EECS130
Integrated Circuit Devices

Professor Ali Javey

12/6/07

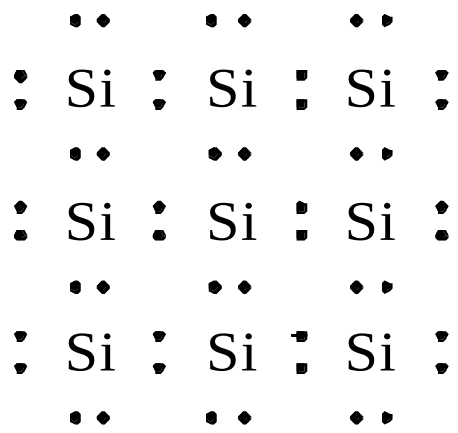
<u>Course Review</u>

EE130 in one day!

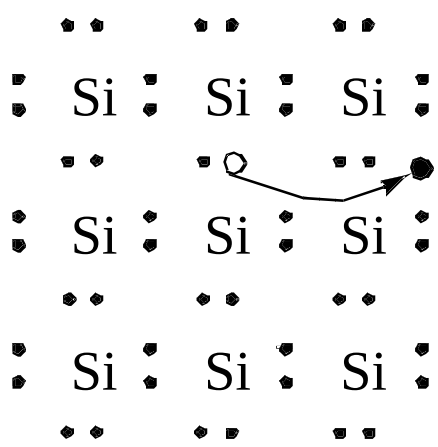
Announcements

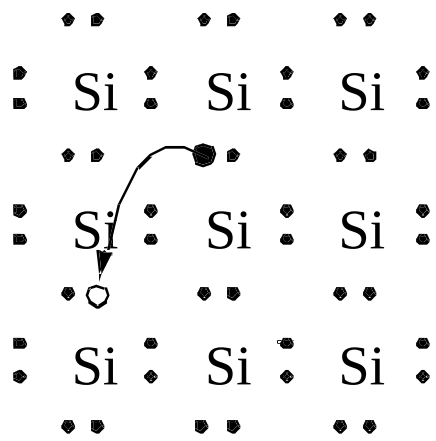
- The final exam is scheduled for Friday, December 14, from 12:30 - 3:30 PM in Rm. 277 Cory.
- The review will be held on Wednesday, December 12, from 6:30 - 8:30 PM (room TBA).
- Project reports are due today!

Bond Model of Electrons and Holes (Intrinsic Si)



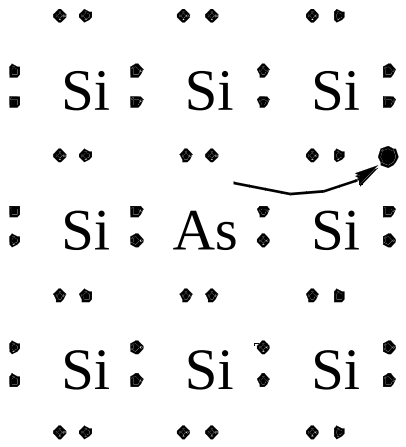
- Silicon crystal in a two-dimensional representation.



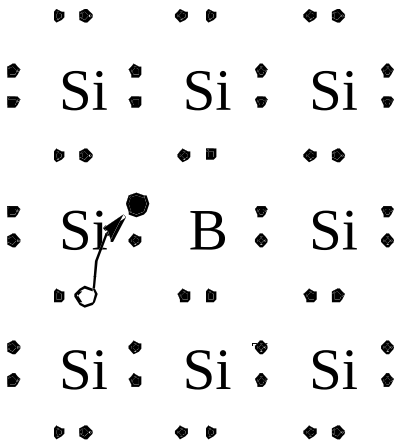


- When an electron breaks loose and becomes a ***conduction electron***, a ***hole*** is also created.

Dopants in Silicon



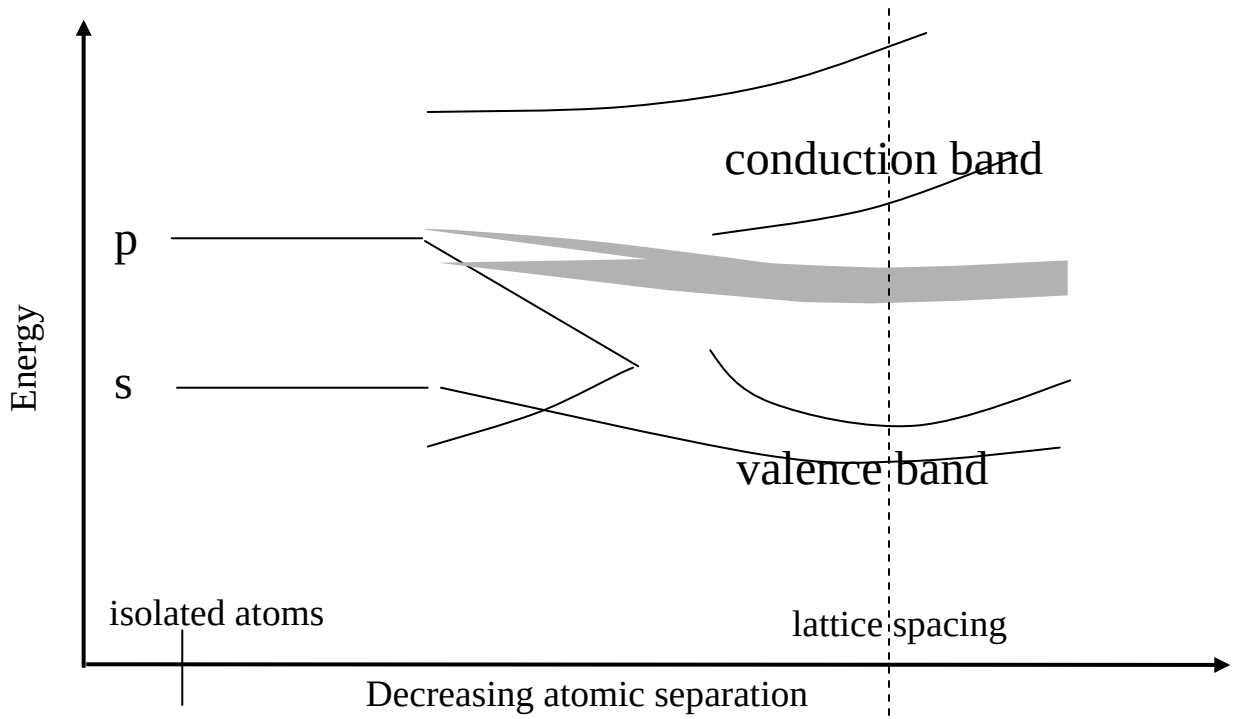
N-type Si



P-type Si

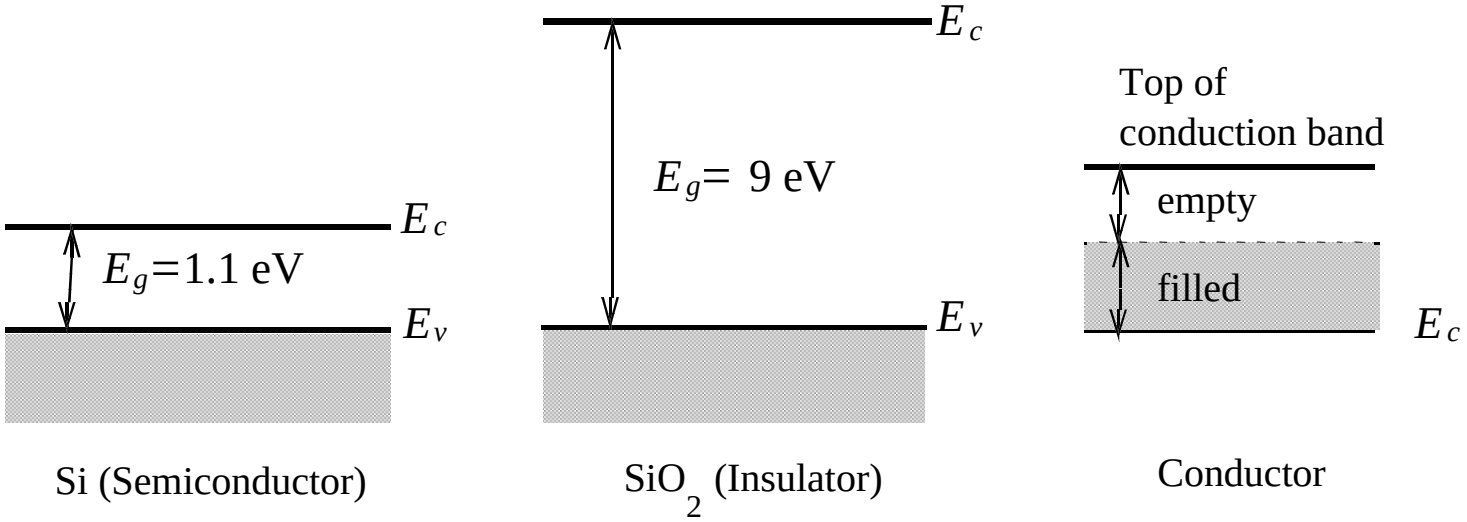
- As (Arsenic), a Group V element, introduces conduction electrons and creates ***N-type silicon,*** and is called a ***donor.***
- B (Boron), a Group III element, introduces holes and creates ***P-type silicon***, and is called an ***acceptor***.
- Donors and acceptors are known as dopants.

From Atoms to Crystals



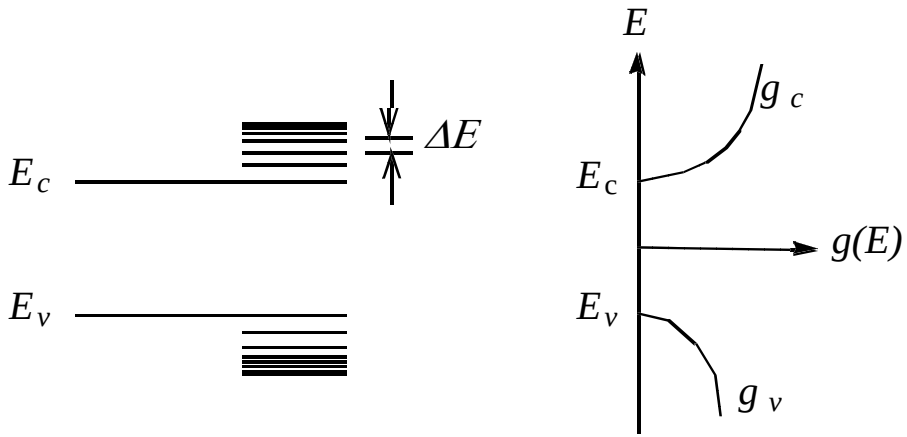
- Energy states of Si atom (a) expand into energy bands of Si crystal (b).
- The lower bands are filled and higher bands are empty in a semiconductor.
- The highest filled band is the ***valence band.***
- The lowest empty band is the ***conduction band*** .

Semiconductors, Insulators, and Conductors



- Totally filled bands and totally empty bands do not allow current flow. (Just as there is no motion of liquid in a totally filled or totally empty bottle.)
- Metal conduction band is half-filled.
- Semiconductors have lower E_g's than insulators and can be doped.

Density of States



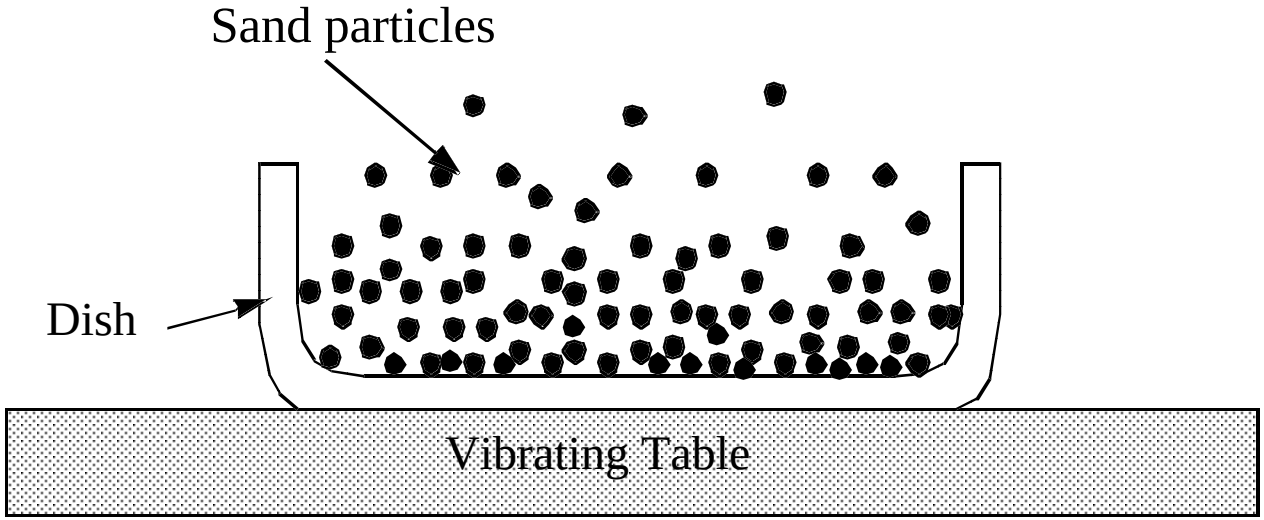
$$g_c(E) \equiv \frac{\text{number of states in } \Delta E}{\Delta E \cdot \text{volume}} \quad \left(\frac{1}{\text{eV} \cdot \text{cm}^3}\right)$$

$$g_c(E) \equiv \frac{m_n^* \sqrt{2m_n^*\left(E - E_c\right)}}{\pi^2 \hbar^3}$$

$$g_v(E) \equiv \frac{m_p^* \sqrt{2m_p^*\left(E_v - E\right)}}{\pi^2 \hbar^3}$$

Thermal Equilibrium

An Analogy for Thermal Equilibrium



- There is a certain probability for the electrons in the conduction band to occupy high-energy states under the agitation of thermal energy (vibrating atoms, etc.)

Fermi Function

Probability that an available state at energy E is occupied:

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

E_F is called the ***Fermi energy*** or the ***Fermi level***

There is only one Fermi level in a system at equilibrium.

At $E = E_F$, $f(E) = 1/2$

Equilibrium Carrier Concentrations

- Integrate $n(E)$ over all the energies in the conduction band to obtain n

$$n = \int_{E_c}^{\text{top of conduction band}} g_c(E) f(E) dE$$

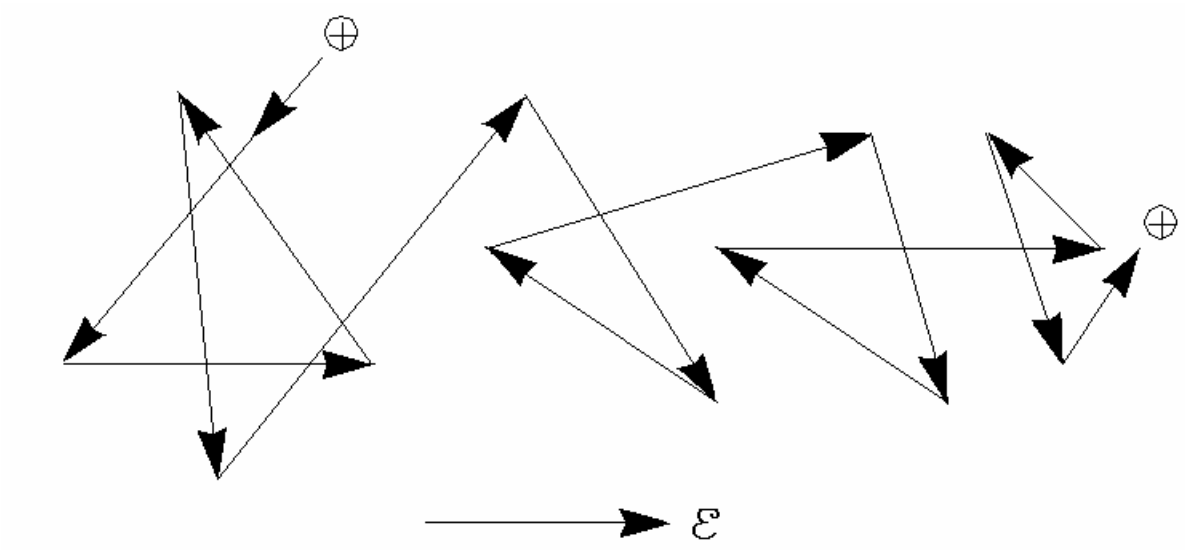
- By using the Boltzmann approximation, and extending the integration limit to ∞, we obtain

$$n = N_c e^{-(E_c - E_F)/kT} \quad \text{where} \quad N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

N_c is called the ***effective density of states (of the conduction band)*** .

Drift

Electron and Hole Mobilities



- ***Drift*** is the motion caused by an electric field.

Electron and Hole Mobilities

$$m_p v = q\mathcal{E}\tau_{mp}$$

$$v = \frac{q\mathcal{E}\tau_{mp}}{m_p}$$

$$v = \mu_p \mathcal{E}$$

$$\mu_p = \frac{q\tau_{mp}}{m_p}$$

$$v = -\mu_n \mathcal{E}$$

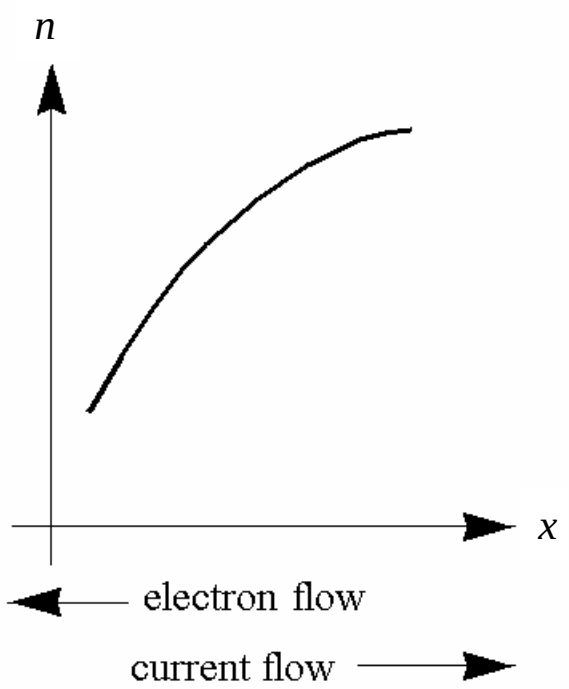
$$\mu_n = \frac{q\tau_{mn}}{m_n}$$

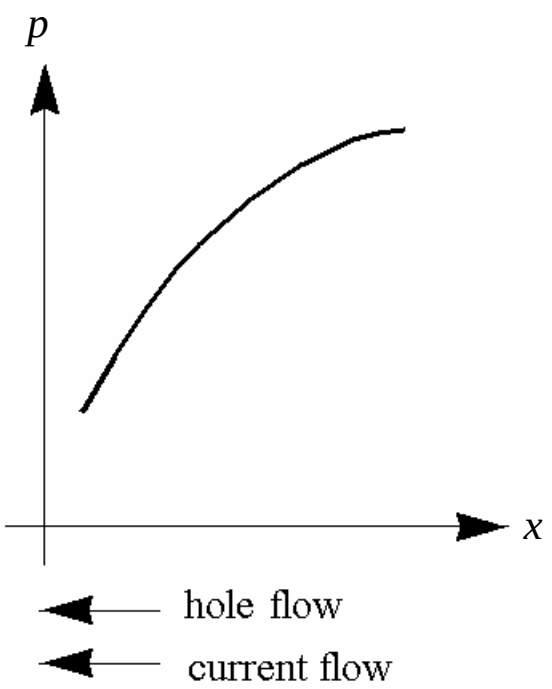
- μ_p is the hole mobility and μ_n is the electron mobility

Diffusion Current

$$J_{n,diffusion} = qD_n \frac{dn}{dx} \qquad J_{p,diffusion} = -qD_p \frac{dp}{dx}$$

D is called the diffusion constant. Signs explained:





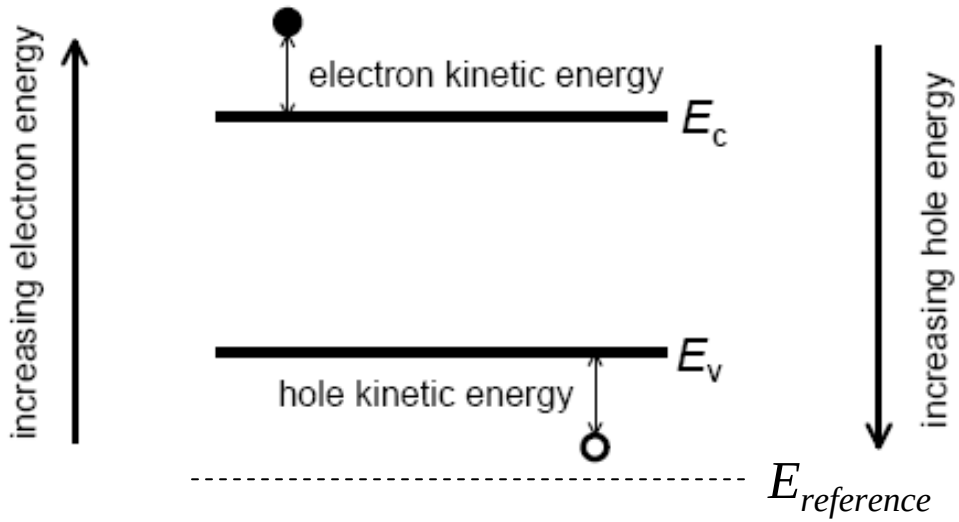
Total Current – Review of Four Current Components

$$J_{TOTAL} = J_n + J_p$$

$$J_n = J_{n,drift} + J_{n,diffusion} = qn\mu_n\mathcal{E} + qD_n \frac{dn}{dx}$$

$$J_p = J_{p,drift} + J_{p,diffusion} = qp\mu_p\mathcal{E} - qD_p \frac{dp}{dx}$$

Band Diagram: Potential *vs.* Kinetic Energy



E_c represents the electron potential energy:

$$\text{P.E.} = E_c - E_{\text{reference}}$$

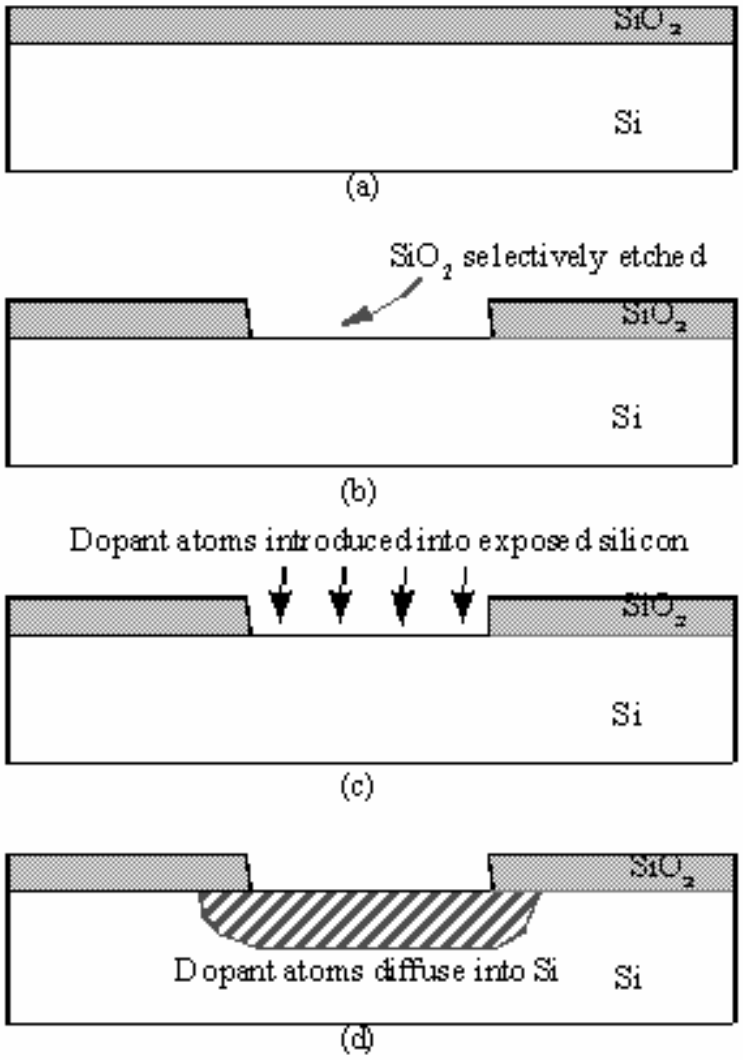
Introduction to Device Fabrication

Oxidation

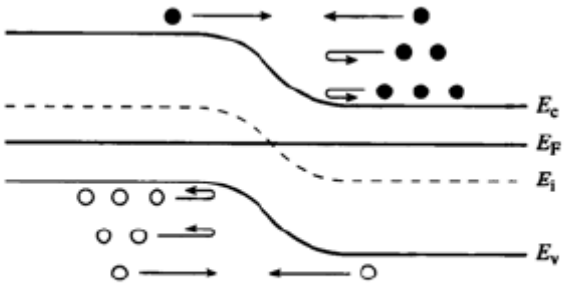
Lithography & Etching

Ion Implantation

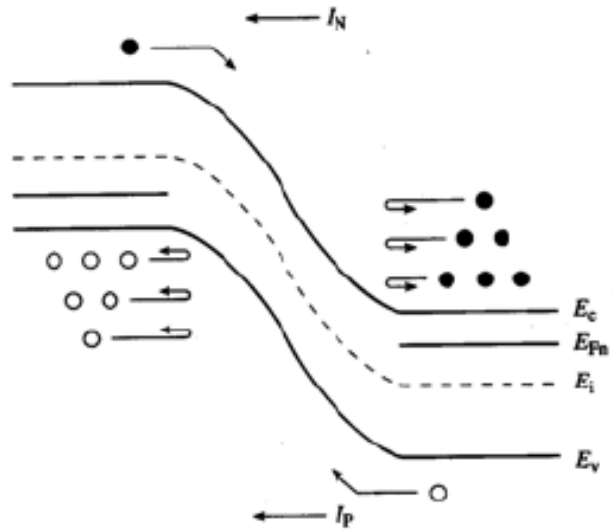
Annealing & Diffusion



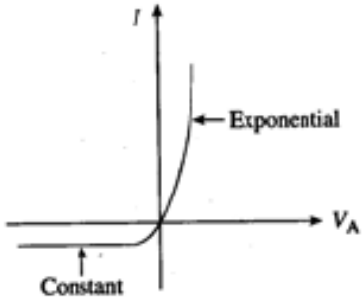
Reverse-Biased PN Junction



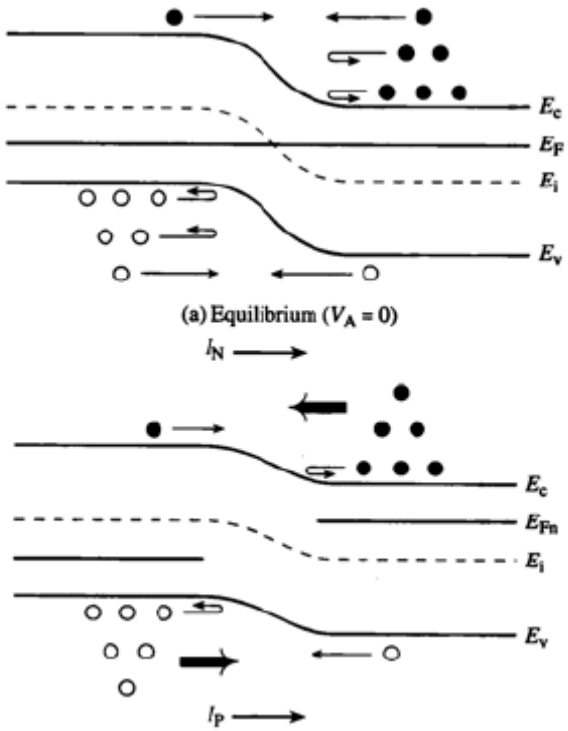
(a) Equilibrium ($V_A = 0$)



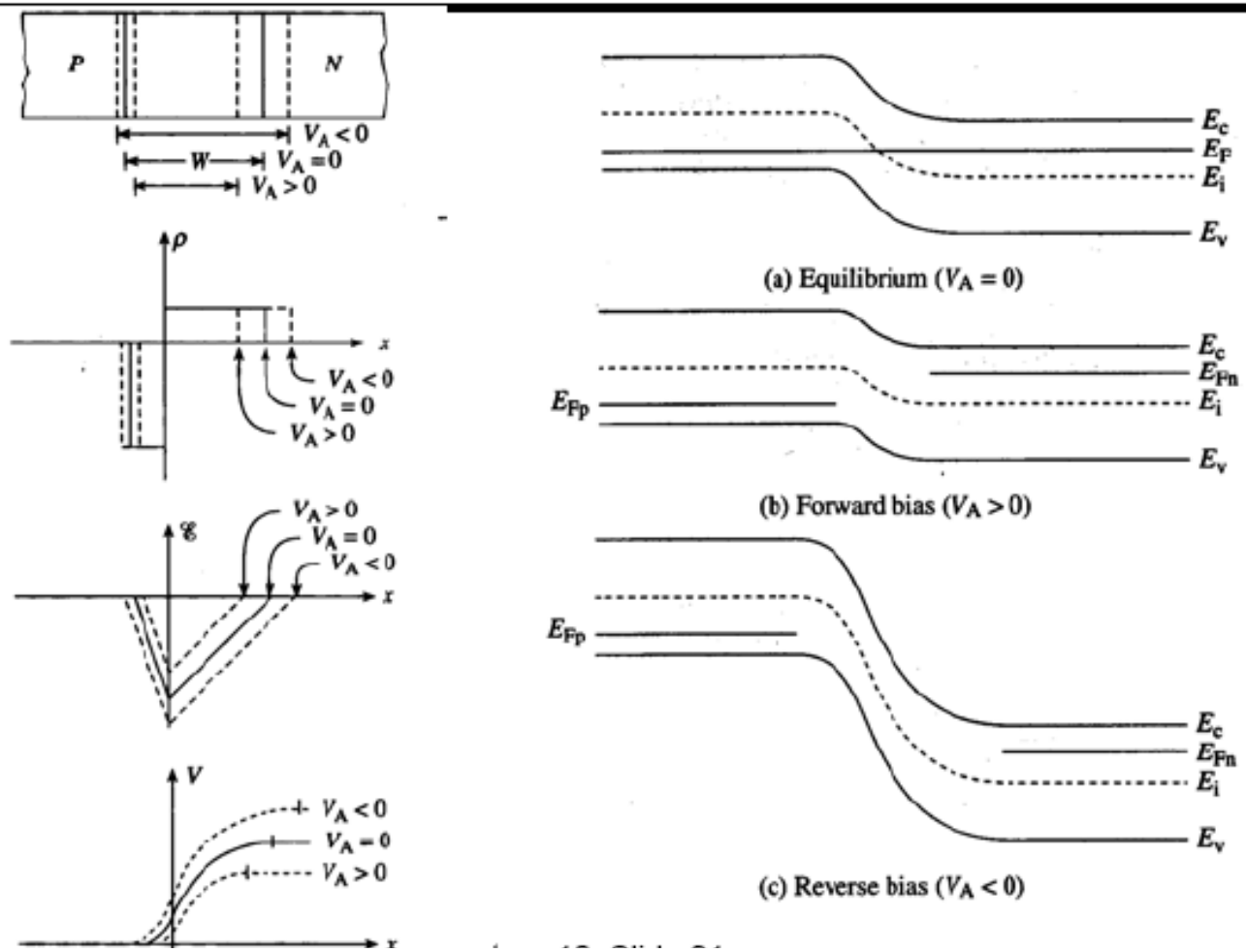
(c) Reverse bias ($V_A < 0$)



Forward Biased PN Junction

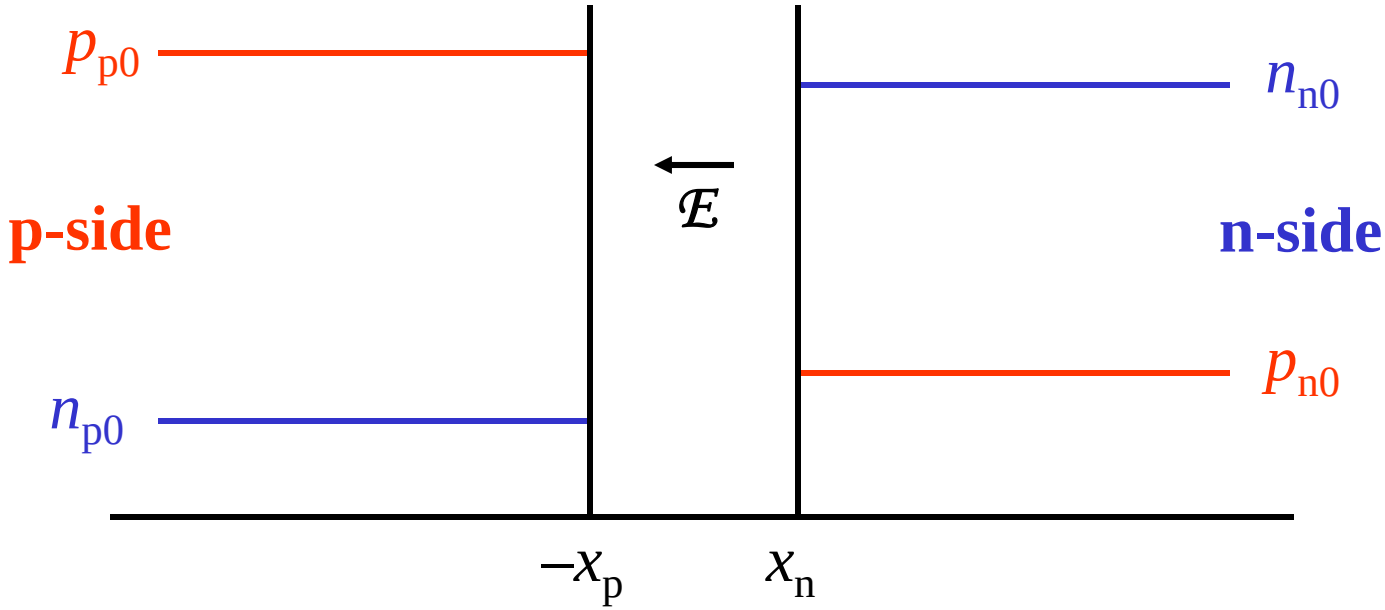


Effect of Bias on Electrostatics



Note: simply replace V_{bi} with V_{bi}-V_A

Carrier Concentrations at Equilibrium



p-side

$$p_{p0}(-x_p) = N_A$$

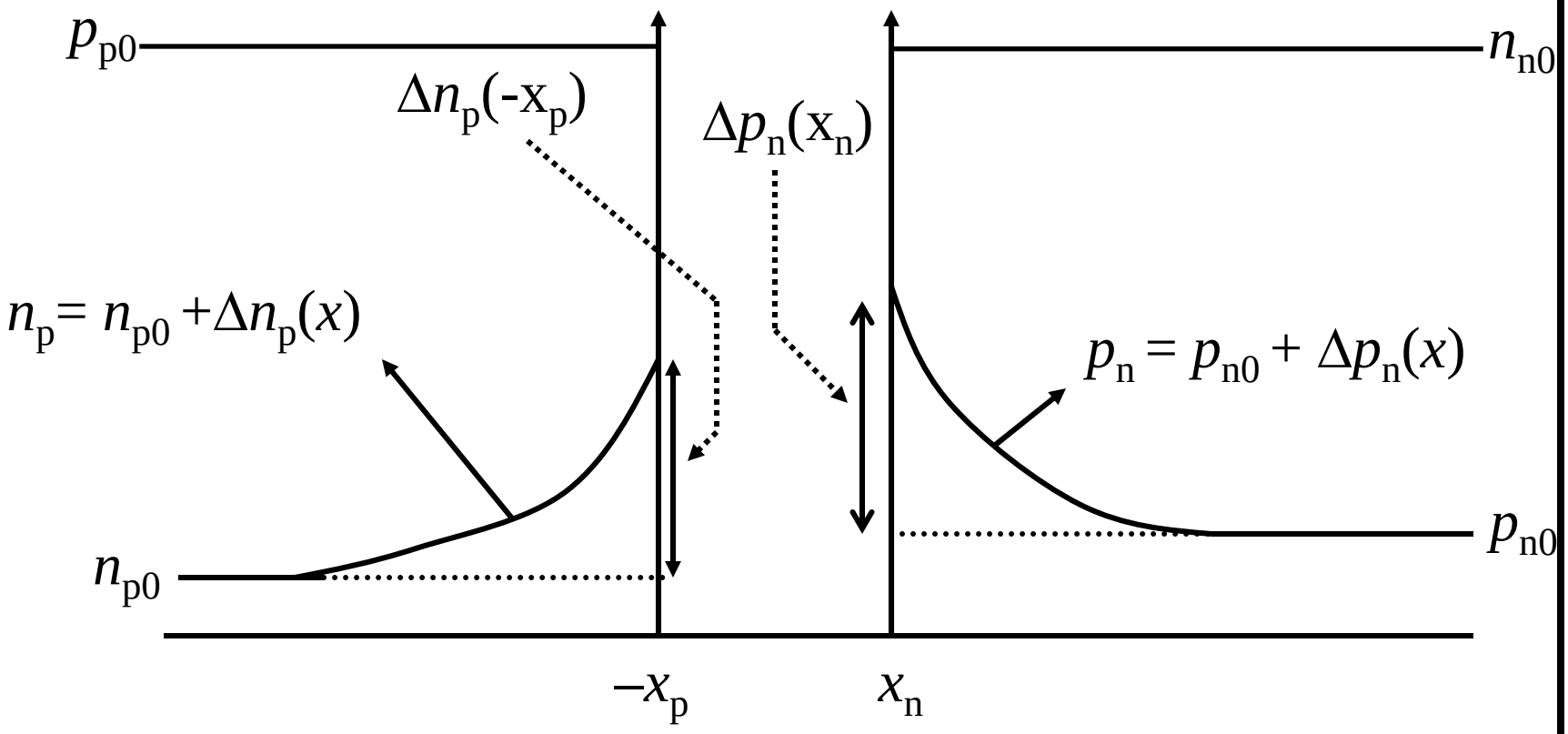
$$n_{p0}(-x_p) = \frac{n_i^2}{N_A}$$

n-side

$$n_{n0}(x_n) = N_D$$

$$p_{n0}(x_n) = \frac{n_i^2}{N_D}$$

Carrier concentration profile under bias



The Junction Law

pn product at the edge of the depletion when junction is biased:

$$pn = n_i^2 e^{qV_A / kT}$$

Excess Carrier Concentrations at $-x_p$, x_n

p-side

$$p_p(-x_p) = N_A$$

$$n_p(-x_p) = \frac{n_i^2 e^{qV_A/kT}}{N_A}$$

$$= n_{p0} e^{qV_A/kT}$$

$$\Delta n_p(-x_p) = \frac{n_i^2}{N_A}\left(e^{qV_A/kT} - 1\right)$$

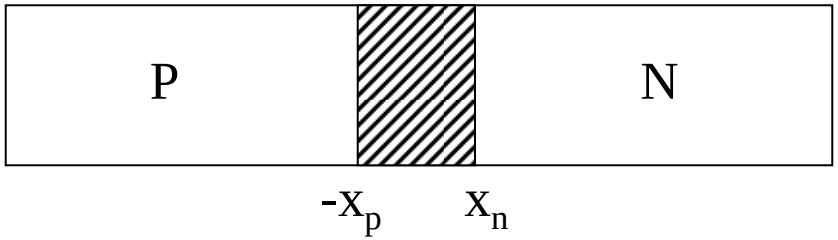
n-side

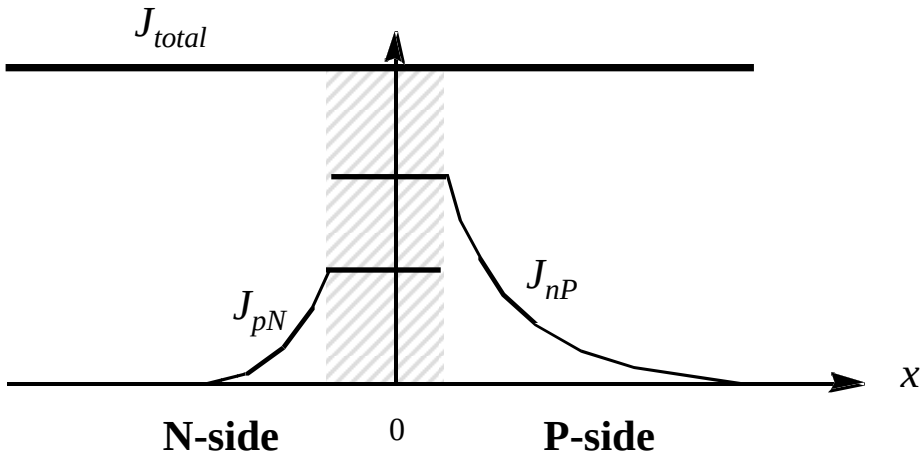
$$n_n(x_n) = N_D$$

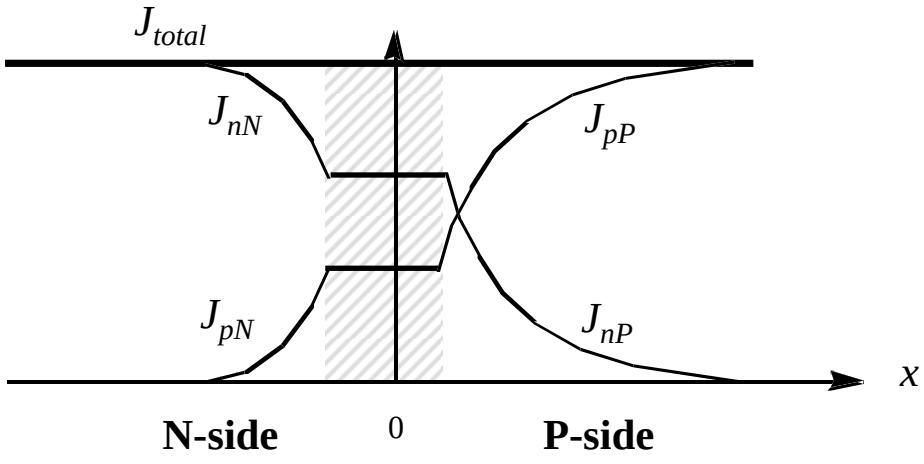
$$p_n(x_n) = \frac{n_i^2 e^{qV_A/kT}}{N_D}$$

$$= p_{n0} e^{qV_A/kT}$$

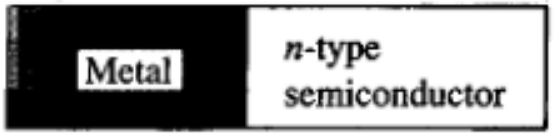
$$\Delta p_n(x_n) = \frac{n_i^2}{N_D}\left(e^{qV_A/kT} - 1\right)$$



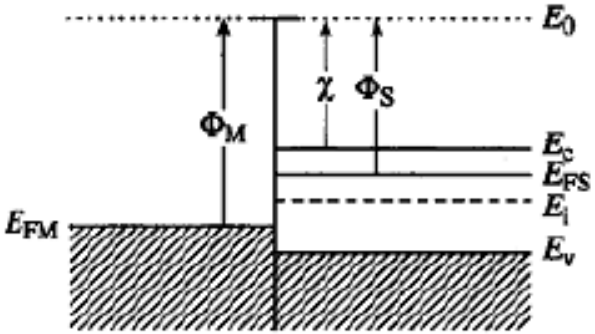

J_{total}
J_{nP}
J_{pN}
x
N-side
0
P-side


J_{total}
J_{nN}
J_{pP}
J_{pN}
J_{nP}
x
N-side
0
P-side

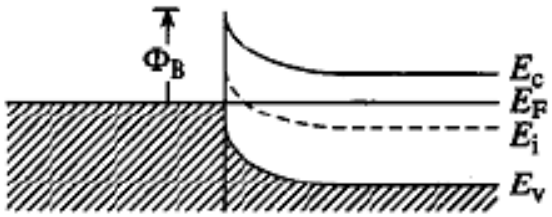
Ideal MS Contact: $\Phi_M > \Phi_S$, n-type



Band diagram instantly after contact formation:



Equilibrium band diagram:

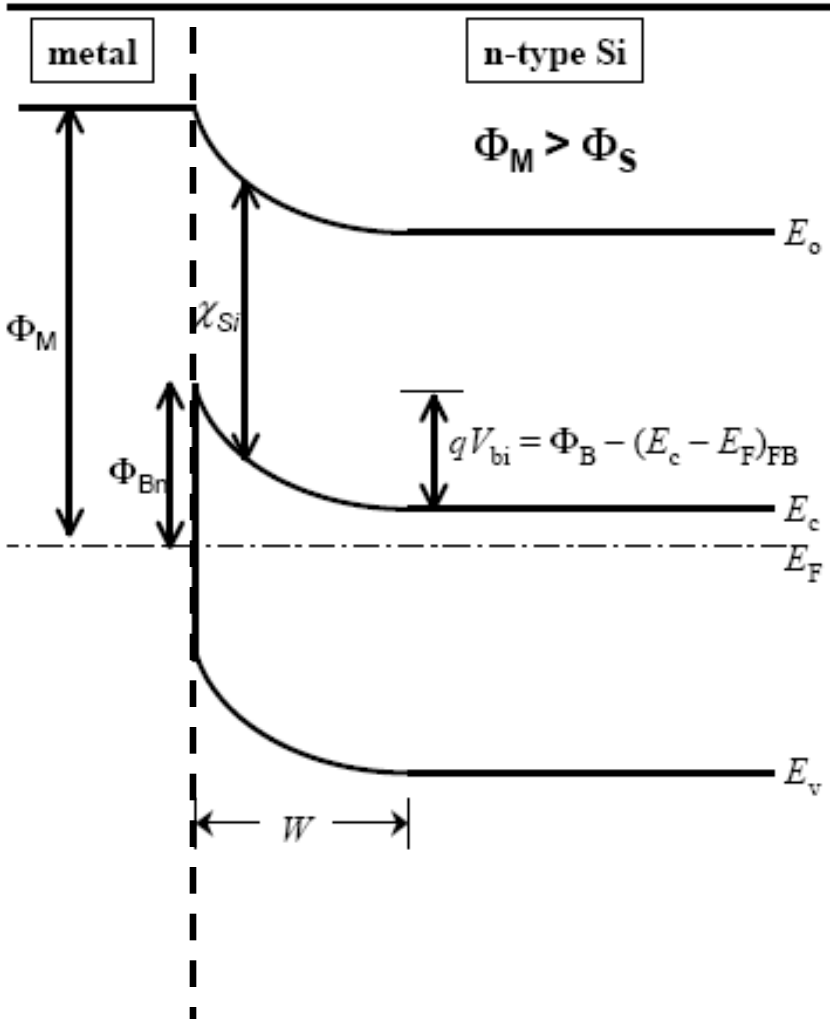


Schottky Barrier **:**

$$\Phi_{Bn} = \Phi_M - \chi$$

Question: how are V_{bi} and Φ_{Bn} related?

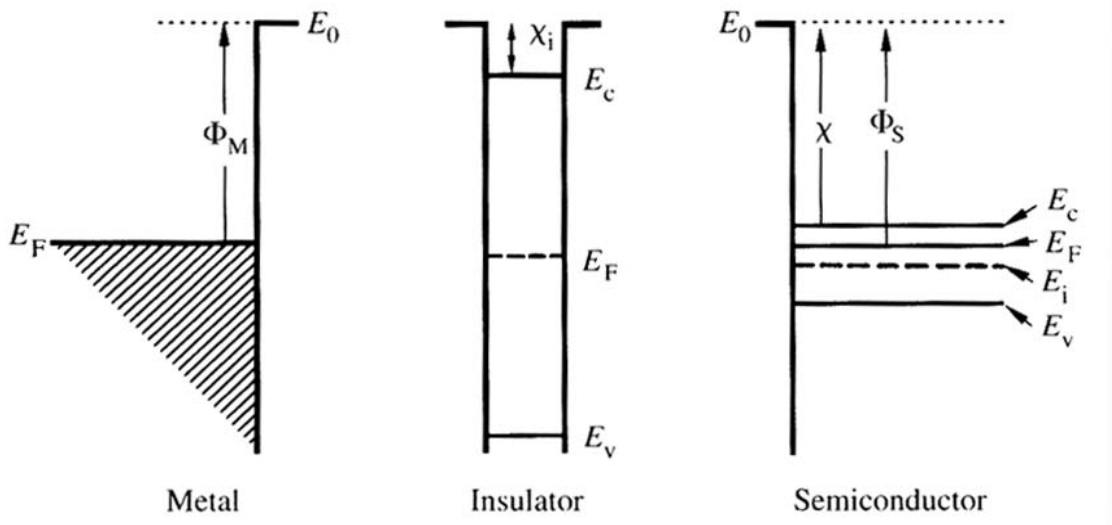
Effect of Interface States on Φ_{Bn}



- **Ideal MS contact:**
  $\Phi_{Bn} = \Phi_M - \chi$
- **Real MS contacts:**
  - A high density of allowed energy states in the band gap at the MS interface pins E_F to the range 0.4 eV to 0.9 eV below E_c

Ideal MOS Capacitor

- Oxide has zero charge, and no current can pass through it.
- No charge centers are present in the oxide or at the oxide-semiconductor interface.
- Semiconductor is uniformly doped
- $\mathbf{\Phi_M = \Phi_S} = \chi + (E_C - E_F)_{FB}$



Ideal MOS Capacitor

At Equilibrium:

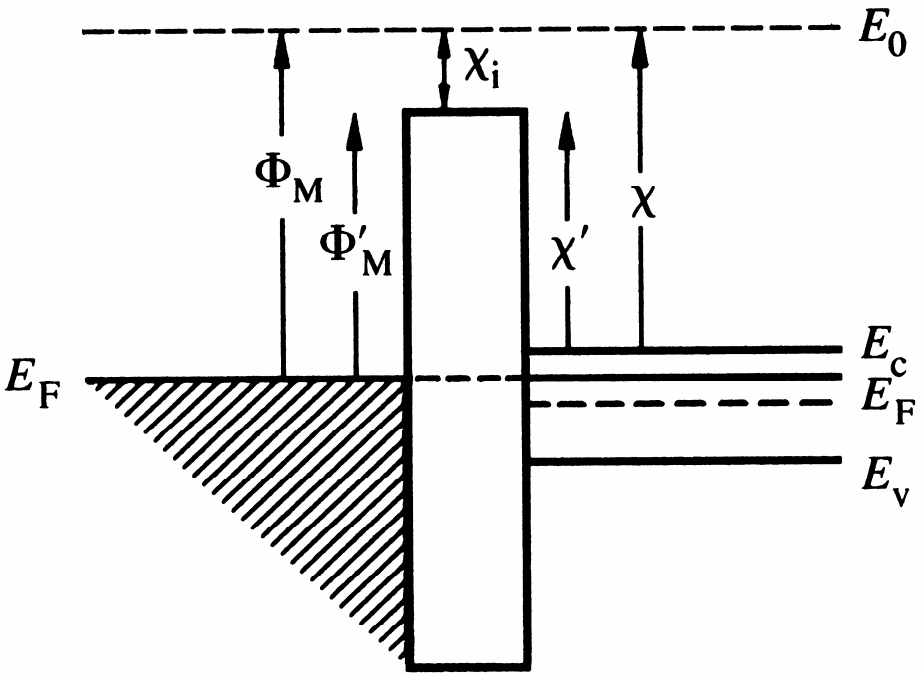


Figure 16.4

Ideal MOS Capacitor

Under Bias

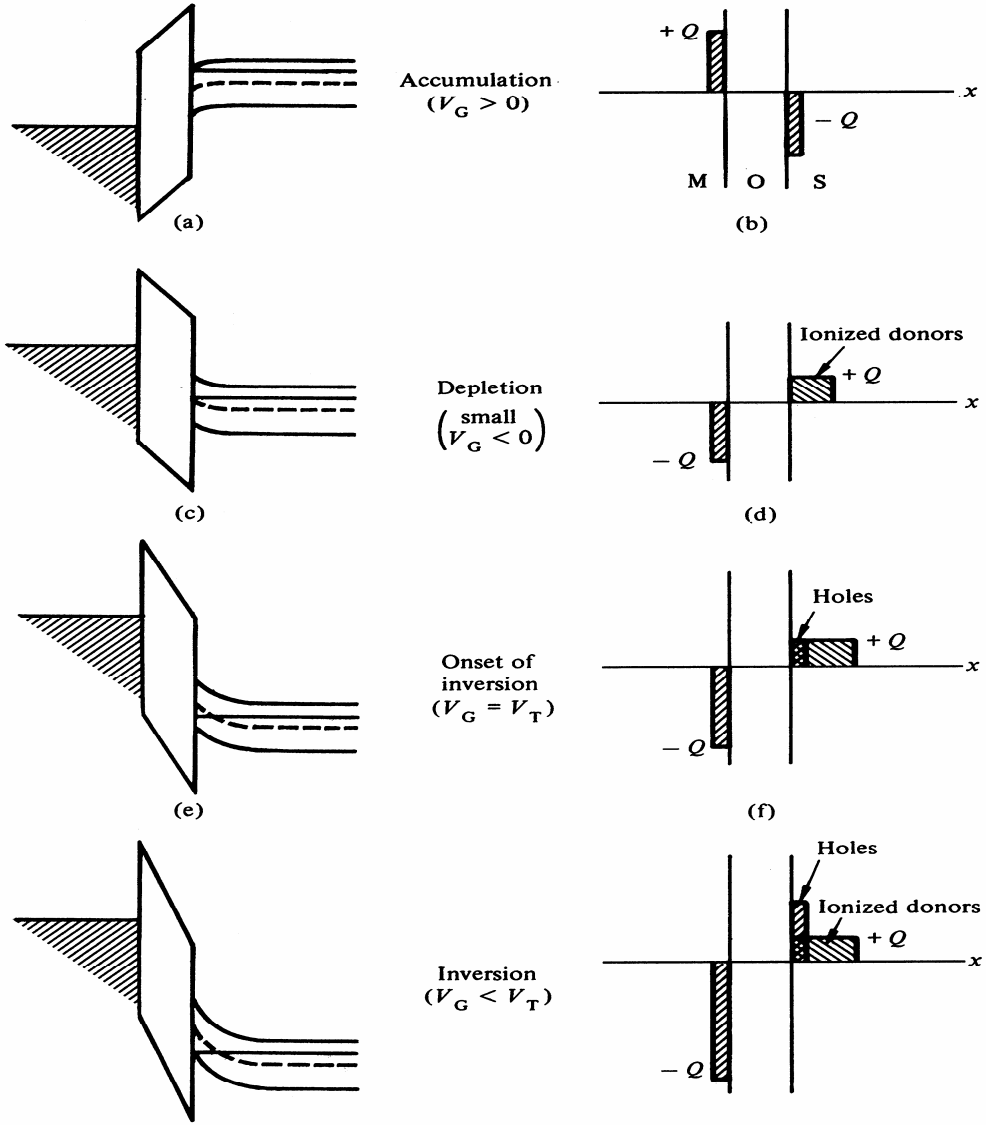
- Let us ground the semiconductor and start applying different voltages, V_G, to the gate

- V_G can be positive, negative or zero with respect to the semiconductor

- $E_{F,metal} - E_{F,semiconductor} = -q\,V_G$

- Since oxide has no charge (it's an insulator with no available carriers or dopants), $d\,E_{oxide} / dx = \rho/\varepsilon = 0$; meaning that the E-field inside the oxide is constant.

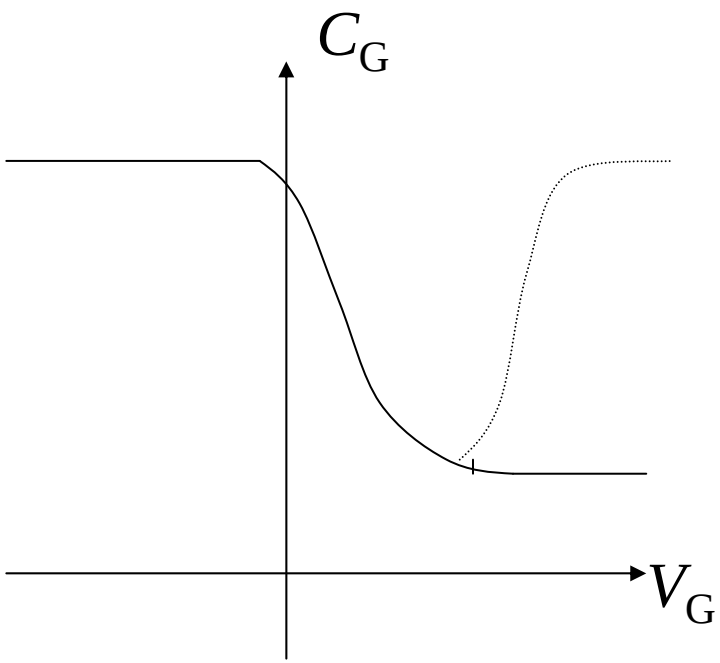
Ideal MOS Capacitor – n-type Si



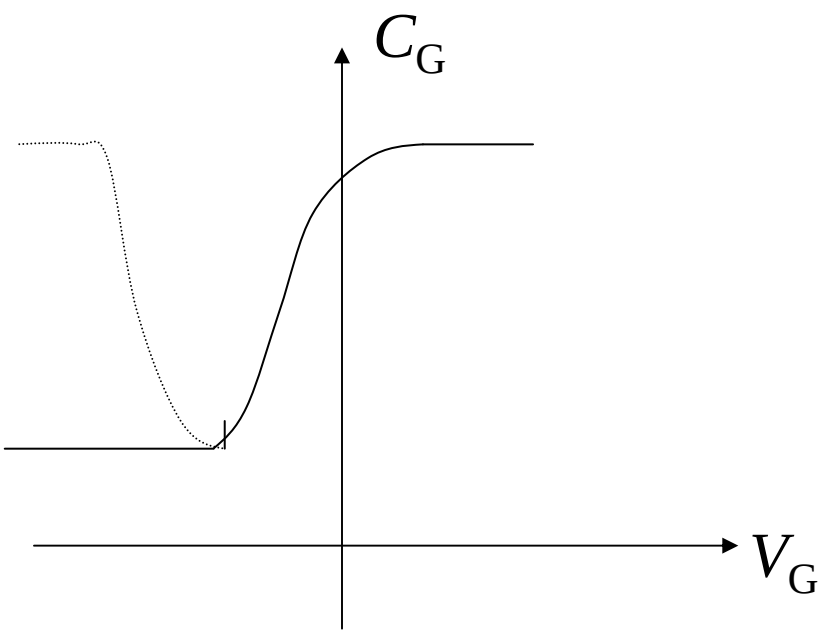
MOS C-V characteristics

- **The measured MOS capacitance (called gate capacitance) varies with the applied gate voltage**
  - A very powerful diagnostic tool for identifying threshold voltage, oxide thickness, substrate doping concentration, and flat band voltage.
  - It also tells you how close to an ideal MOSC your structure is.
- **Measurement of C-V characteristics**
  - Apply any dc bias, and superimpose a small (15 mV) ac signal (typically 1 kHz – 1 MHz)

MOSC with n- and p- type substrate

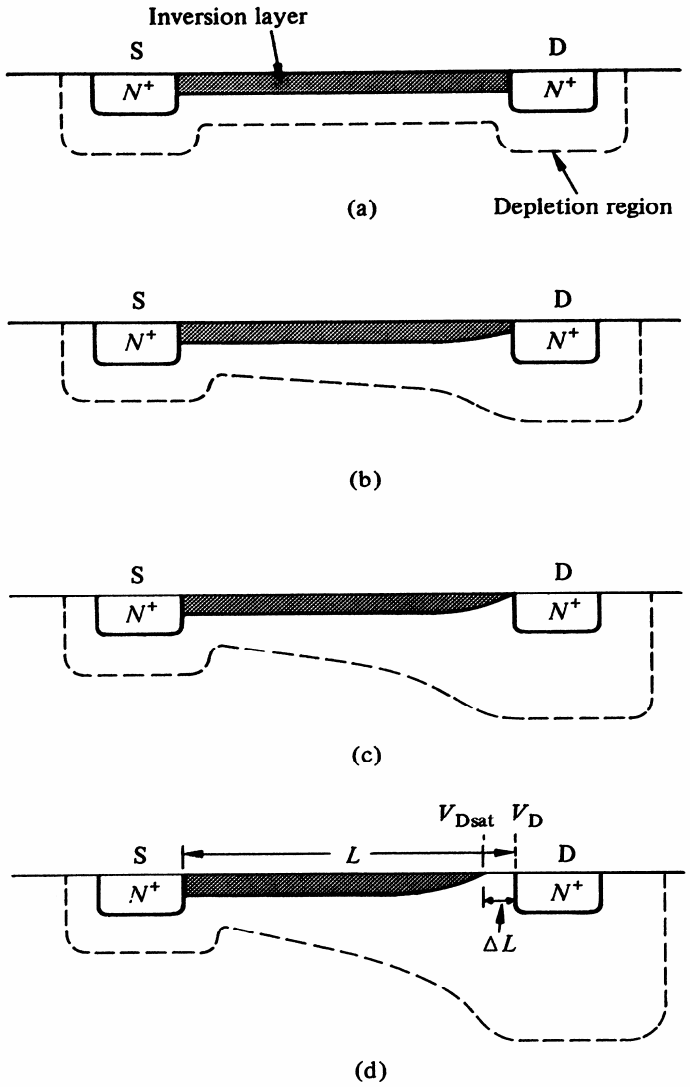


p-type



n-type

Qualitative discussion: n-MOSFET



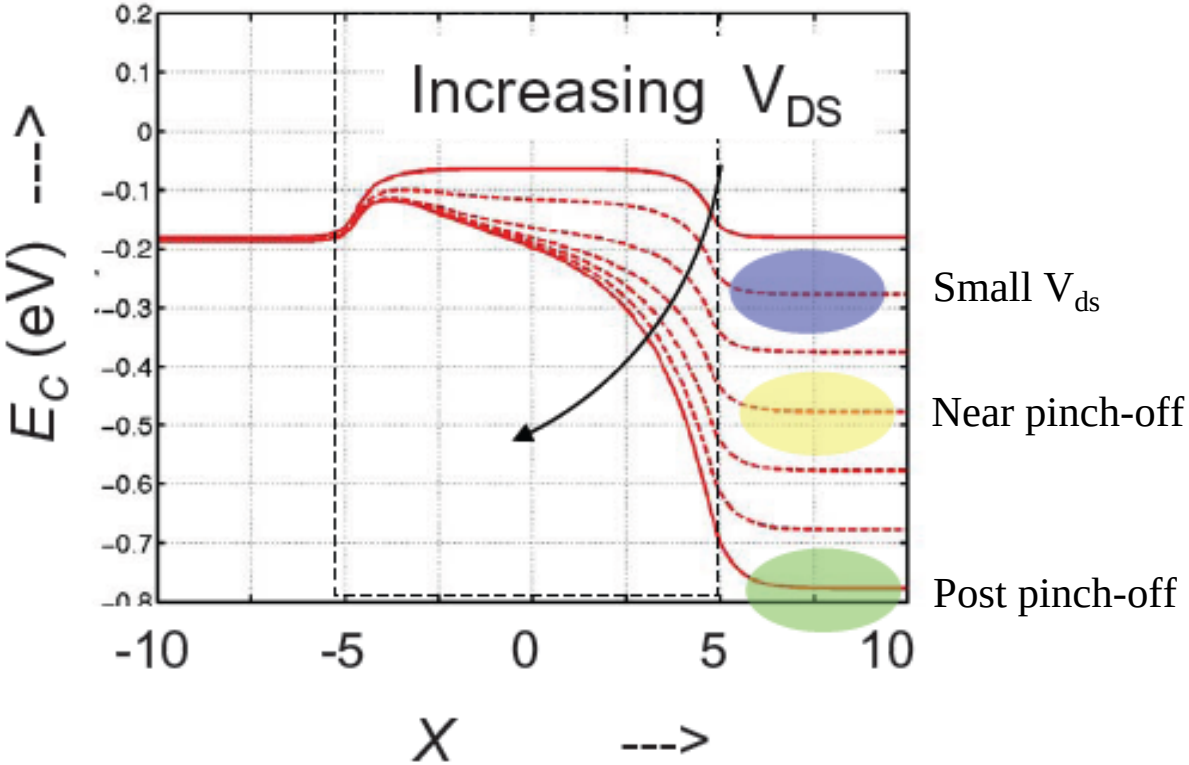
$V_G > V_T$; $V_{DS} \approx 0$
I_D increases with V_{DS}

$V_G > V_T$; V_{DS} small, > 0
I_D increases with V_{DS} , but rate of increase decreases.

$V_G > V_T$; $V_{DS} \approx$ pinch-off
I_D reaches a saturation value, $I_{D,sat}$
The V_{DS} value is called $V_{DS,sat}$

$V_G > V_T$; $V_{DS} > V_{DS,sat}$
I_D does not increase further, saturation region.

Band Diagram at various V_{ds}



Quantitative I_D-V_{DS} Relationships – 1st attempt "Square Law"

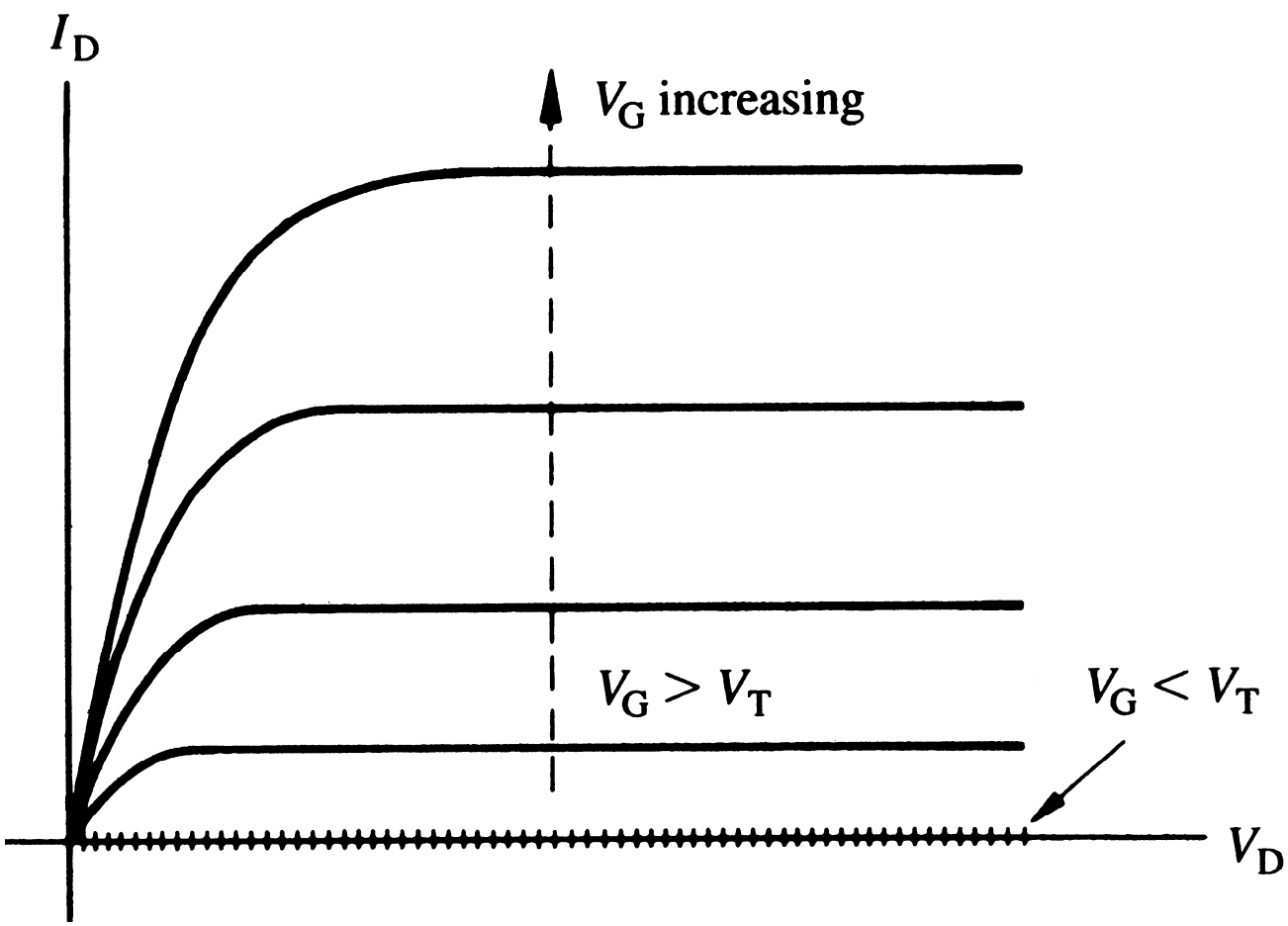
$$I_D = \frac{Z\mu_n}{L} C_{ox} \left[(V_G - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] \qquad 0 < V_{DS} < V_{DS,sat} \;; \qquad V_G > V_T$$

I_D will increase as V_{DS} is increased, but when $V_G - V_{DS} = V_T$, pinch-off occurs, and current saturates when V_{DS} is increased further. This value of V_{DS} is called $V_{DS,sat}$. i.e., $V_{DS,sat} = V_G - V_T$ and the current when $V_{DS} = V_{DS,sat}$ is called $I_{DS,sat}$.

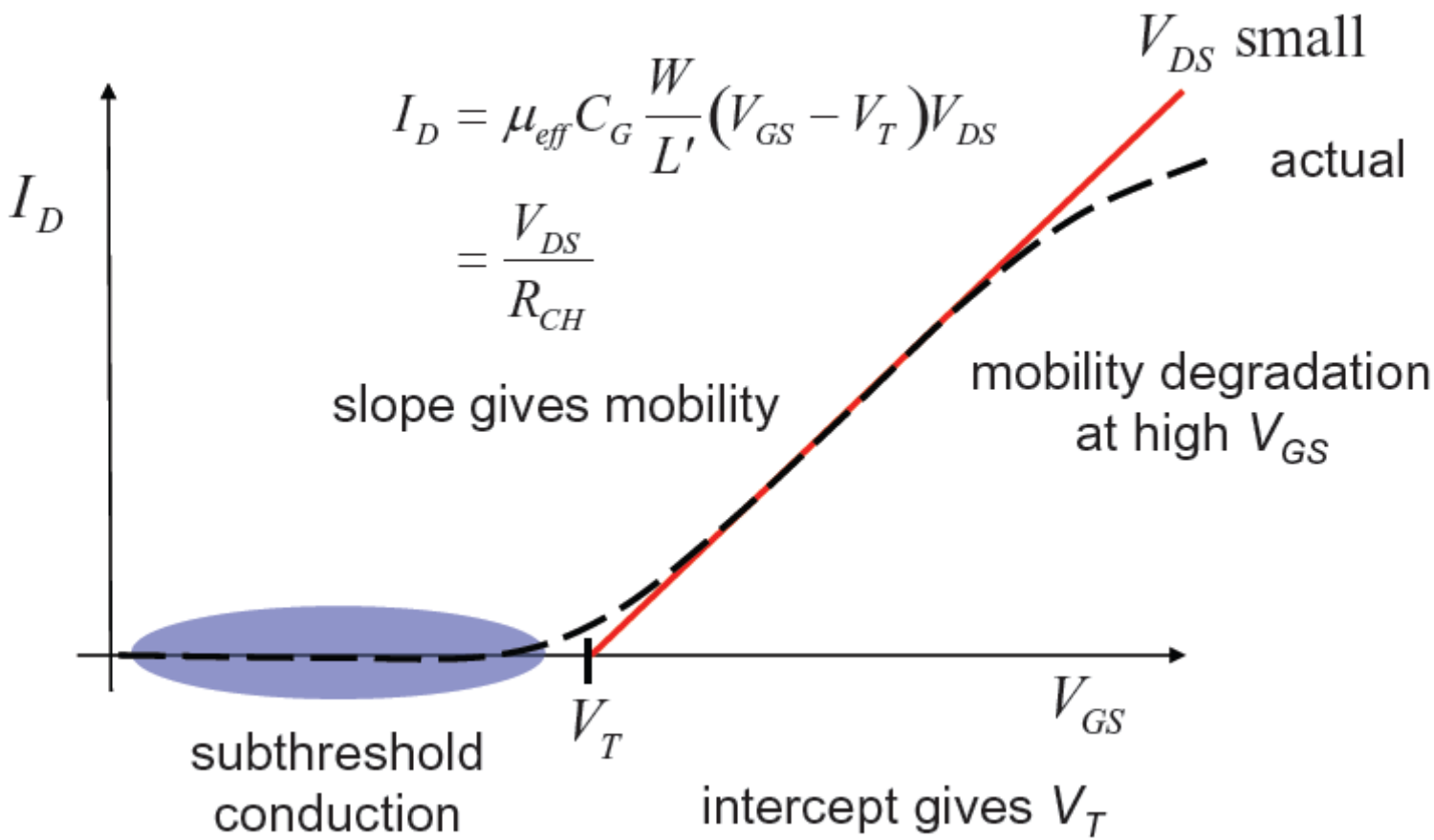
$$I_{D,sat} = \frac{Z\mu C_{ox}}{2L} (V_G - V_T)^2 \qquad V_D > V_{DS,sat} \;; \quad V_G > V_T$$

Here, C_{ox} is the oxide capacitance per unit area, $C_{ox} = \varepsilon_{ox} / x_{ox}$

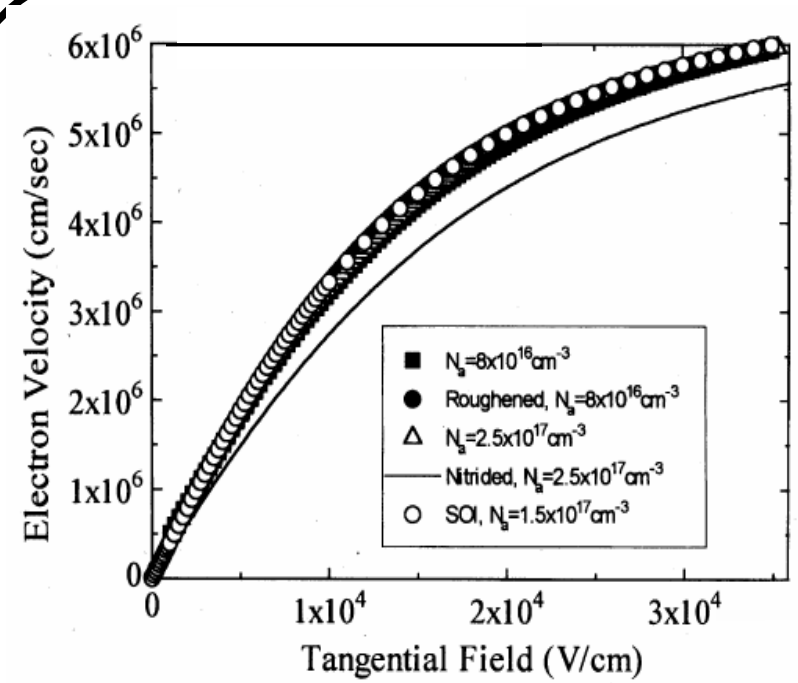
I_D-V_{DS} characteristics expected from a long channel ($\Delta L << L$) MOSFET (n-channel), for various values of V_G



Threshold and Subthreshold



Velocity Saturation

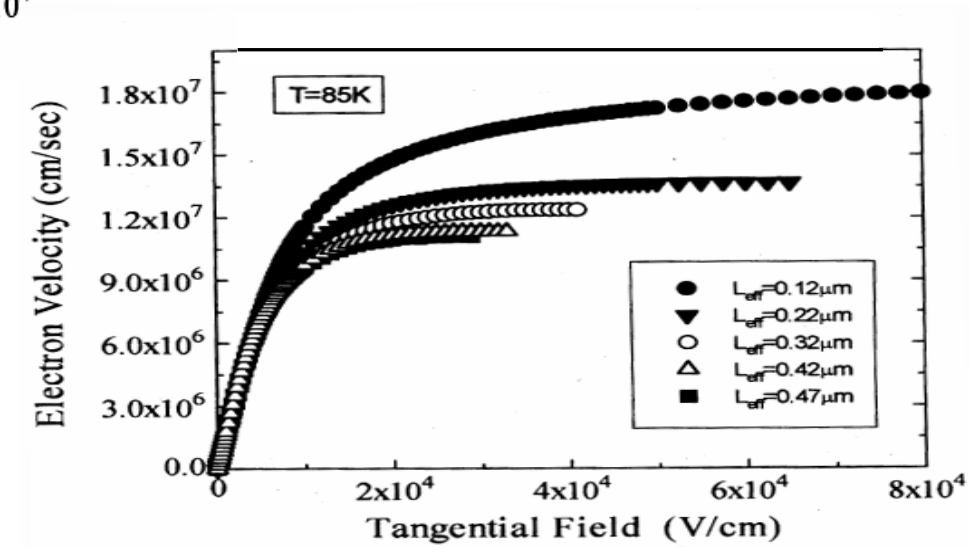


$$v = \frac{\mu_s \mathcal{E}}{1 + \frac{\mathcal{E}}{\mathcal{E}_{sat}}}$$

$$\mathcal{E} << \mathcal{E}_{sat} : v = \mu_s \mathcal{E}$$

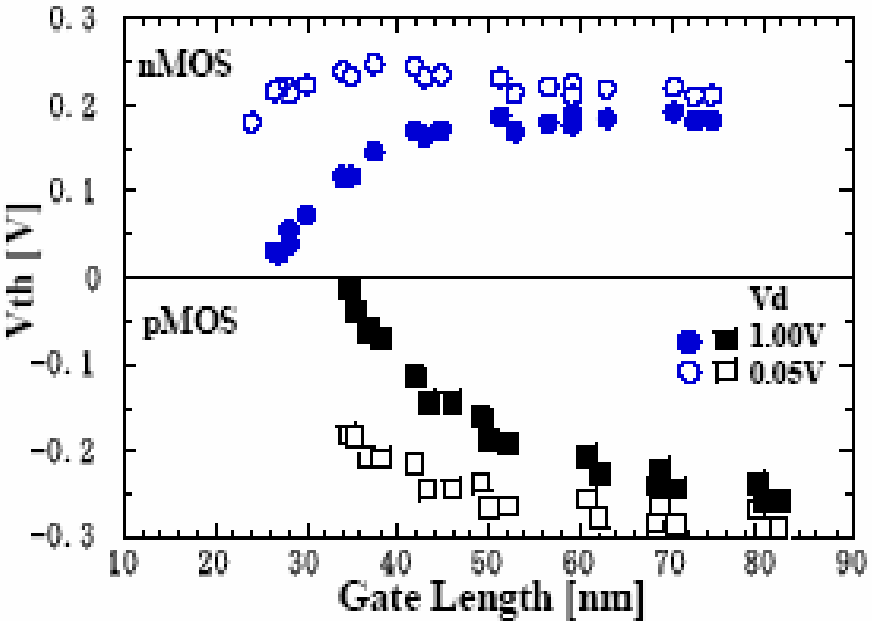
$$\mathcal{E} >> \mathcal{E}_{sat} : v = \mu_s \mathcal{E}_{sat}$$

- velocity saturation has large and deleterious effect on the I_{on} of MOSFETS



V_t Roll-off

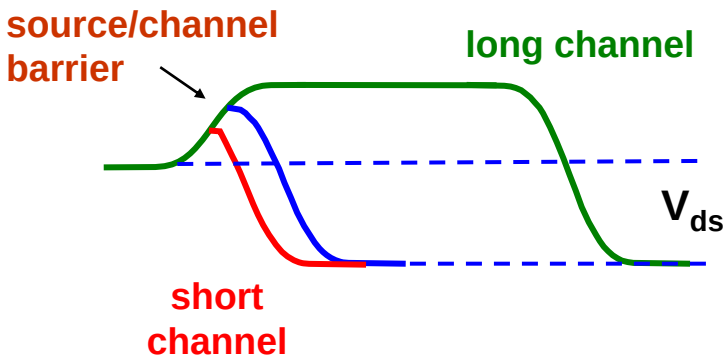
- V_t roll-off: V_t decreases with decreasing L_g.
- It determines the minimum acceptable L_g because I_{off} is too large if V_t becomes too small.



K. Goto et al., (Fujitsu) IEDM 2003 65nm technology. EOT=1.2nm, V_{dd}=1V

Energy-Band Diagram from Source to Drain

- L dependence



- V_{ds} dependence