6.012 - Microelectronic Devices and Circuits

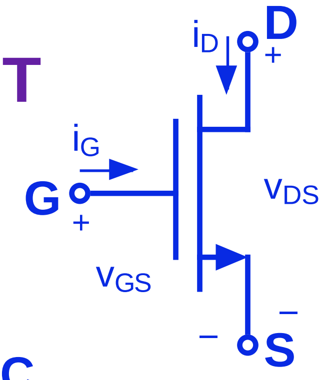
Lecture 9 - MOS Capacitors I - Outline

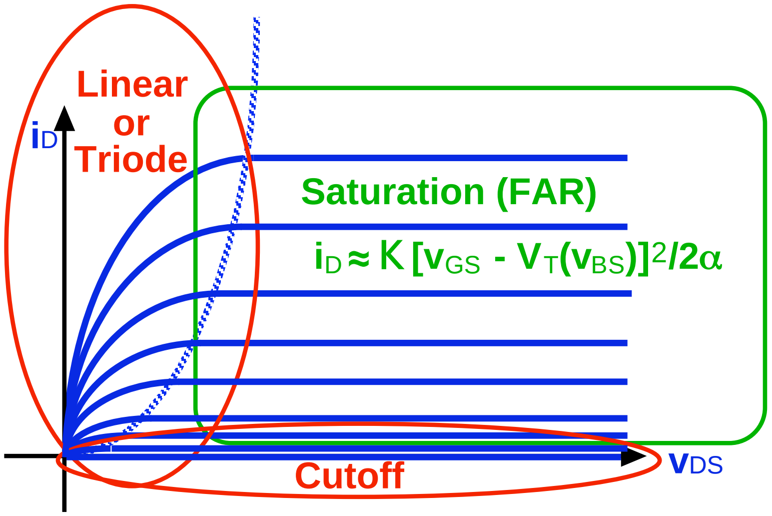
- **Announcements**
  Problem set 5 - Posted on Stellar. Due next Wednesday.
- **Qualitative description - MOS in thermal equilibrium**
  Definition of structure: metal/silicon dioxide/p-type Si **(Example: n-MOS)**
  Electrostatic potential of metal relative to silicon: ϕ_m
  Zero bias condition: Si surface depleted if $\phi_m > \phi_{p\text{-}Si}$ **(typical situation)**
  Negative bias on metal: depletion to flat-band to accumulation
  Positive bias on metal: depletion to threshold to inversion
- **Quantitative modeling - MOS in thermal equilibrium, $v_{BC} = 0$**
  Depletion approximation applied to the MOS capacitor:
  1. Flat-band voltage, V_{FB}
  2. Accumulation layer sheet charge density, $q_A{}^*$
  3. Maximum depletion region width, X_{DT}
  4. Threshold voltage, V_T
  5. Inversion layer sheet charge density, $q_N{}^*$
- **Quantitative modeling - $v_{BC} \neq 0$; impact of $v_{BC} < 0$**
  Voltage between n+ region and p-substrate: $|2\phi_{p\text{-}Si}| \rightarrow |2\phi_{p\text{-}Si}| - v_{BC}$

n-Channel MOSFET: Connecting with the npn MOSFET

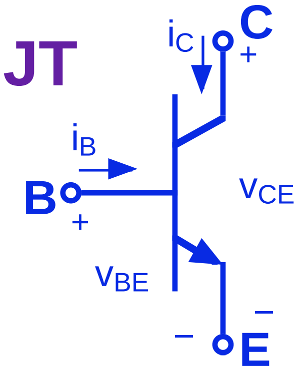
A very similar behavior, and very similar uses.

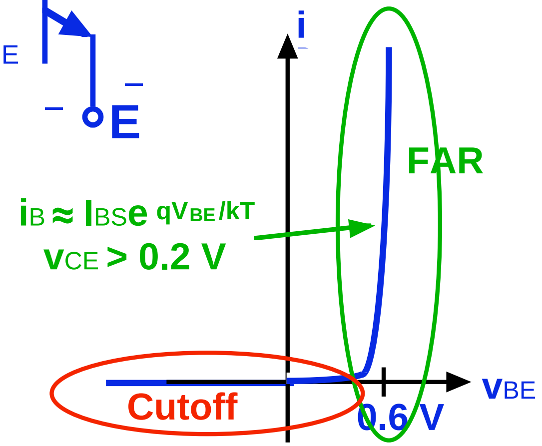
MOSET



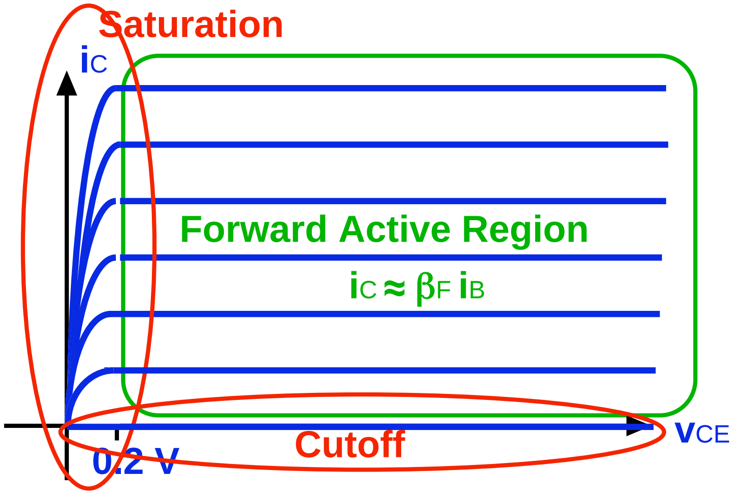


BJT



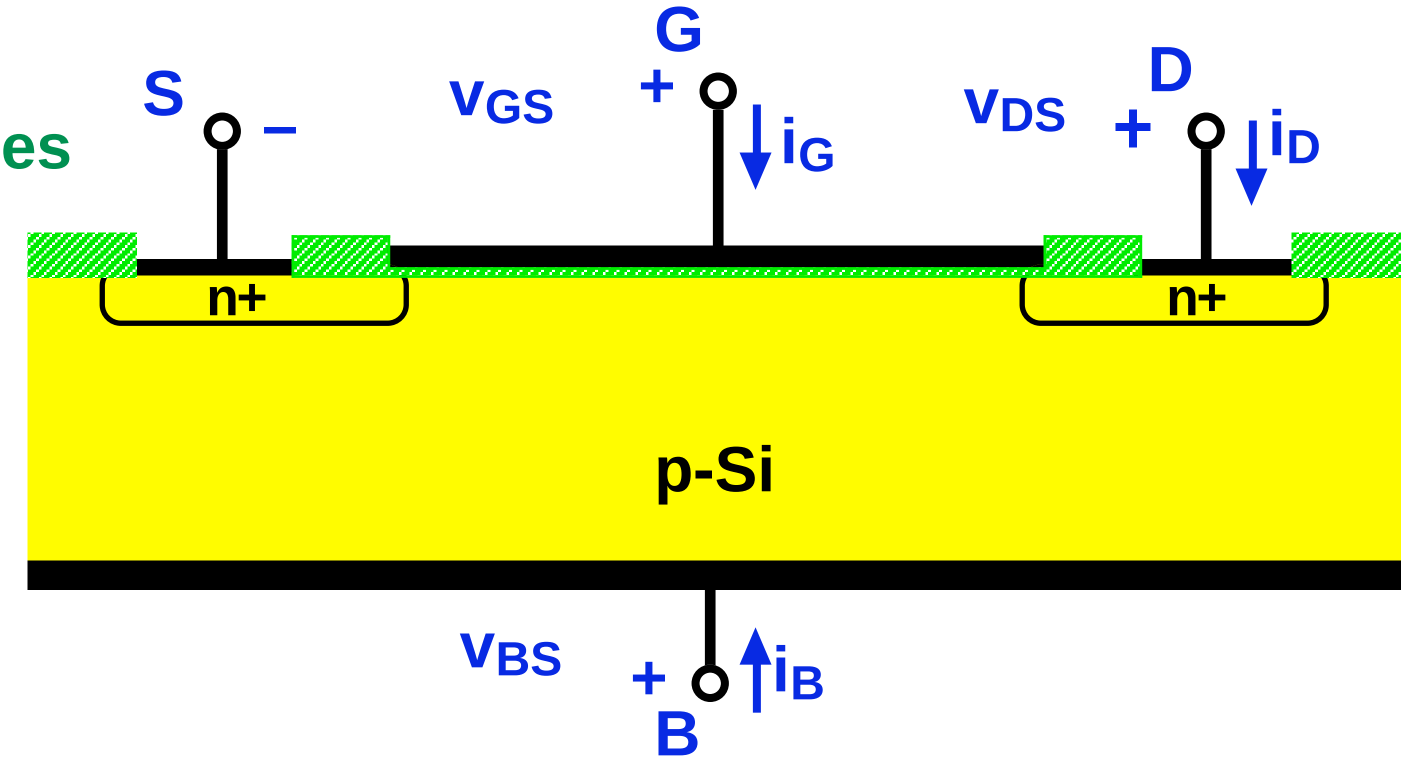


Input curve



Output family

MOS structures



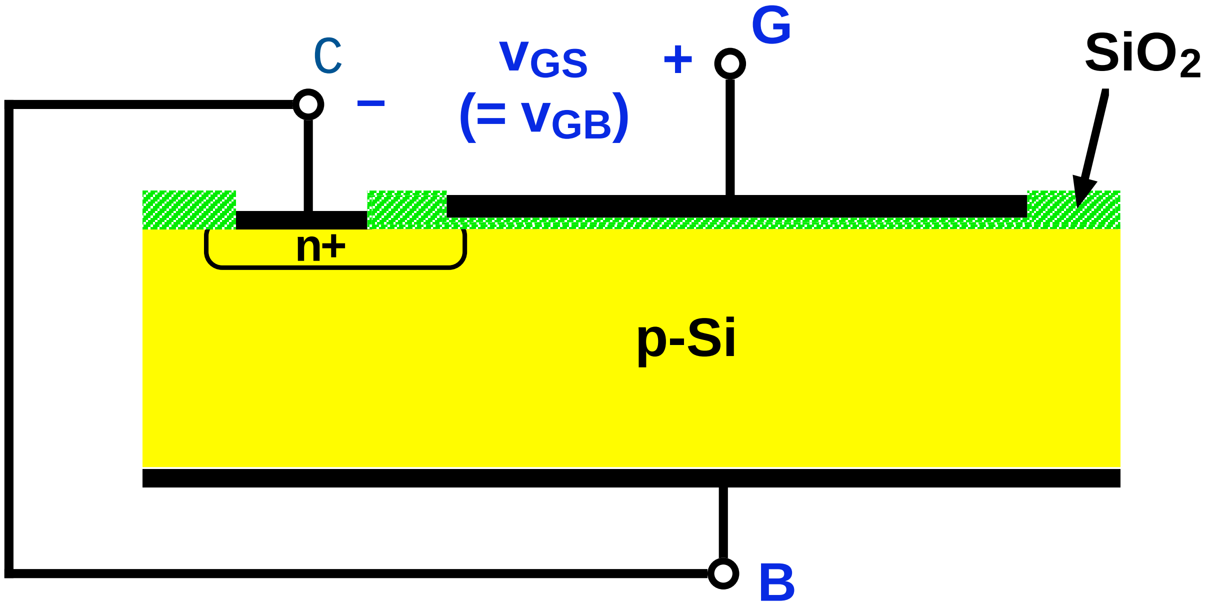
An n-channel MOSFET

In an n-channel MOSFET, we have two n-regions (the source and the drain), as in the npn BJT, with a p-region producing a potential barrier for electrons between them. In this device, however, it is the voltage on the gate, v_{GS}, that modulates the potential barrier height.

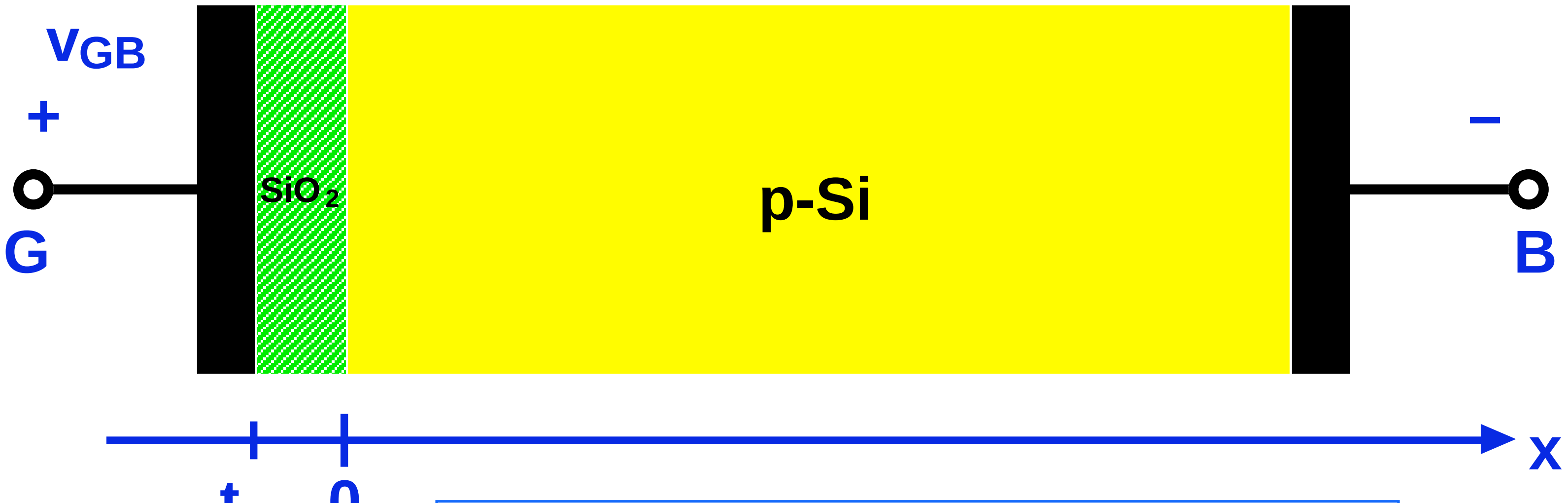
The heart of this device is the MOS capacitor, which we will study today. To analyze the MOS capacitor we will use the same depletion approximation that we introduced in conjunction with p-n junctions.

The n-MOS capacitor

Right: Basic device with $v_{BC} = 0$

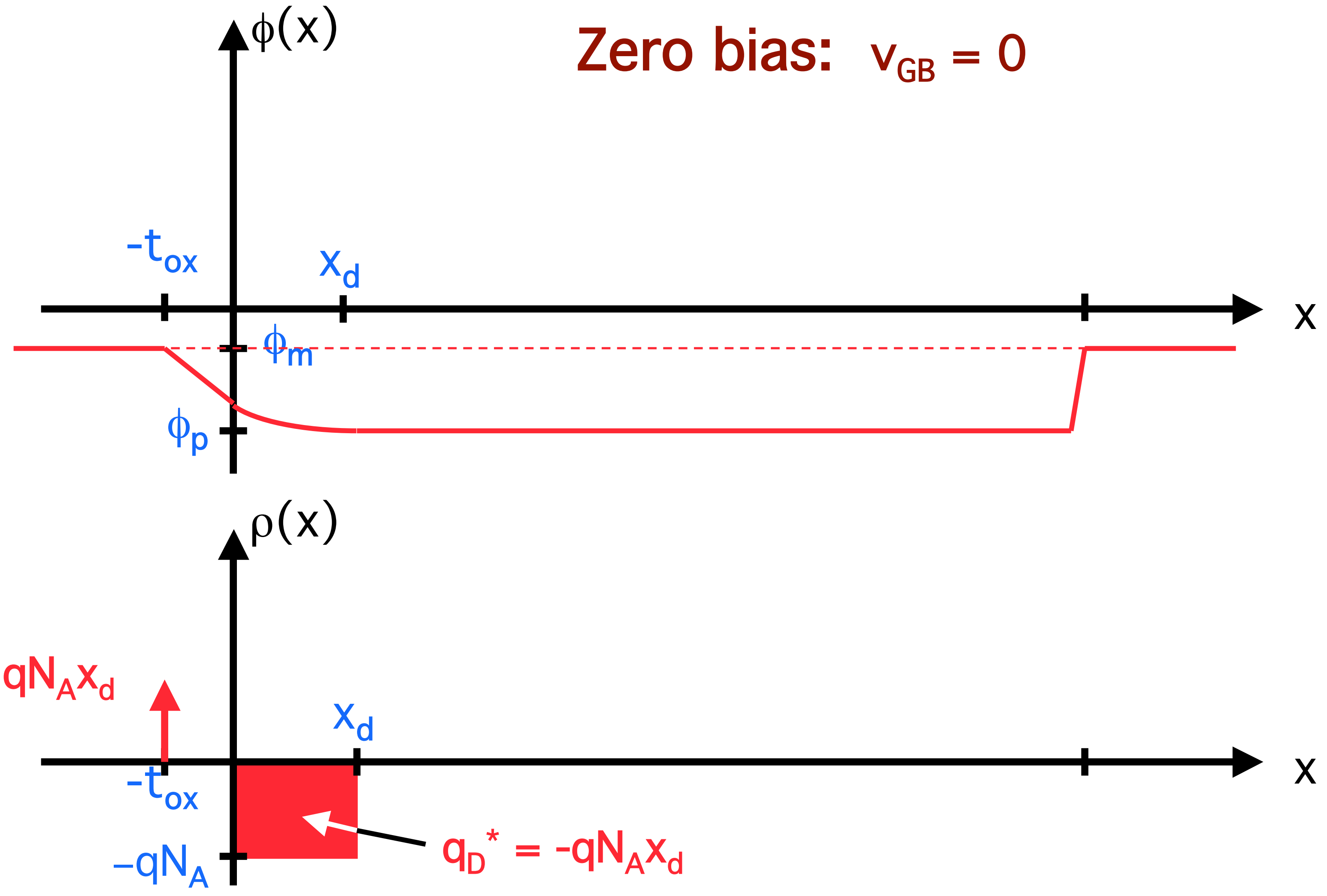


Below: One-dimensional structure for depletion approximation analysis*



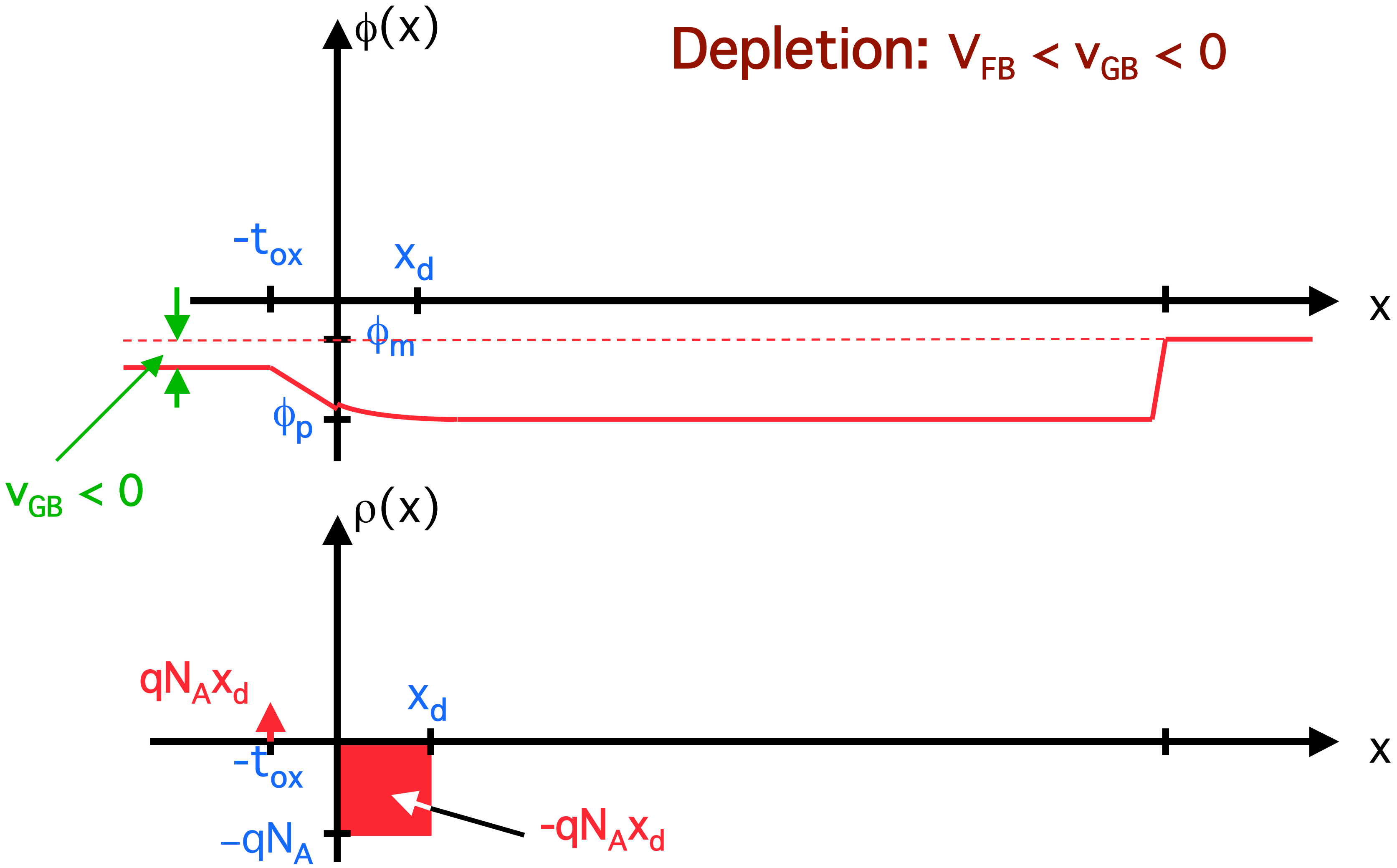
* Note: We can't forget the n+ region is there; we will need electrons, and they will come from there.

Electrostatic potential and net charge profiles



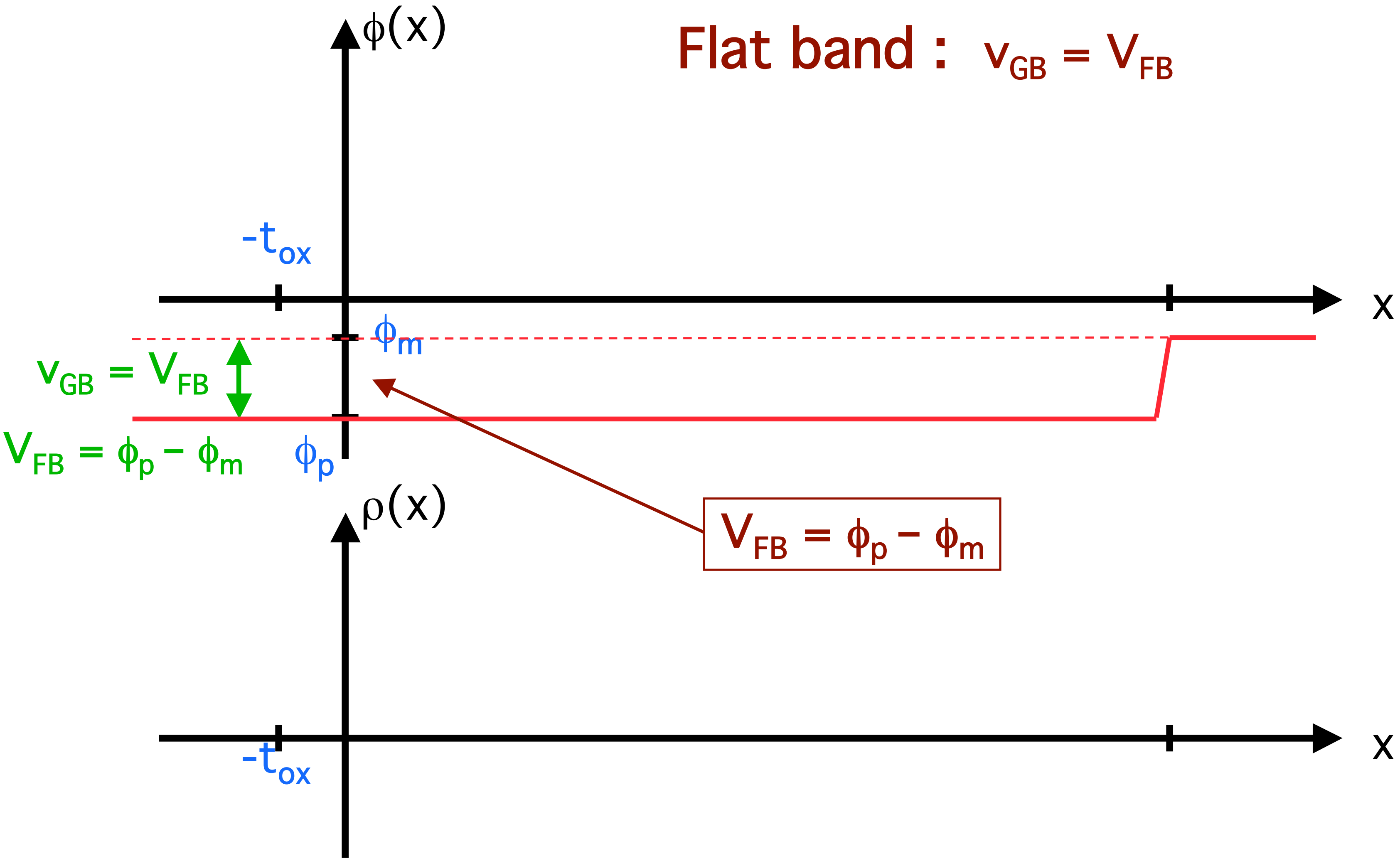
Electrostatic potential and net charge profiles

Depletion: $V_{FB} < v_{GB} < 0$



Electrostatic potential and net charge profiles

Flat band : $v_{GB} = V_{FB}$

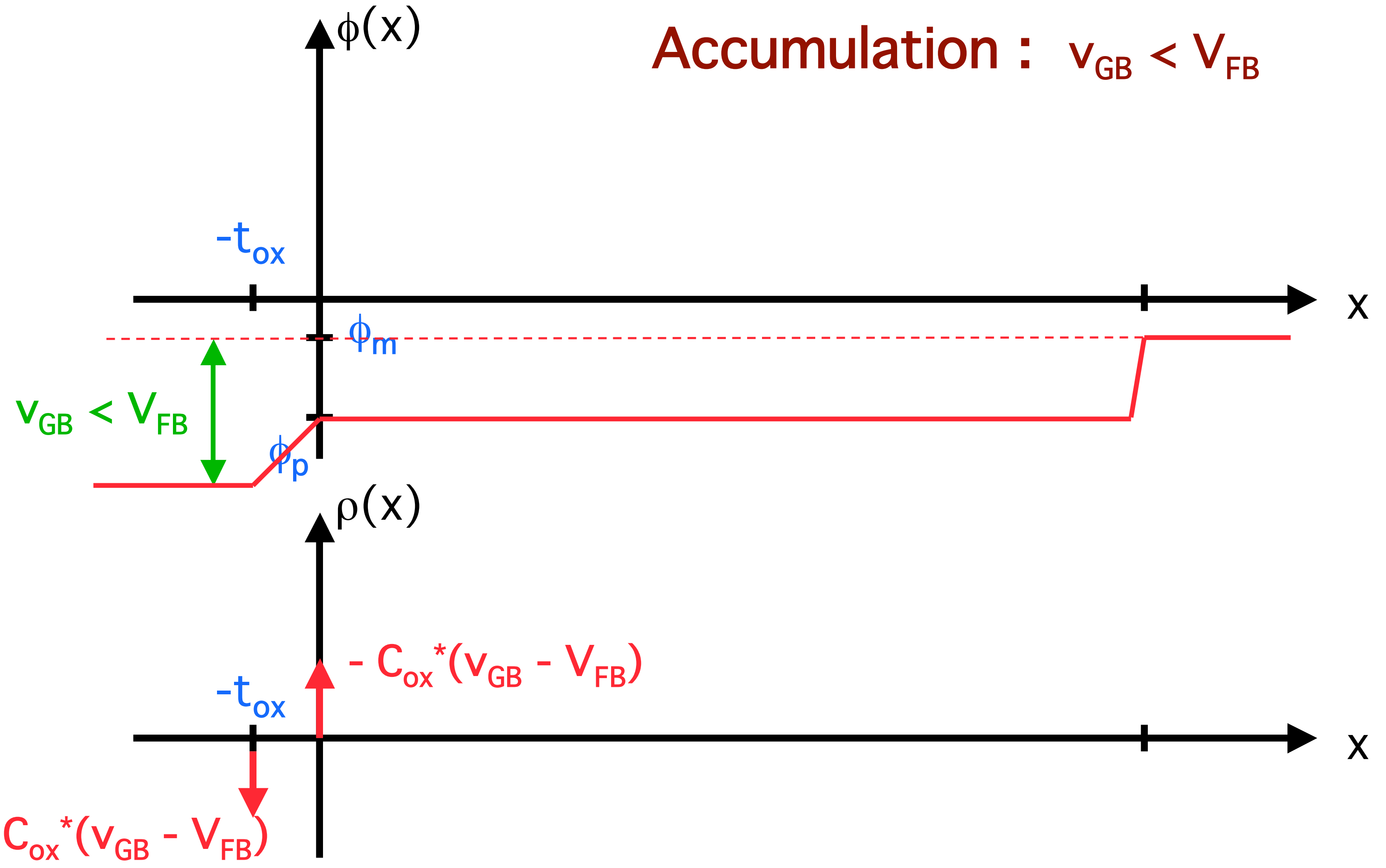


$v_{GB} = V_{FB}$

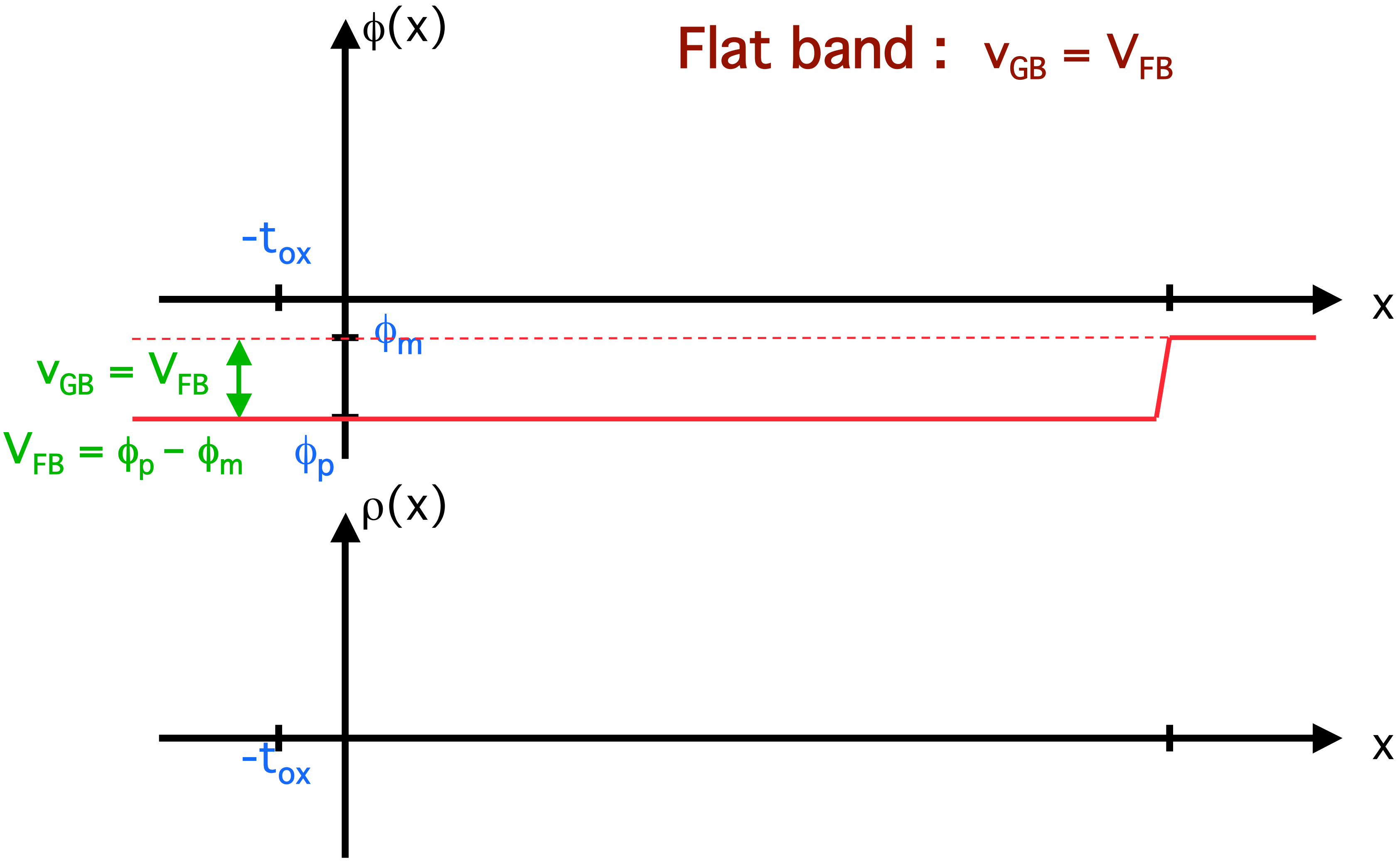
$V_{FB} = \phi_p - \phi_m$

$$\boxed{V_{FB} = \phi_p - \phi_m}$$

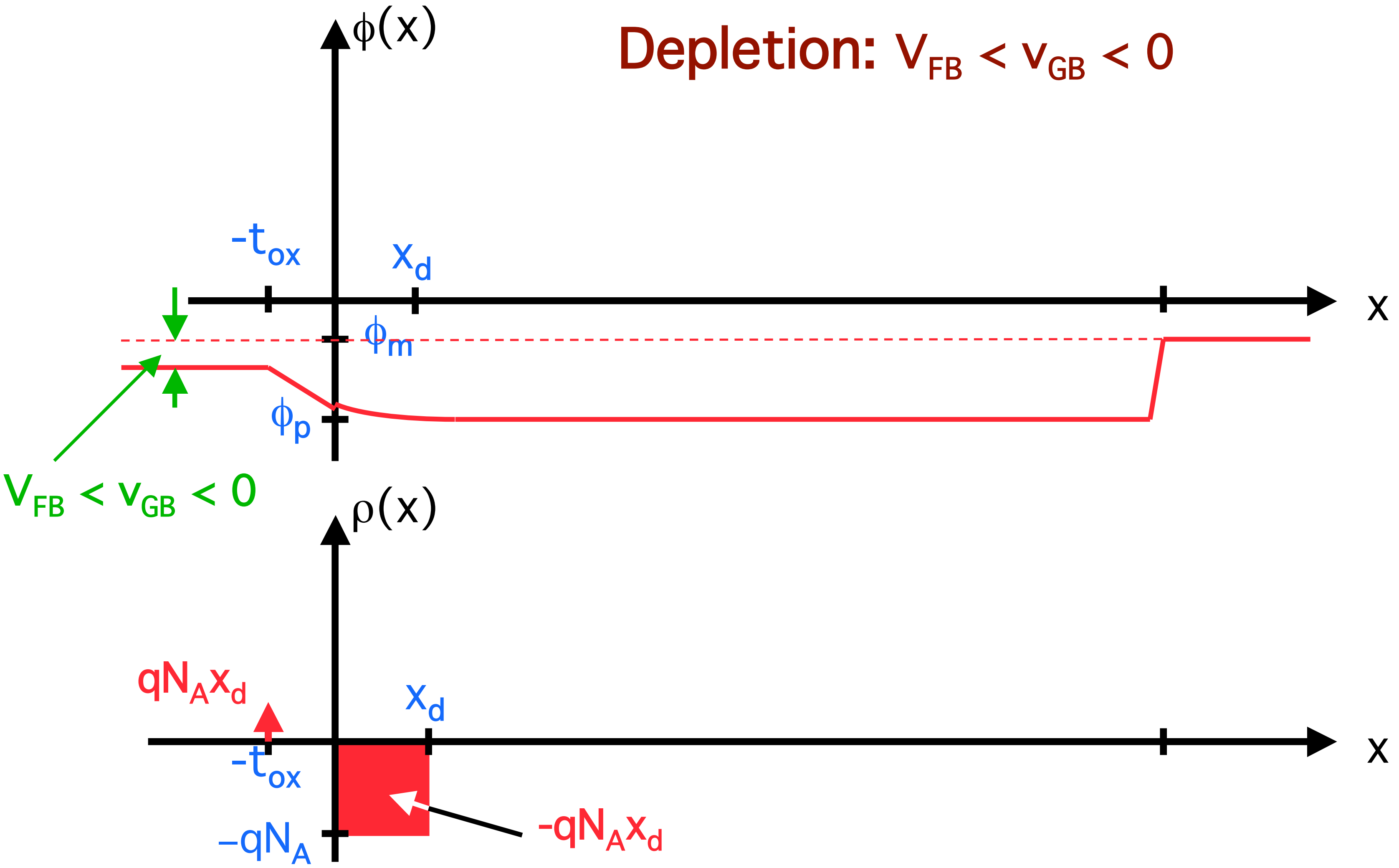
Electrostatic potential and net charge profiles



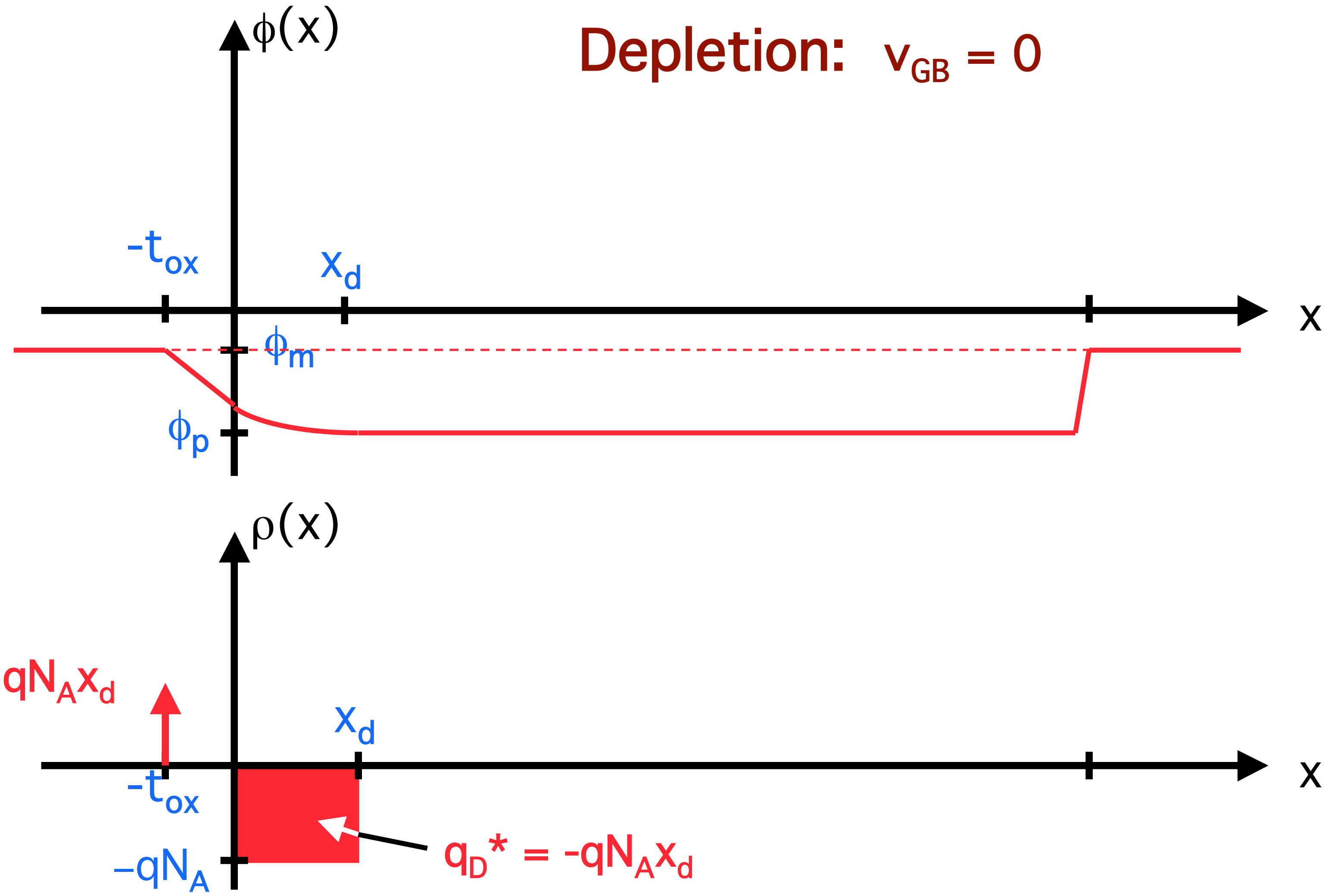
Electrostatic potential and net charge profiles



Electrostatic potential and net charge profiles



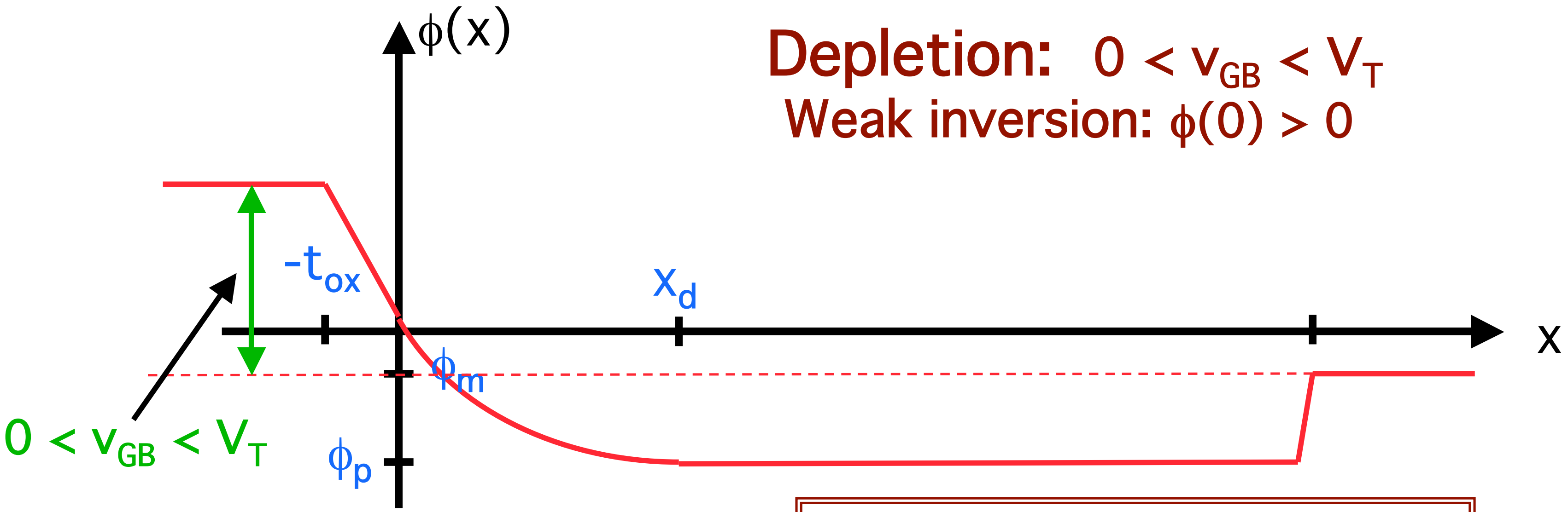
Electrostatic potential and net charge profiles



Electrostatic potential and net charge profiles

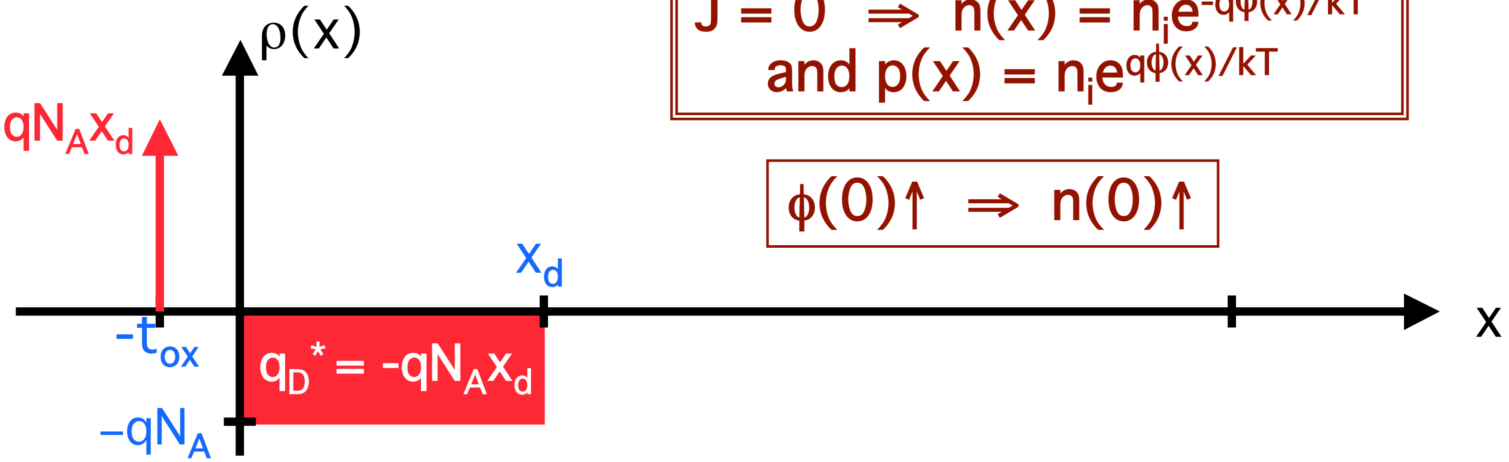
Depletion: $0 < v_{GB} < V_T$

Weak inversion: $\phi(0) > 0$



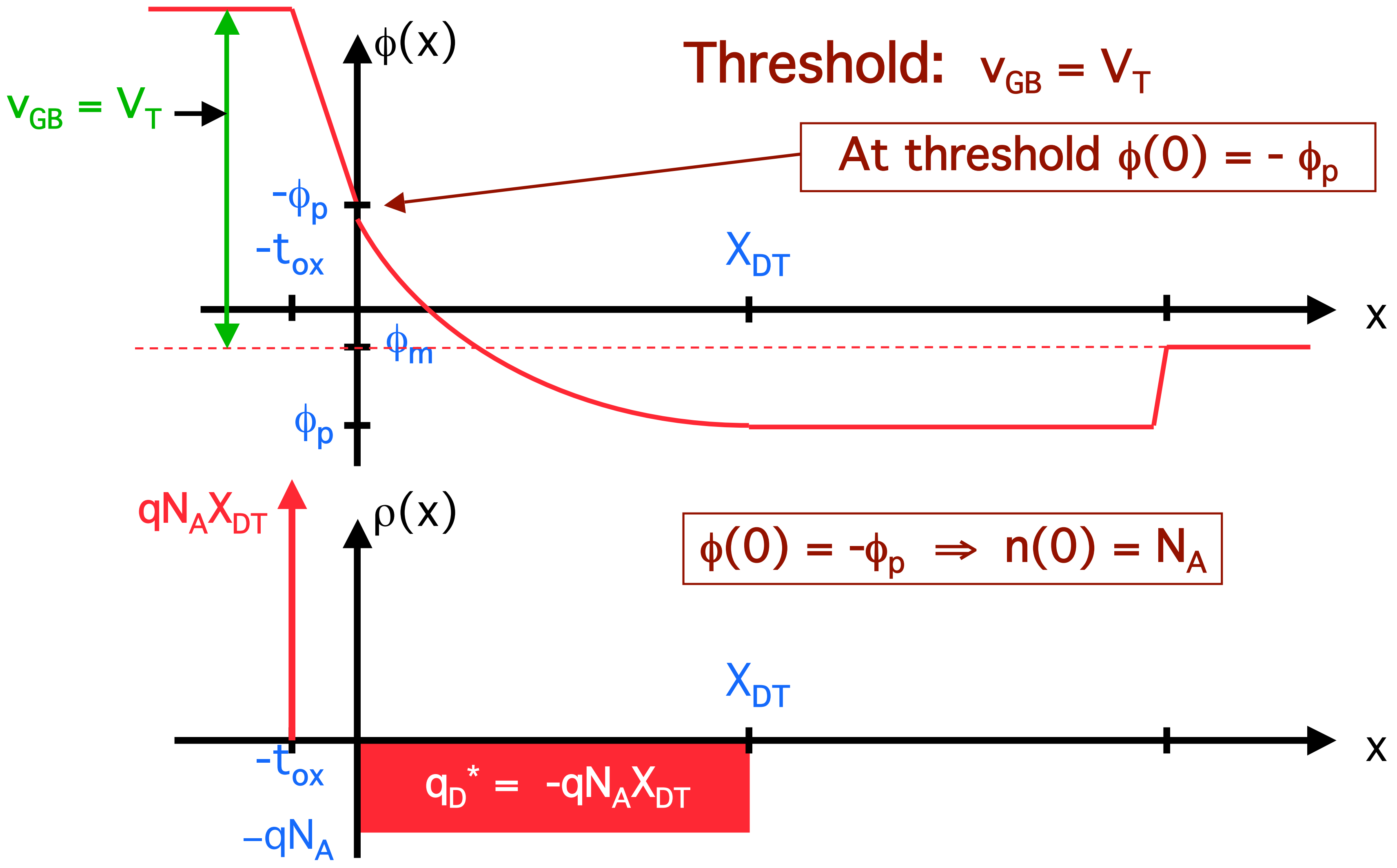
$J = 0 \Rightarrow n(x) = n_i e^{-q\phi(x)/kT}$
and $p(x) = n_i e^{q\phi(x)/kT}$

$\phi(0)\uparrow \Rightarrow n(0)\uparrow$



Weak inversion: $\phi(0) > 0 \Rightarrow n(0) > p(0)$

Electrostatic potential and net charge profiles



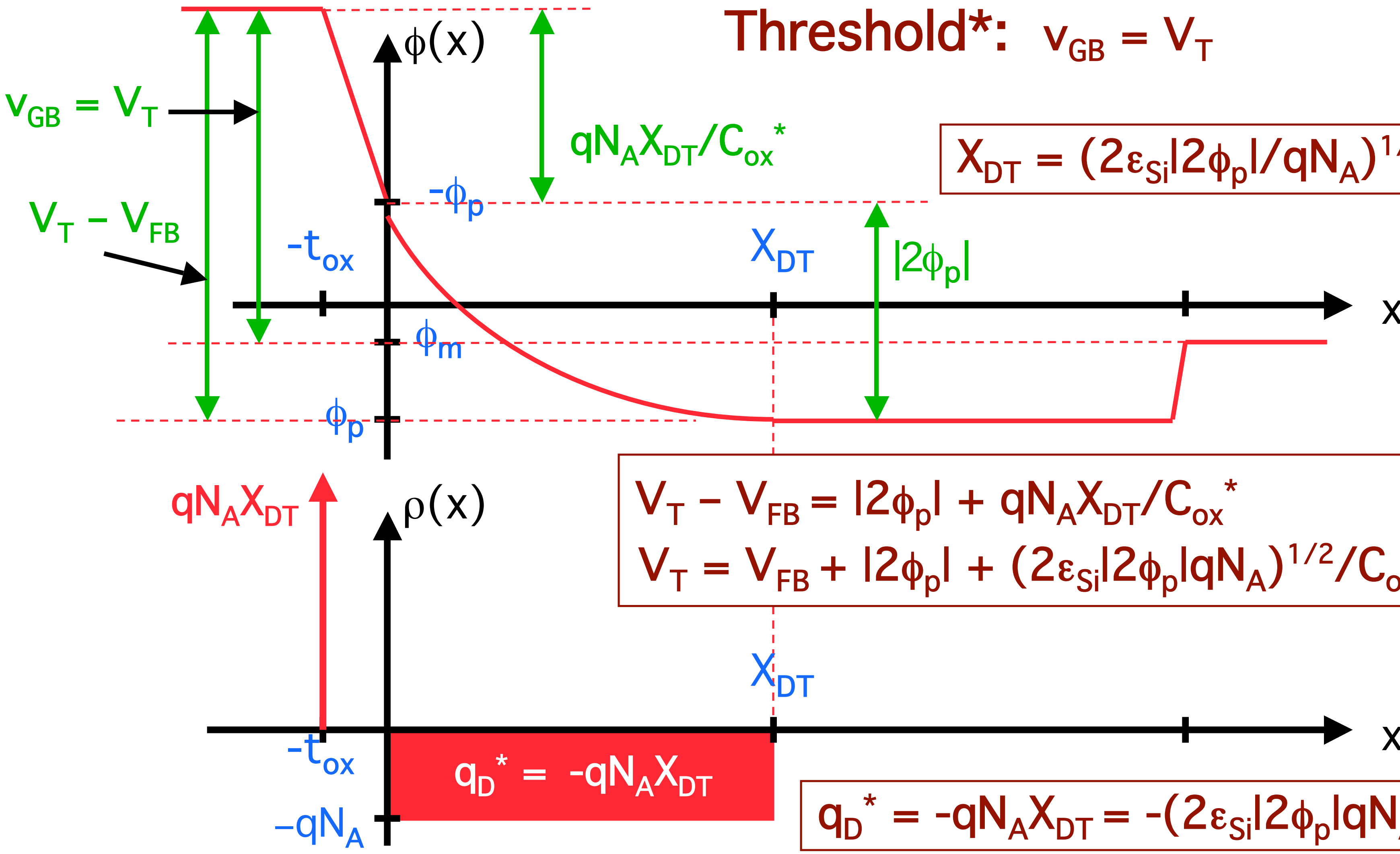
Threshold: $v_{GB} = V_T$

At threshold $\phi(0) = -\phi_p$

$\phi(0) = -\phi_p \Rightarrow n(0) = N_A$

Electrostatic potential and net charge profiles

Threshold*: $v_{GB} = V_T$



$X_{DT} = (2\varepsilon_{Si}|2\phi_p|/qN_A)^{1/2}$

$V_T - V_{FB} = |2\phi_p| + qN_AX_{DT}/C_{ox}^*$

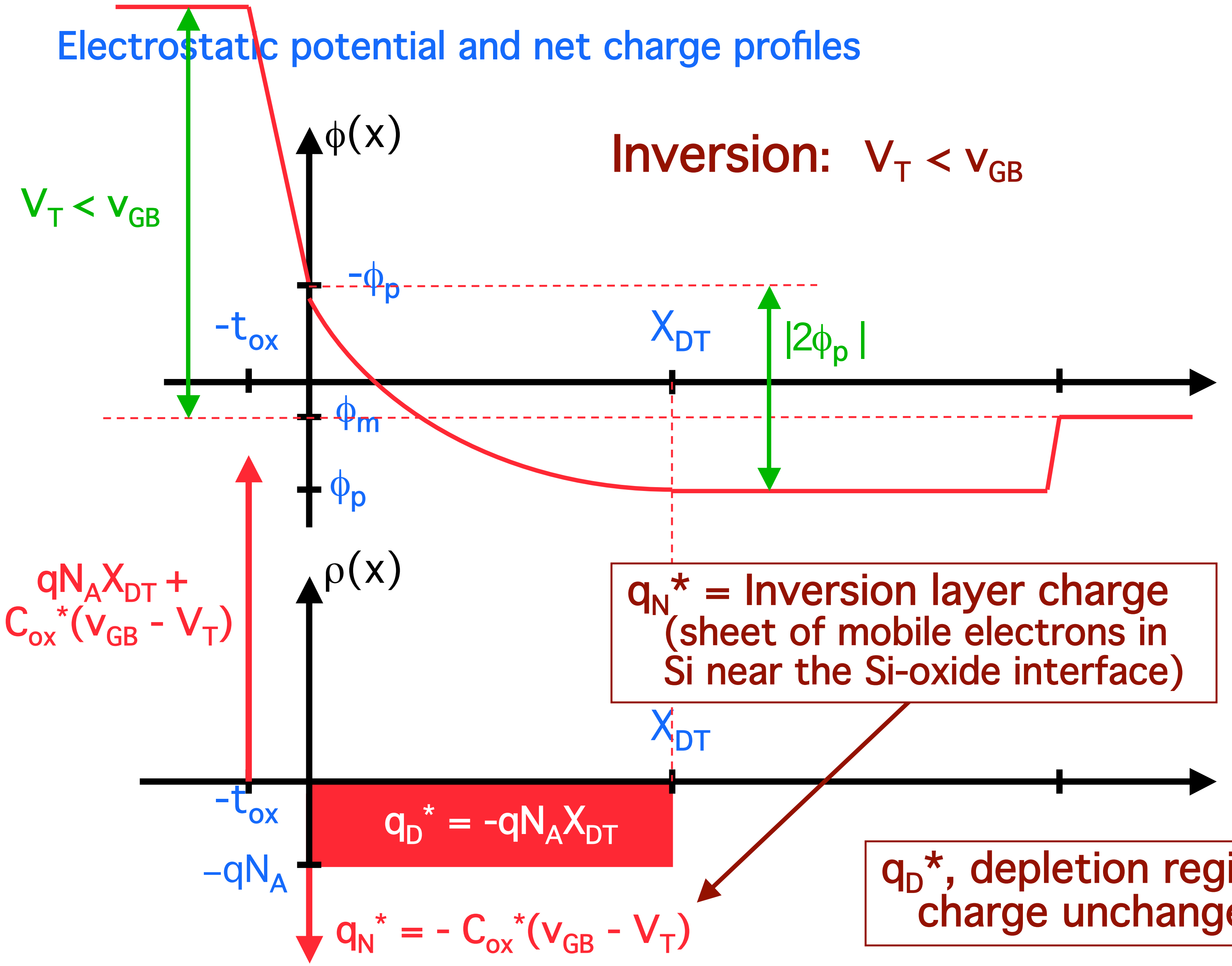
$V_T = V_{FB} + |2\phi_p| + (2\varepsilon_{Si}|2\phi_p|qN_A)^{1/2}/C_{ox}^*$

$q_D^* = -qN_AX_{DT} = -(2\varepsilon_{Si}|2\phi_p|qN_A)^{1/2}$

* At threshold $\phi(0) = -\phi_p$

Electrostatic potential and net charge profiles

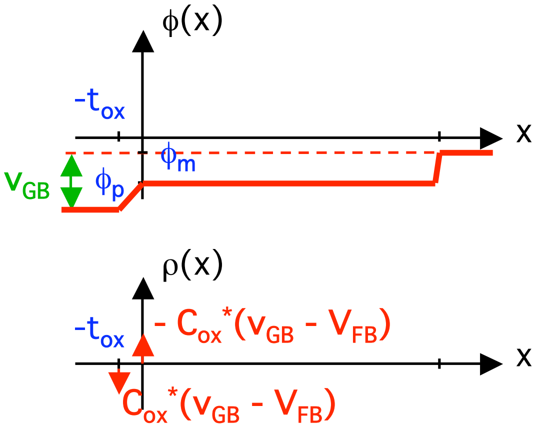
Inversion: $V_T < v_{GB}$

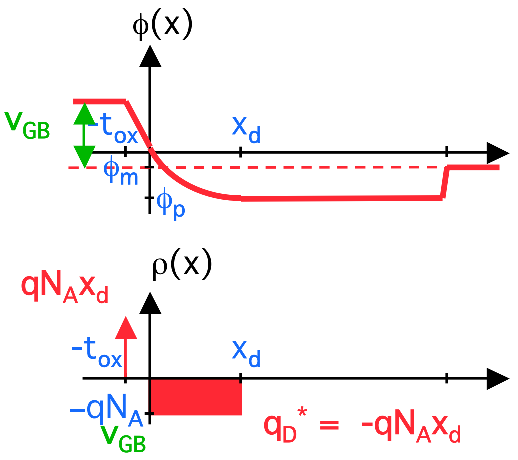


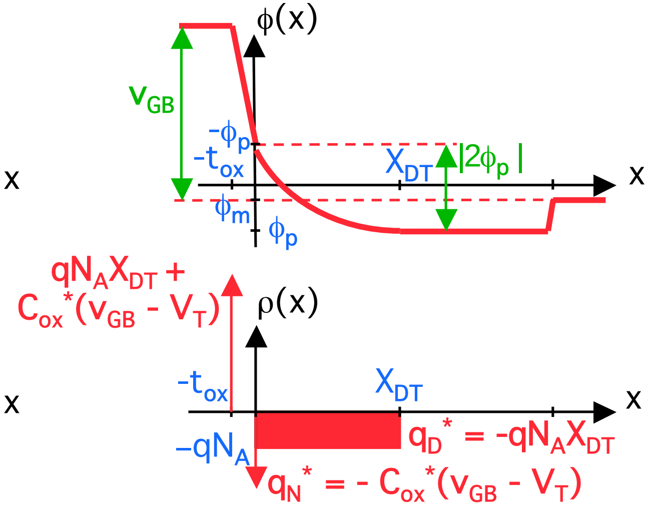
q_N^* = Inversion layer charge
(sheet of mobile electrons in
Si near the Si-oxide interface)

q_D^*, depletion region
charge unchanged

Electrostatic potential and net charge profiles - *regions and boundaries*







Acccumulation

$v_{GB} < V_{FB}$

Depletion

$V_{FB} < v_{GB} < V_T$

Inversion

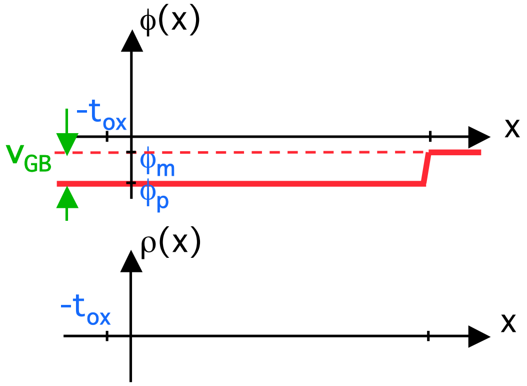
$V_T < v_{GB}$

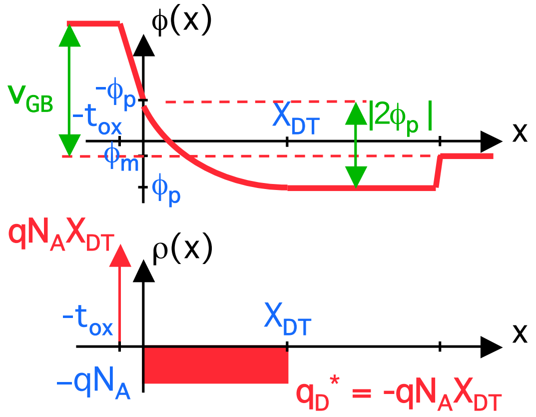
Flat Band Voltage

$V_{FB} = \phi_p - \phi_m$

Threshold Voltage

$V_T = V_{FB} + |2\phi_p| + (2\varepsilon_{Si}|2\phi_p|qN_A)^{1/2}/C_{ox}^*$

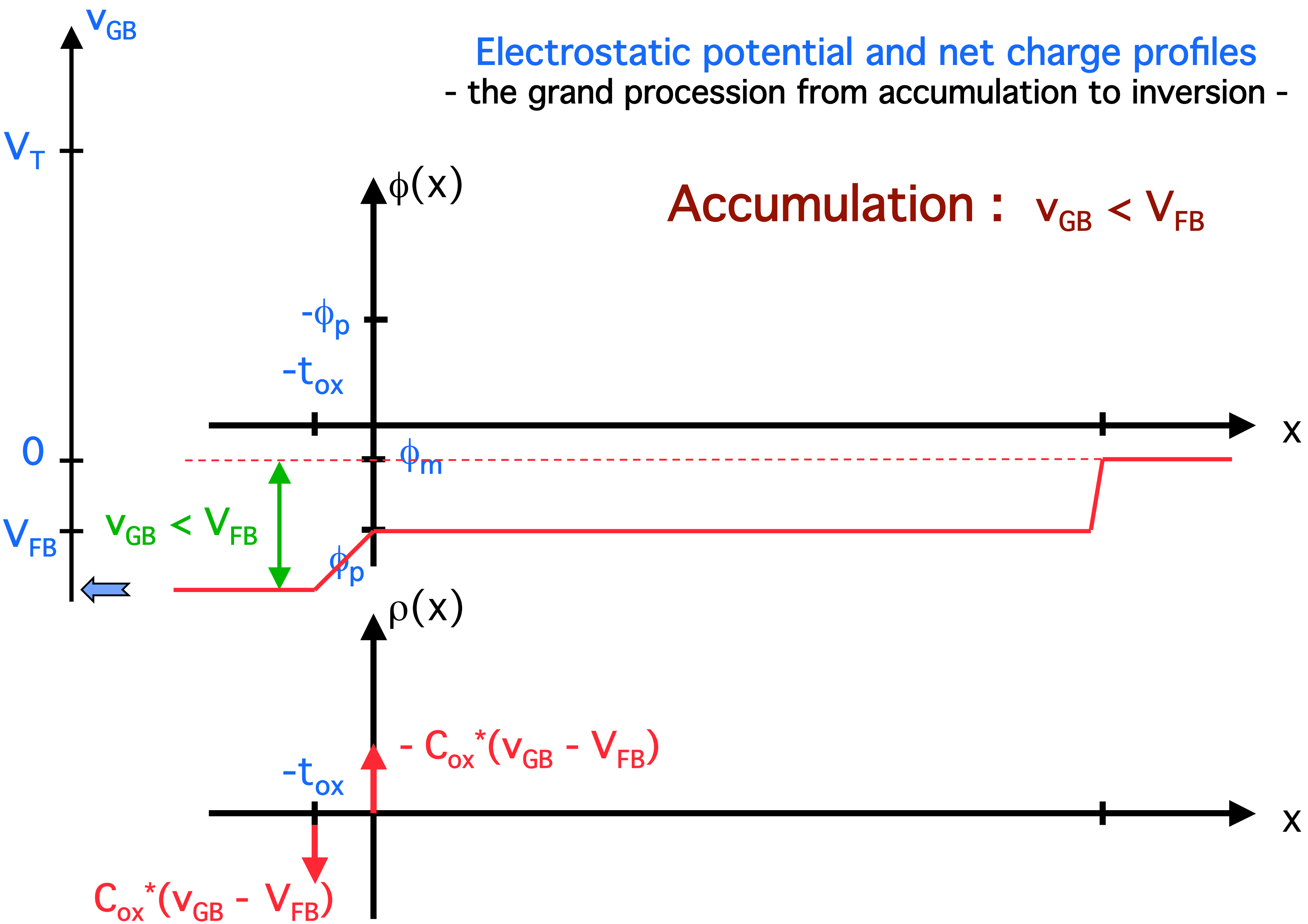




Electrostatic potential and net charge profiles

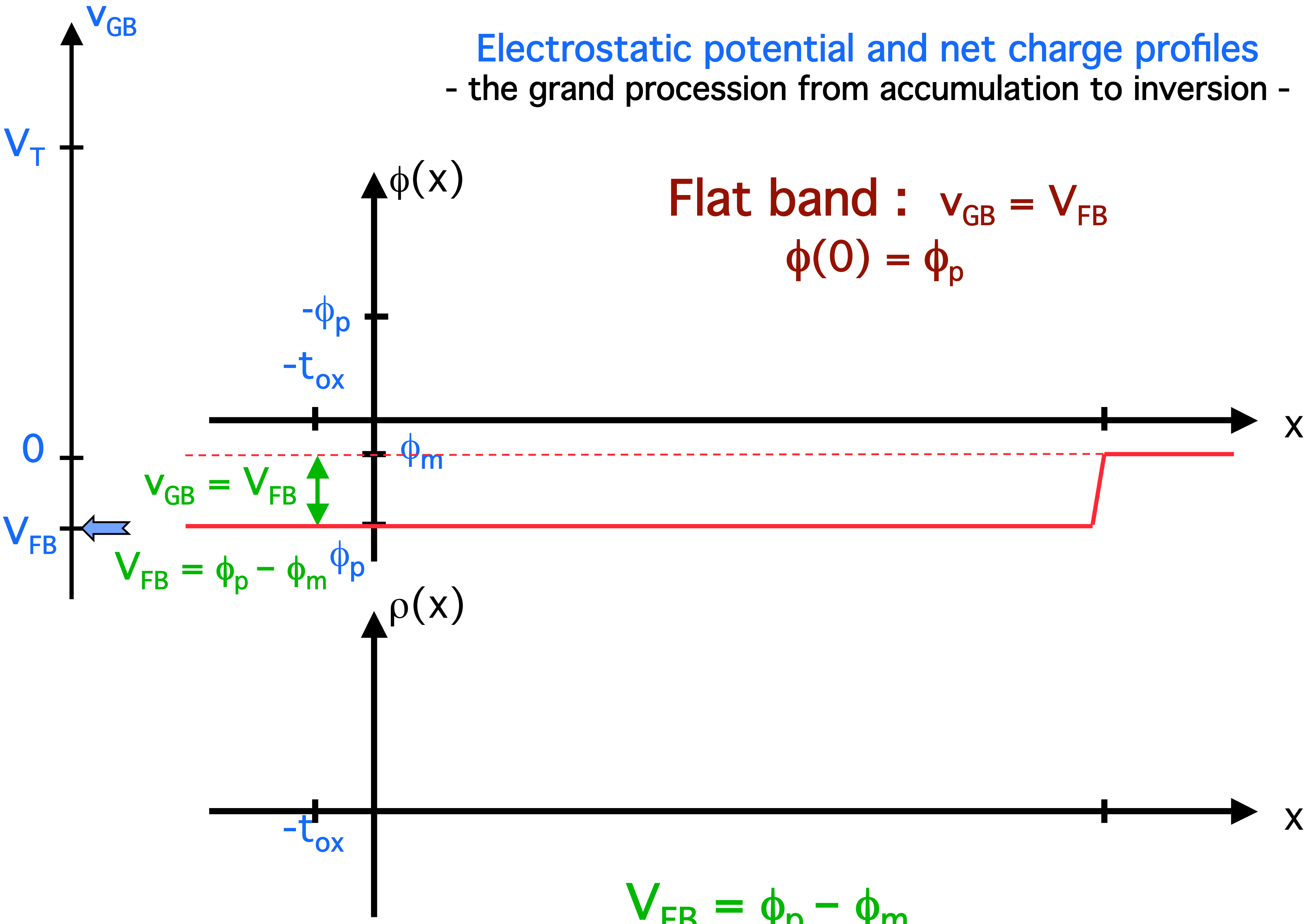
- the grand procession from accumulation to inversion -

Accumulation : $v_{GB} < V_{FB}$



Electrostatic potential and net charge profiles

- the grand procession from accumulation to inversion -



Flat band : $v_{GB} = V_{FB}$

$\phi(0) = \phi_p$

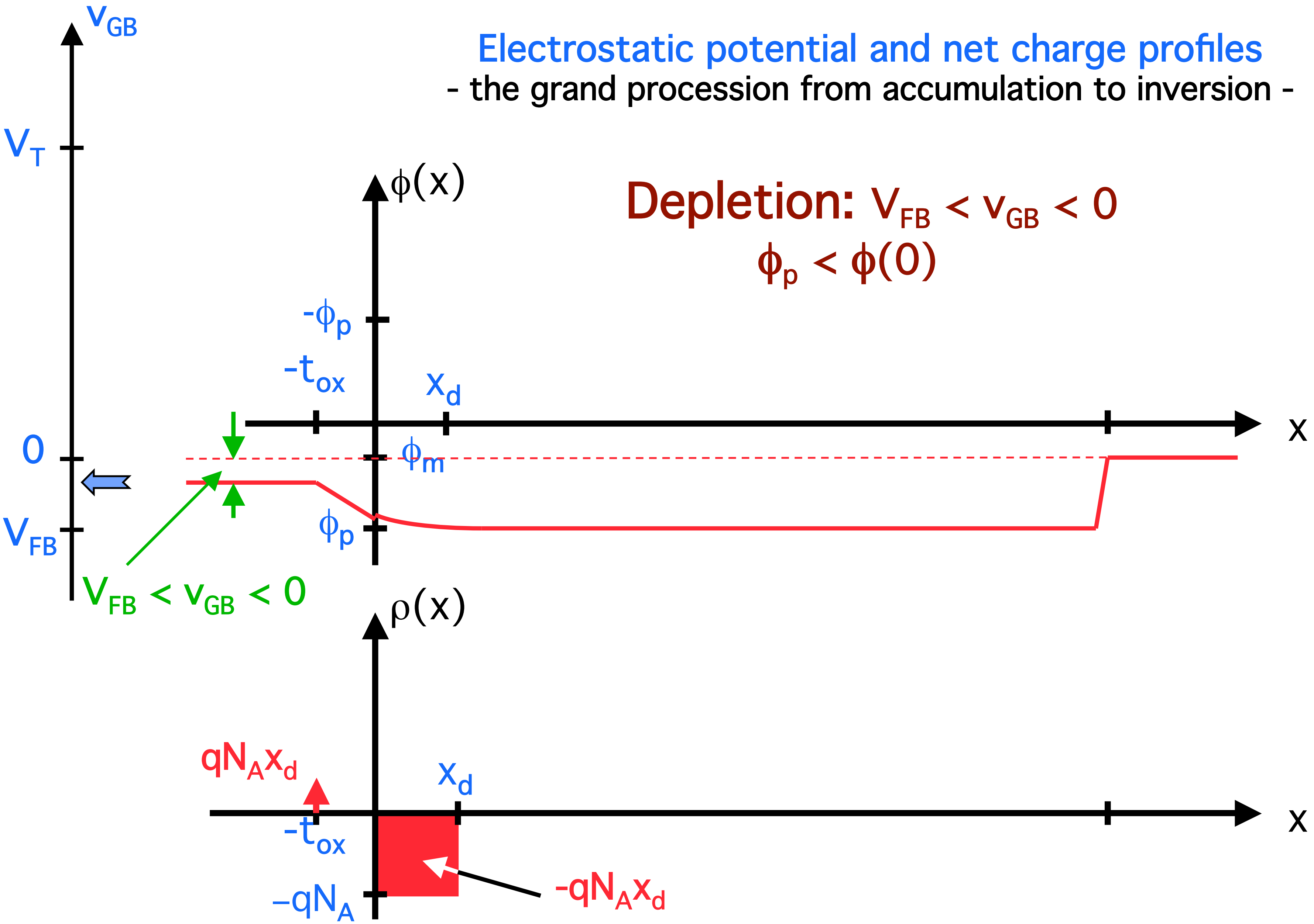
$$V_{FB} = \phi_p - \phi_m$$

Electrostatic potential and net charge profiles

- the grand procession from accumulation to inversion -

Depletion: $V_{FB} < v_{GB} < 0$

$\phi_p < \phi(0)$

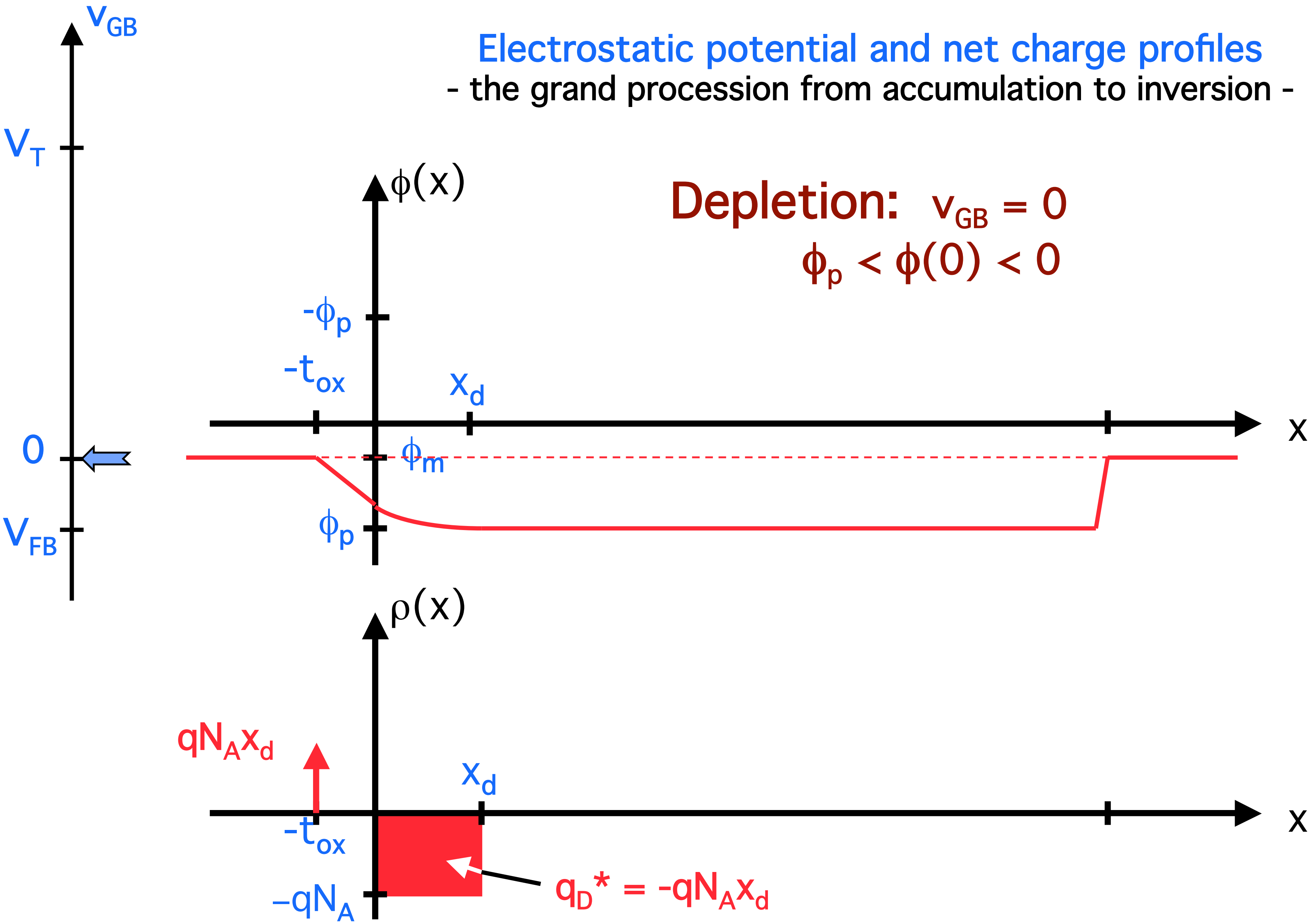


Electrostatic potential and net charge profiles

- the grand procession from accumulation to inversion -

Depletion: $v_{GB} = 0$

$\phi_p < \phi(0) < 0$

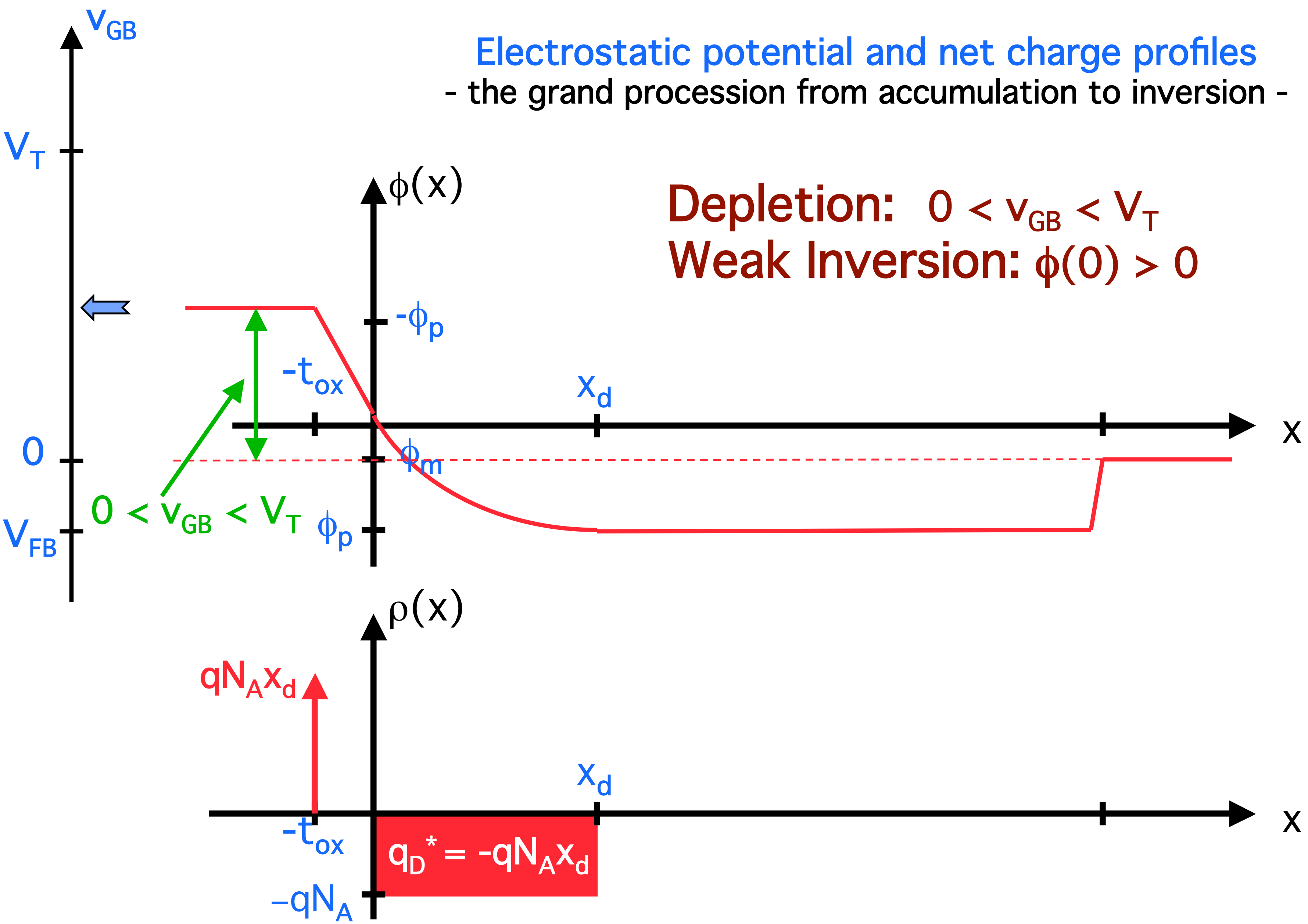


Electrostatic potential and net charge profiles

- the grand procession from accumulation to inversion -

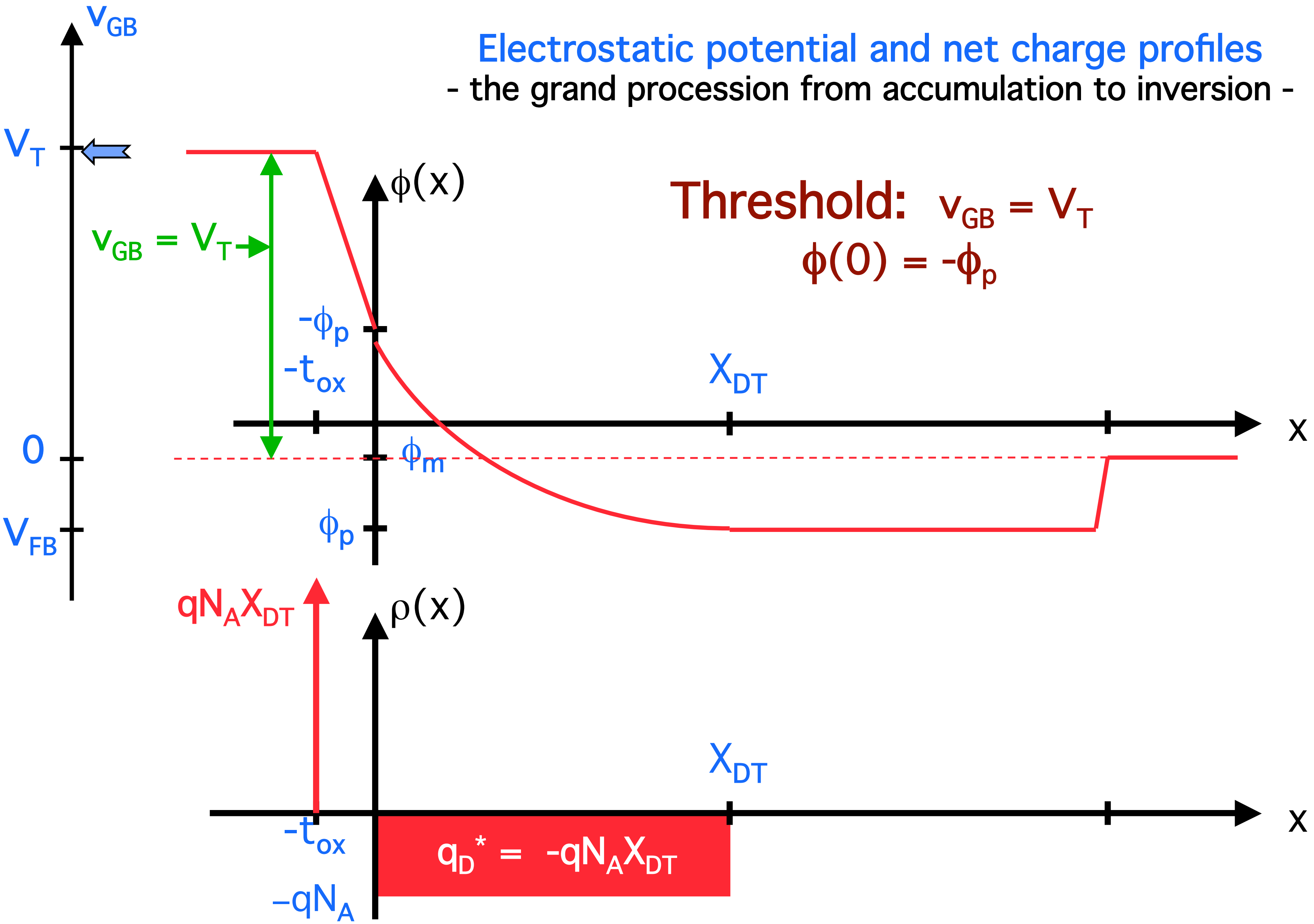
Depletion: $0 < v_{GB} < V_T$

Weak Inversion: $\phi(0) > 0$



Electrostatic potential and net charge profiles

- the grand procession from accumulation to inversion -



Threshold: $v_{GB} = V_T$

$\phi(0) = -\phi_p$

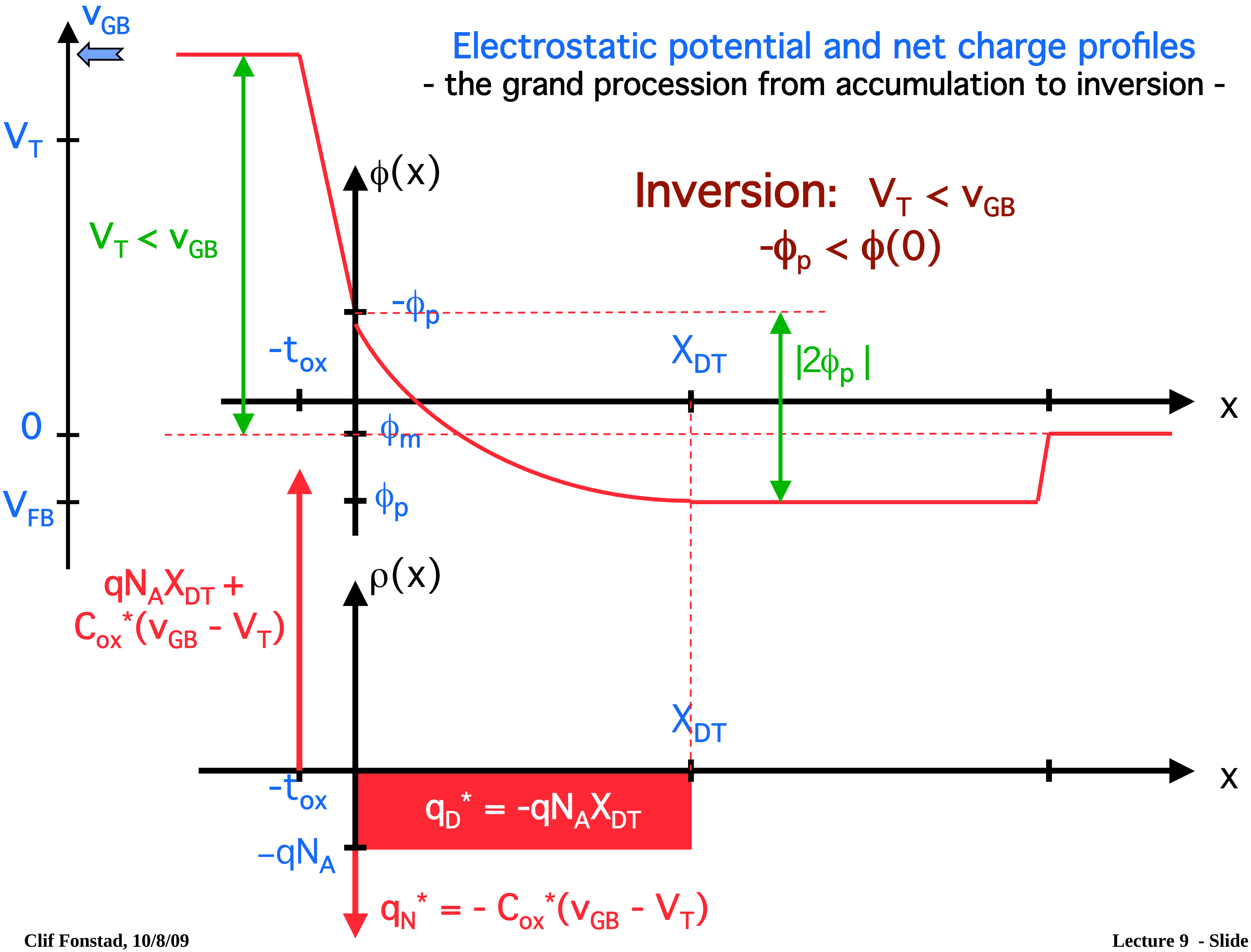
$$V_T = V_{FB} + |2\phi_p| + (2\varepsilon_{Si}|2\phi_p|qN_A)^{1/2}/C_{ox}^*$$

Electrostatic potential and net charge profiles

- the grand procession from accumulation to inversion -

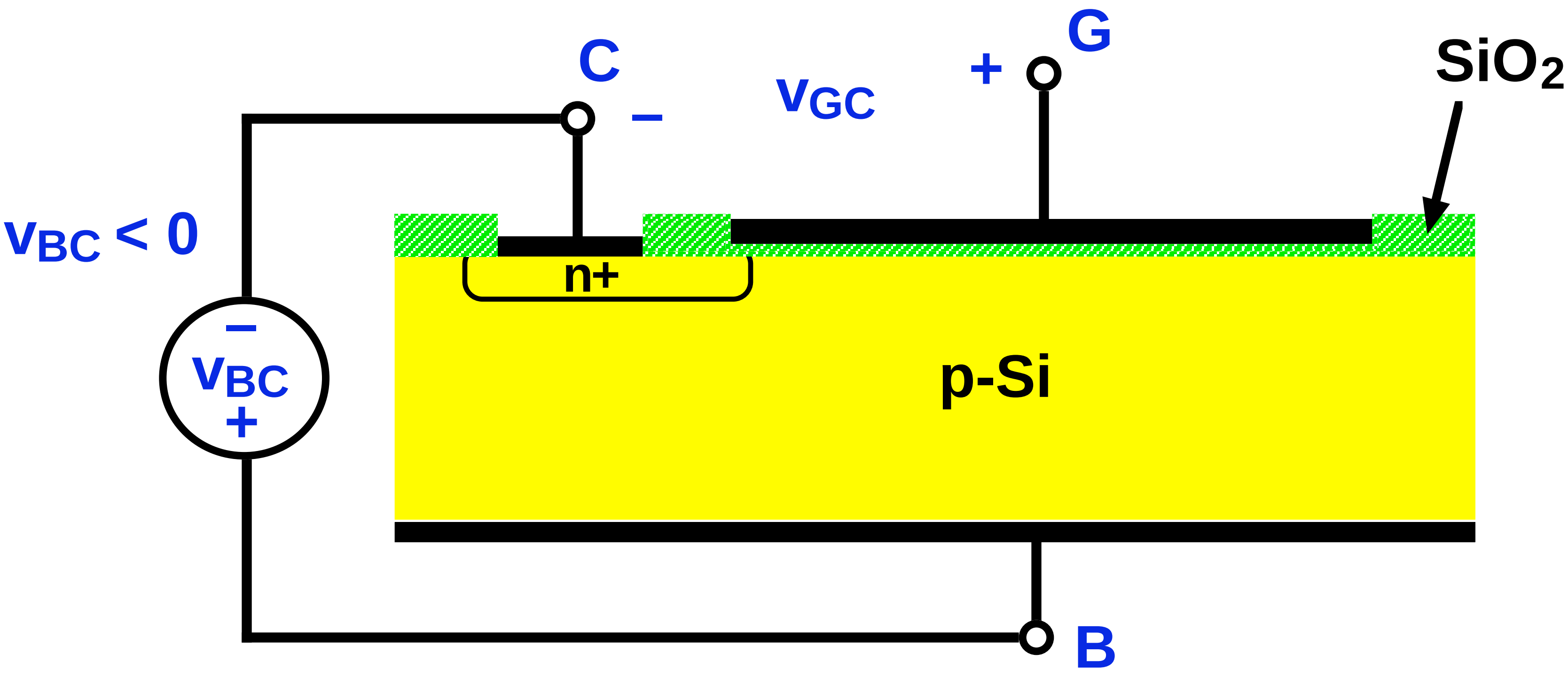
Inversion: $V_T < v_{GB}$

$-\phi_p < \phi(0)$



Bias between n+ region and substrate, cont.

Reverse bias applied to substrate, I.e. $v_{BC} < 0$

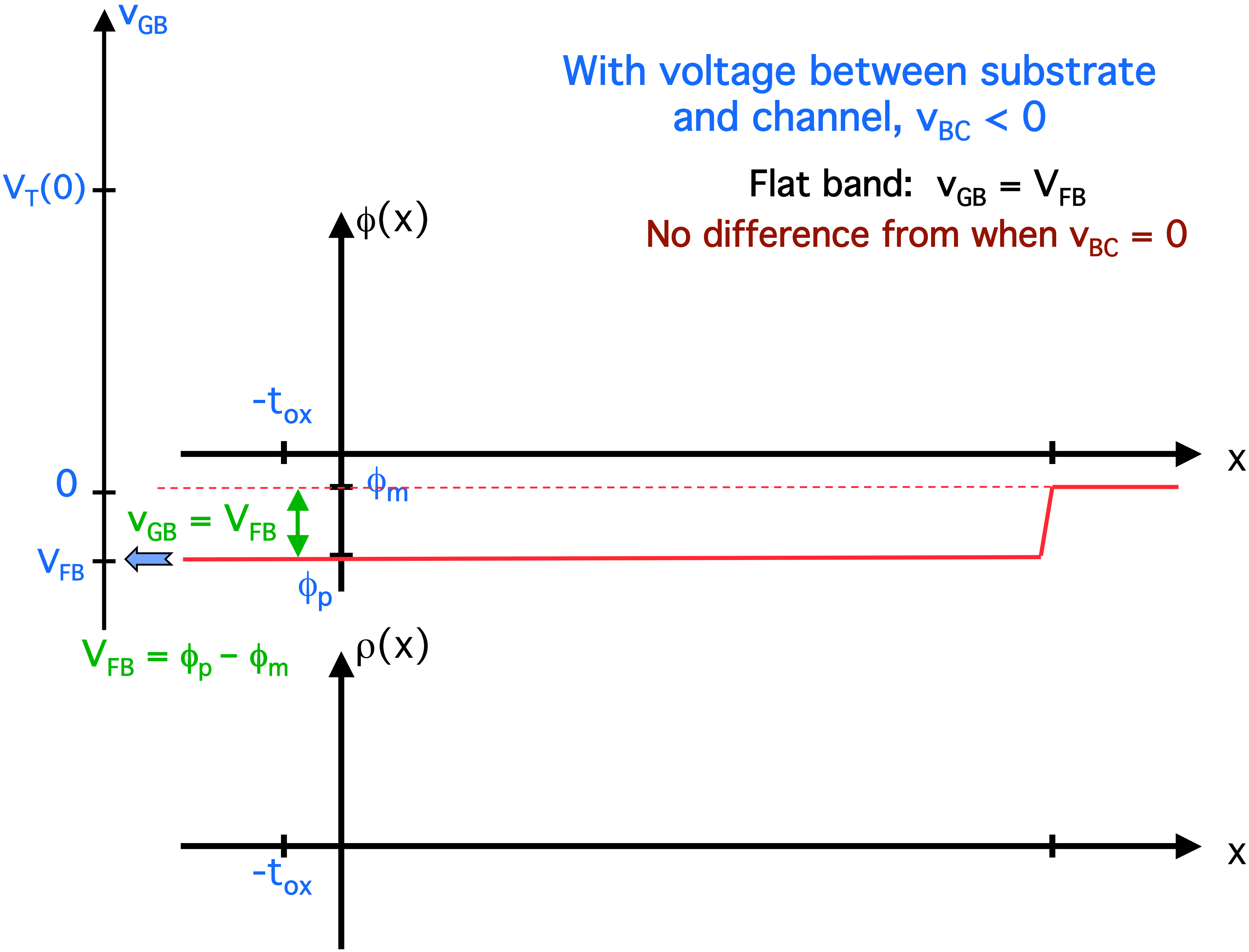


Soon we will see how this will let us electronically adjust MOSFET threshold voltages when it is convenient for us to do so.

With voltage between substrate and channel, $v_{BC} < 0$

Flat band: $v_{GB} = V_{FB}$

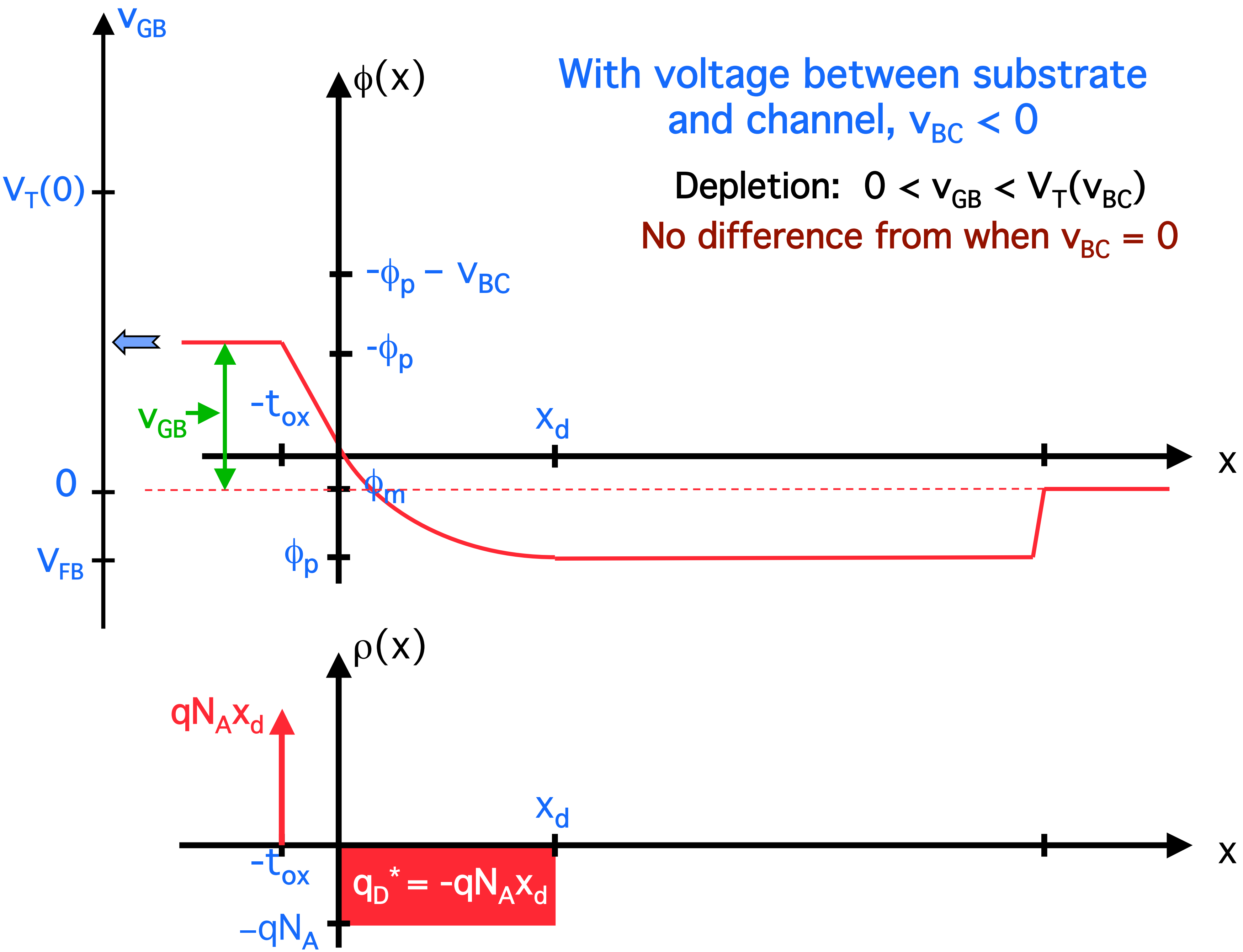
No difference from when $v_{BC} = 0$



With voltage between substrate and channel, $v_{BC} < 0$

Depletion: $0 < v_{GB} < V_T(v_{BC})$

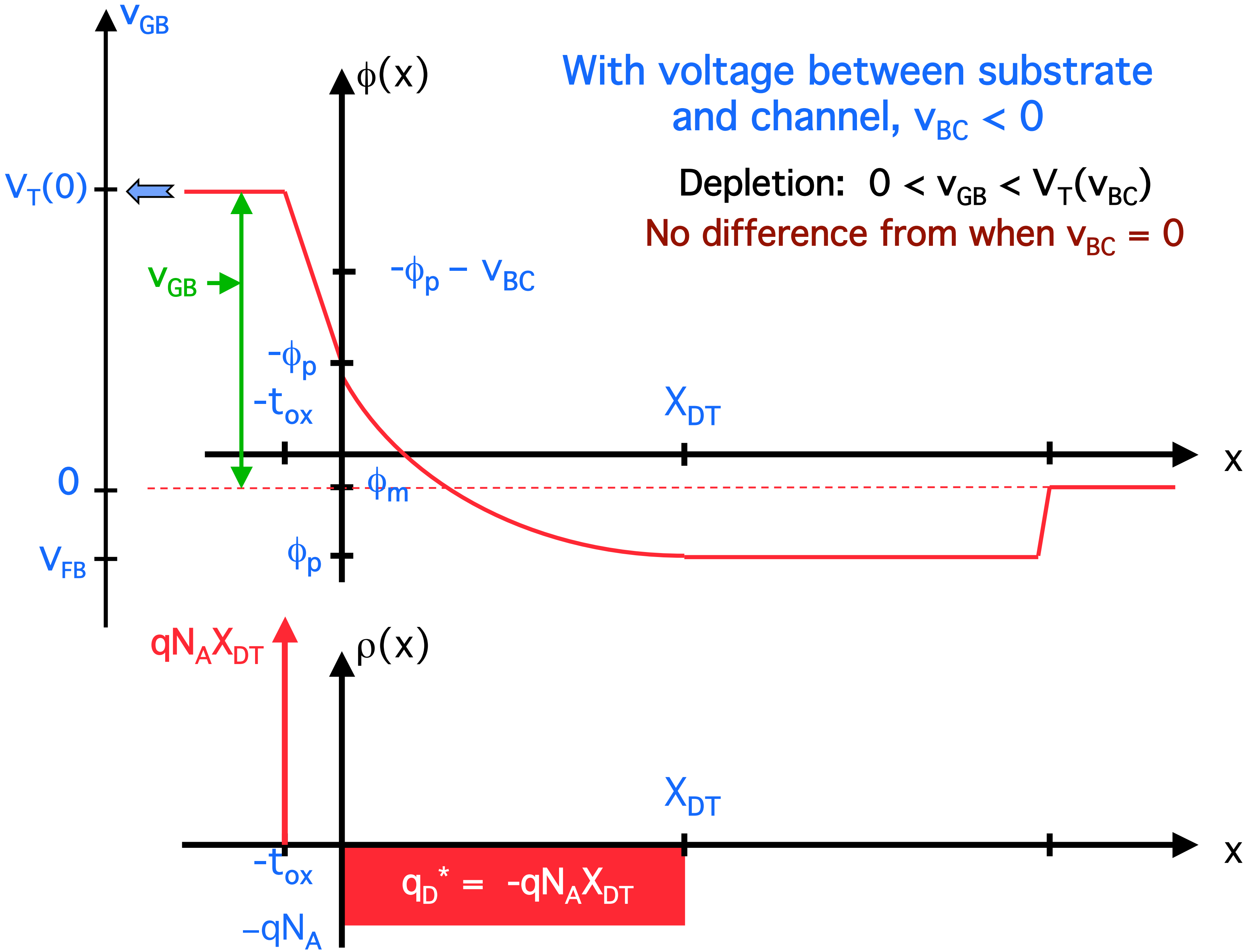
No difference from when $v_{BC} = 0$



With voltage between substrate and channel, $v_{BC} < 0$

Depletion: $0 < v_{GB} < V_T(v_{BC})$

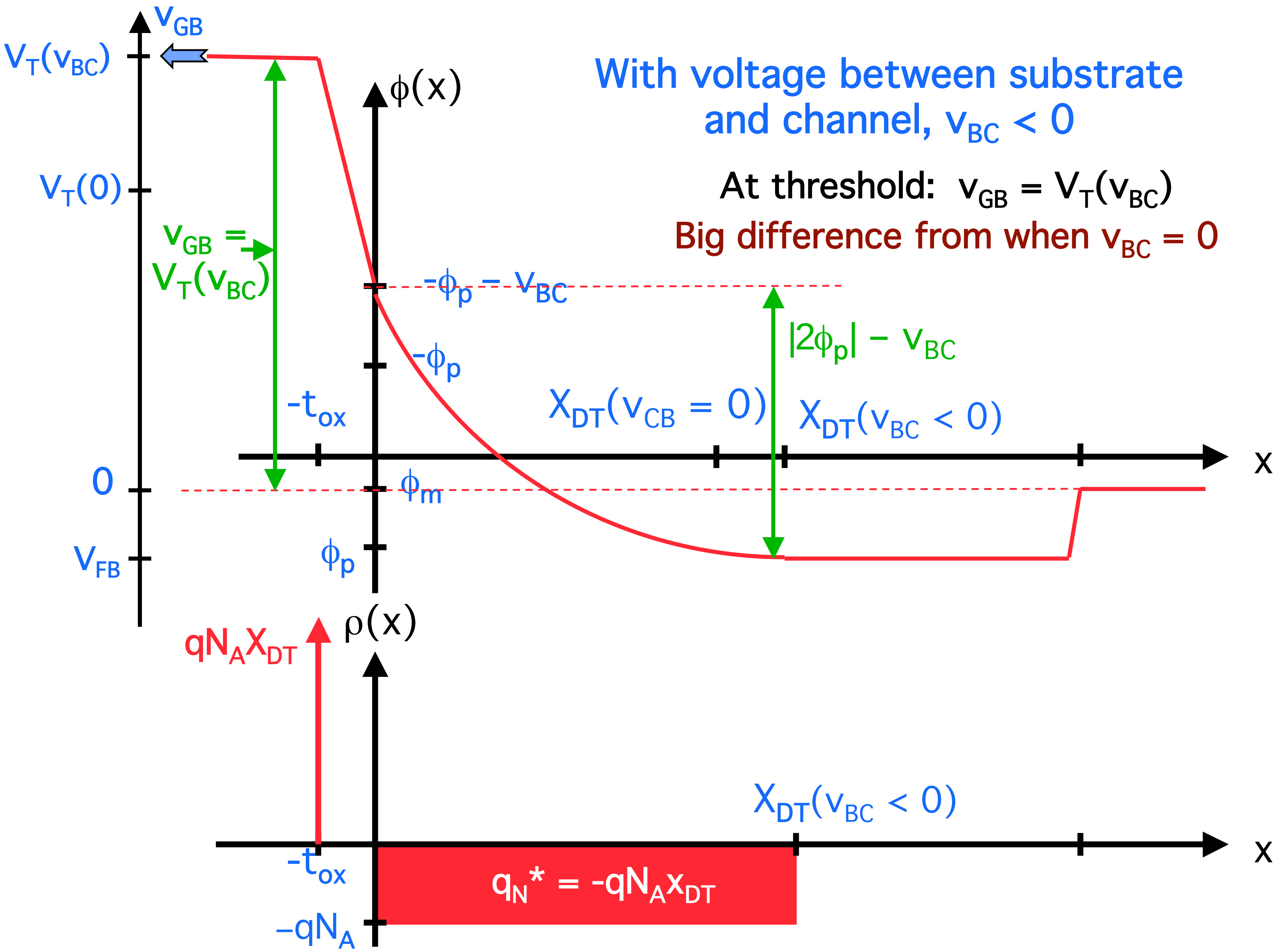
No difference from when $v_{BC} = 0$



With voltage between substrate and channel, $v_{BC} < 0$

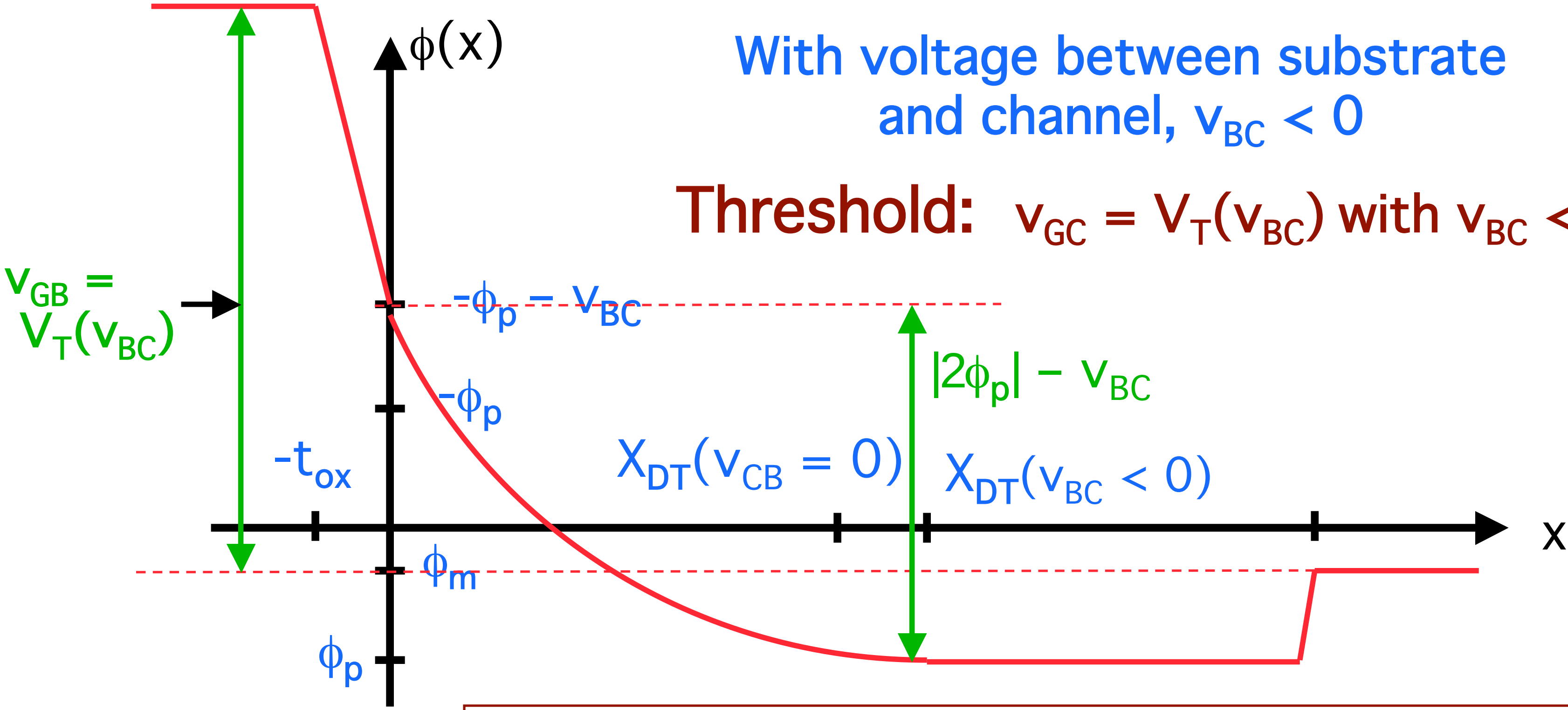
At threshold: $v_{GB} = V_T(v_{BC})$

Big difference from when $v_{BC} = 0$



With voltage between substrate and channel, $v_{BC} < 0$

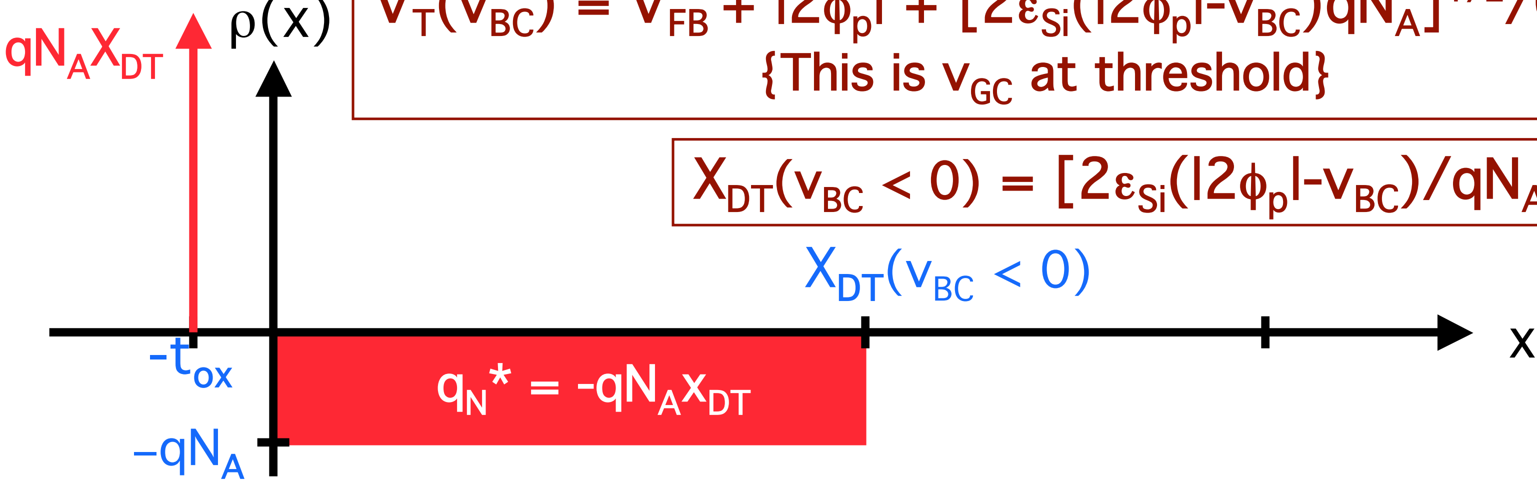
Threshold: $v_{GC} = V_T(v_{BC})$ with $v_{BC} < 0$



$$V_T(v_{BC}) = V_{FB} + |2\phi_p| + [2\varepsilon_{Si}(|2\phi_p|-v_{BC})qN_A]^{1/2}/C_{ox}^*$$

{This is v_{GC} at threshold}

$$X_{DT}(v_{BC} < 0) = [2\varepsilon_{Si}(|2\phi_p|-v_{BC})/qN_A]^{1/2}$$



$$q_N^* = -[2\varepsilon_{Si}(|2\phi_p|-v_{BC})qN_A]^{1/2}$$

6.012 - Microelectronic Devices and Circuits

Lecture 9 - MOS Capacitors I - Summary

- **Qualitative description**

  Three surface conditions: accumulated, depleted, inverted

  Two key voltages: flat-band voltage, V_{FB}; threshold voltage, V_T

  The progression: accumulation through flat-band to depletion, then depletion through threshold to inversion

- **Quantitative modeling**

  Apply depletion approximation to the MOS capacitor, $v_{BC} = 0$

  Definitions: $V_{FB} \equiv v_{GB}$ such that $\phi(0) = \phi_{p\text{-}Si}$
  $V_T \equiv v_{GB}$ such that $\phi(0) = -\phi_{p\text{-}Si}$
  $C_{ox}^* \equiv \varepsilon_{ox}/t_{ox}$

  Results and expressions **(For n-MOS example)**

  1. Flat-band voltage, $V_{FB} = \phi_{p\text{-}Si} - \phi_m$
  2. Accumulation layer sheet charge density, $q_A^* = -C_{ox}^*(v_{GB} - V_{FB})$
  3. Maximum depletion region width, $X_{DT} = [2\varepsilon_{Si}(|2\phi_{p\text{-}Si}|-v_{BC})/qN_A]^{1/2}$
  4. Threshold voltage, $V_T = V_{FB} - 2\phi_{p\text{-}Si} + [2\varepsilon_{Si}\, qN_A(|2\phi_{p\text{-}Si}|-v_{BC})]^{1/2}/C_{ox}^*$
  5. Inversion layer sheet charge density, $q_N^* = -C_{ox}^*(v_{GB} - V_T)$

6.012 Microelectronic Devices and Circuits
Fall 2009