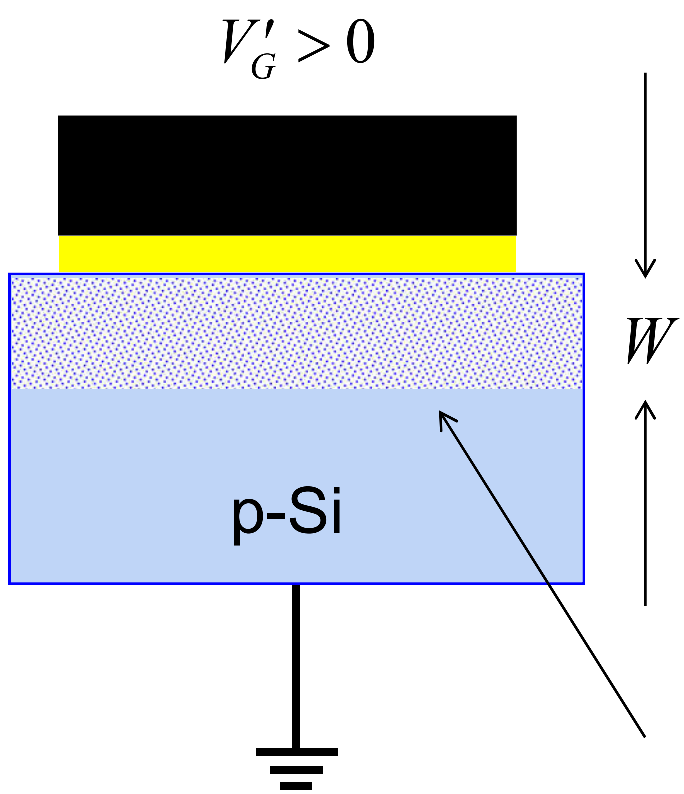


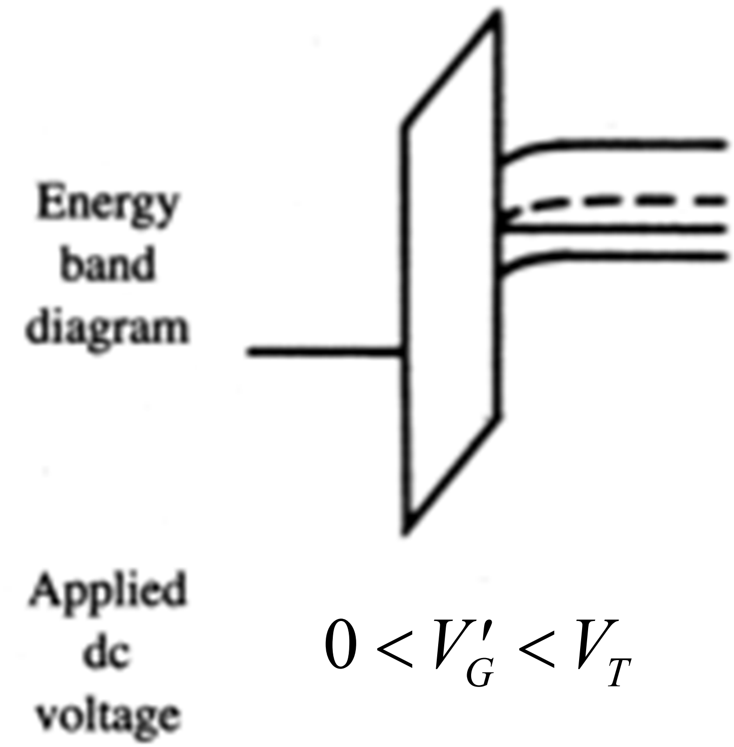


$V_G' < 0$

$\rho > 0 \quad p_0 > N_A^-$

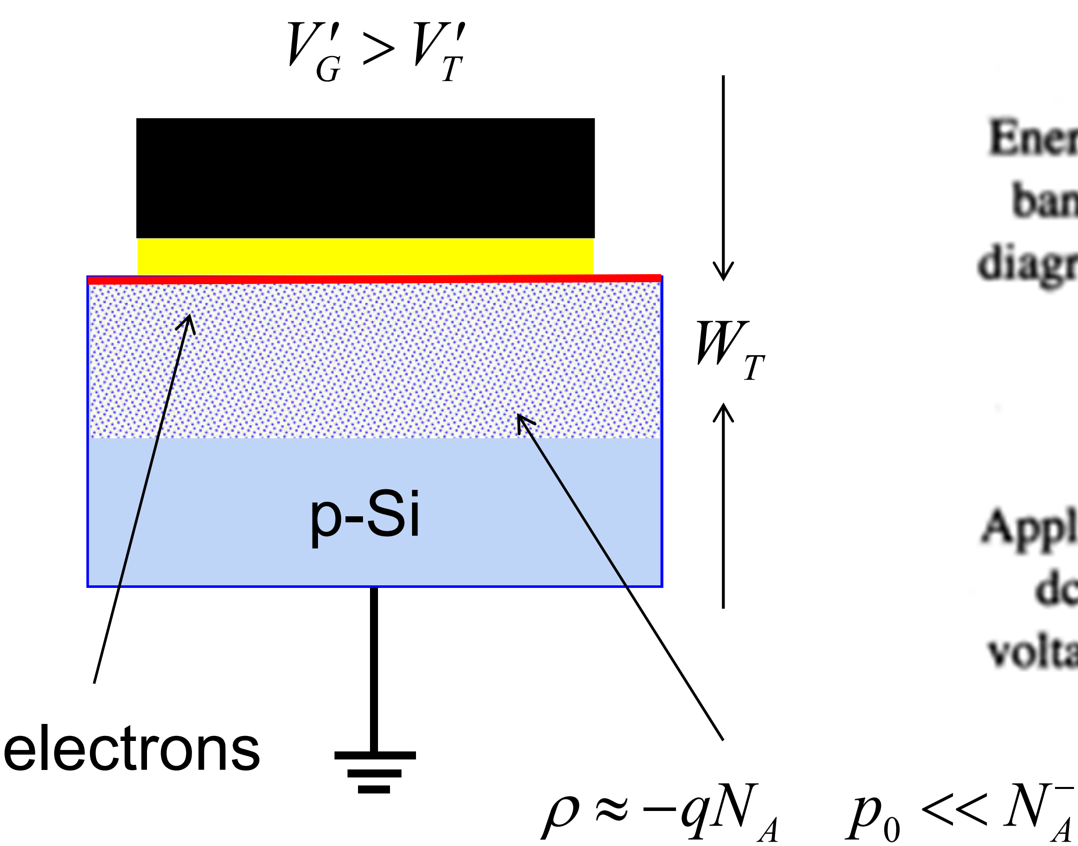
MOS capacitor (depletion)

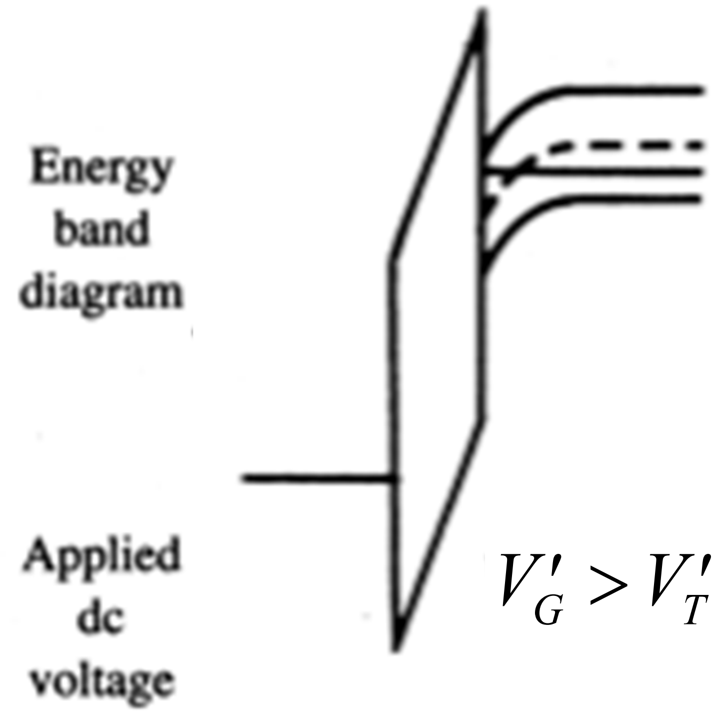




$$\rho \approx -qN_A \quad p_0 << N_A^-$$

MOS capacitor (inversion)





band bending in an MOS device

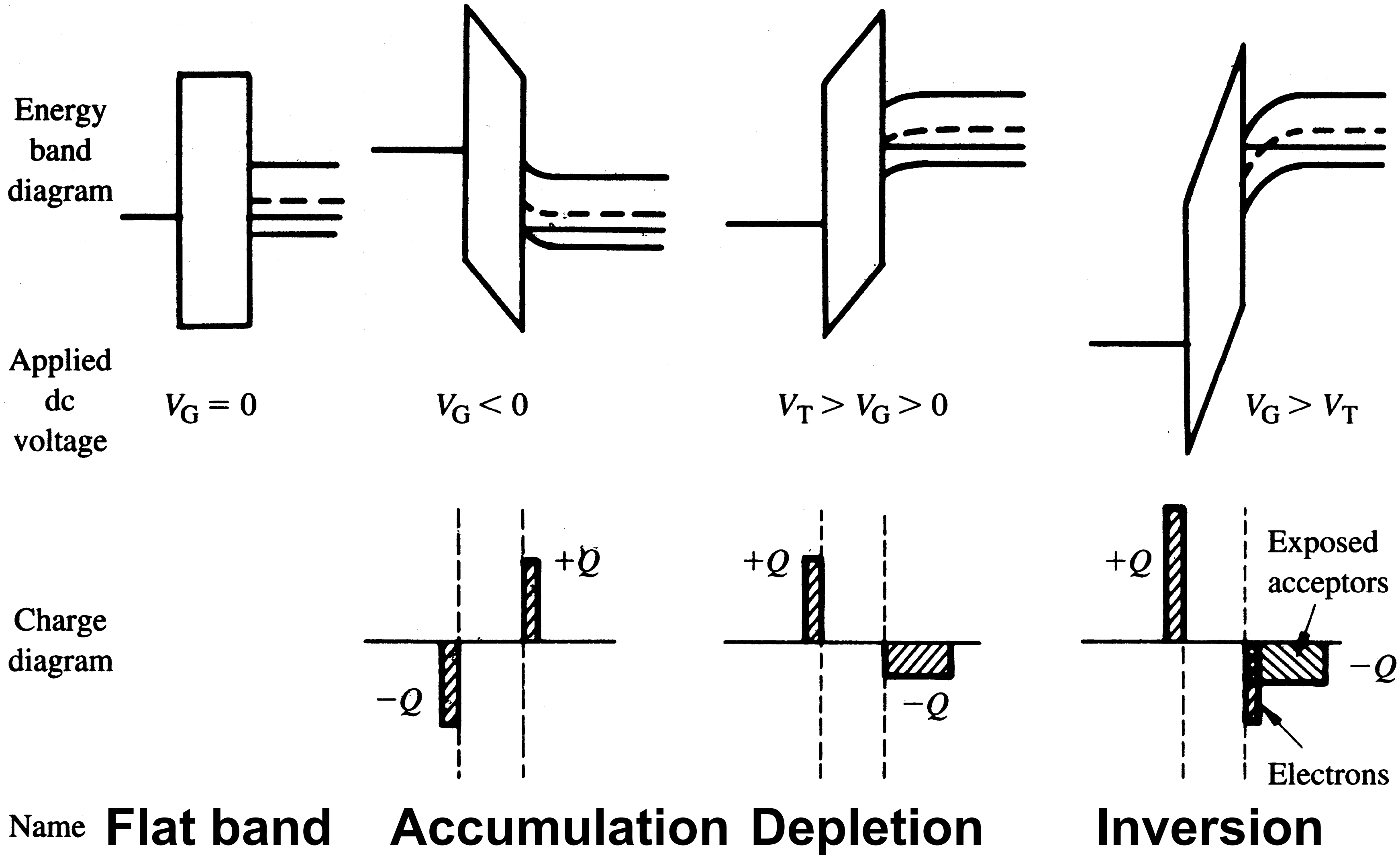
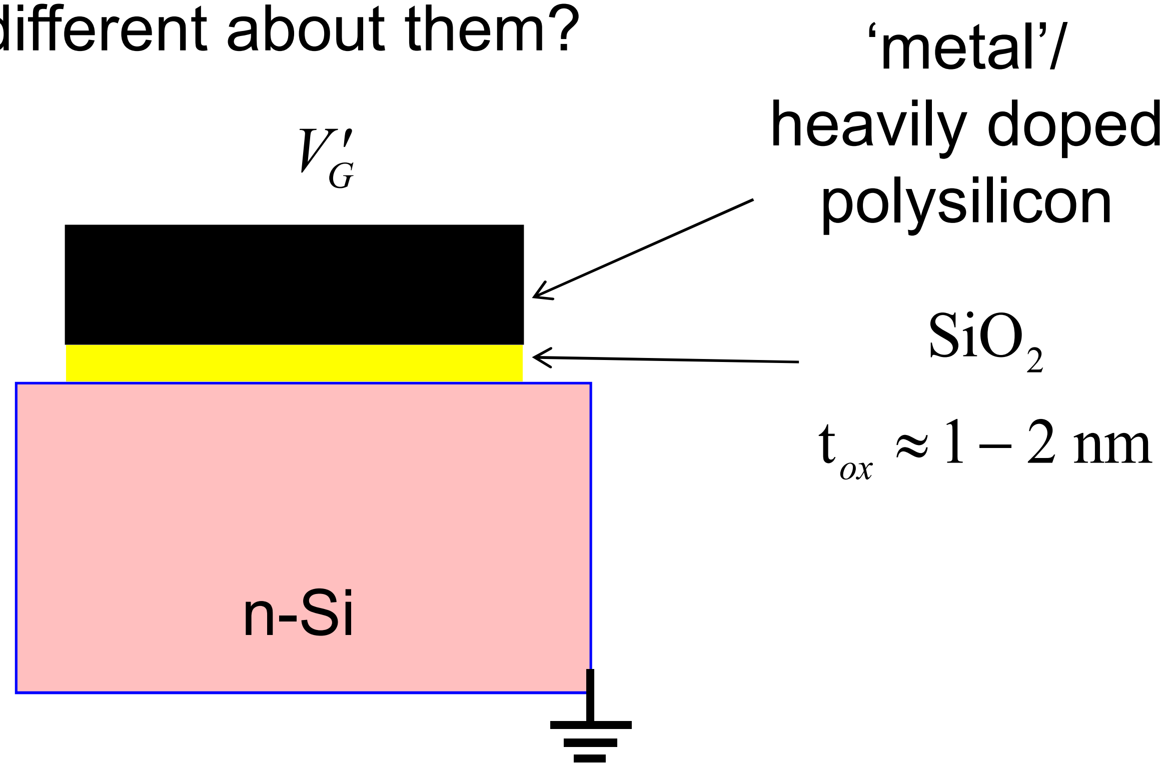


Fig. 16.6, Semiconductor Device Fundamentals, R.F. Pierret

what if we had an N-type MOS-C?

1) Can we still achieve the same operating regimes?
2) What similarities should occur across devices in common regimes?
3) What might be different about them?



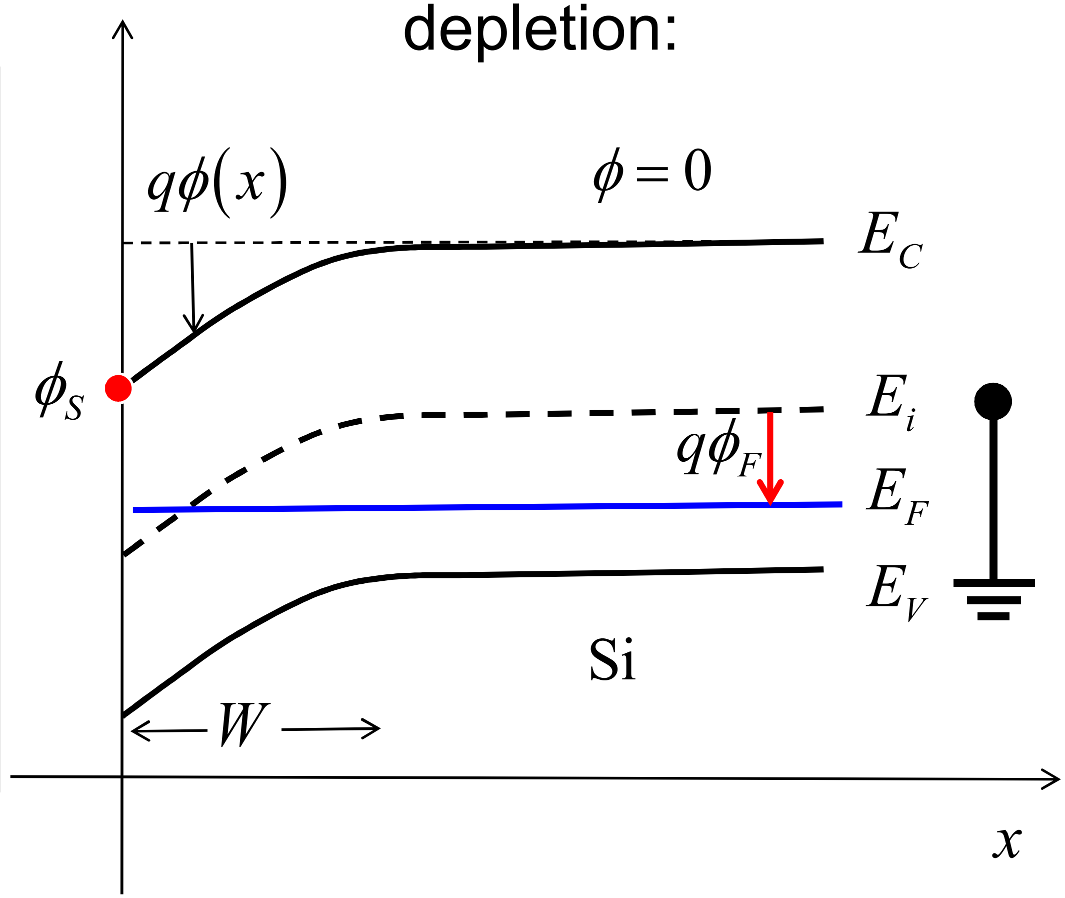
hole density in the bulk

$$p_{bulk} = N_A = n_i e^{\left(E_i(bulk)-E_F\right)/k_BT}$$

$$p_{bulk} = N_A = n_i e^{q\phi_F/k_BT}$$

$$\phi_F = \frac{k_BT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

depletion:



electron density at the surface

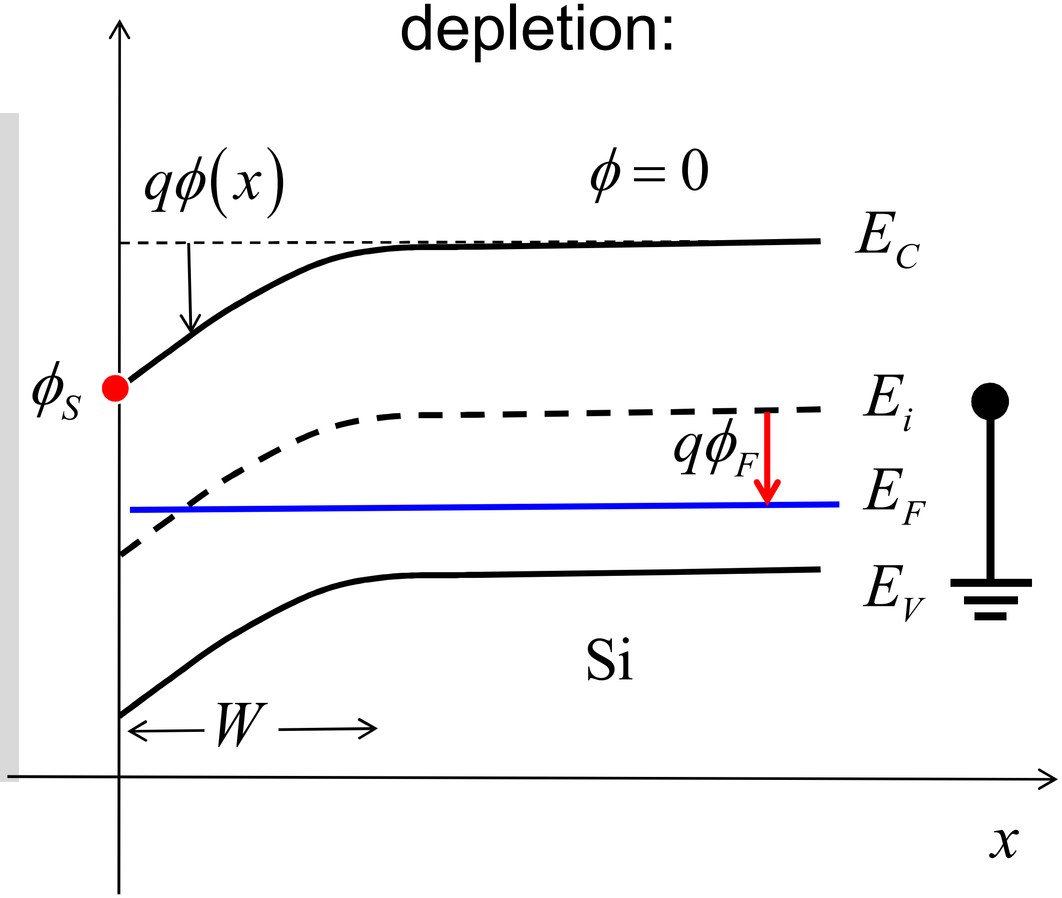
$$n_{surface} = n_i e^{\left(E_F - E_i(x=0)\right)/k_B T}$$

$$n_{surface} = n_i e^{\left(E_F - E_i(bulk) + q\phi_S\right)/k_B T}$$

$$= n_{bulk} e^{q\phi_S/k_B T}$$

$$n_{bulk} = N_A \rightarrow \phi_S = 2\phi_F$$

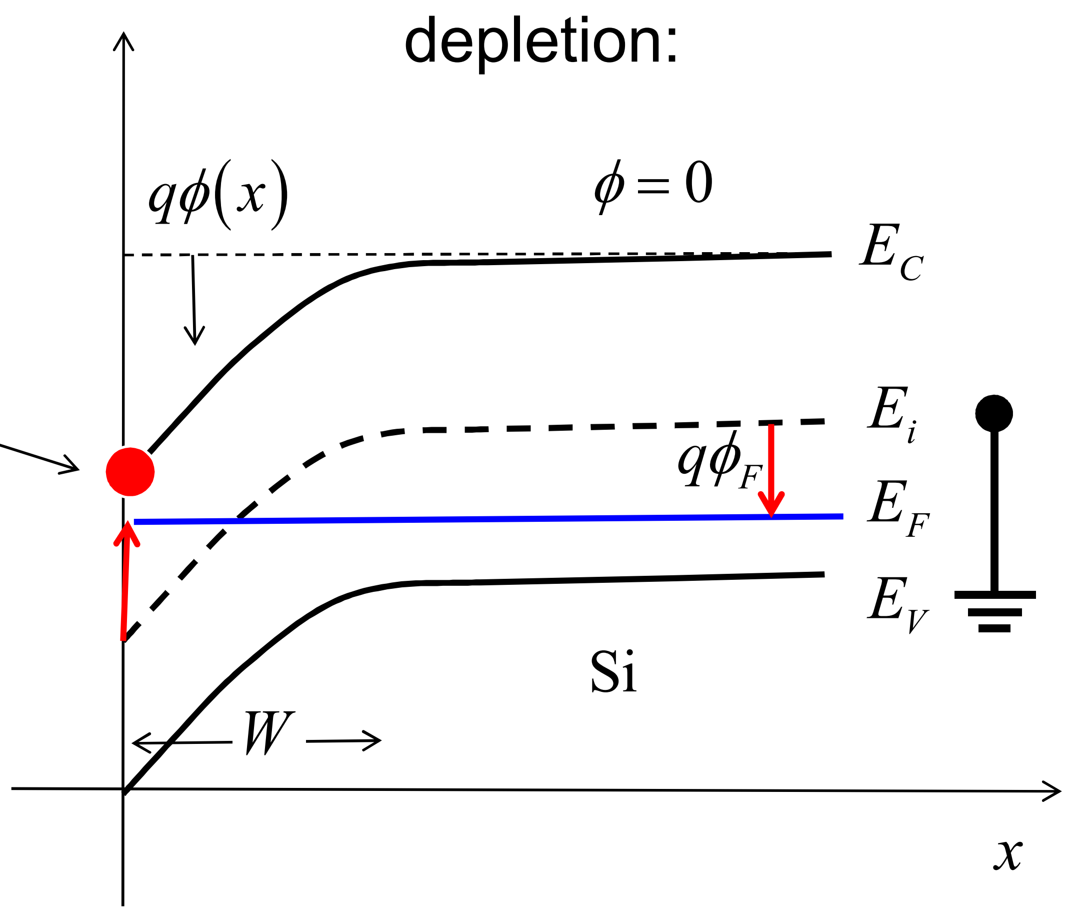
depletion:



onset of inversion

$$\phi_S = 2\phi_F$$

$$\phi_F = \frac{k_B T}{q} \ln\left(\frac{N_A}{n_i}\right)$$



accumulation, depletion, inversion

depletion:

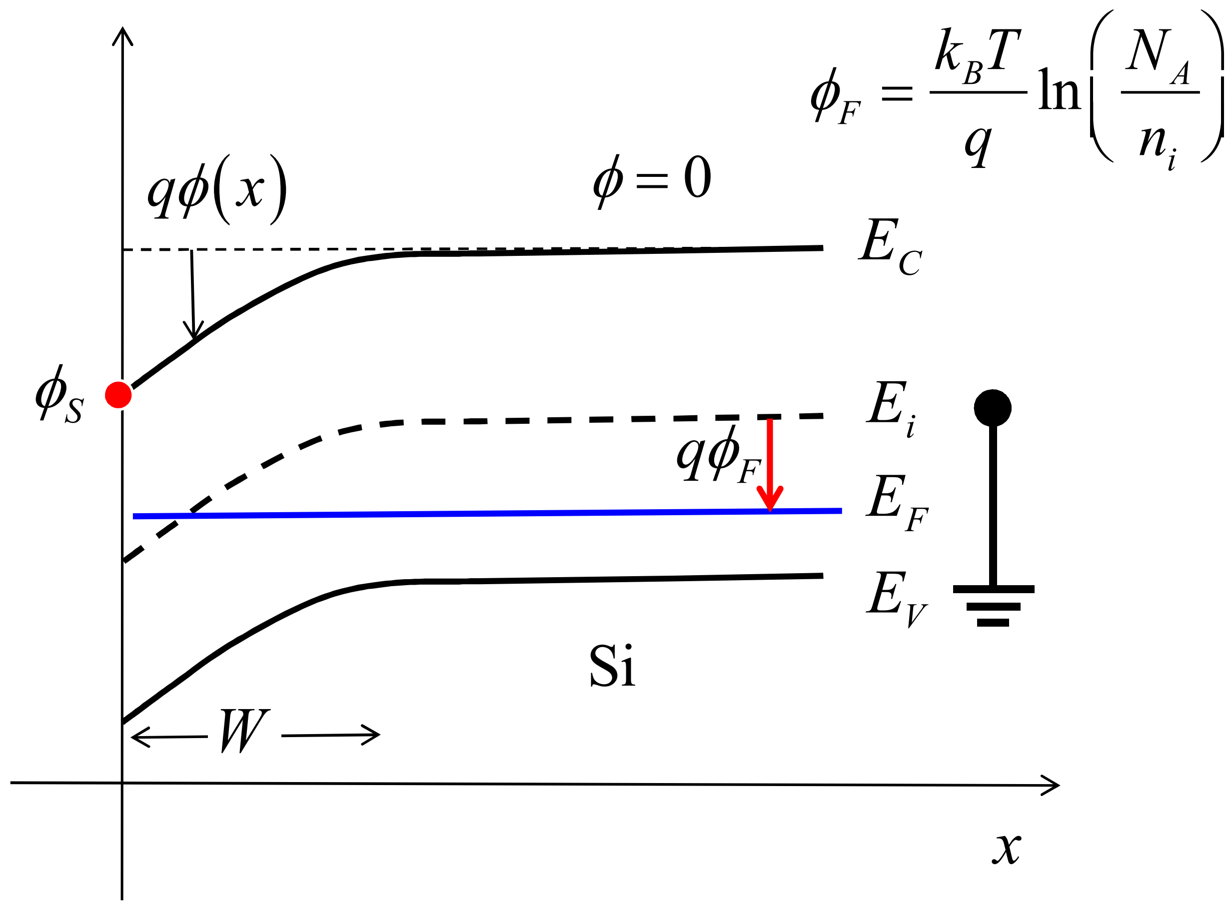
$$0 < \phi_S < 2\phi_F$$

inversion:

$$\phi_S > 2\phi_F$$

accumulation:

$$\phi_S < 0$$



MOS electrostatics: depletion

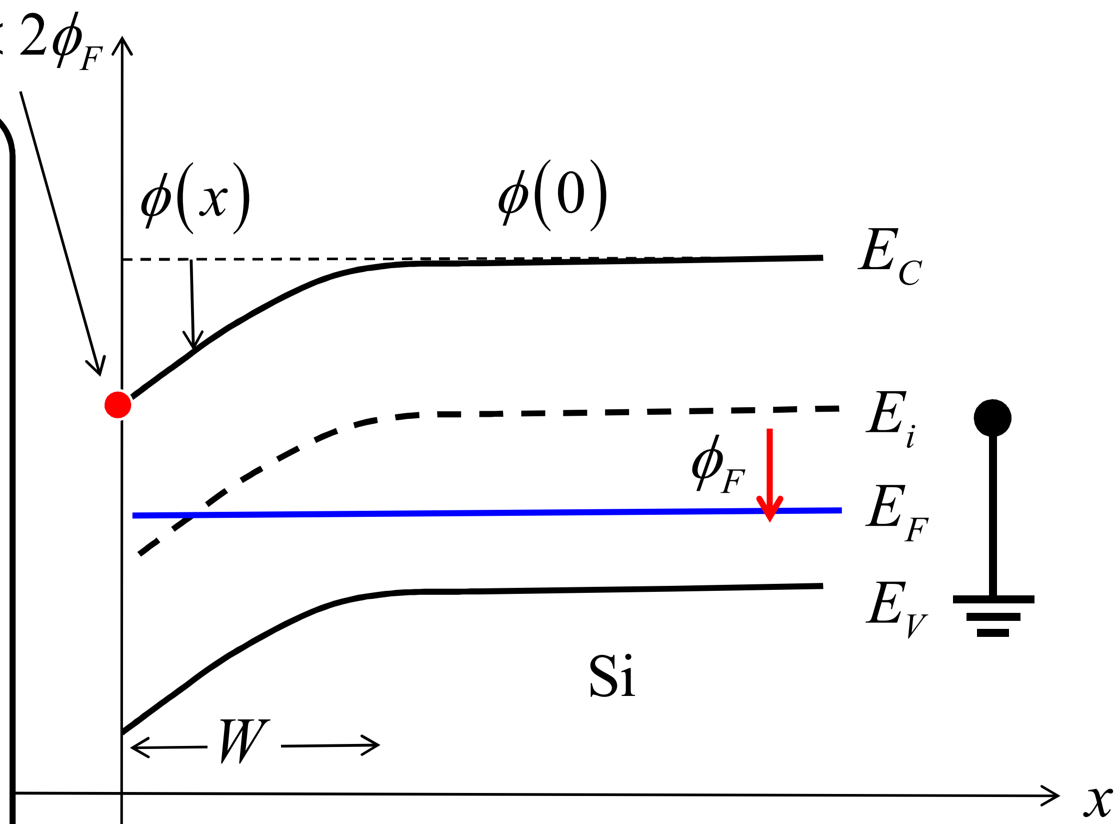
Given the surface potential: ϕ_S

$\mathcal{E}_S(\phi_S)$

$W(\phi_S)$

$Q_S(\phi_S) = -qN_A W(\phi_S)$

What gate voltage produced this surface potential?



Depletion approximation for the charge in the semiconductor.

MOS capacitor

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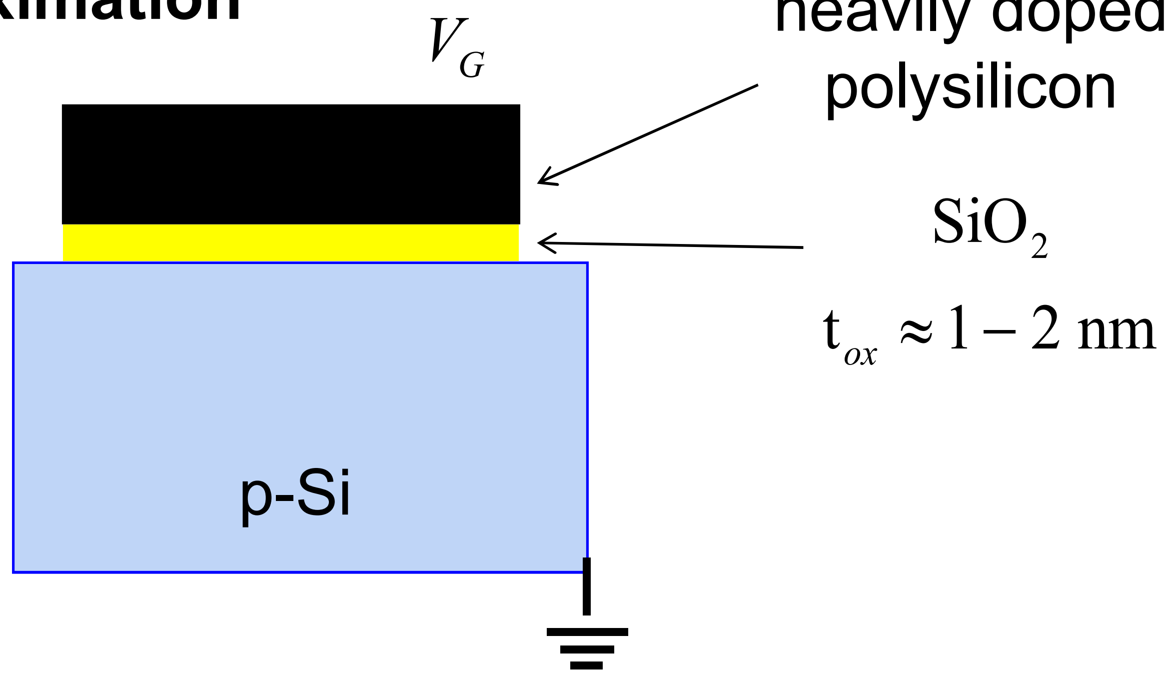
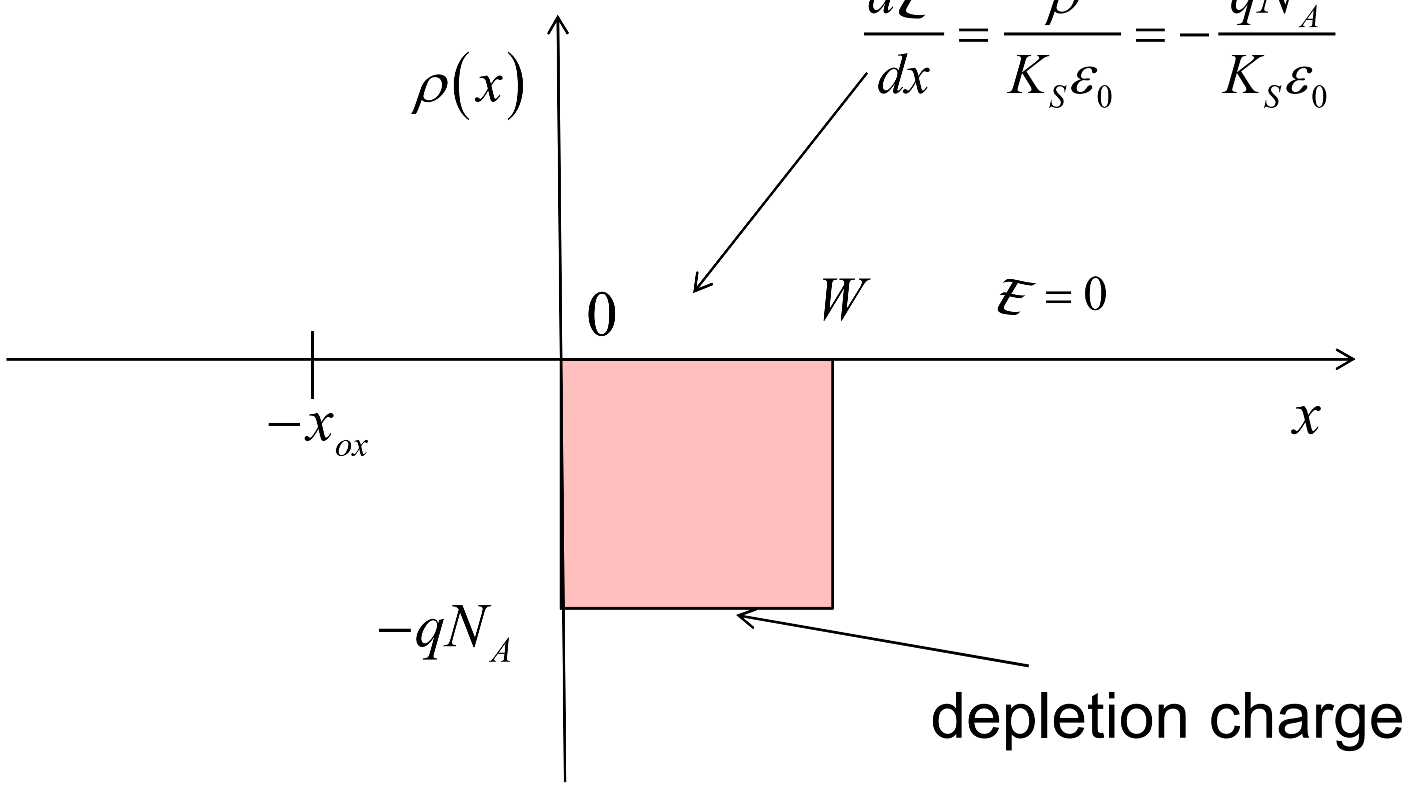
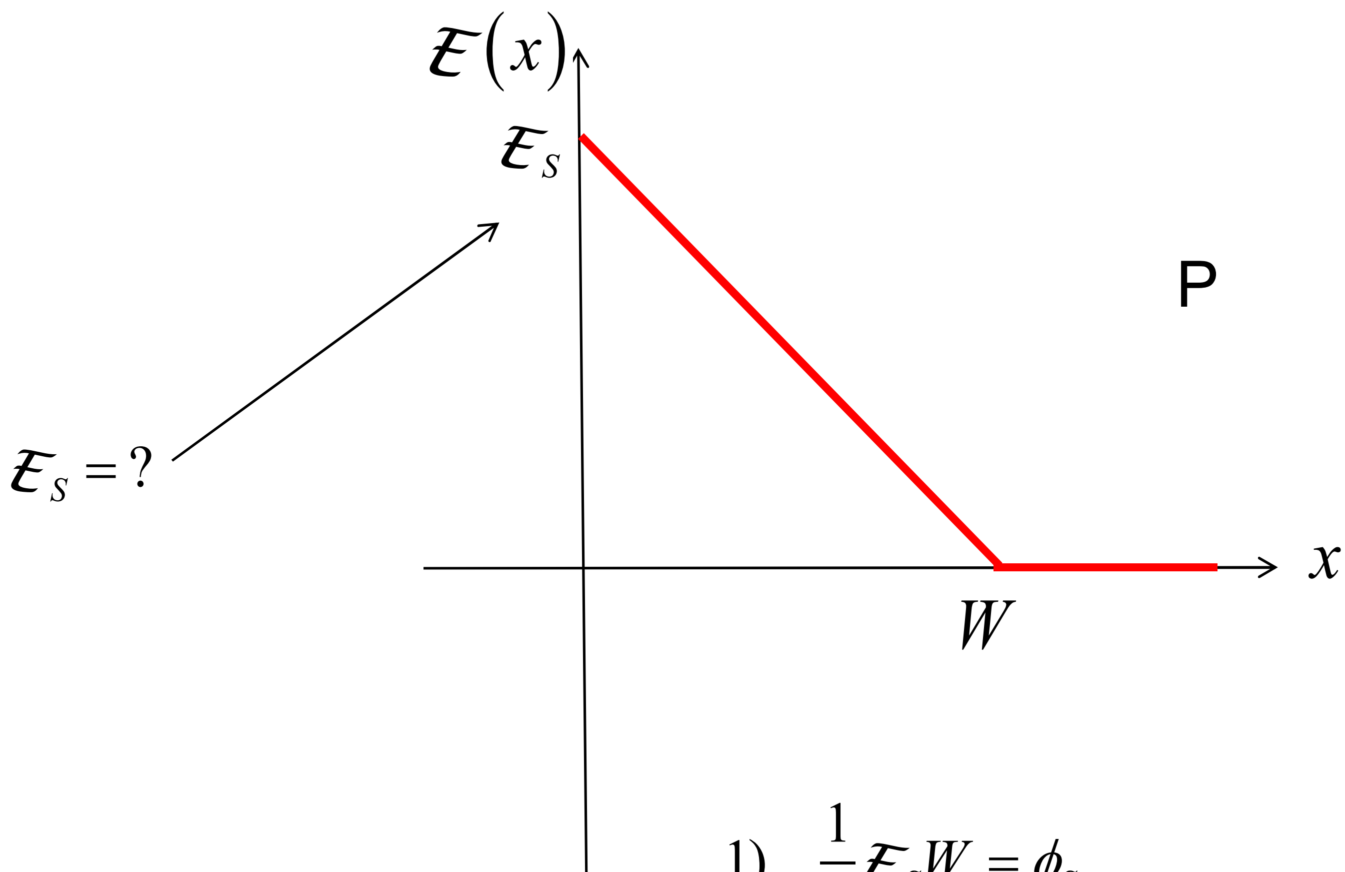


space charge density vs. position



$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{K_S \varepsilon_0} = -\frac{qN_A}{K_S \varepsilon_0}$$

electric field (semiconductor)



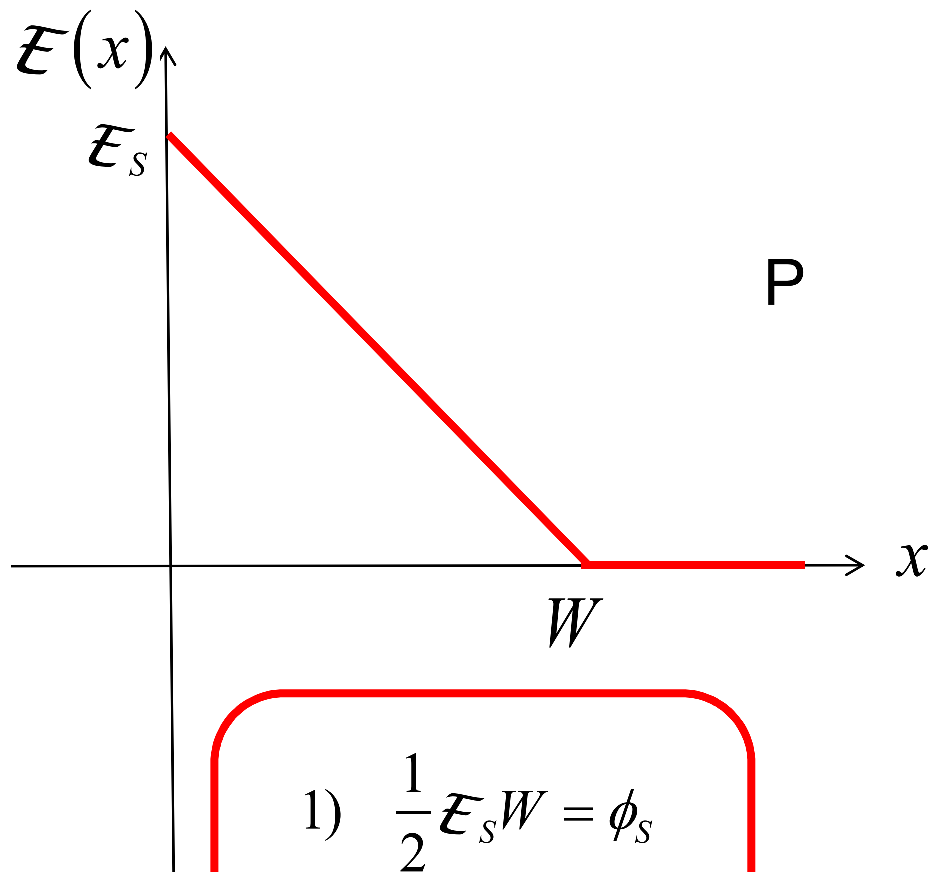
1) $\frac{1}{2}\mathcal{E}_S W = \phi_S$

surface electric field (semiconductor)

$$\frac{d\mathcal{E}}{dx} = -\frac{qN_A}{K_S\varepsilon_0}$$

$$d\mathcal{E} = -\frac{qN_A}{K_S\varepsilon_0}dx$$

$$\int_{\mathcal{E}(W)}^{\mathcal{E}(0)} d\mathcal{E} = -\frac{qN_A}{K_S\varepsilon_0}\int_W^0 dx$$



2) $$\mathcal{E}_S = \frac{qN_AW}{K_S\varepsilon_0}$$

1) $$\frac{1}{2}\mathcal{E}_S W = \phi_S$$

2) $$\mathcal{E}_S = \frac{qN_AW}{K_S\varepsilon_0}$$

final answers (semiconductor)

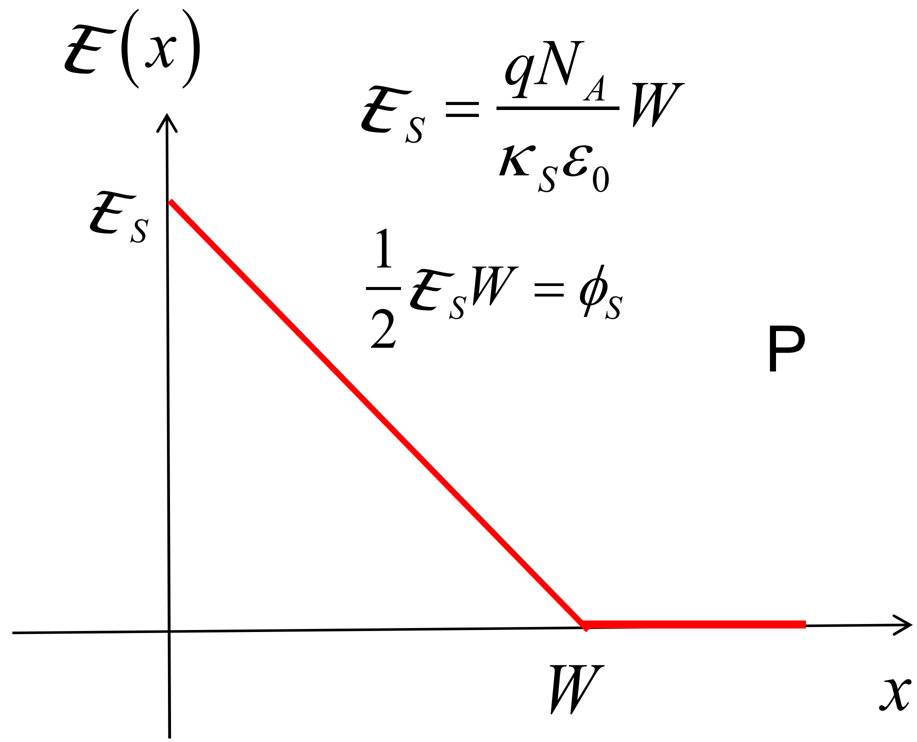
$$W = \sqrt{\frac{2\kappa_S \varepsilon_0 \phi_S}{qN_A}} \text{ cm}$$

$$\mathcal{E}_S = \sqrt{\frac{2qN_A \phi_S}{\kappa_s \varepsilon_0}} \text{ V/cm}$$

$$Q_B = -qN_A W(\phi_S) \text{ C/cm}^2$$

$$Q_B(\phi_S) = -\sqrt{2q\kappa_s \varepsilon_0 N_A \phi_S} \text{ C/cm}^2$$

$$0 < \phi_S < 2\phi_F$$



$$\mathcal{E}_S = \frac{qN_A}{\kappa_S \varepsilon_0} W$$

$$\frac{1}{2}\mathcal{E}_S W = \phi_S$$

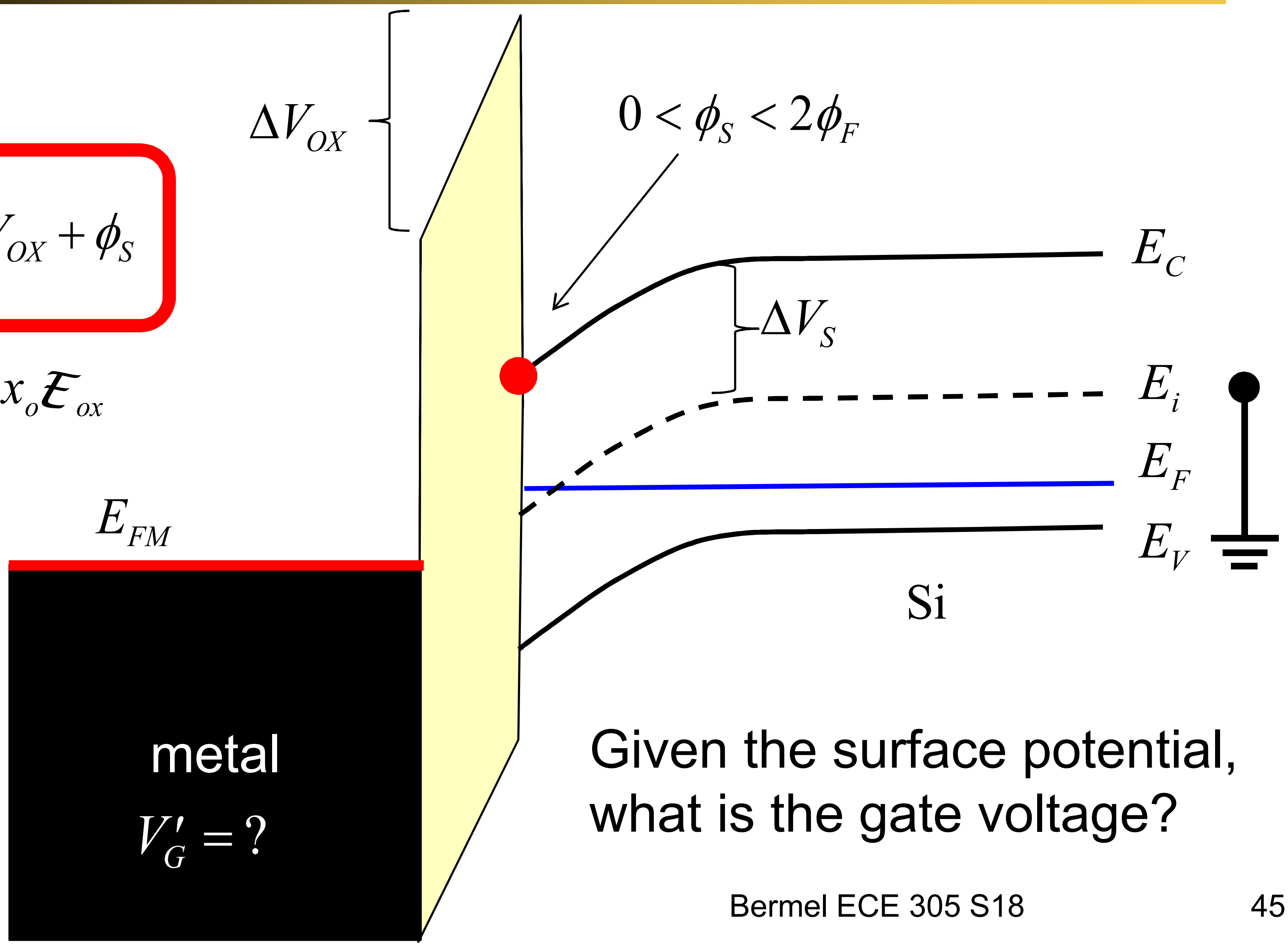
P

What gate voltage produced this surface potential?

gate voltage and surface potential

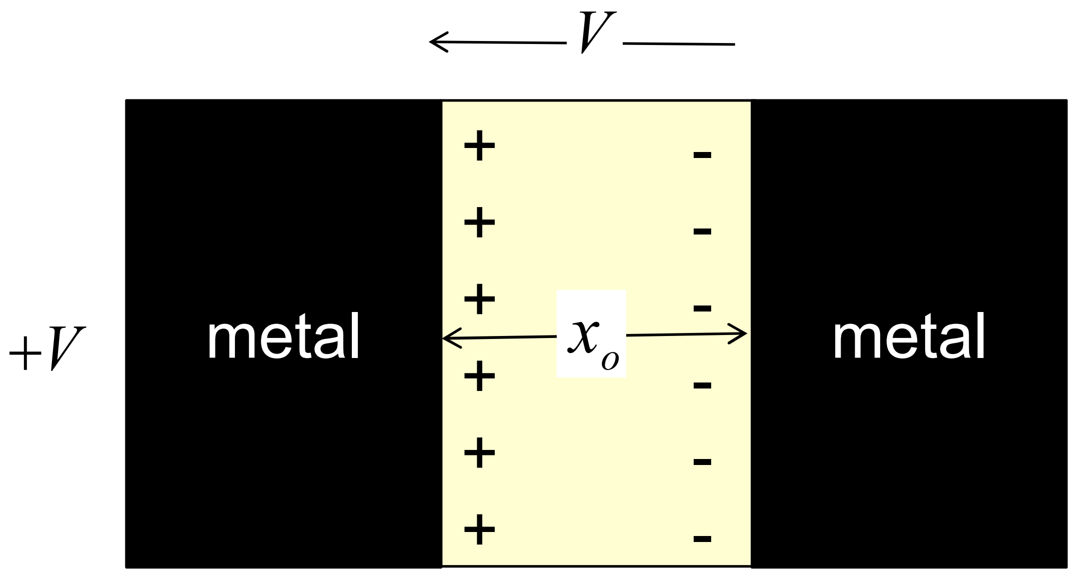
$$V_G' = \Delta V_{OX} + \phi_S$$

$$\Delta V_{ox} = x_o \mathcal{E}_{ox}$$



Given the surface potential, what is the gate voltage?

voltage drop across a capacitor



$$C_{ox} = -\frac{Q/A}{V}$$

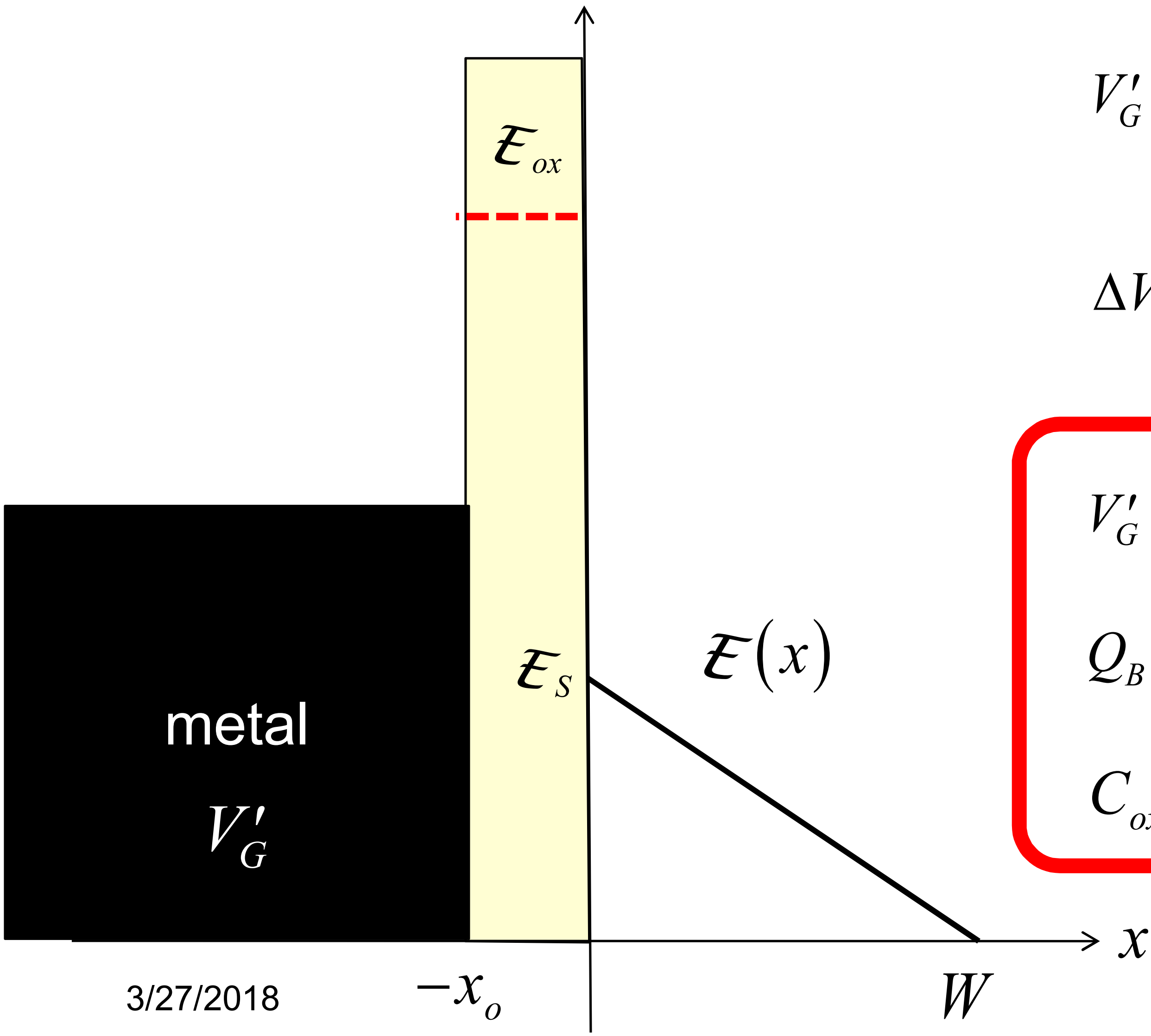
$$V = -\frac{Q/A}{C_{ox}}$$

$$C \equiv \frac{Q}{V} = \frac{K_O \varepsilon_0 A}{x_o} = \text{F}$$

Q/A C/cm^2

$$\frac{C}{A} \equiv \frac{Q/A}{V} = \frac{K_O \varepsilon_0}{x_o} = C_{ox} \ \text{F/cm}^2$$

relation to gate voltage



$$V_G' = \Delta V_{ox} + \phi_S$$

$$\Delta V_{ox} = \frac{-Q_B(\phi_S)}{C_{OX}}$$

$$V_G' = -\frac{Q_B(\phi_S)}{C_{ox}} + \phi_S$$

$$Q_B(\phi_S) = -qN_A W(\phi_S)$$

$$C_{ox} = K_O \varepsilon_0 / x_o$$

summary

$$W = \sqrt{\frac{2\kappa_S \varepsilon_0 \phi_S}{qN_A}} \text{ cm}$$

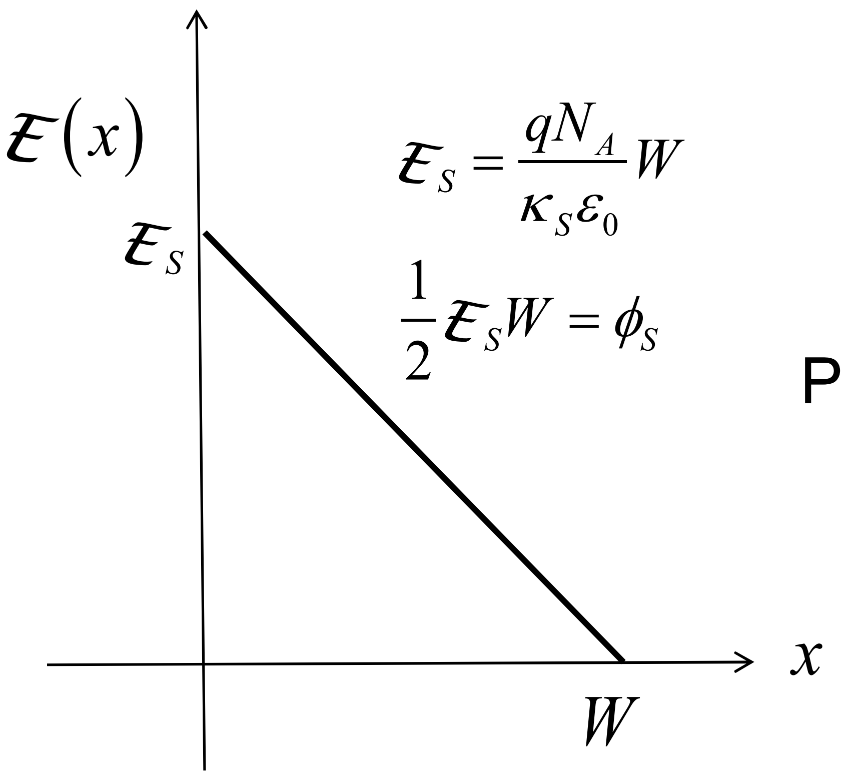
$$\mathcal{E}_S = \sqrt{\frac{2qN_A \phi_S}{\kappa_s \varepsilon_0}} \text{ V/cm}$$

$$Q_B = -qN_A W(\phi_S) \text{ C/cm}^2$$

$$Q_B = -\sqrt{2q\kappa_s \varepsilon_0 N_A \phi_S} \text{ C/cm}^2$$

$$V_G' = -\frac{Q_B(\phi_S)}{C_{ox}} + \phi_S$$

$$0 < \phi_S < 2\phi_F$$



$$\mathcal{E}_S = \frac{qN_A}{\kappa_S \varepsilon_0} W$$

$$\frac{1}{2}\mathcal{E}_S W = \phi_S$$

P

conclusions

- Introducing an oxide layer between a metal and semiconductor creates a new type of band structure
- This also allows for a new type of device, known as a metal-oxide-semiconductor field effect transistor (MOSFET)
- Discussed the primary MOS operational regimes: flat band, accumulation, depletion, and inversion
- The depletion approximation allows us to calculate the charge distribution and surface potentials of each regime
- This can then be translated into gate voltage thresholds