University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

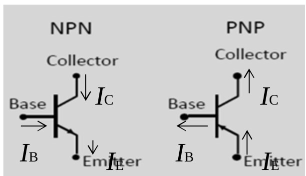
VE 320 – Summer 2012
Introduction to Semiconductor Device

MOS Electrostatics

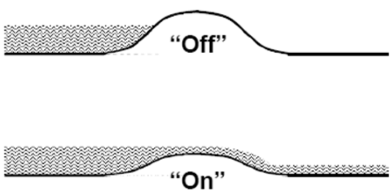
Instructor: Professor Hua Bao

BJT Analogy

Goal: Control output with small input



Analogy: Bump controls water flow



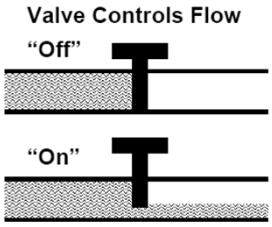
Input controls bump height
Output = water flow

Electronics analogy

Water flow = electron or hole current
Bump = electronic potential

FET Analogy

Analogy: Valve controls water flow



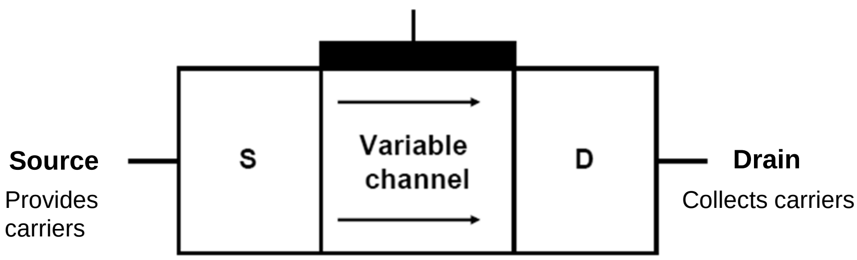
- Input controls aperture
- Output = water flow

Electronics analogy

- **Water flow = electron or hole current**
- **Valve = channel conductance controlled by electric field**

Field Effect Transistor

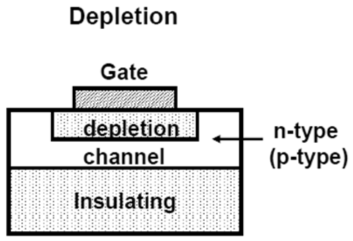
Gate
Controls conductance of channel through application of electric field

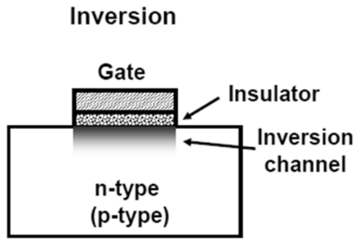


Control source to drain current with gate voltage

Gates For FETs

How do we control conductance of a channel?

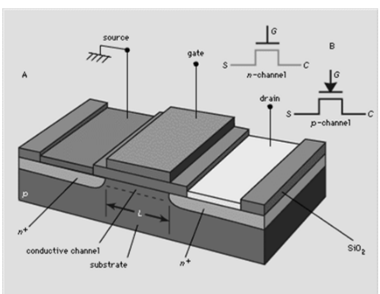


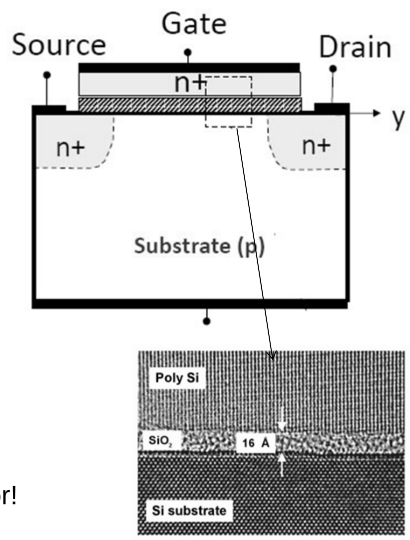


- Field controls depletion width, channel depth
- Reverse-bias p-n (JFET)
- Reverse-bias Schottky(MESFET)

- Field inverts surface, controls surface charge density
- Metal-Insulator-Semiconductor (MISFET, MOSFET)

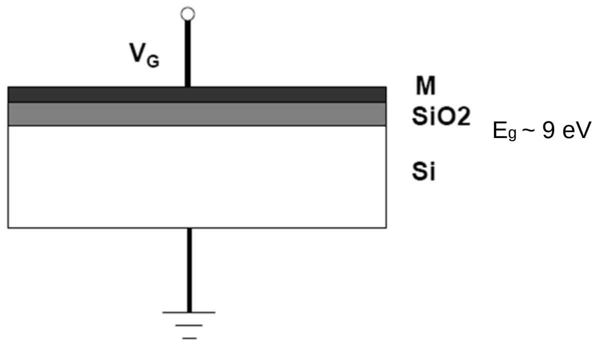
Basic Configuration of a MOSFET





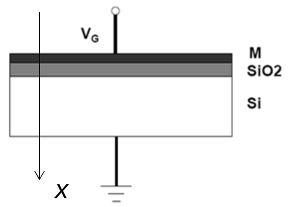
Four terminal device.
Almost like a lateral bipolar transistor!

MOS Capacitor

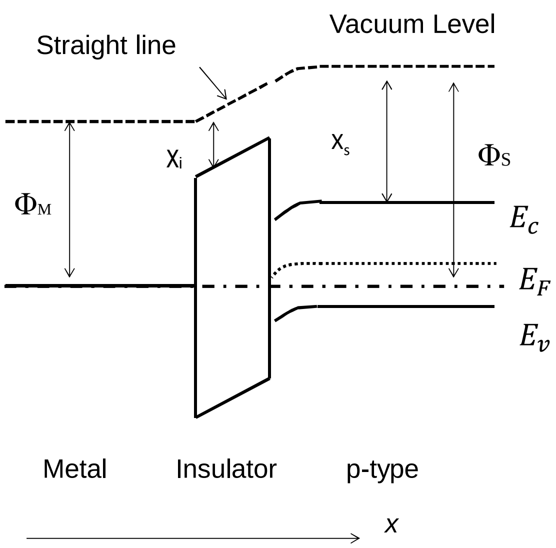


In order to understand the operation of MOSFET, we need to understand MOS capacitor first.

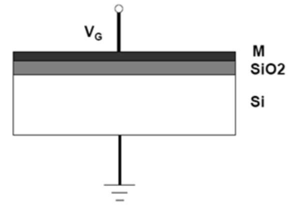
Electrostatics (Band Diagram)

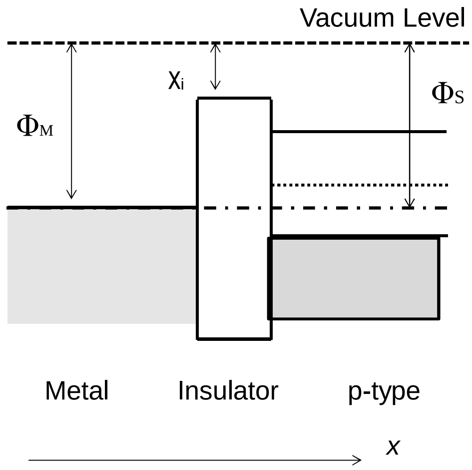


Schottky barrier with an interposed dielectric



Idealized MOS Capacitor

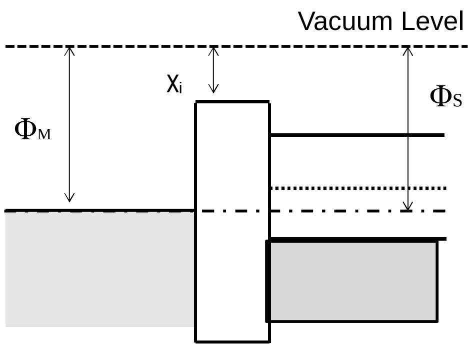


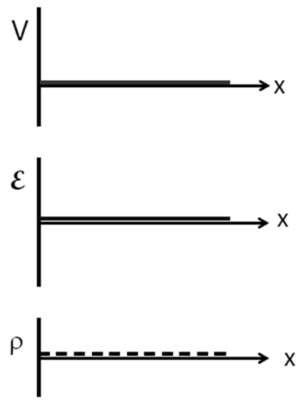


Assume $\Phi_M = \Phi_S$

It is unnecessary to make this assumption but this helps to simplify the analysis.

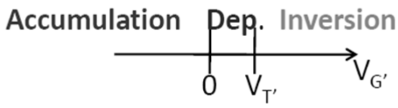
Potential, Field, Charges

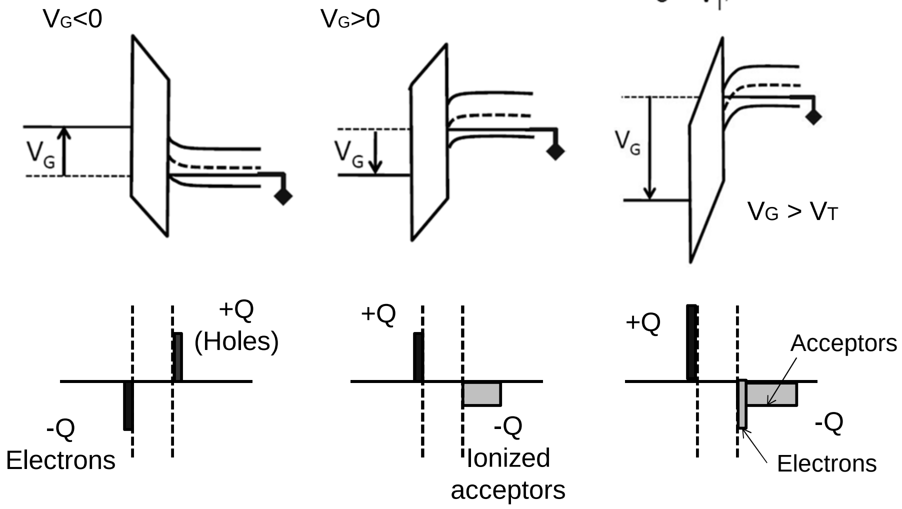




No net charge! $V_{bi}=0$

Under Bias

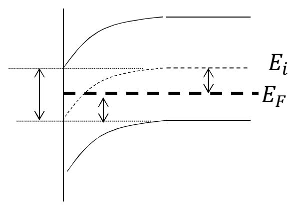


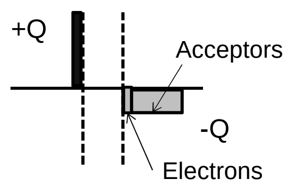


A Few Notes

- Quasi-Fermi Level is flat (no current!)
- Large potential drop in the insulator
- Onset of inversion, at V_T

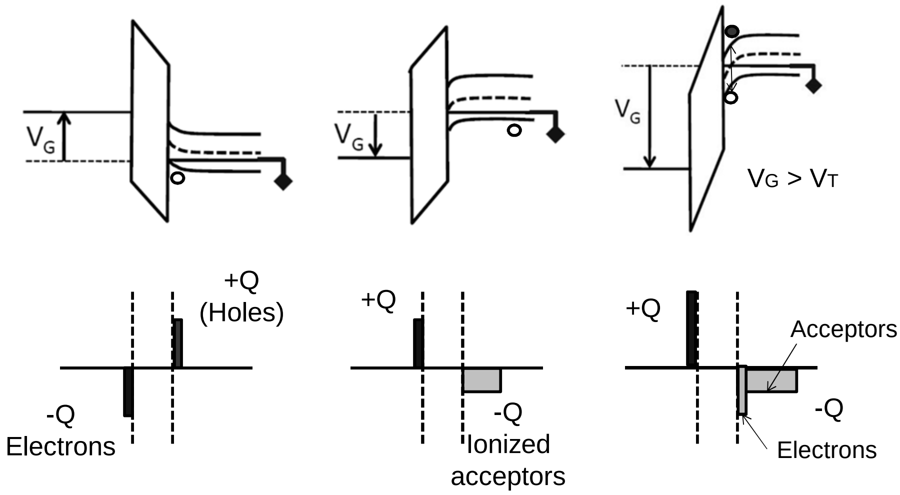
$$\boxed{E_i(\text{surface}) - E_i(\text{bulk}) = 2[E_F - E_i(\text{bulk})]}$$



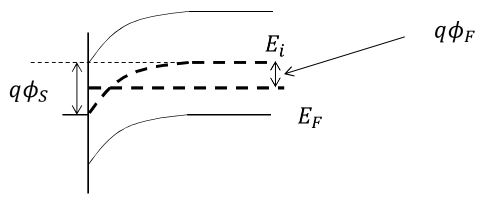


$$n(\text{surface}) = n_i e^{[E_i - E_F]/kT} = p(\text{bulk}) = N_D$$

Where do charges come from?



Before Quantitative Analysis…



$$\phi_S = \frac{1}{q}\left[E_i(bulk) - E_i(surface)\right]$$

$$\phi_F = \frac{1}{q}\left[E_i(bulk) - E_F\right]$$

Surface potential
not semiconductor
workfunction

Potential related to doping

Inversion Condition

What is φF for a given doping level?

p-type Semiconductor

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

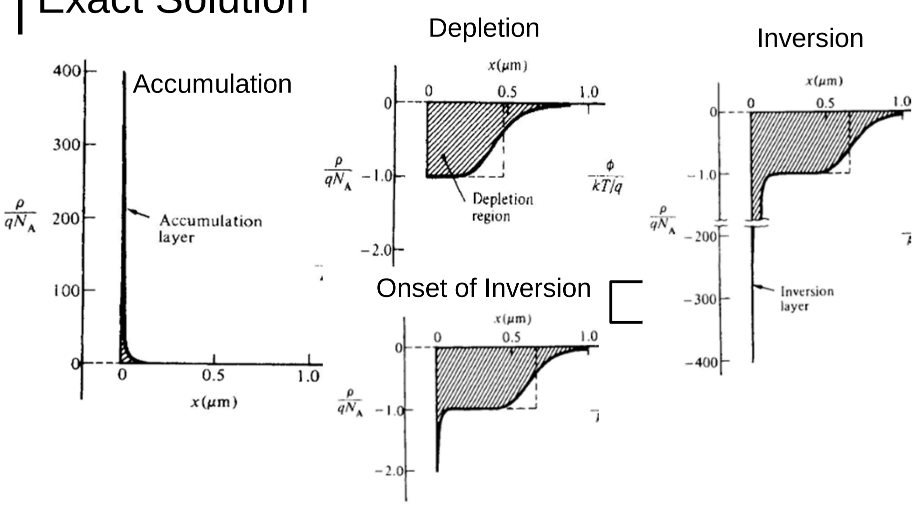
n-type Semiconductor

$$\phi_F = -\frac{kT}{q}\ln\left(N_D/n_i\right)$$

Inversion condition $\boxed{\phi_S = 2\phi_F}$

Accumulation: $\phi_S < 0$
Depletion: $0 < \phi_S < 2\phi_F$
Inversion: $\phi_S > 2\phi_F$

Exact Solution



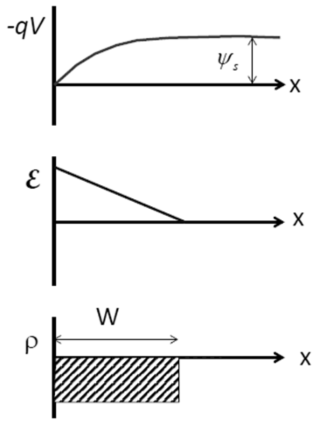
We can invoke the depletion approximation. The mobile charges can be treated as a delta function.

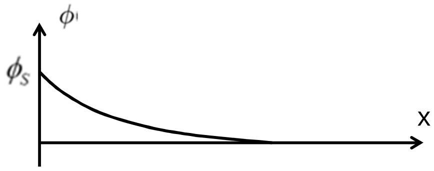
(Depletion) Potential, Field, Charges

$$\rho = -qN_A$$

$$\mathscr{E}(x) = -\frac{d\phi}{dx} = \frac{qN_A}{K_S\varepsilon_0}(W - x)$$

$$\phi(x) = \frac{qN_A}{2K_S\varepsilon_0}(W - x)^2$$





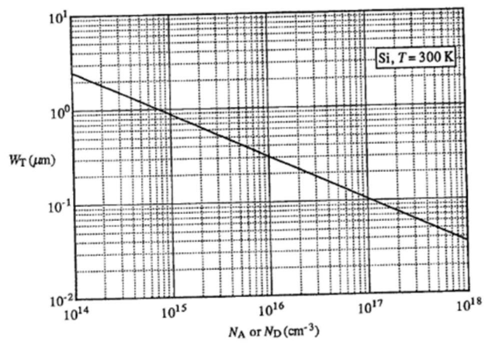
Maximum Depletion Width

Depletion width changes slowly beyond inversion

$$W = \left[\frac{2K_S\varepsilon_0}{qN_A}\phi_S\right]^{1/2}$$

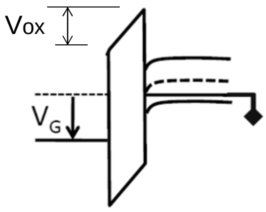
At inversion transition

$$W_T = \left[\frac{2K_S\varepsilon_0}{qN_A}(2\phi_F)\right]^{1/2}$$



Gate Voltage

Voltage drop $V_G = \phi_S + V_{ox}$



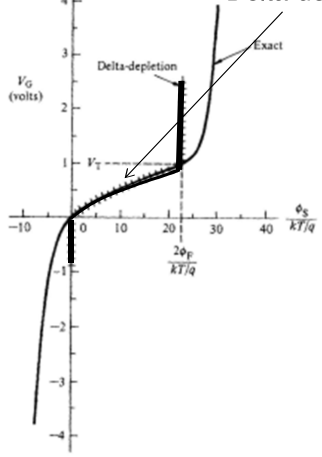
No charge in the oxide $\mathscr{E}_{ox} = \dfrac{K_S}{K_O}\mathscr{E}_S$

$$V_G = \phi_S + \frac{K_S}{K_O} x_o \mathscr{E}_S$$

$$\mathscr{E}_S = \left[\frac{2qN_A}{K_S\varepsilon_0}\phi_S\right]^{1/2} \Rightarrow V_G = \phi_S + \frac{K_S}{K_O} x_o \sqrt{\frac{2qN_A}{K_S\varepsilon_0}\phi_S}$$

Exact Solution

Delta-depletion

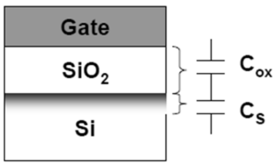


- Φ_S changes with V_G in the depletion bias
- For accumulation and inversion, potential drop is mostly across the oxide layer
- Depletion bias is only 1 V in extent
- Electrical property of the semiconductor changes drastically over a narrow range of voltages.

C-V Characteristics

MOS: 2 capacitors in series

- Oxide capacitance
- Semiconductor capacitance

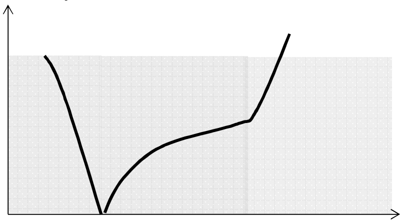


$$C = \frac{C_O C_S}{C_O + C_S}$$

$$C_O = \frac{K_O \varepsilon_0 A_G}{x_o}$$

$$C_S = \frac{K_S \varepsilon_0 A_G}{W}$$

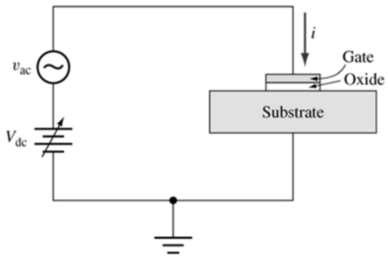
Q_S (log scale)

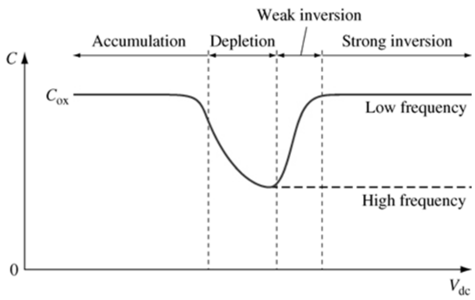


Φ_S

accumulation Depletion Inversion

Capacitance





Accumulation: majority carrier response very fast to applied bias
Inversion: the R-G of minority carriers are slower

C=

C_O	$\dfrac{C_O}{1+\frac{K_O W}{K_S x_o}}$	C_O	$\dfrac{C_O}{1+\frac{K_O W_T}{K_S x_o}}$
acc	depl	Inv (low f)	Inv (high f)

Depletion

With depletion bias, C is a function of W.

C= $\dfrac{C_O}{1+\frac{K_O W}{K_S x_o}}$

It should be expressed in terms of V_G

$$W = \frac{K_S}{K_O} x_o \left[\sqrt{1+\frac{V_G}{V_\delta}} - 1\right]$$

$$V_\delta = \frac{q}{2}\frac{K_S x_o^2}{K_O^2 \varepsilon_0} N_A$$

$$C = \frac{C_O}{\sqrt{1+V_G/V_\delta}}$$ (depletion bias)

Doping and Oxide Thickness