Chapter 16.

MOS FUNDAMENTALS

Sung June Kim

kimsj@snu.ac.kr

http://helios.snu.ac.kr

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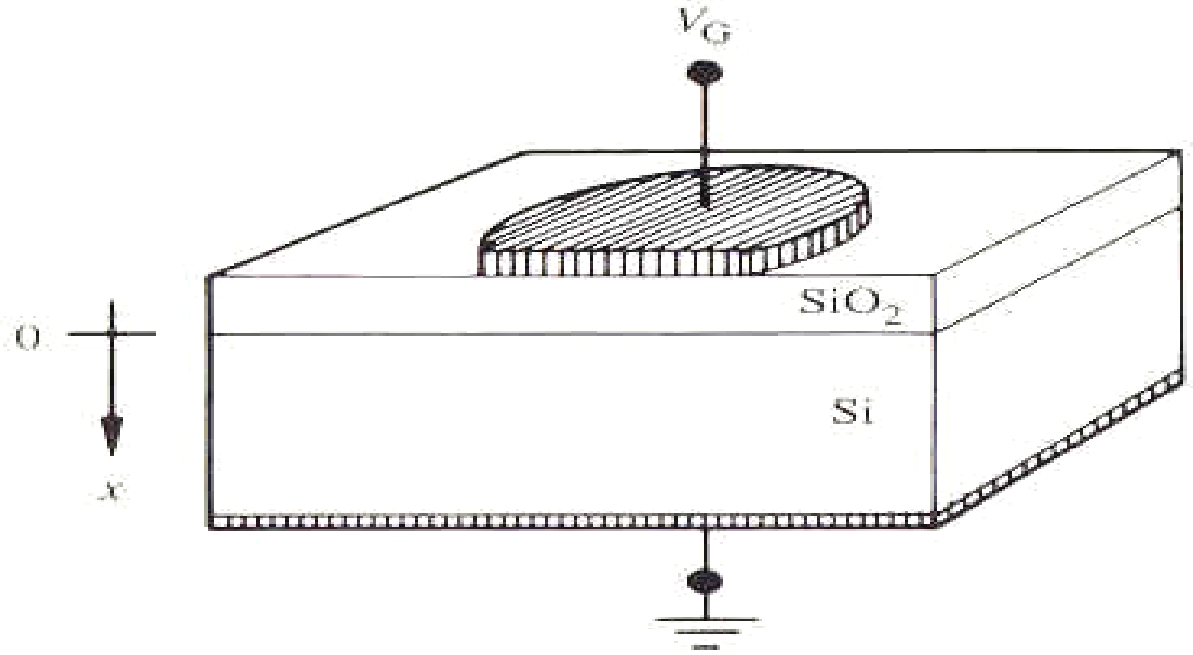
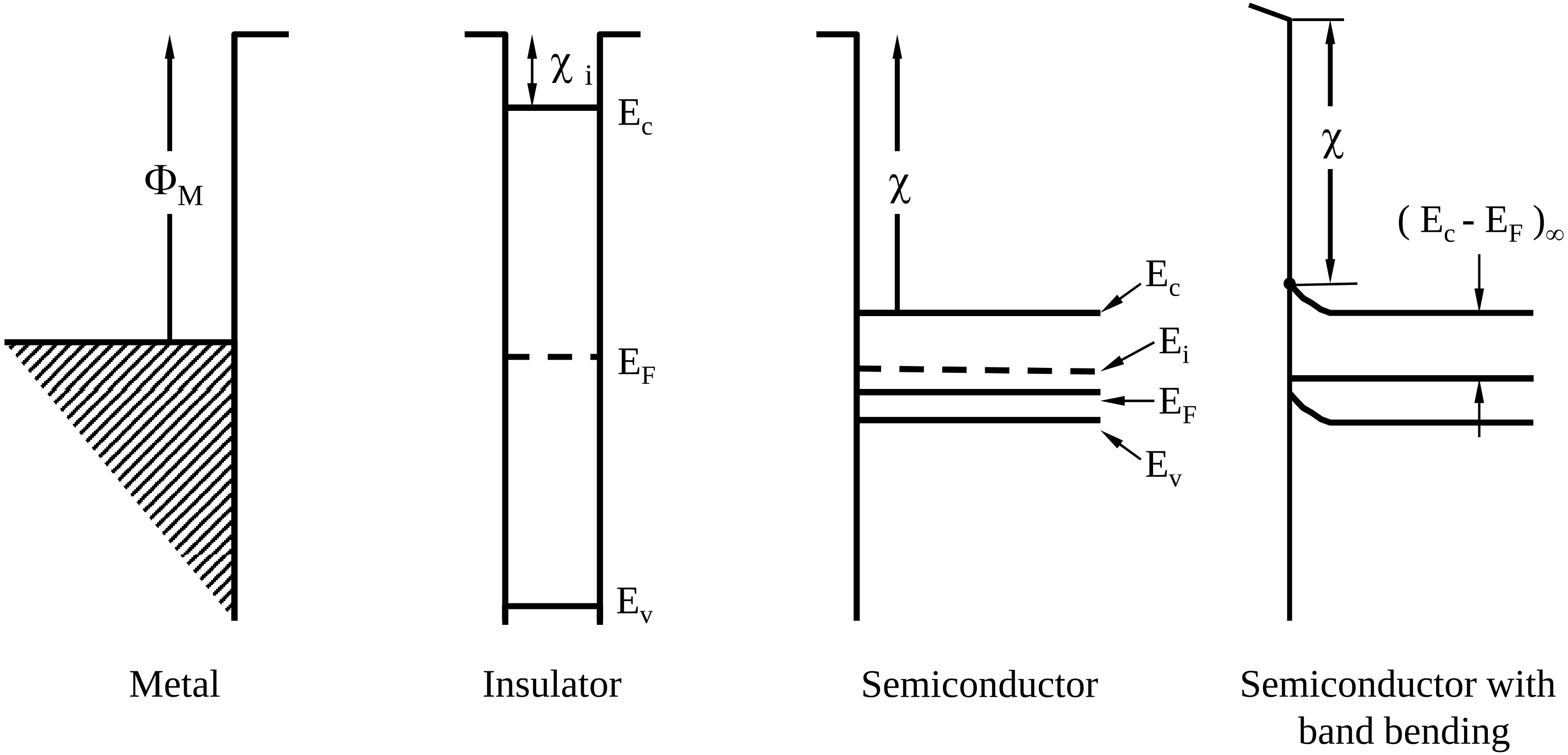
MOS Structure

Metal - Oxide (SiO_2) - Semiconductor (Si)



- The most common field plate (gate) materials are heavily doped polycrystalline silicon.
- The silicon-side terminal is called the back or substrate contact.
- The more general designation: metal-insulator-semiconductor (MIS)

Individual energy band diagrams for the metal, insulator, and semiconductor components.



Ideal Structure Assumption

(1) The metallic gate is sufficiently thick so that it can be considered an equipotential region.

(2) The oxide is a perfect insulator.

(3) No charge centers located in the oxide or at the interface.

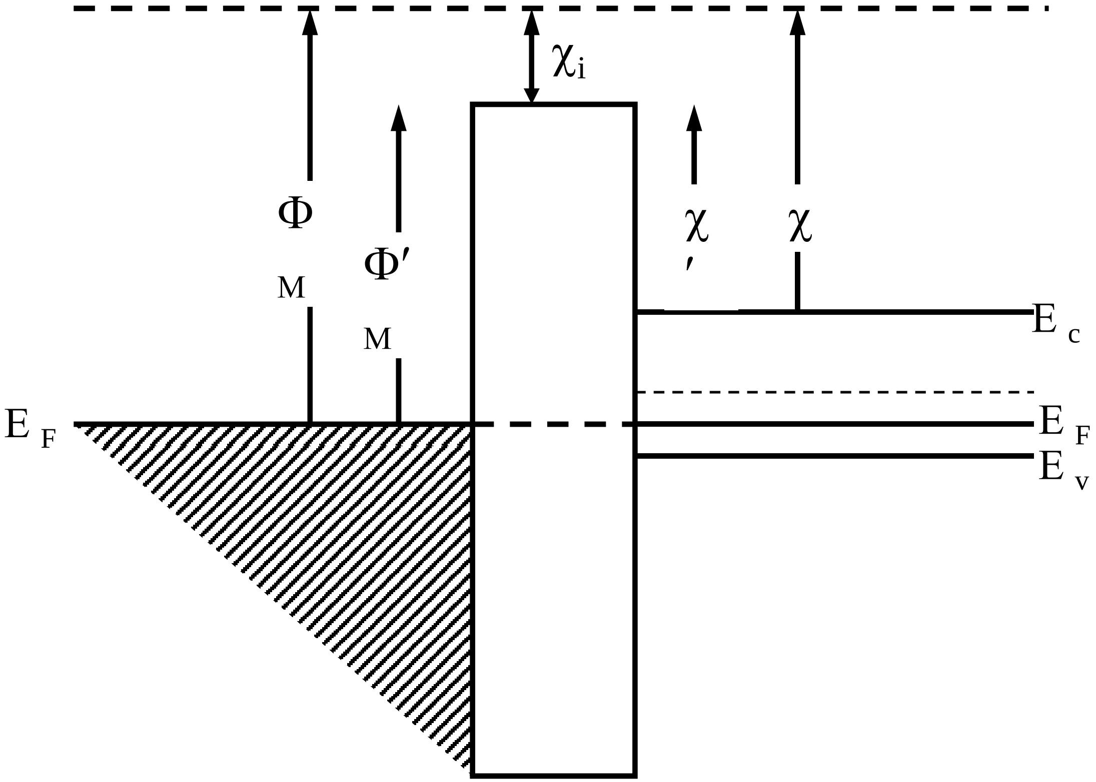
(4) Uniformly doped.

(5) The semiconductor is sufficiently thick so that a field-free region("bulk") is encountered before reaching the back contact.

(6) An ohmic contact between the semiconductor and the metal on the back side.

(7) One-dimensional structure.

(8) No work function difference between metal and semiconductor.



Energy band diagram of an ideal MOS structure with no bias.

Effect Of An Applied Bias
- Qualitative description

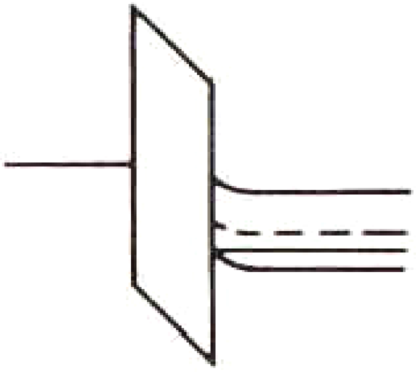
- General observations
  - $E_F(metal) - E_F(semiconductor) = -qV_G$
  - With $V_G \neq 0$, semiconductor Fermi energy is unaffected by the bias and remains invariant as a function of position because of the assumed zero current flow.

– Since the barrier heights are fixed quantities, the movement of the metal Fermi level leads to a band bending.
  - In the metal, no bend-bending.
  - In the oxide and semiconductor,

    an upward slope when $V_G > 0$

    a downward slope when $V_G < 0$.
  - With no oxide charges, the Poisson's equation yields a constant slope in the oxide.
  - Band bending in the semiconductor is somewhat more complex.

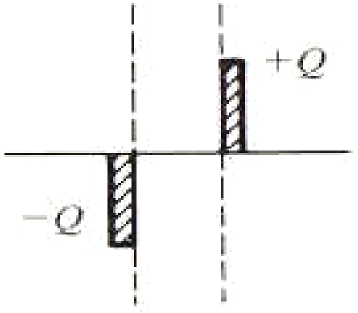
- Specific biasing regions
  - Accumulation ($V_G < 0$)



- VG < 0 raises EF(metal) and the hole concentration inside the semiconductor,

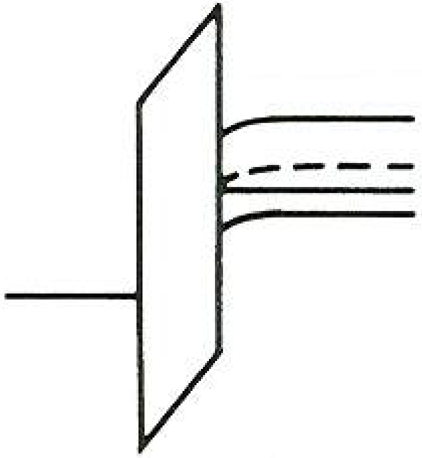
$$p = n_i \exp\left[-\left(E_F - E_i\right)/kT\right]$$

increases as one approaches the oxide-semiconductor interface.

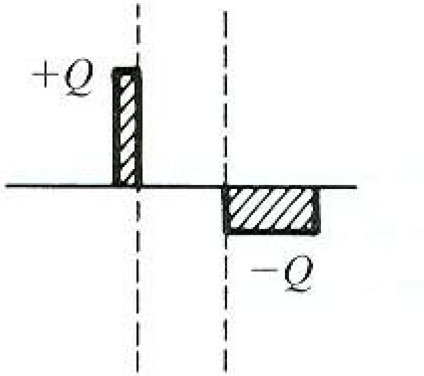


- VG < 0 places negative charges on the gate. To maintain a balance of charge, positively charged holes must be drawn toward the Si-SiO2 interface.

– Depletion ($0 < V_G < V_T$)



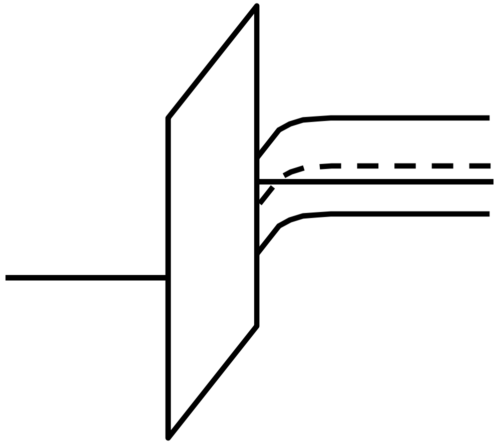
$V_T > V_G > 0$



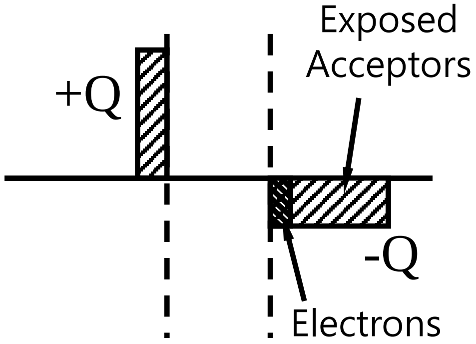
Depletion

- VG > 0 slightly lowers EF(metal) and the hole concentration is decreased (depleted) in the vicinity of the Si-SiO2 interface.
- VG > 0 places positive charges on the gate, which in turn repels holes from the interface and exposes the negatively charged acceptor sites.

– Onset of Inversion ($V_G = V_T$)



$V_G = V_T$



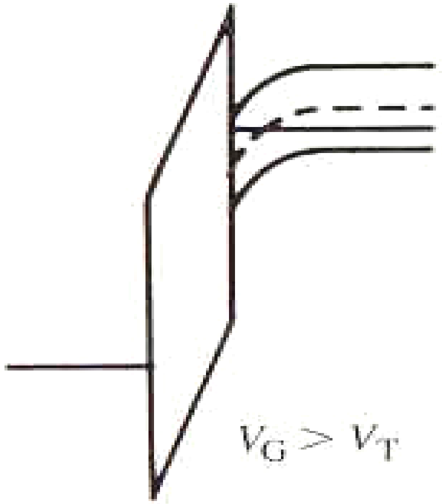
- As VG is increased positively, the bands at the Si surface will bend down more and the electron concentration at the surface (ns) will increase from less than ni when E i (surface) > EF, to ni when Ei (surface) = EF, to greater than ni when Ei (surface) < EF.
- At VG=VT,

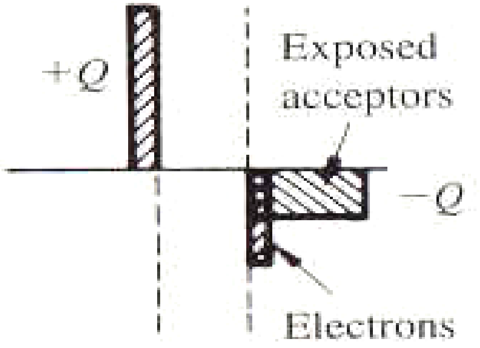
$$E_i(bulk) - E_i(surface) = 2[E_i(bulk) - E_F]$$

$$n_s = n_i \exp\left[\frac{E_F - E_i(surface)}{kT}\right]$$

$$= n_i \exp\left[\frac{E_i(bulk) - E_F}{kT}\right] = p_{bulk} = N_A$$

– Inversion (VG > VT)

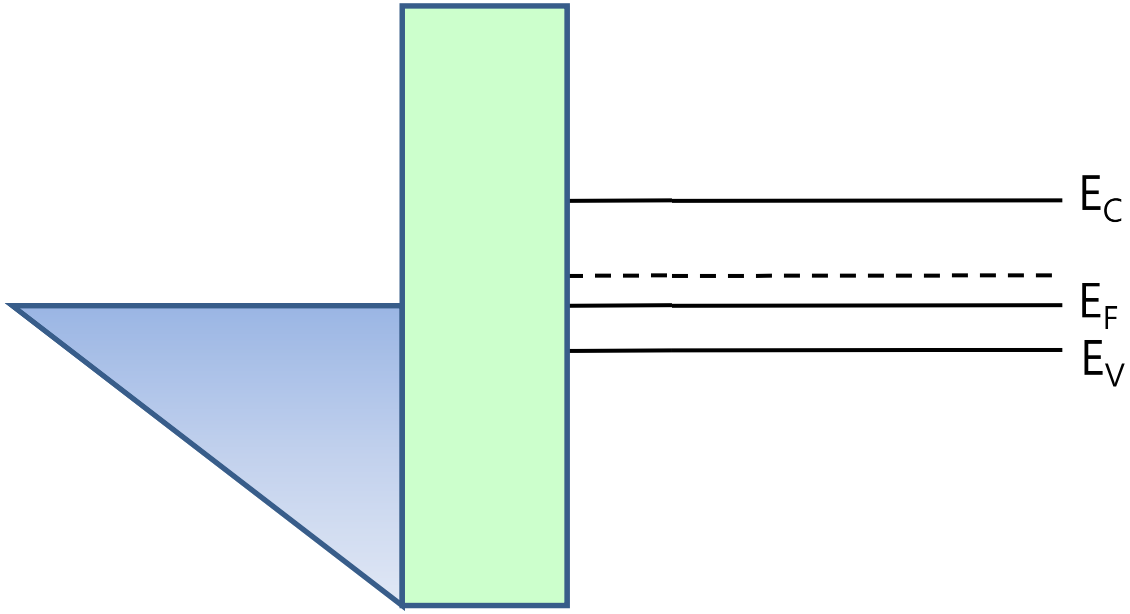




- For VG > VT , ns > NA.
- The surface region :p-type n-type
- In inversion, the depletion width changes little since

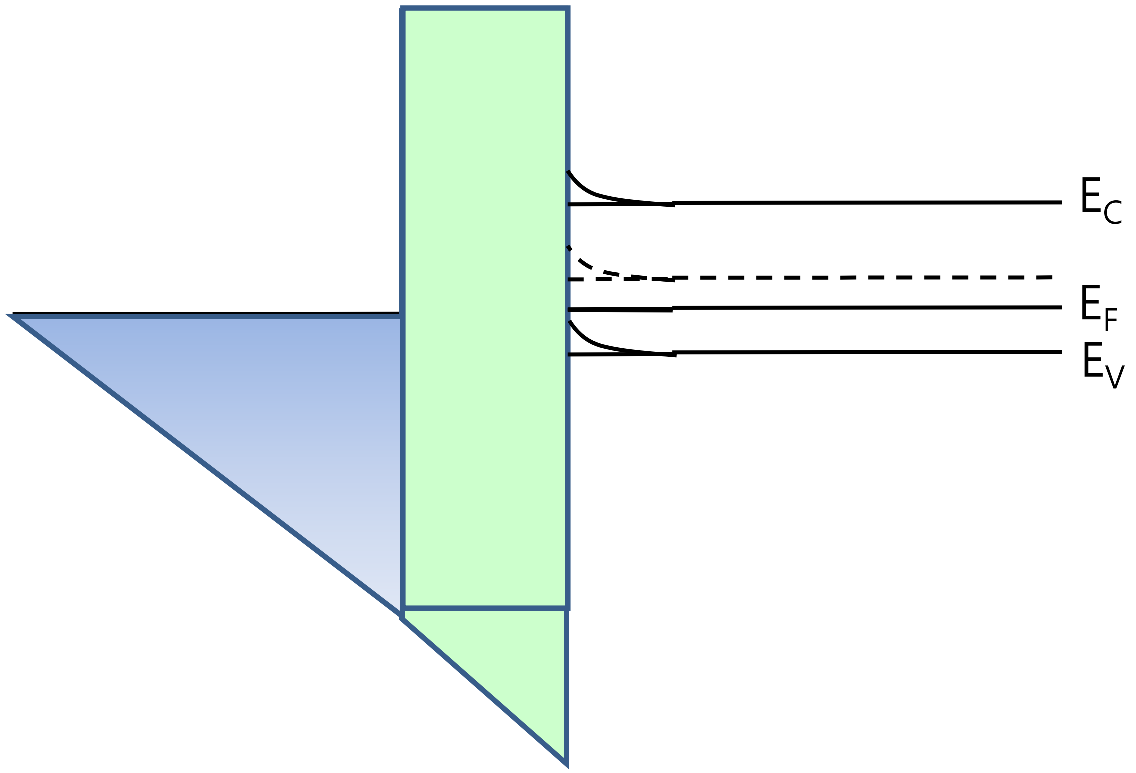
$$n_s \propto \exp\left[\frac{E_F - E_i(surface)}{kT}\right]$$

No Bias (V_G = 0)



Metal Insulator Si

Accumulation ($V_G < 0$)

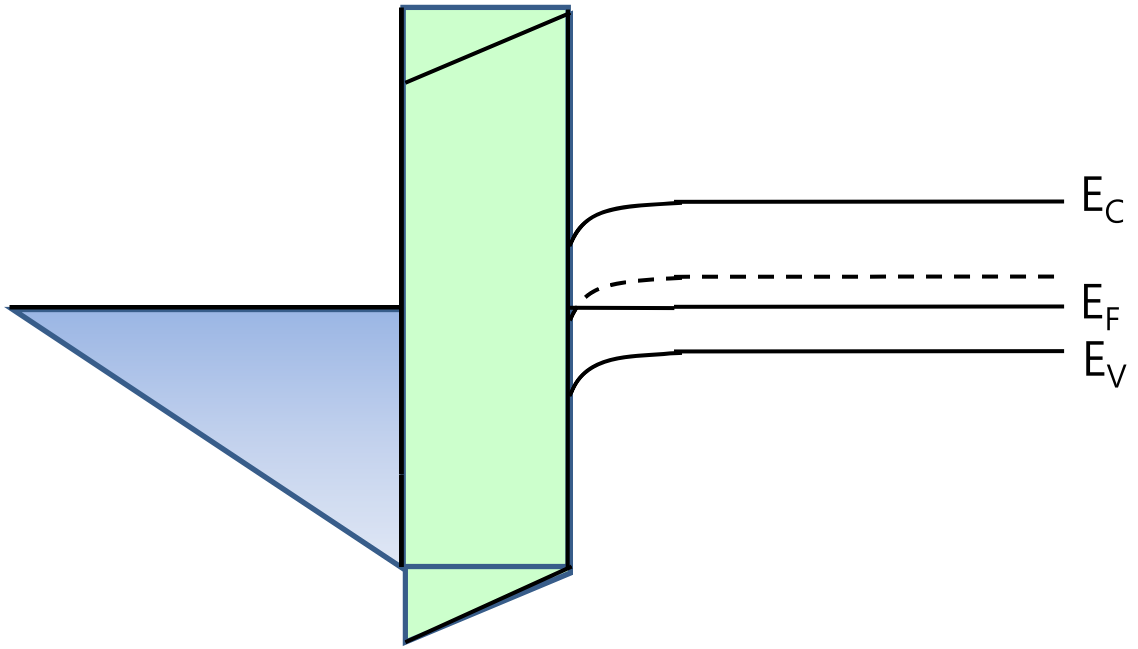


Metal

Insulator

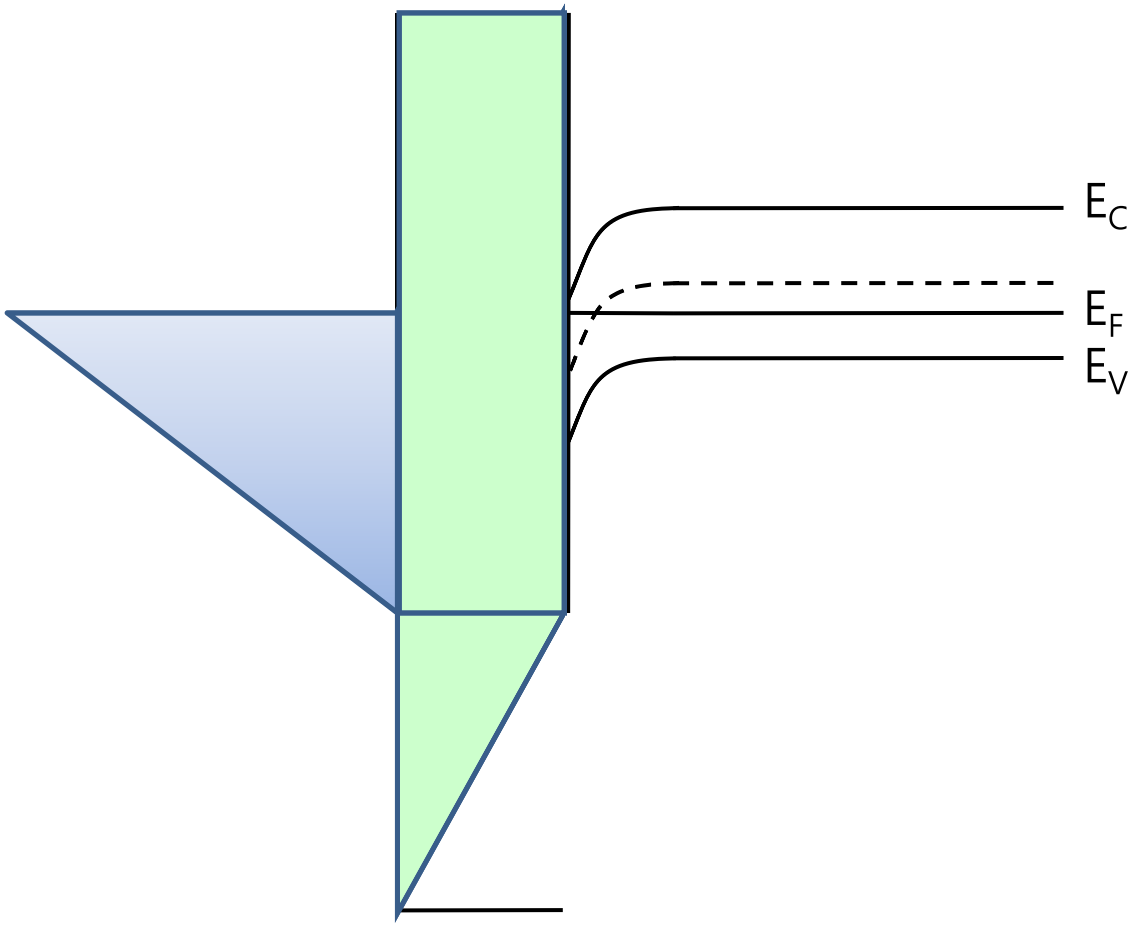
Si

Depletion ($0 < V_G < V_T$)



Metal Insulator Si

Inversion ($V_G > V_T$)



Metal Insulator Si

Effect Of An Applied Bias
- Quantitative formulation

- Preparatory considerations

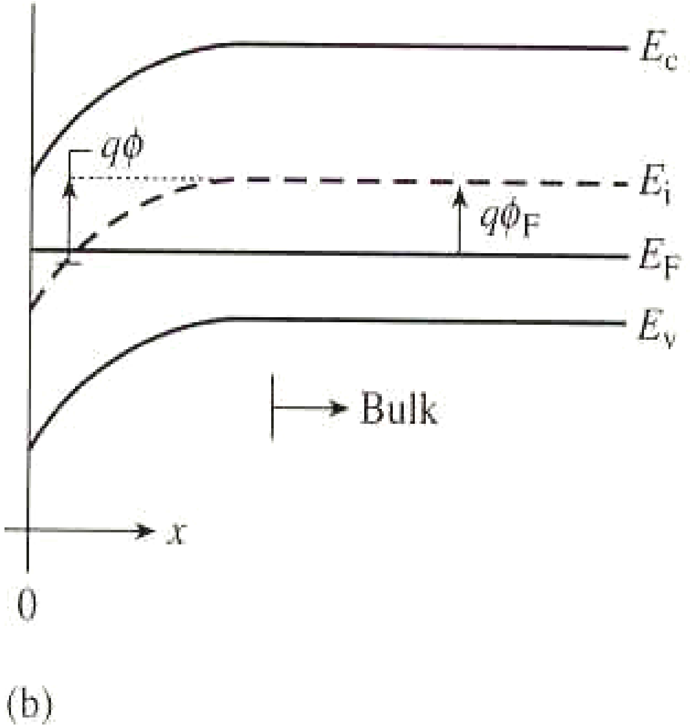
$$\phi(x) = \frac{1}{q}\left[E_i(bulk) - E_i(x)\right]$$

ϕ_S : the surface potential.

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

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

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



For an p-type semiconductor,

- Accumulation : $\phi_s < 0$
- Flat band : $\phi_s = 0$
- Depletion : $0 < \phi_s < 2\phi_F$
- Onset of inversion : $\phi_s = 2\phi_F$
- Inversion : $\phi_s > 2\phi_F$

• Delta-depletion solution

Delta-depletion assumption :

- The functional form of the accumulation charge & the inversion charge : δ - function.
- Because the depletion width increases only slightly once the semiconductor inverts, it is assumed the δ - function of charge added in inversion precisely balances the charge added to the gate.
- The actual depletion charge is replaced with a squared-off distribution

- Accumulation :
  - Because of the assumed δ - function, the electric field and potential are zero for all $x > 0$.
- Depletion :

For $0 \le x \le W$,

$$\frac{dE}{dx} = \frac{\rho}{K_S \varepsilon_0} \cong -\frac{qN_A}{K_S \varepsilon_0}$$

$$E(x) = \frac{qN_A}{K_S \varepsilon_0}(W - x)$$

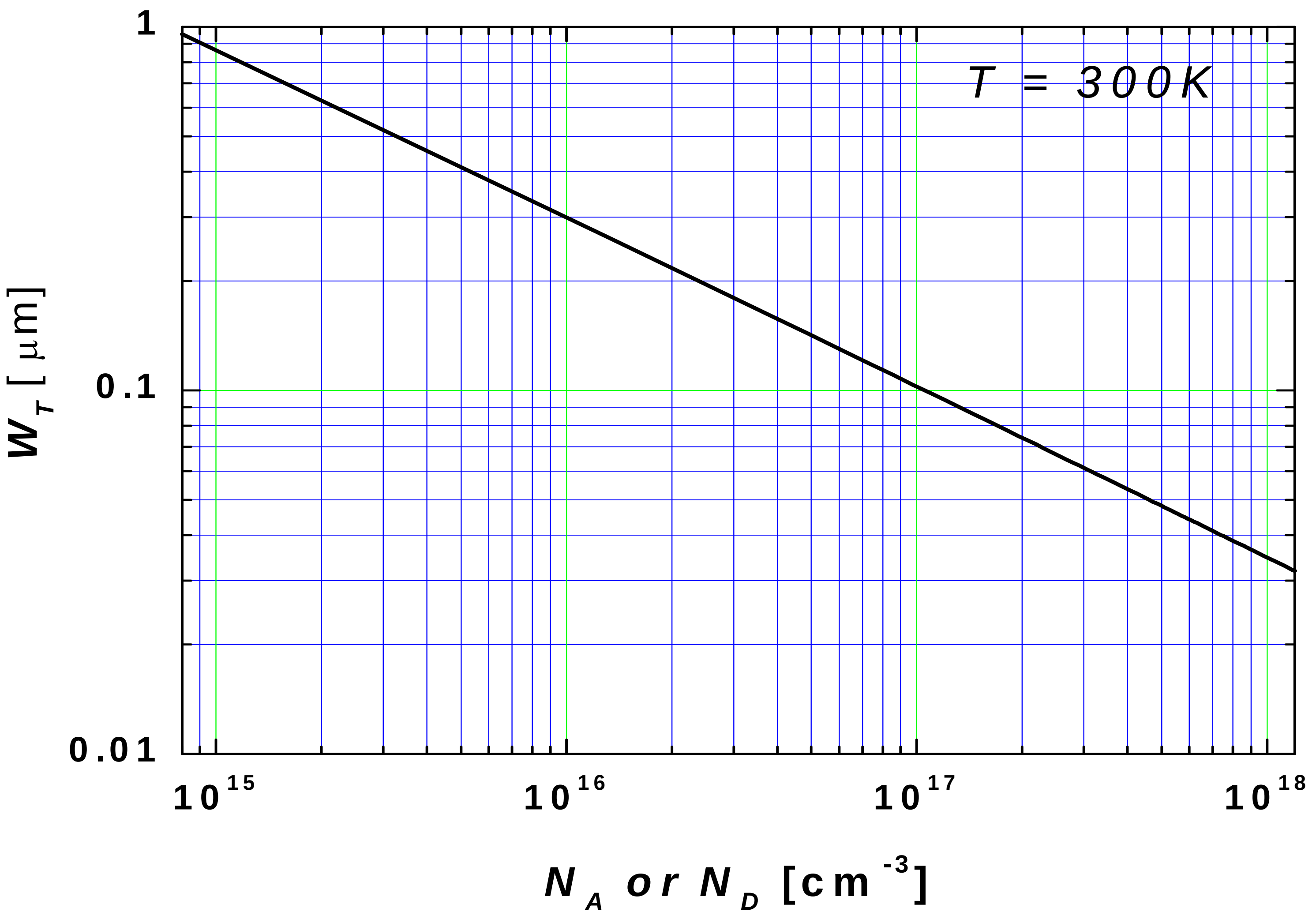
$$\phi(x) = \frac{qN_A}{2K_S \varepsilon_0}(W - x)^2$$

with $\phi = \phi_S$ **at** $x = 0$,

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

The maximum depletion width,

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


1
0.1
0.01
W_T [μm]
T = 300K
10^{15}
10^{16}
10^{17}
10^{18}
N_A or N_D [cm^{-3}]

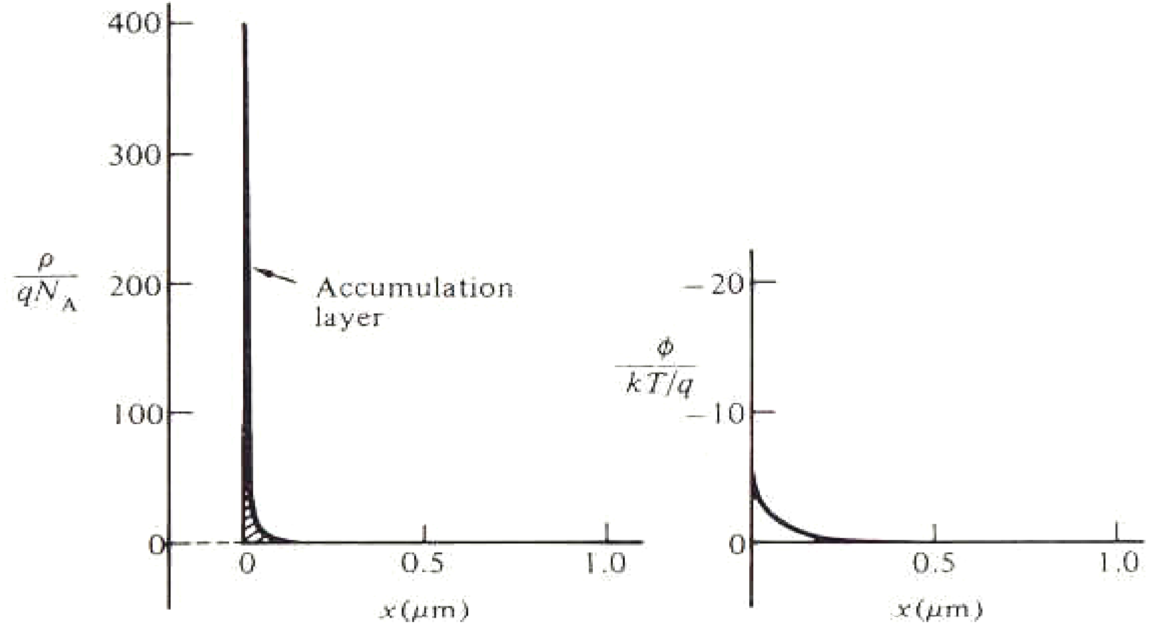
- Inversion :
  - The solution is established by merely adding a δ - function of surface charge to the solution existing at the end of depletion.
  - The depletion charge, the $x > 0$ electric field, and the $x > 0$ potential remain fixed at their values.

$$\phi_s = 2\phi_F$$

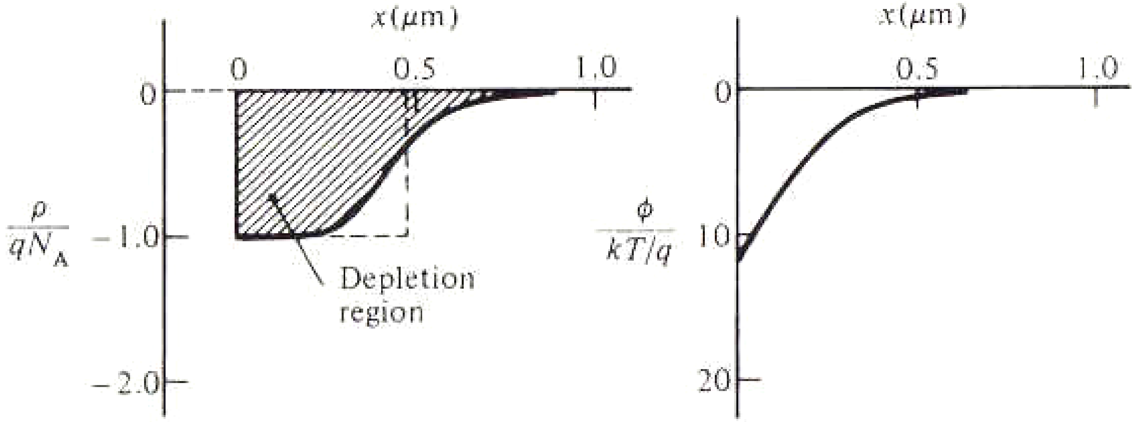
Exact solution for the charge density and potential assuming

$$\phi_F = 12kT/q \text{ and } T = 300K$$

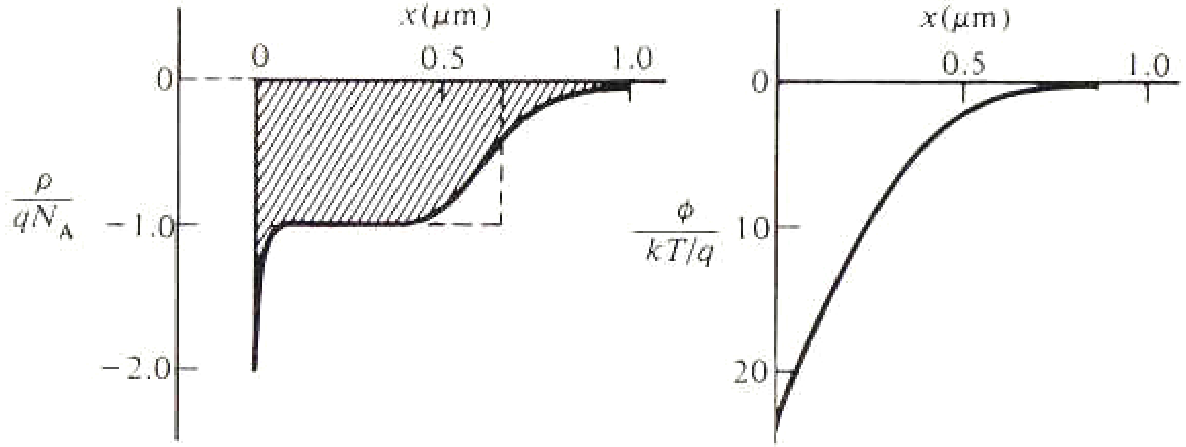
(a) Accumulation (f_s = -6kT/q)



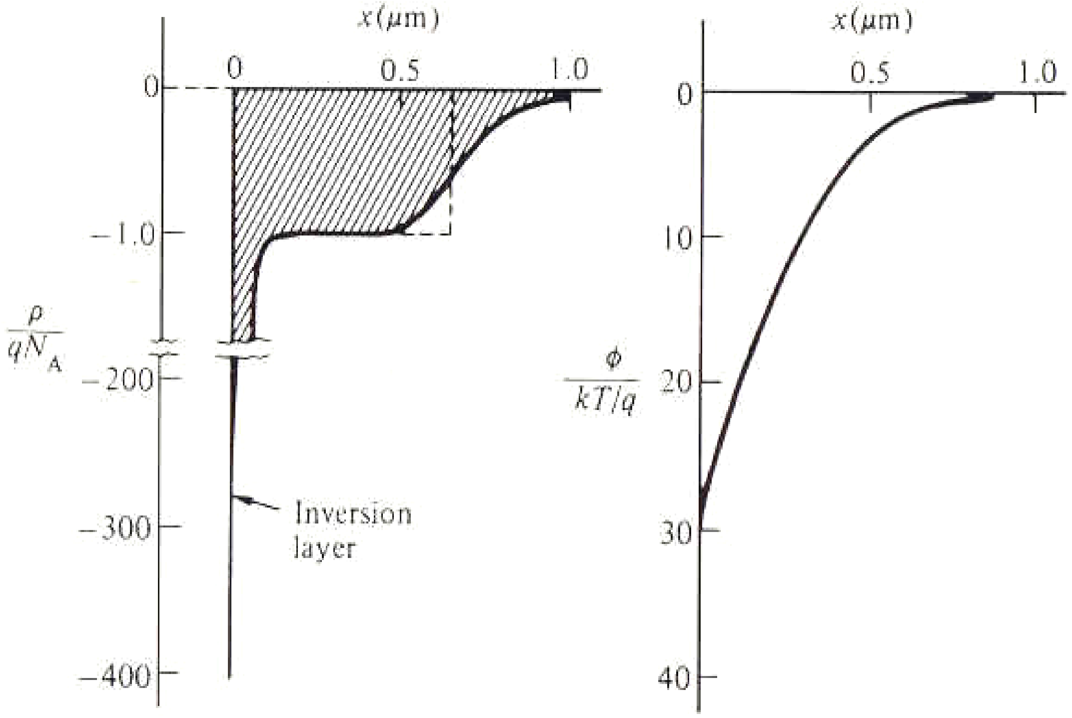
(b) Middle of depletion ($f_s = f_F = 12kT/q$)



(c) Onset of inversion ($f_s = 2f_F = 24kT/q$)



(d) Deep into inversion



- # Gate voltage relationship (delta-depletion solution)

$$V_G = \Delta\phi_{Semi} + \Delta\phi_{OX}$$

Because ε_{OX} is constant in an ideal oxide with no charges,

$$\Delta\phi_{ox} = x_o\,\varepsilon_{ox}$$

Since there is no charges at the interface, (in the depletion region)

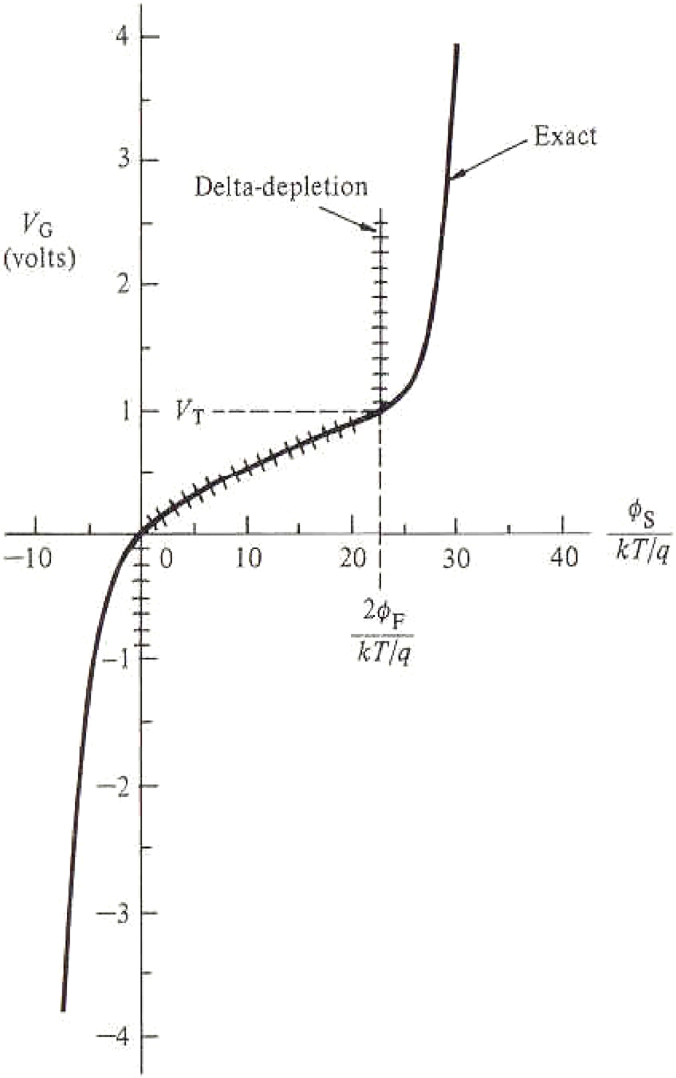
$$D_{ox} = D_{Semi}\Big|_{x=0}$$

$$E_{ox} = \frac{K_s}{K_o}E_s$$

$$\boxed{V_G = \phi_S + \frac{K_s}{K_o}\mathrm{x}_o E_s = \phi_S + \frac{K_s}{K_o}\mathrm{x}_o\sqrt{\frac{2qN_A}{K_s\varepsilon_0}\phi_S} \quad \left(0 \le \phi_S \le 2\phi_F\right)}$$

At threshold, $\phi_S = 2\phi_F$

$$V_T = 2\phi_F + \frac{K_s\, \mathrm{x}_o}{K_o}\sqrt{\frac{4qN_A}{K_s\varepsilon_0}\phi_F}$$



ϕ_s is a rather rapidly varying function of V_G when the device is in depletion. However,

when it is accumulated or inverted, it takes a large change in V_G to produce a small change in ϕ_s.

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