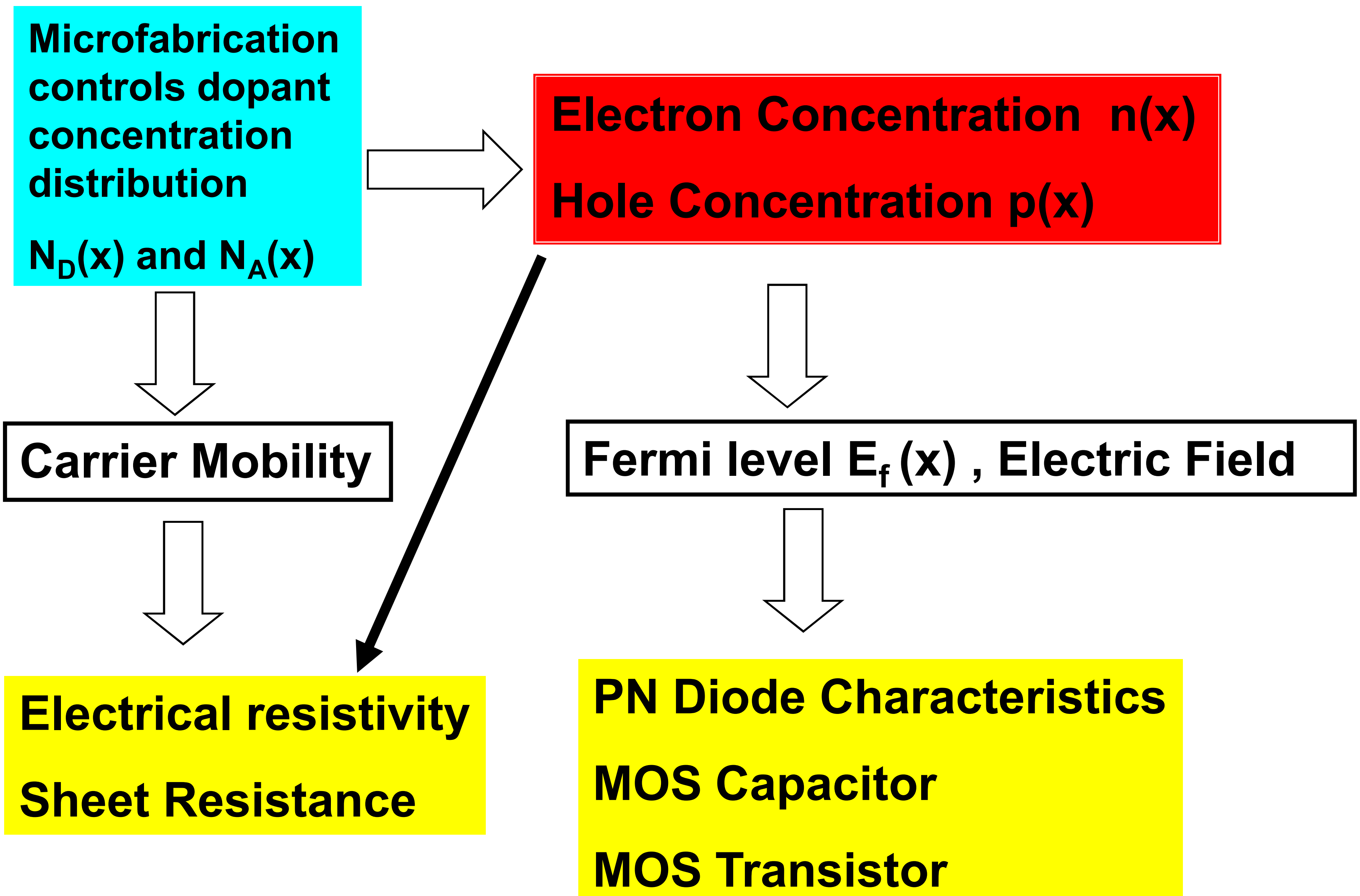

Microfabrication controls dopant concentration distribution
$N_D(x)$ and $N_A(x)$
Electron Concentration n(x)
Hole Concentration p(x)
Carrier Mobility
Fermi level E_f (x) , Electric Field
Electrical resistivity
Sheet Resistance
PN Diode Characteristics
MOS Capacitor
MOS Transistor

Electron and Hole Concentrations for homogeneous semiconductor at thermal equilibrium

n: electron concentration (cm^{-3})

p : hole concentration (cm^{-3})

N_D: donor concentration (cm^{-3})

N_A: acceptor concentration (cm^{-3})

Assume **completely ionized** to form N_D^+ and N_A^-

1) Charge neutrality condition: $N_D + p = N_A + n$

2) Law of Mass Action : $n \bullet p = n_i^2$

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

Note: Carrier concentrations depend on *NET* dopant concentration (N_D - N_A) !

How to find n, p when Na and Nd are known

$$n - p = N_d - N_a \quad (1)$$

$$pn = n_i^2 \quad (2)$$

(i) If $N_d - N_a > 10\, n_i$: $n \equiv N_d - N_a$

(ii) If $N_a - N_d > 10\, n_i$: $p \equiv N_a - N_d$

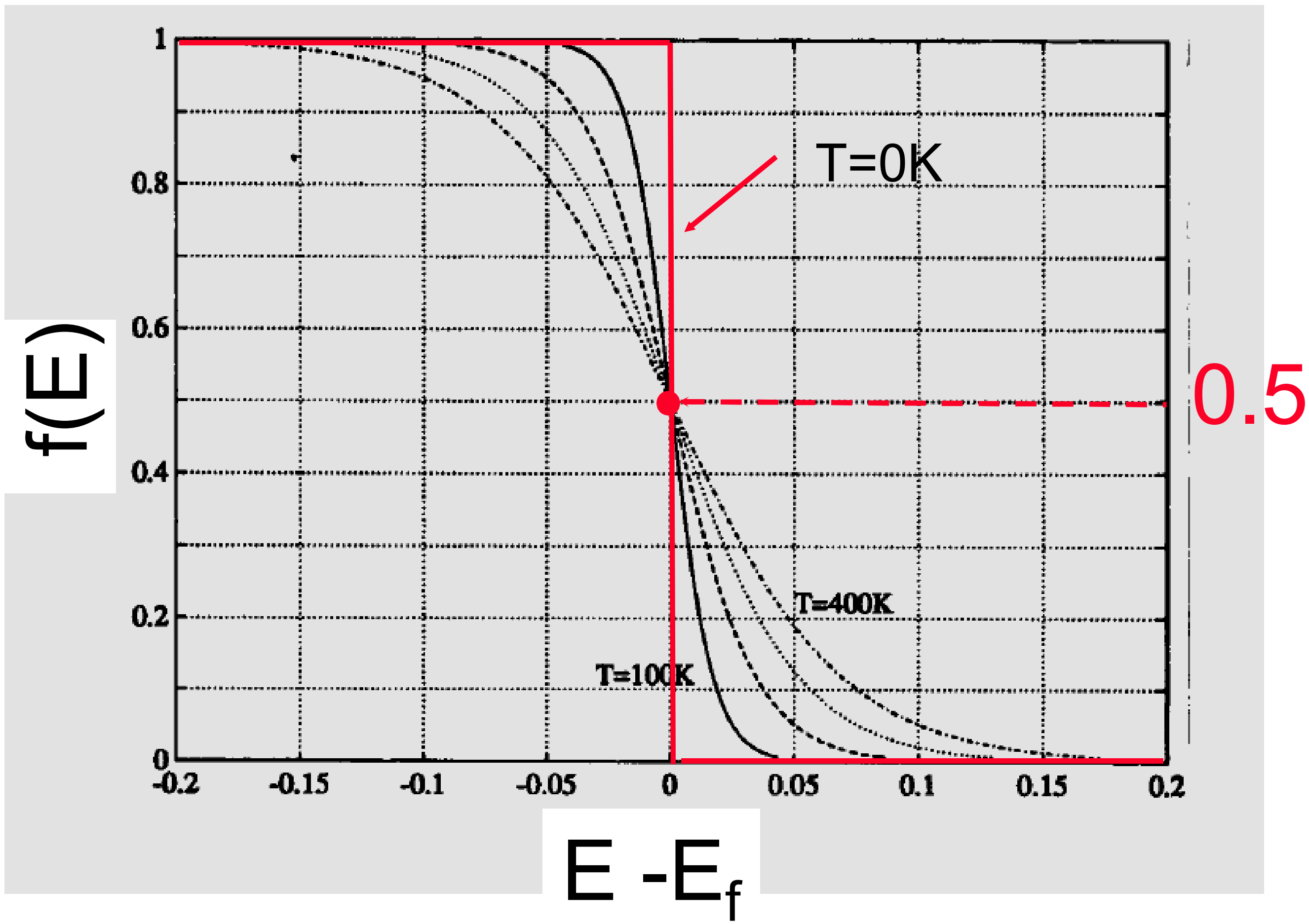
*** Either n or p will dominate for typical doping situations**

The Fermi-Dirac Distribution (Fermi Function)

Probability of available states at energy E being occupied

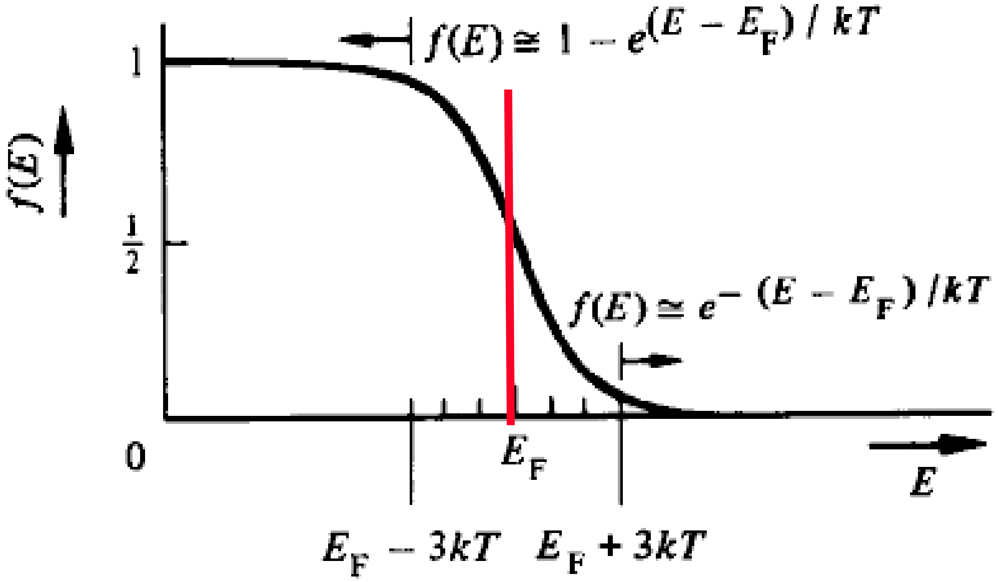
$f(E) = 1/ [1+ \exp (E- E_f) / kT]$

where E_f is the Fermi energy and k = Boltzmann constant=$8.617 * 10^{-5}$ eV/K



Properties of the Fermi-Dirac Distribution

Probability of electron state at energy E will be occupied



(b) $T > 0$ K

(1) $f(E) \cong \exp[-(E - \mathbf{E_f}) / kT]$ for $(E - E_f) > 3kT$

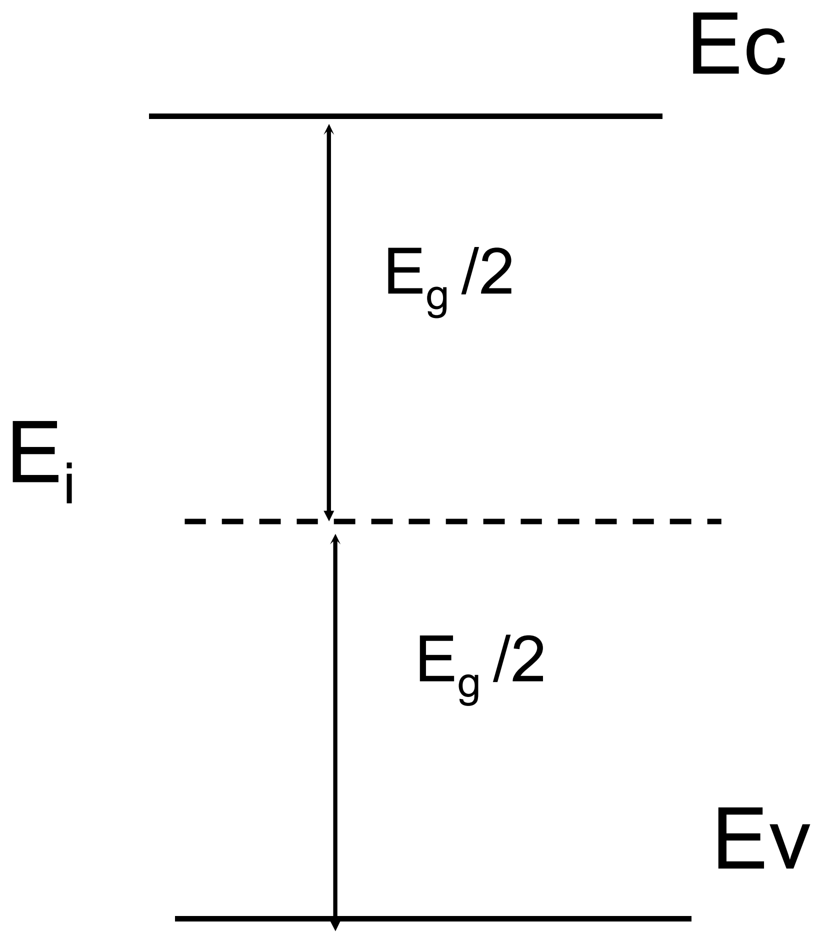
•This approximation is called Boltzmann approximation

Note:
At 300K,
kT= 0.026eV

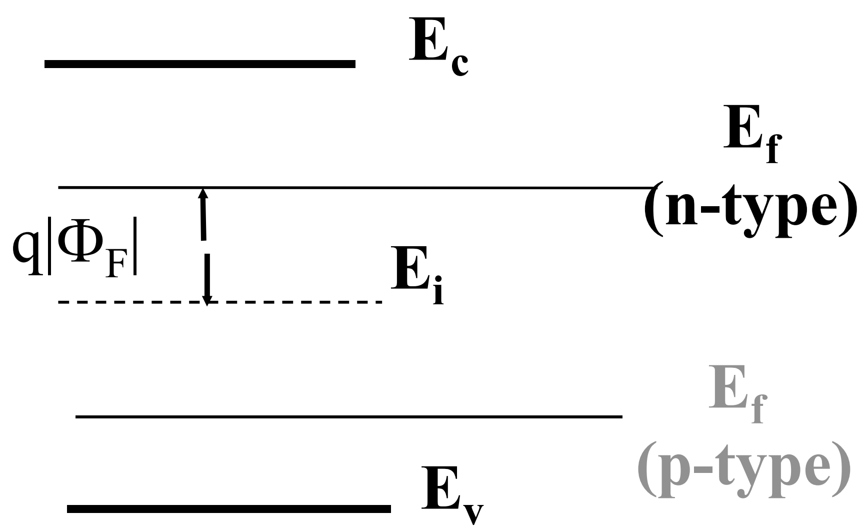
(2) Probability of available states at energy E **NOT** being occupied

$1 - f(E) = 1/ [\, 1 + \exp(\mathbf{E_f} - E) / kT]$

Fermi Energy (E_i) of Intrinsic Semiconductor



How to find E_f when n(or p) is known



Note: E_f is not very sensitive to carrier concentration

When n doubles, E_f changes by $kT/q \bullet (\ln 2)$ = 18mV

$$n = n_i \exp[(E_f - E_i)/kT]$$

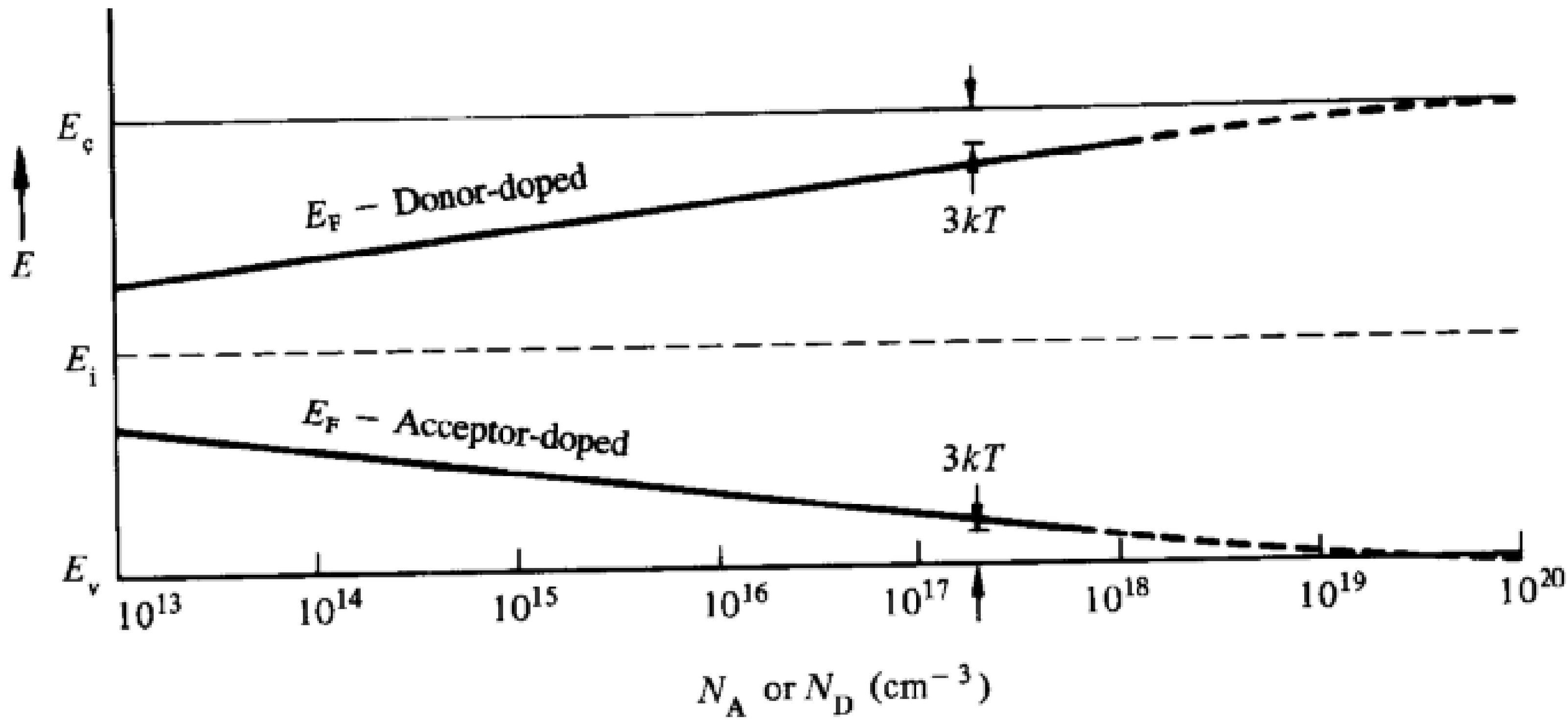
Let $q\Phi_F \equiv E_f - E_i$

$$\therefore n = n_i \exp[q\Phi_F/kT]$$

Dependence of Fermi Level with Doping Concentration

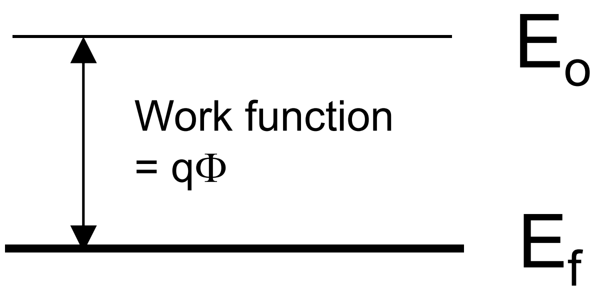
$E_i \equiv (E_C+E_V)/2$ Middle of energy gap

When Si is undoped, $E_f = E_i$; also $n = p = n_i$



Work Function of Materials

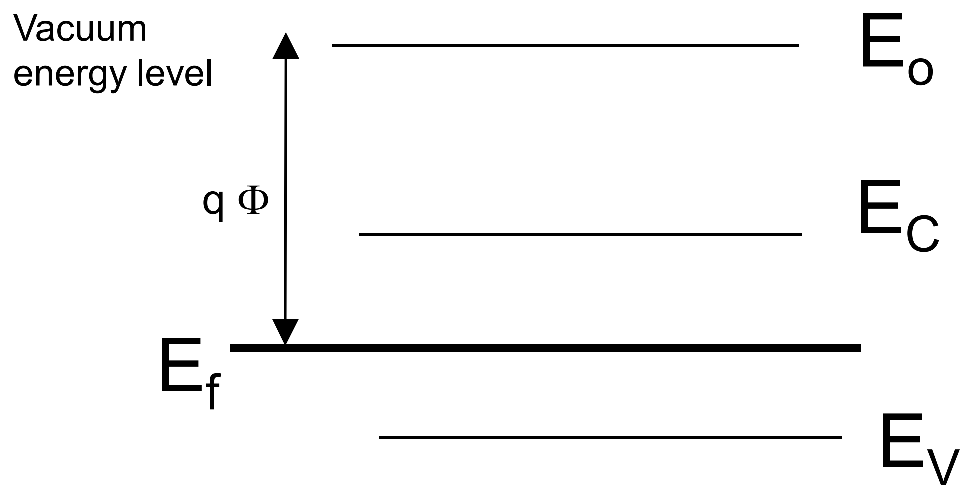
METAL



$q\Phi_M$ is determined

by the metal material

SEMICONDUCTOR



$q\Phi_S$ is determined

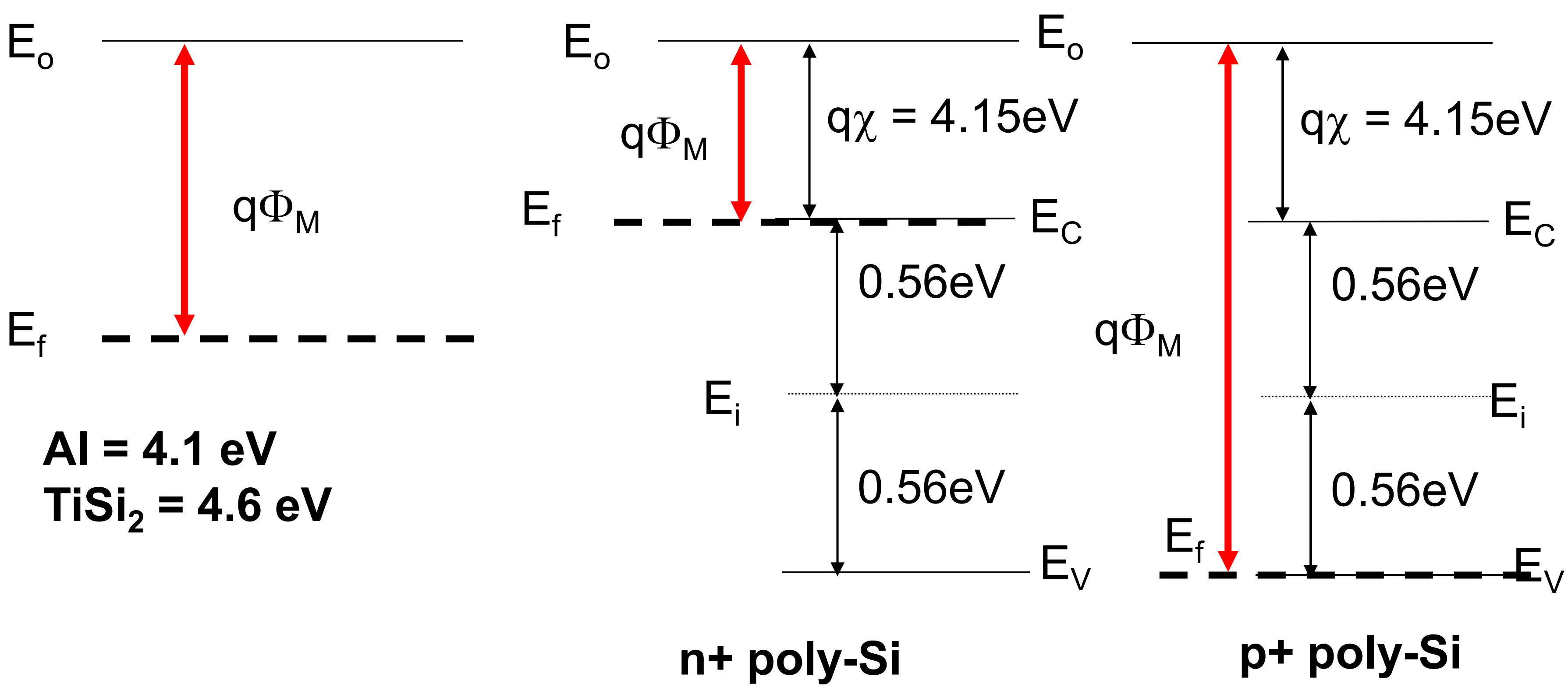
by the semiconductor material,

the dopant type,

and doping concentration

Work Function ($q\Phi_M$) of MOS Gate Materials

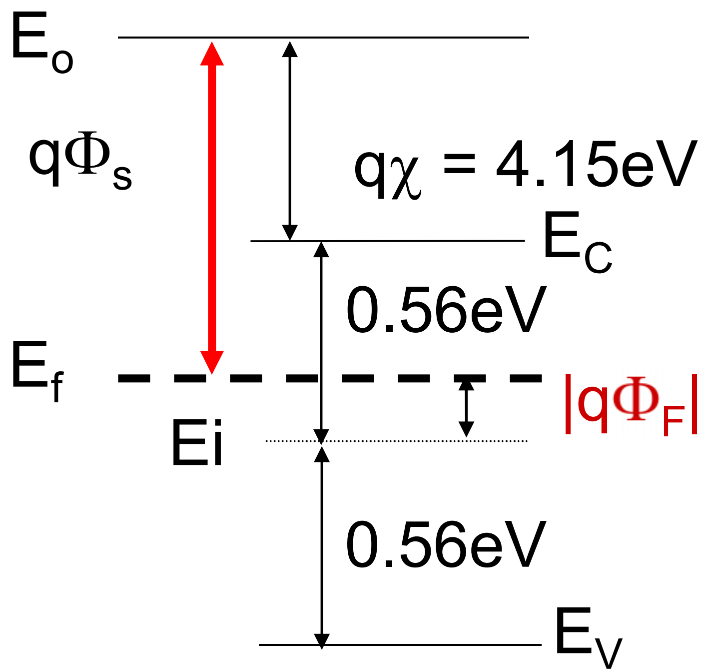
E_o = vacuum energy level **E_f** = Fermi level
E_C = bottom of conduction band **E_V** = top of conduction band
$q\chi$ = 4.15eV (**electron affinity**)



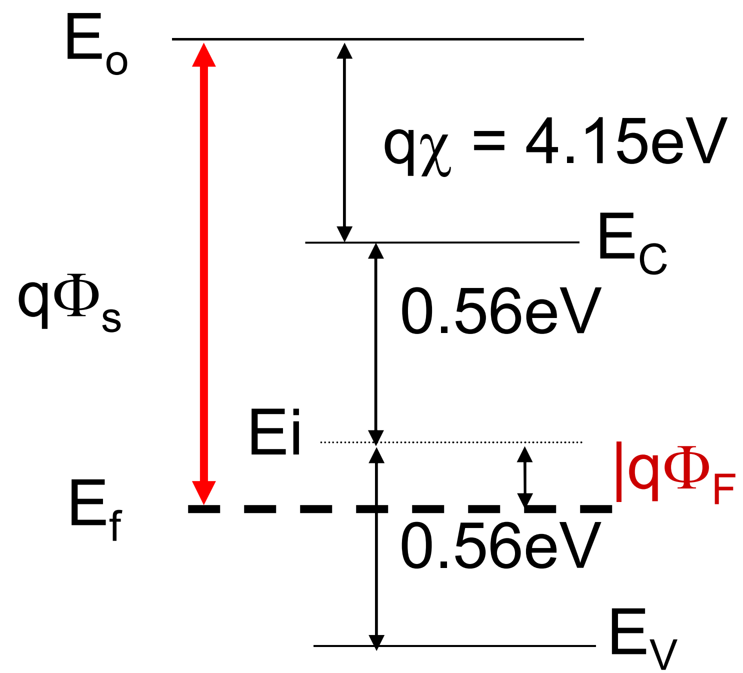
Work Function of doped Si substrate

* Depends on substrate concentration N_B

$$|\Phi_F| = \frac{kT}{q}\ln\left(\frac{N_B}{n_i}\right)$$



n-type Si



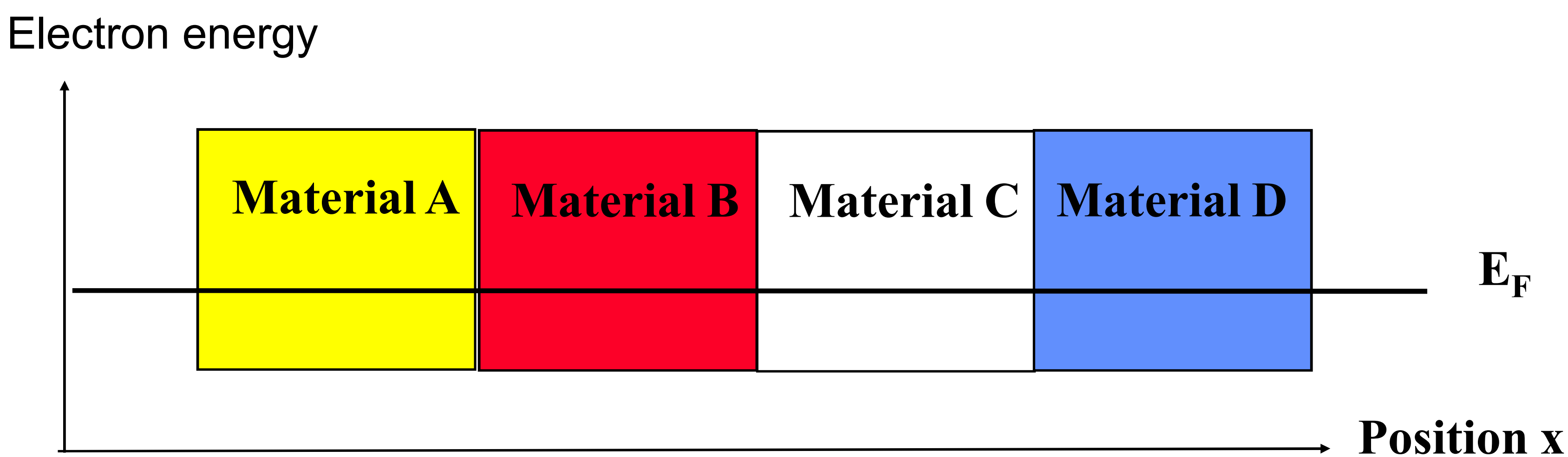
p-type Si

Φ_s (volts) = 4.15 +0.56 - $|\Phi_F|$

Φ_s (volts) = 4.15 +0.56 + $|\Phi_F|$

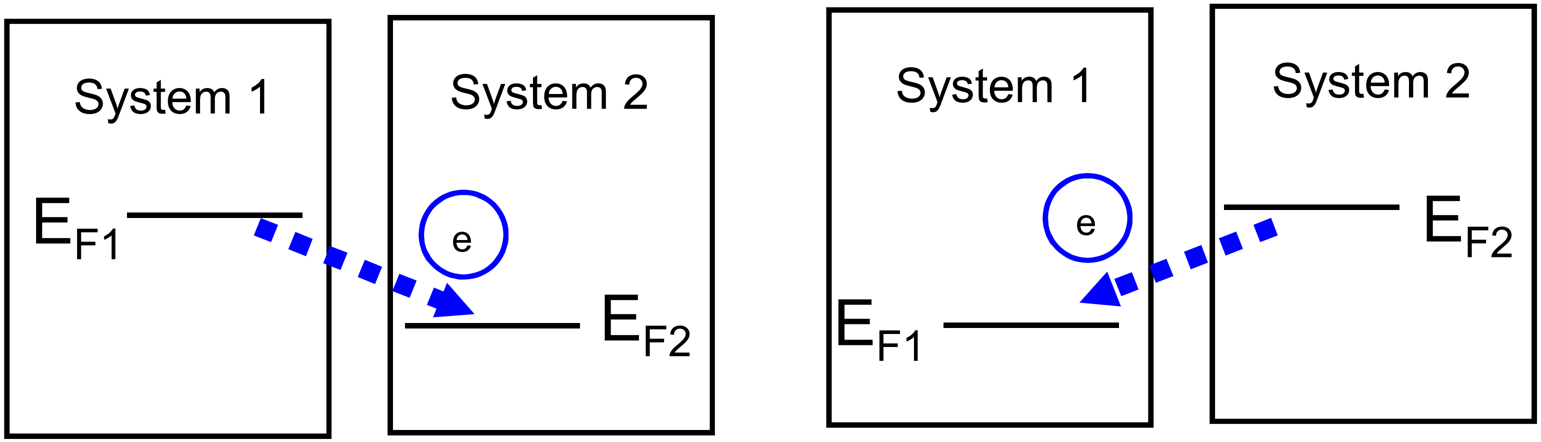
The Fermi Energy at thermal equilibrium

At thermal equilibrium (i.e., no external perturbation), The Fermi Energy must be constant for all positions

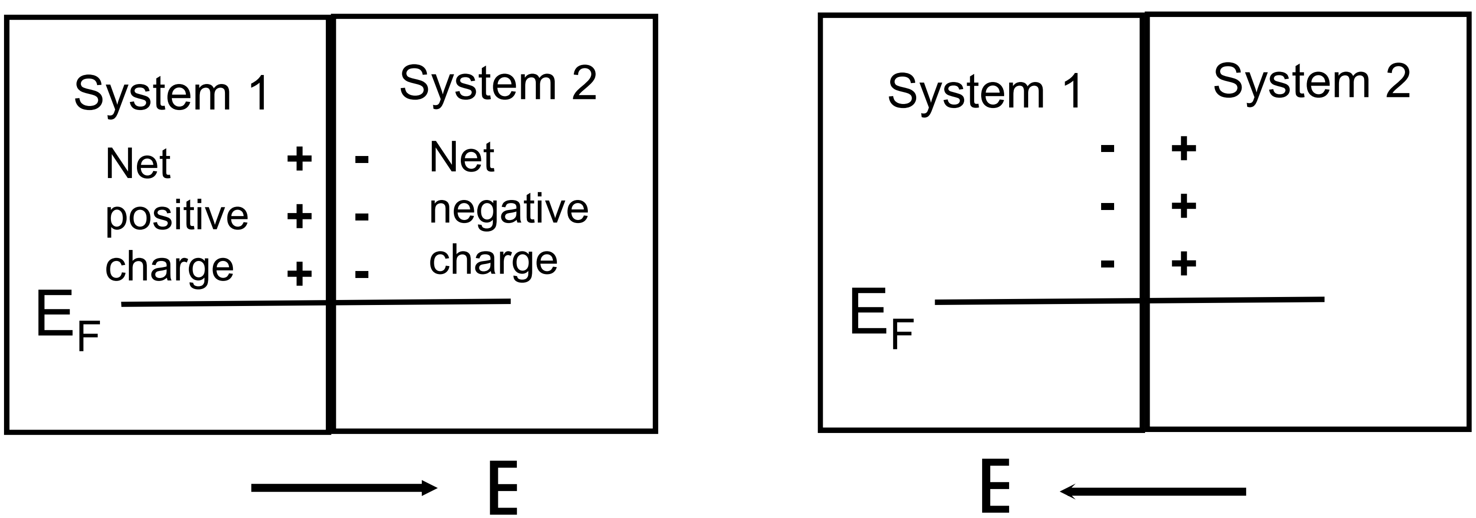


Electron Transfer during contact formation

Before contact formation

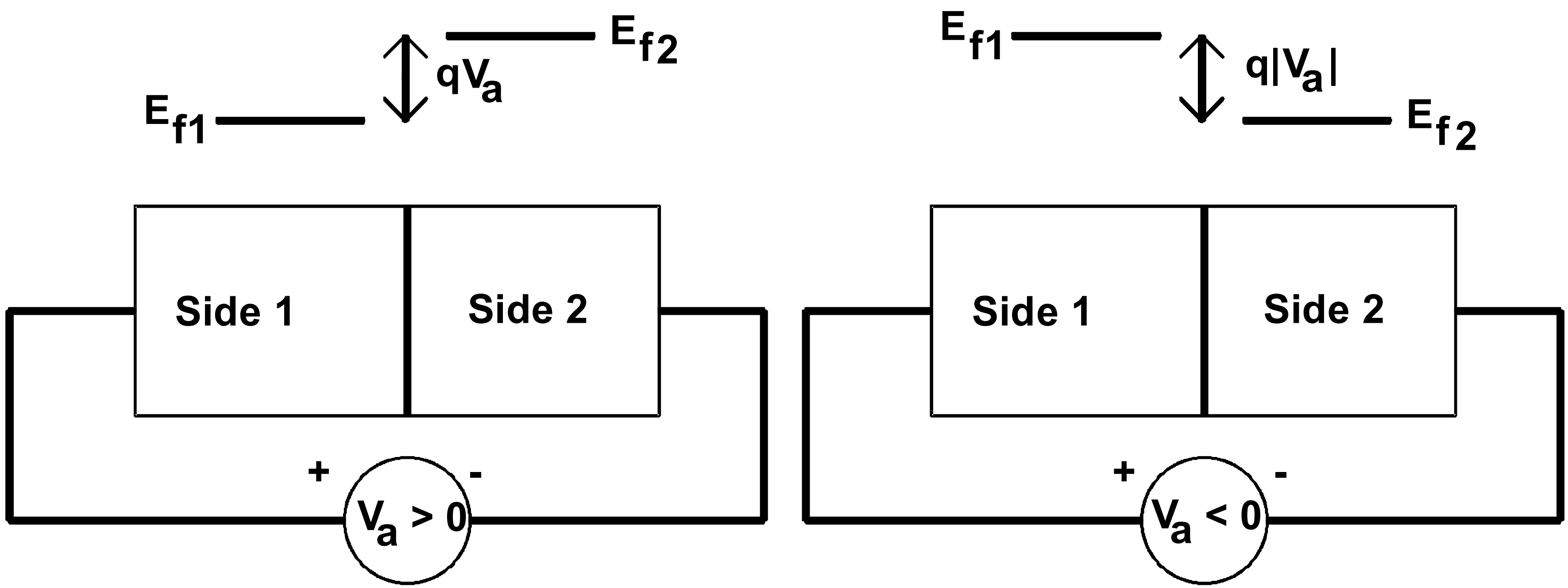


After contact formation



Applied Bias and Fermi Level

Fermi level of the side which has a relatively higher electric potential will have a relatively lower electron energy (Potential Energy = -q • electric potential.) Only difference of the E 's at both sides are important, not the absolute position of the Fermi levels.

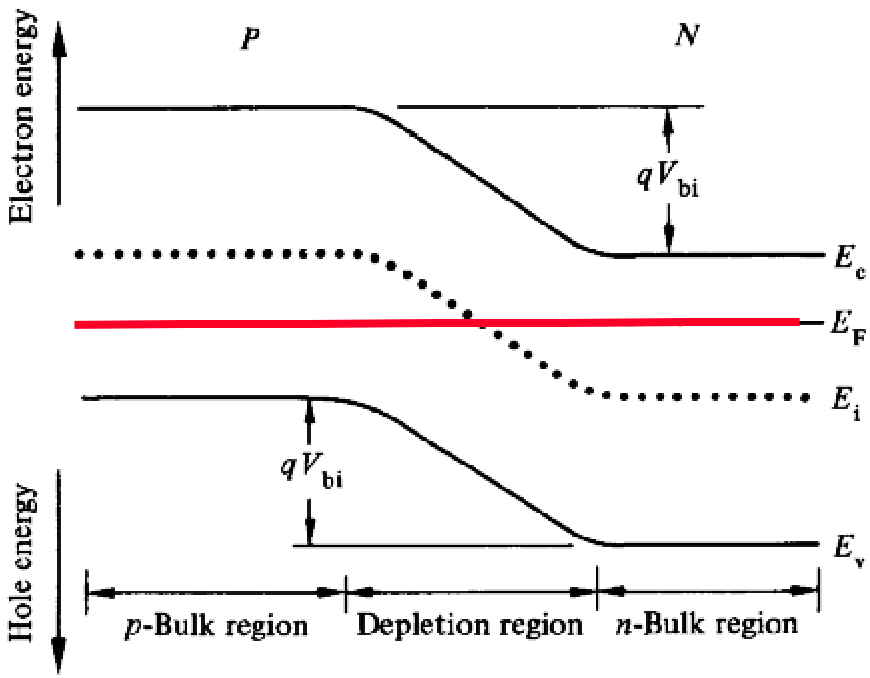


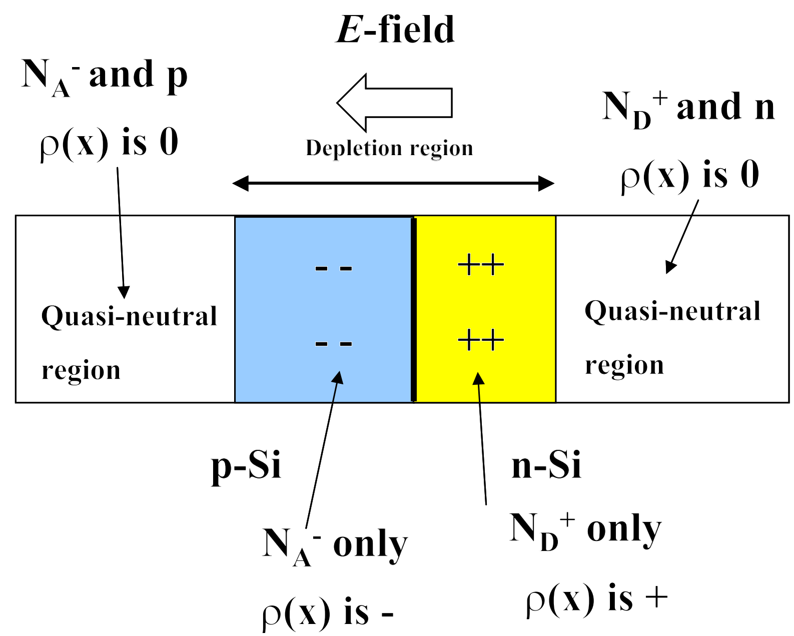
Potential difference across depletion region

$= V_{bi} - V_a$

PN junctions

Thermal Equilibrium



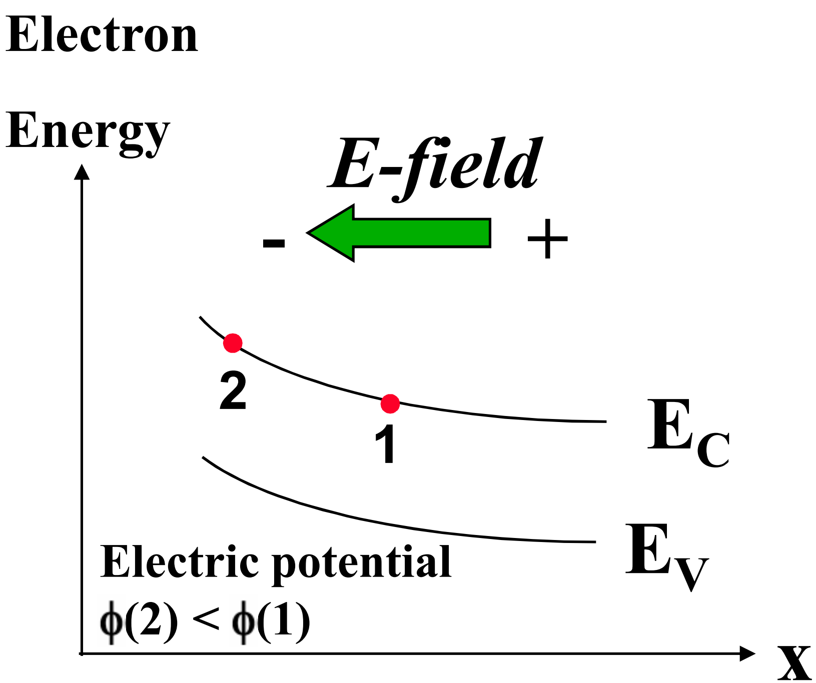


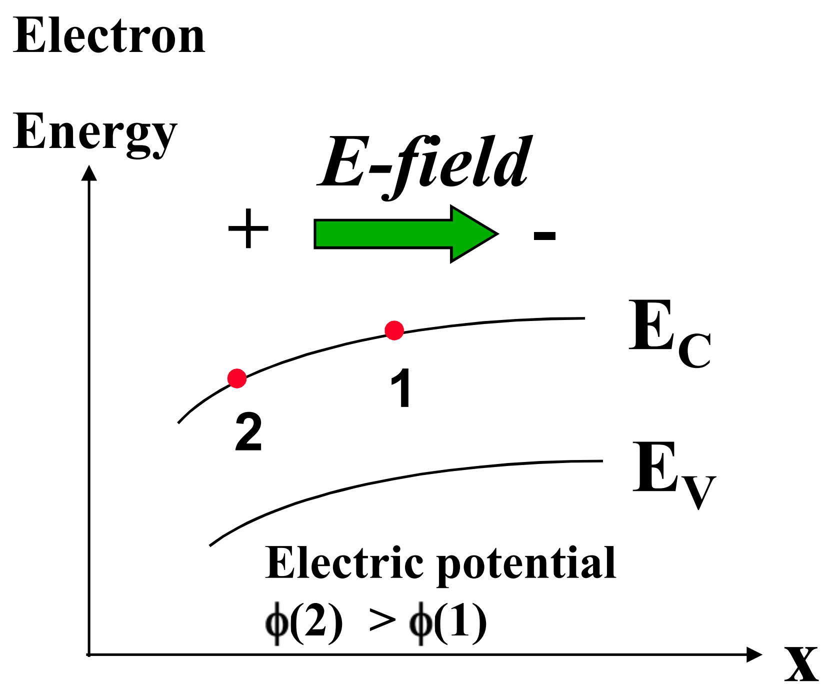
Complete Depletion Approximation used for charges inside depletion region

$$\rho(x) \approx N_D^+(x) - N_A^-(x)$$

http://jas.eng.buffalo.edu/education/pn/pnformation2/pnformation2.html

Energy Band Diagram with *E*-field





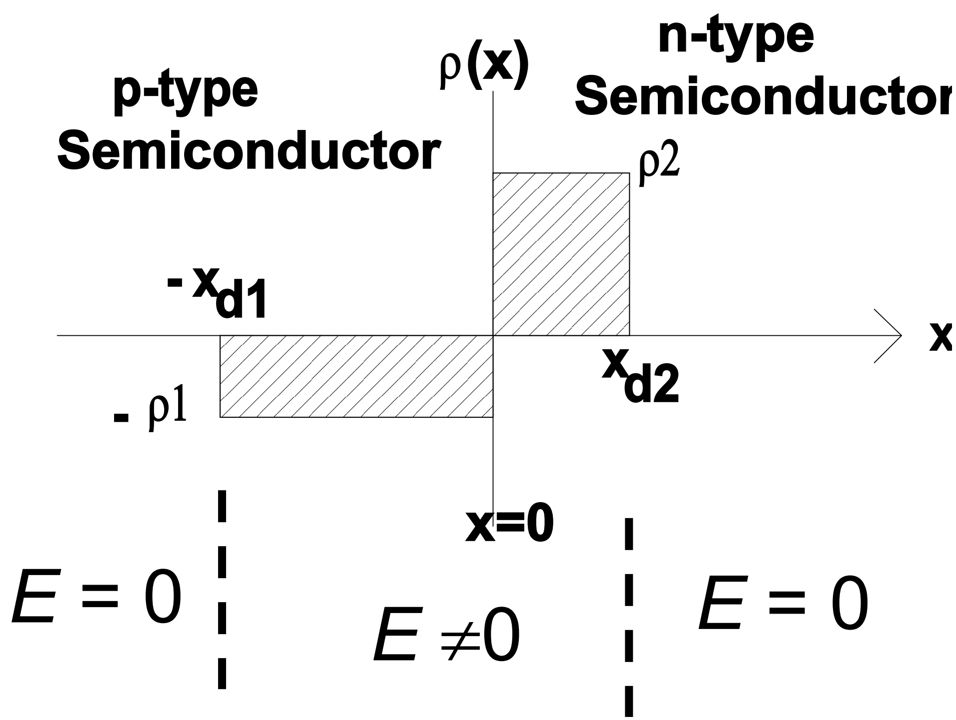
Electron concentration n

$$\frac{n(2)}{n(1)} = \frac{e^{q\phi(2)/kT}}{e^{q\phi(1)/kT}} = e^{q[\phi(2)-\phi(1)]/kT}$$

Electrostatics of Device Charges

1) Summation of all charges = 0 $\rho_2 \bullet x_{d2} = \rho_1 \bullet x_{d1}$

2) E-field =0 outside depletion regions



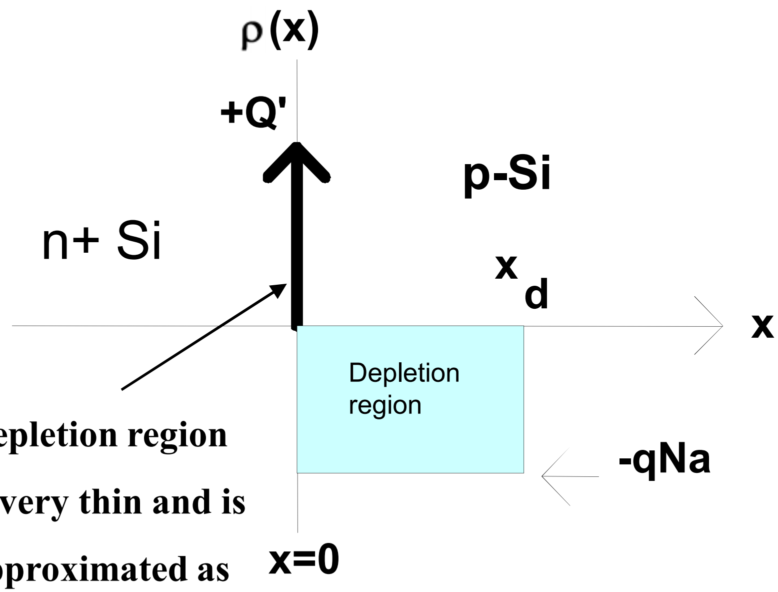
3) Relationship between E-field and charge density $\rho(x)$

$$d\,[\varepsilon\, E(x)]\,/dx = \rho(x)$$ "Gauss Law"

4) Relationship between E-field and potential ϕ

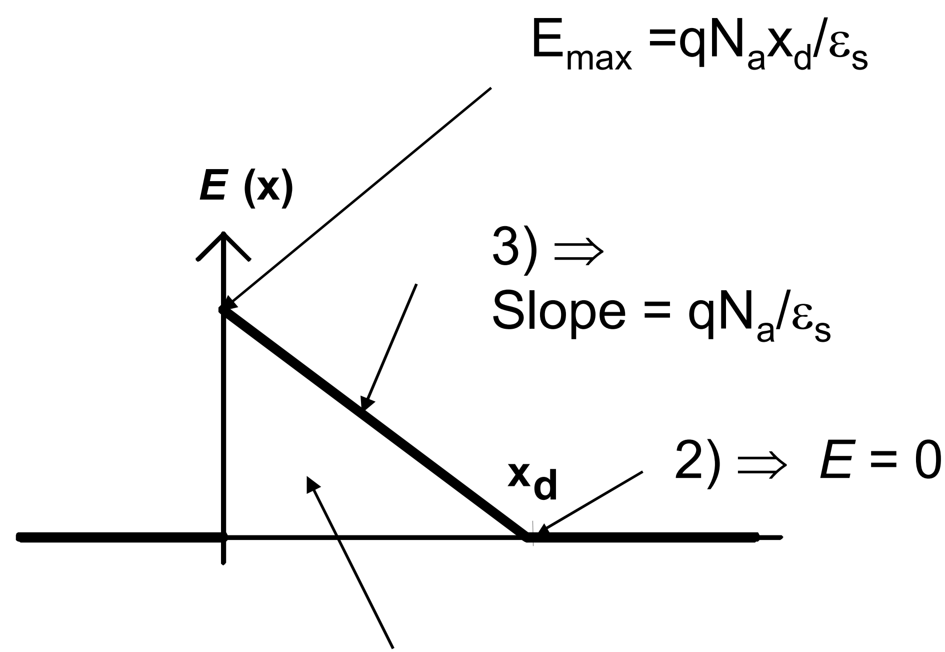
$$E(x) = -\,d\phi(x)/dx$$

Example Analysis : n+/ p-Si junction



Depletion region is very thin and is approximated as a thin sheet charge

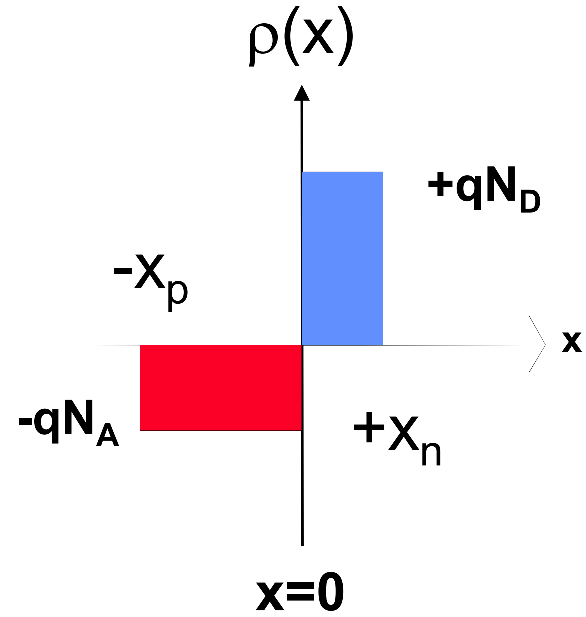
1) ⇒ $Q' = qN_a x_d$

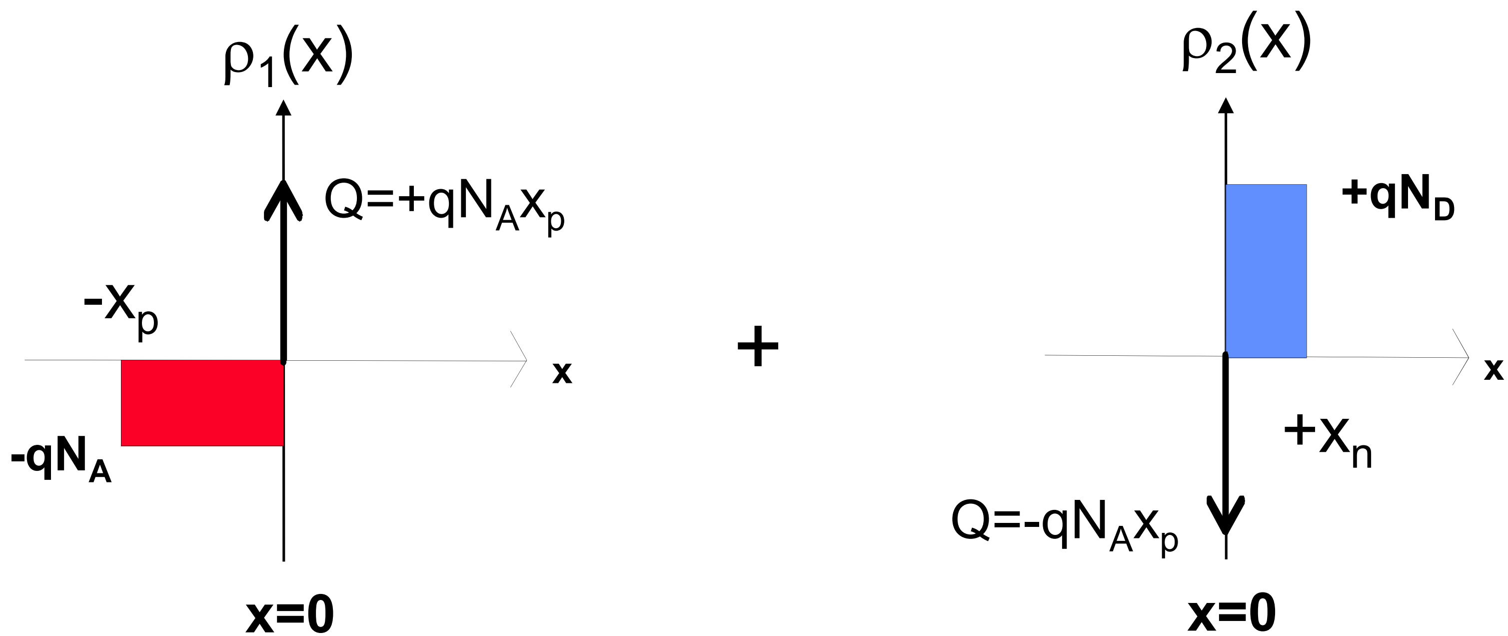


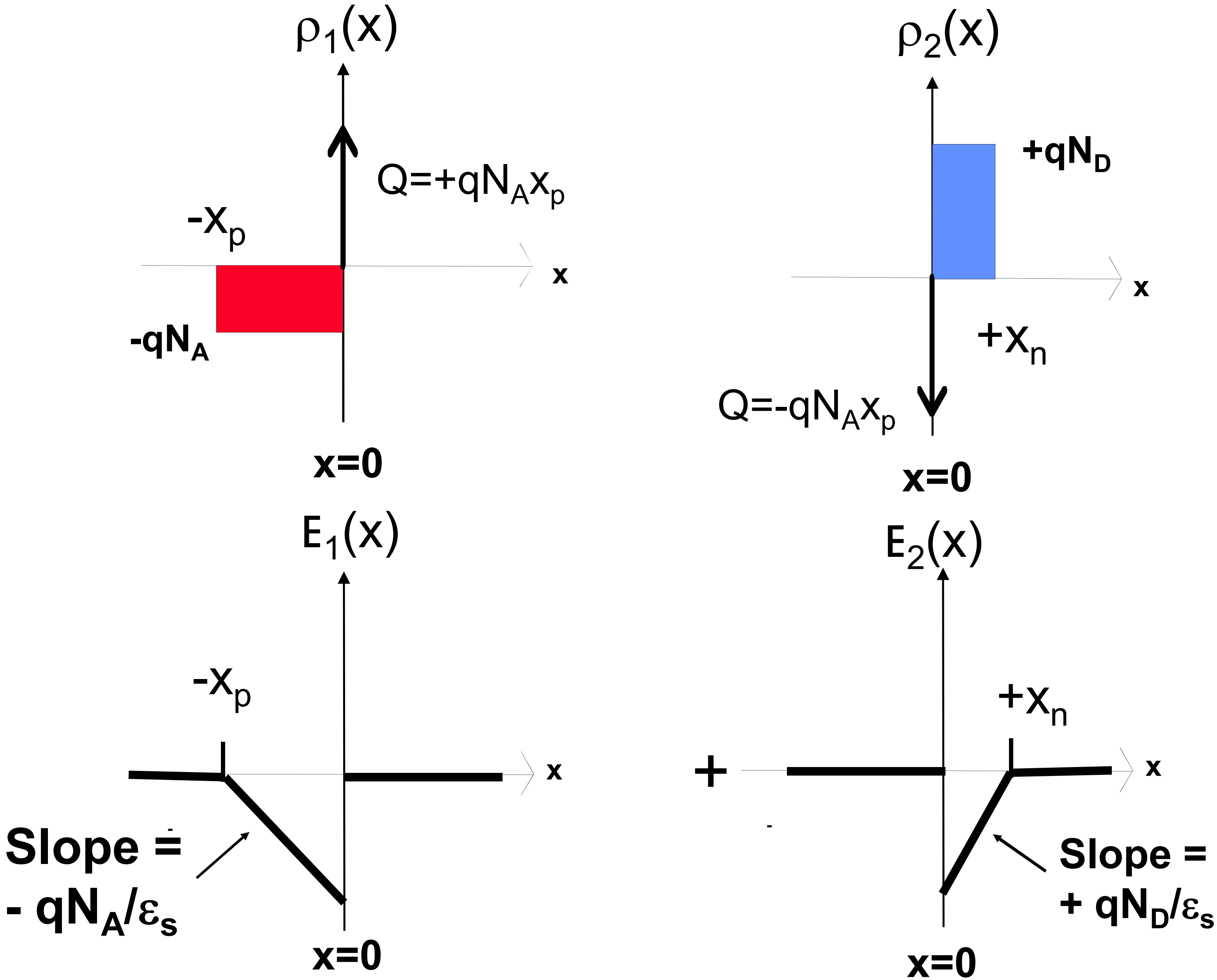
4) ⇒ Area under E-field curve
= voltage across depletion region
$= qN_a x_d^2/2\varepsilon_s$

Superposition Principle

If $\rho_1(x) \Rightarrow E_1(x)$ and $V_1(x)$
$\rho_2(x) \Rightarrow E_2(x)$ and $V_2(x)$
then
$\rho_1(x) + \rho_2(x) \Rightarrow E_1(x) + E_2(x)$ and $V_1(x) + V_2(x)$

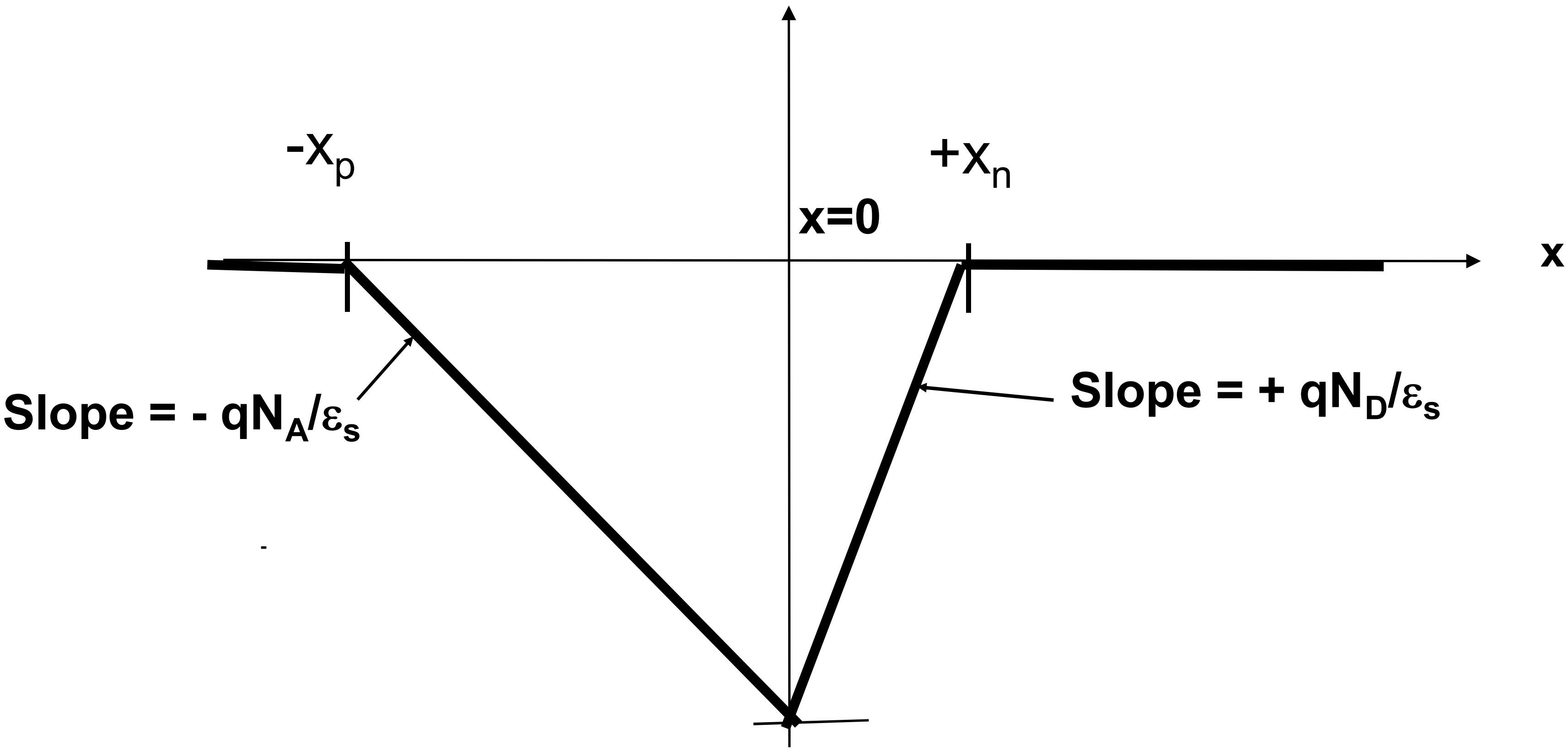





ρ1(x)
Q=+qNAxp
-xp
x
-qNA
x=0
ρ2(x)
+qND
x
+xn
Q=-qNAxp
x=0
E1(x)
-xp
x
Slope =
- qNA/εs
x=0
E2(x)
+xn
+
x
Slope =
+ qND/εs
x=0

Sketch of E(x)

$$E(x) = E_1(x) + E_2(x)$$

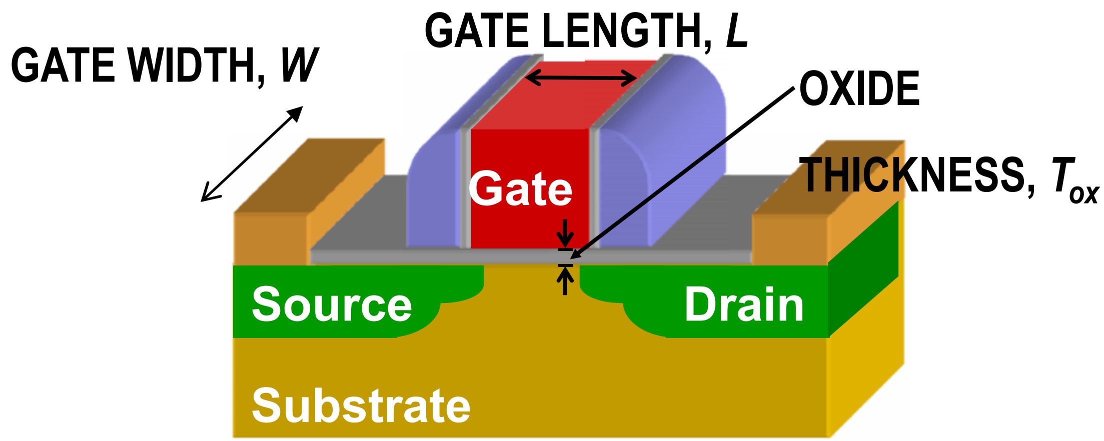


$$E_{max} = -qN_A x_p/\varepsilon_s$$
$$= -qN_D x_n/\varepsilon_s$$

The MOSFET

Metal-Oxide-Semiconductor

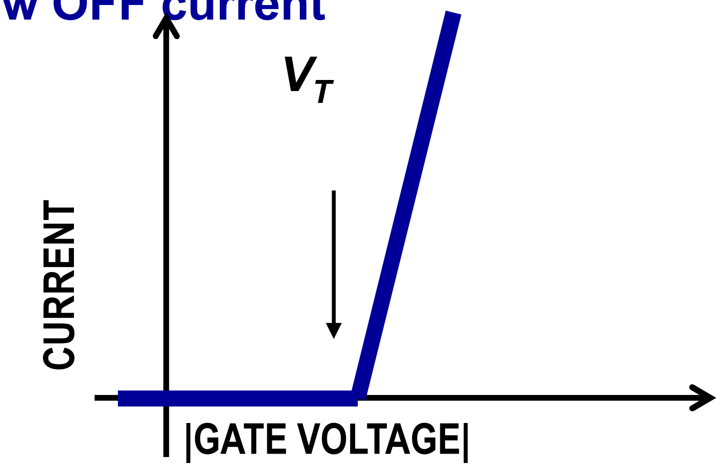
Field-Effect Transistor



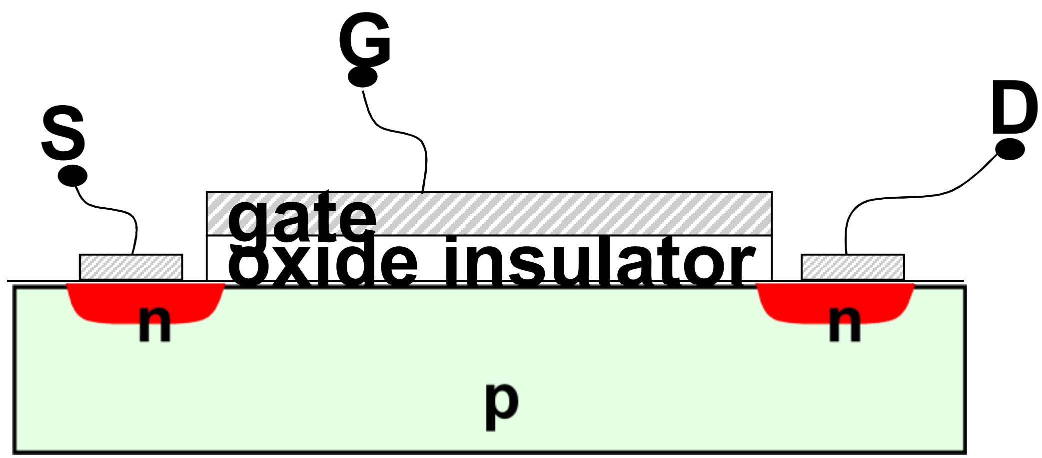
- No current through the gate to channel
- Current flowing between the SOURCE and DRAIN is controlled by the voltage on the GATE electrode

Desired characteristics:

- High ON current
- Low OFF current



n-channel MOSFET



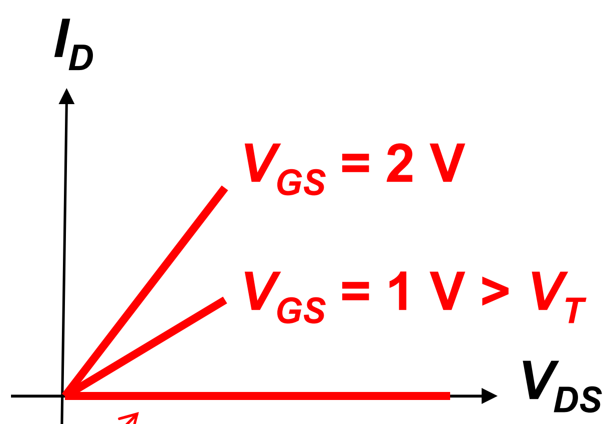
- **Without a gate voltage applied, no current can flow between the source and drain regions (2 pn diodes back-to -back)**
- **Above a certain gate-to-source voltage (*threshold voltage V_T*), a conducting layer of mobile electrons is formed at the Si surface beneath the oxide. These electrons can carry current between the source and drain.**

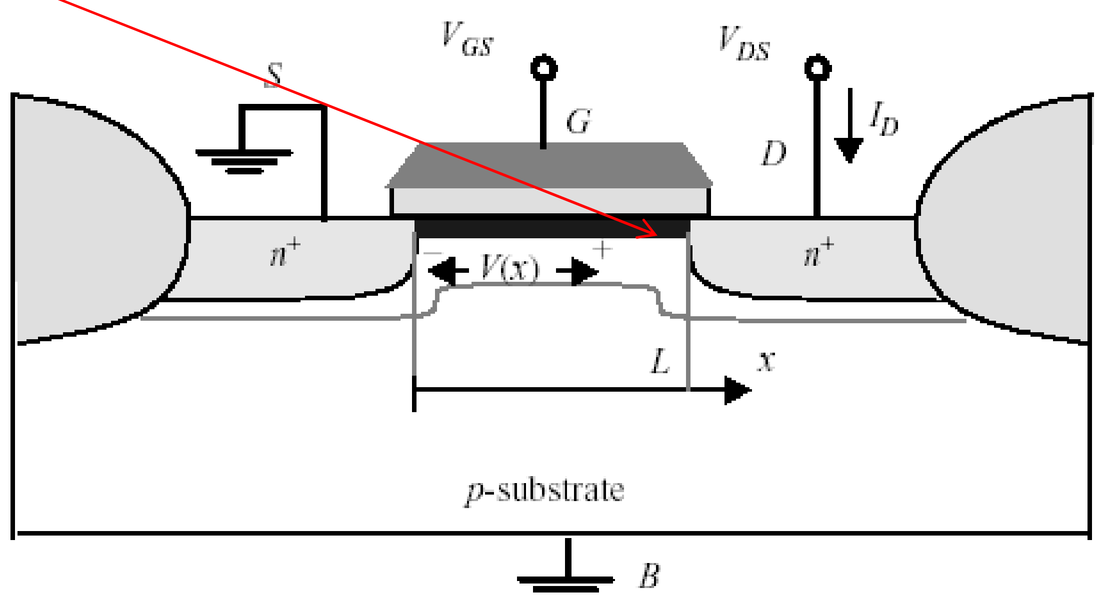
The MOSFET as a Controlled Resistor

- When V_{DS} is low, I_D increases linearly with V_{DS}

Inversion charge density $Q_i(x) = -C_{ox}[\ V_{GS} - V_T - V(x)\ ]$

where $C_{ox} \equiv \varepsilon_{ox} / t_{ox}$.





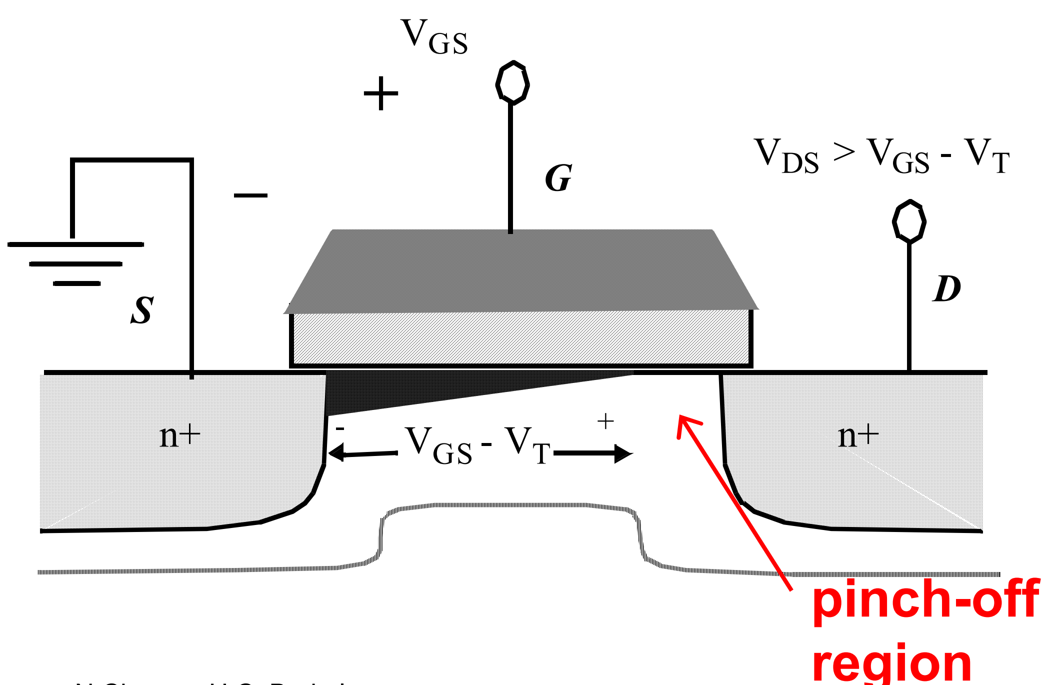
$I_{DS} = 0$ if $V_{GS} < V_T$

Pinch-off and Saturation

- As V_{DS} increases, V(x) along channel increases.

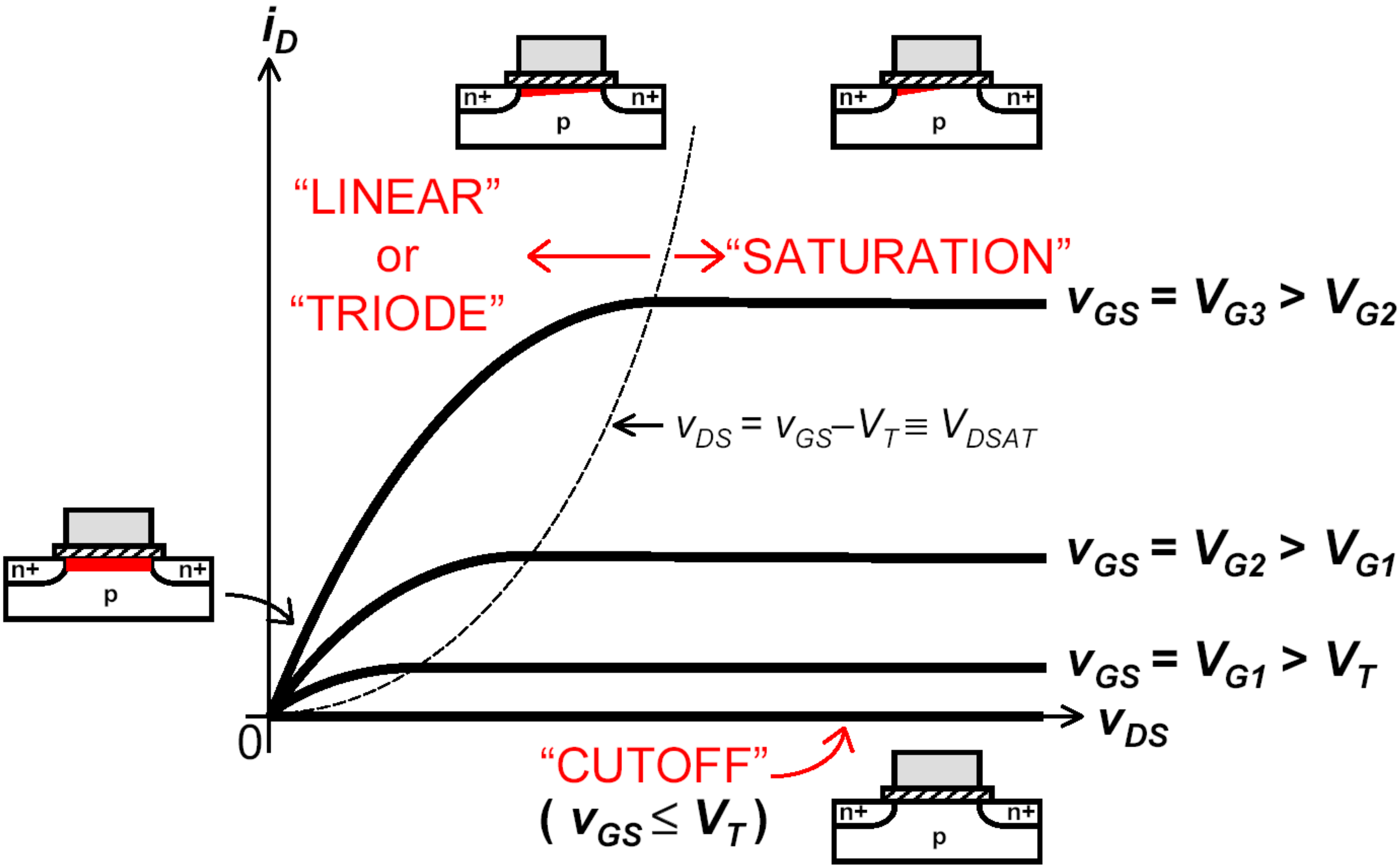
Inversion-layer charge density Qn at the drain end of the channel is reduced; therefore, I_D increases slower than linearly with V_{DS}.

- When V_{DS} reaches $V_{GS} - V_T$, the channel is "pinched off" at the drain end, and I_D saturates (*i.e.* it does not increase with further increases in V_{DS}).



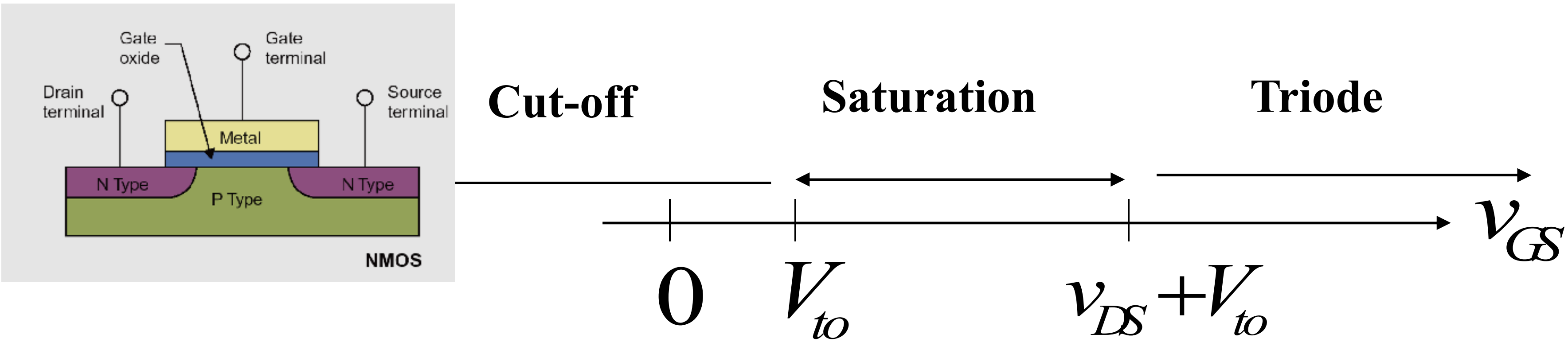
$$I_{DSAT} = \mu_n C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2$$

NMOSFET Summary: *I-V* Characteristics

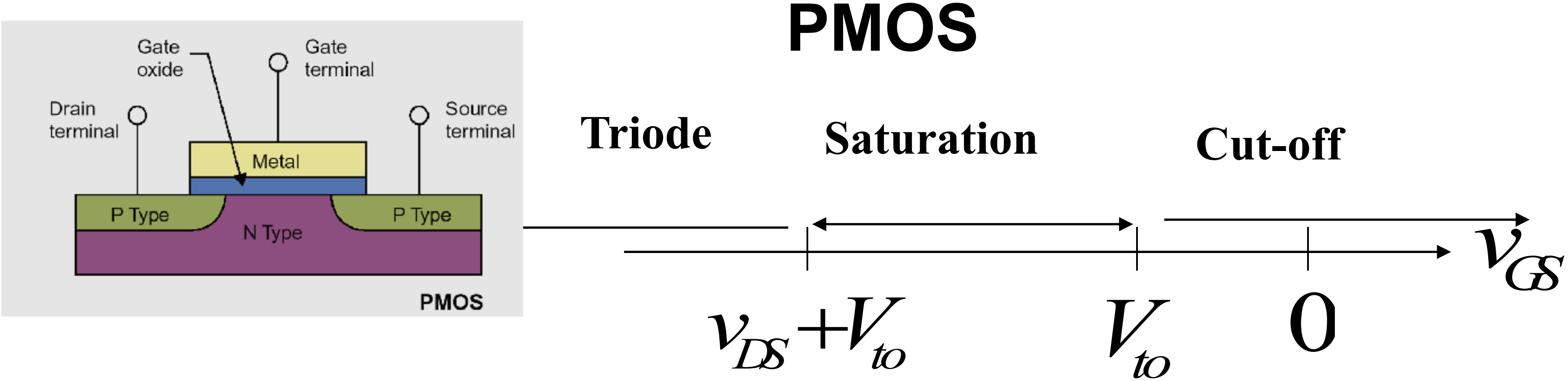


NMOS versus PMOS

NMOS



PMOS



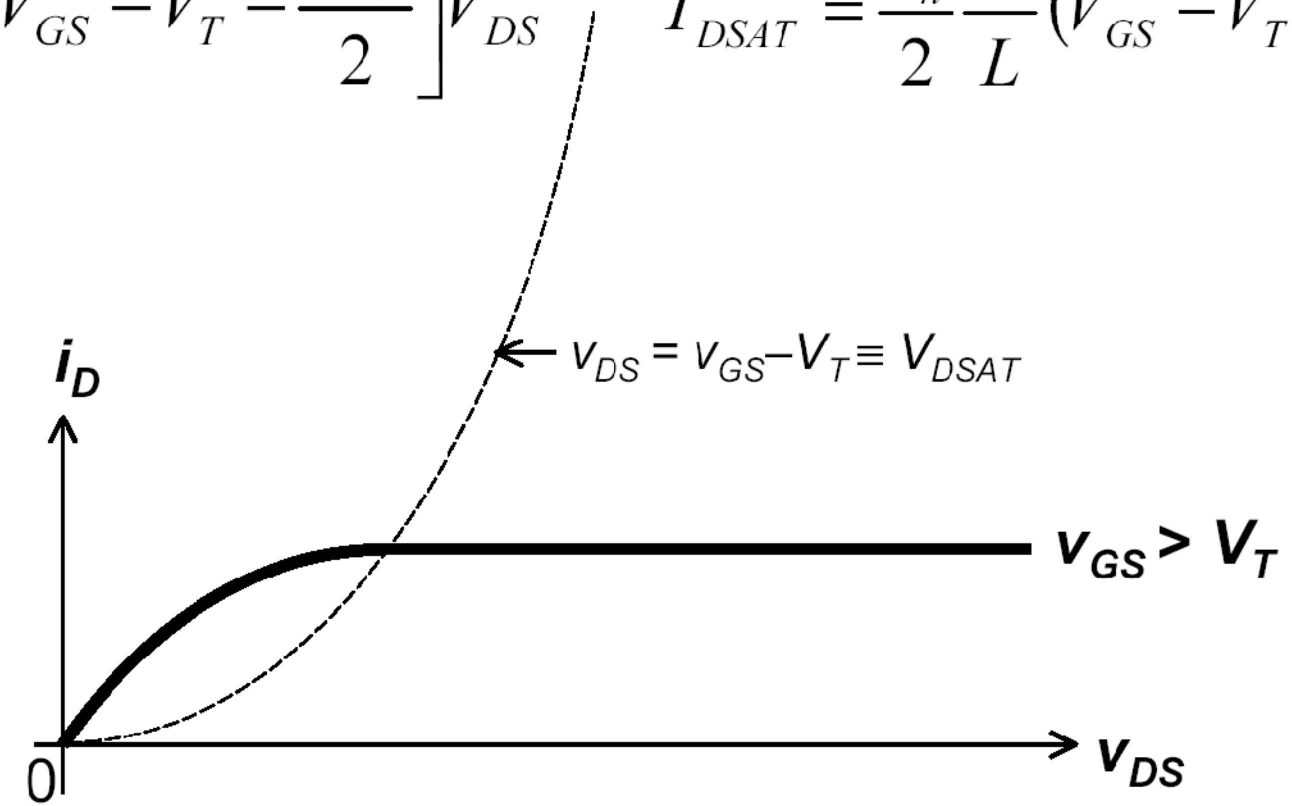
NMOSFET Summary: *I-V* Equations

"LINEAR" or "TRIODE"

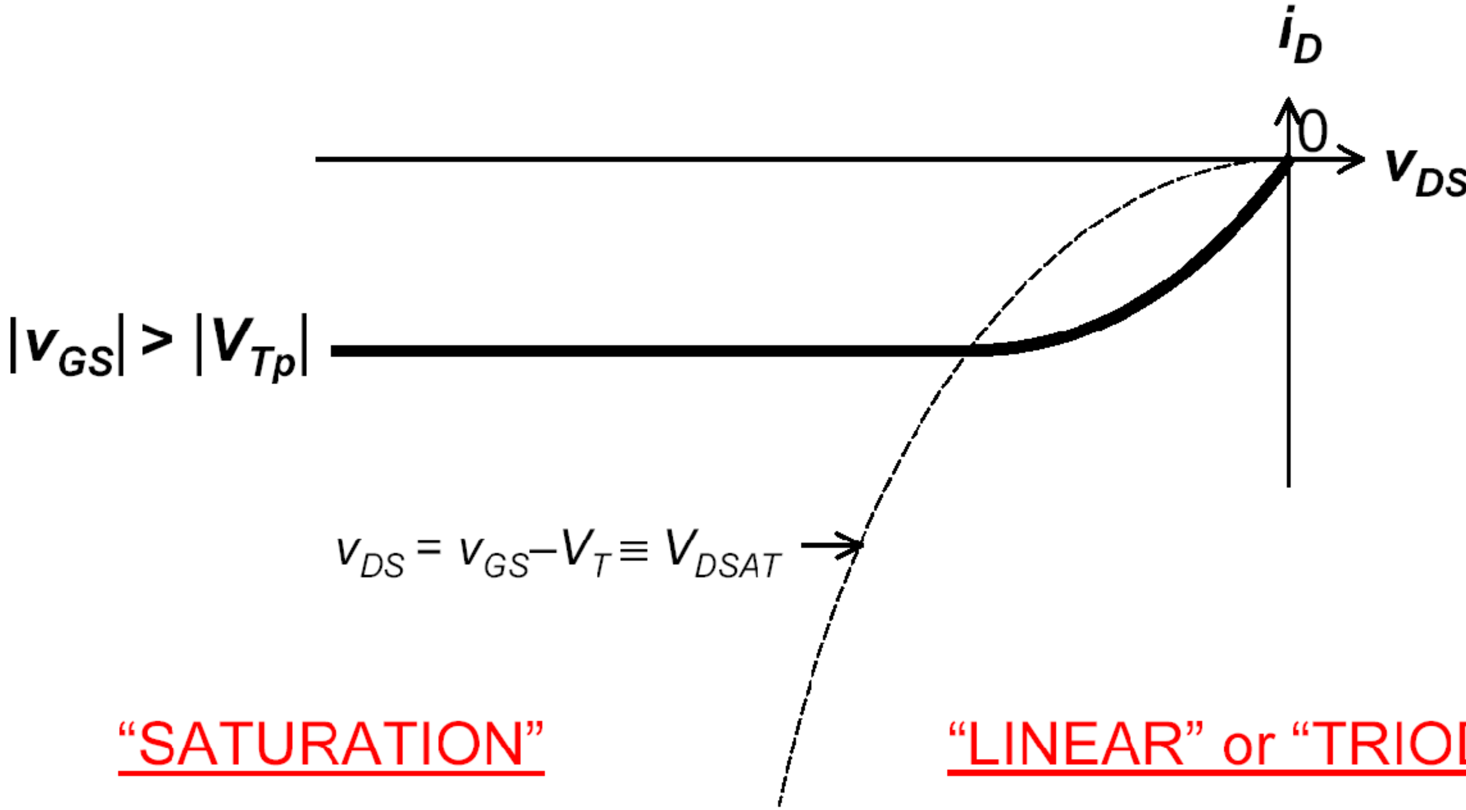
$$I_D = k_n' \frac{W}{L}\left[V_{GS} - V_T - \frac{V_{DS}}{2}\right]V_{DS}$$

"SATURATION"

$$I_{DSAT} = \frac{k_n'}{2}\frac{W}{L}(V_{GS} - V_T)^2$$



PMOSFET *I-V* Equations



"SATURATION"

$$I_{DSAT} = -\frac{k_p'}{2}\frac{W}{L}\left(V_{GS} - V_{Tp}\right)^2$$

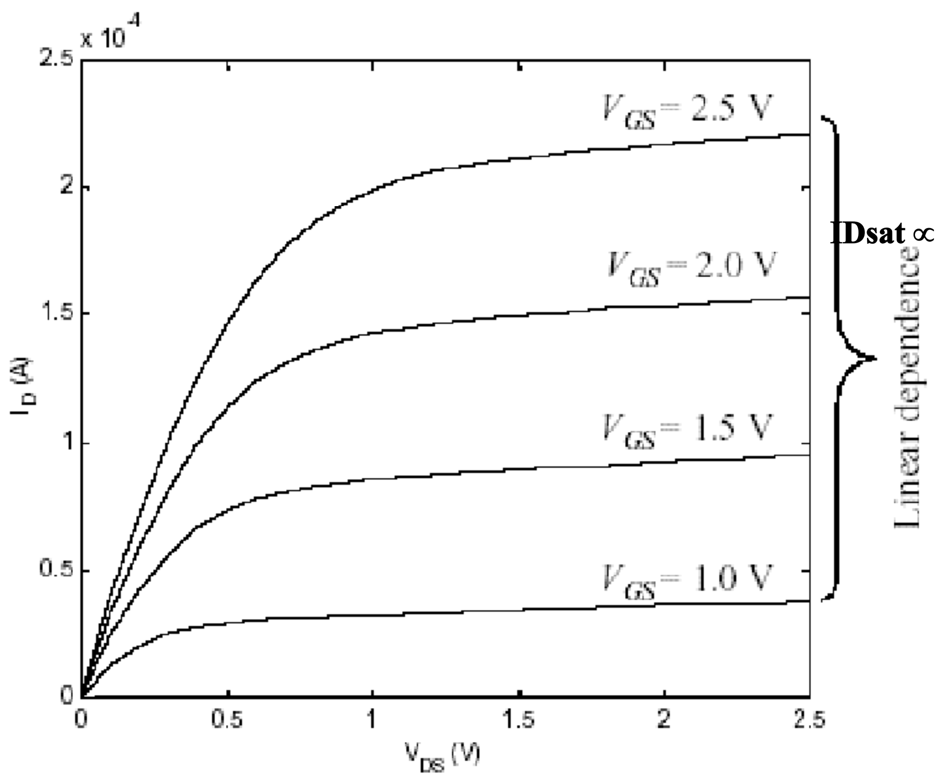
"LINEAR" or "TRIODE"

$$I_D = -k_p'\frac{W}{L}\left[V_{GS} - V_{Tp} - \frac{V_{DS}}{2}\right]V_{DS}$$

Velocity Saturation:

- In a very-short-channel MOSFET, i_D saturates because the carrier velocity is limited to ~10^7 cm/sec

→ i_D reaches a limit before pinch-off occurs



Not proportional to $(V_{GS}-V_t)^2$

$$I_{DSAT} = WC_{ox}\left[V_{GS} - V_T - \frac{V_{DSAT}}{2}\right]v_{sat}$$

where $V_{DSAT} = \frac{L}{\mu_n} v_{sat}$ **< $V_{GS}-V_T$**