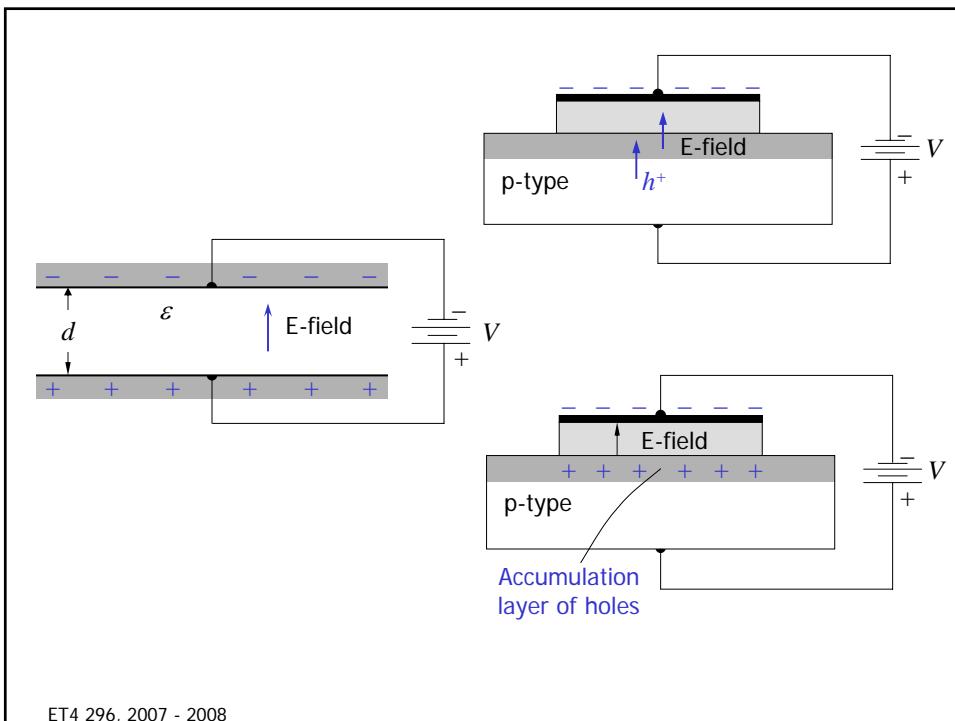
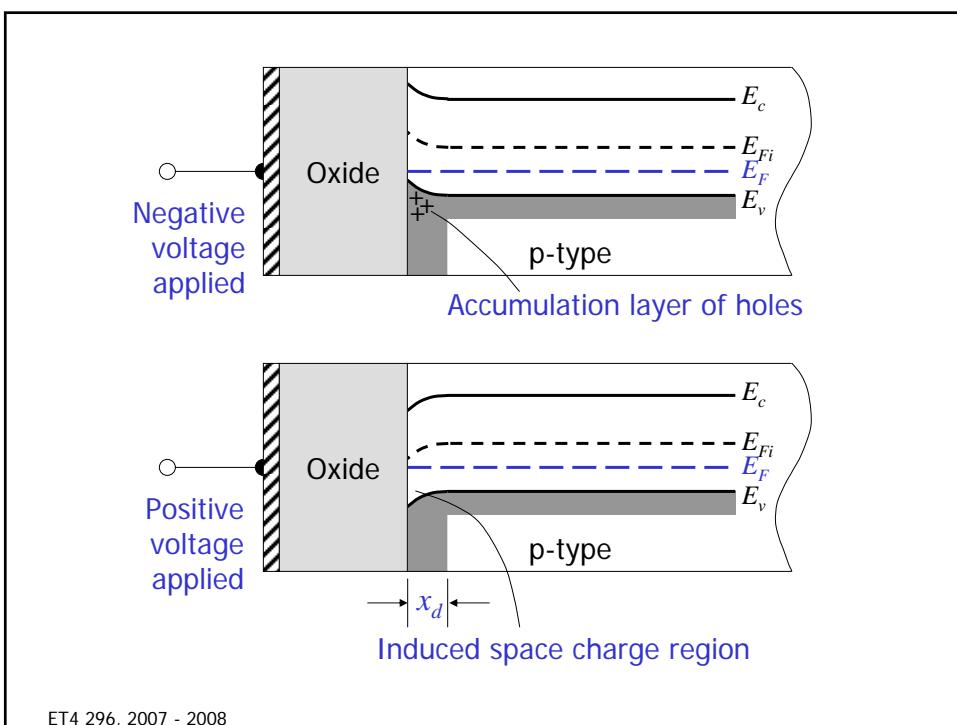
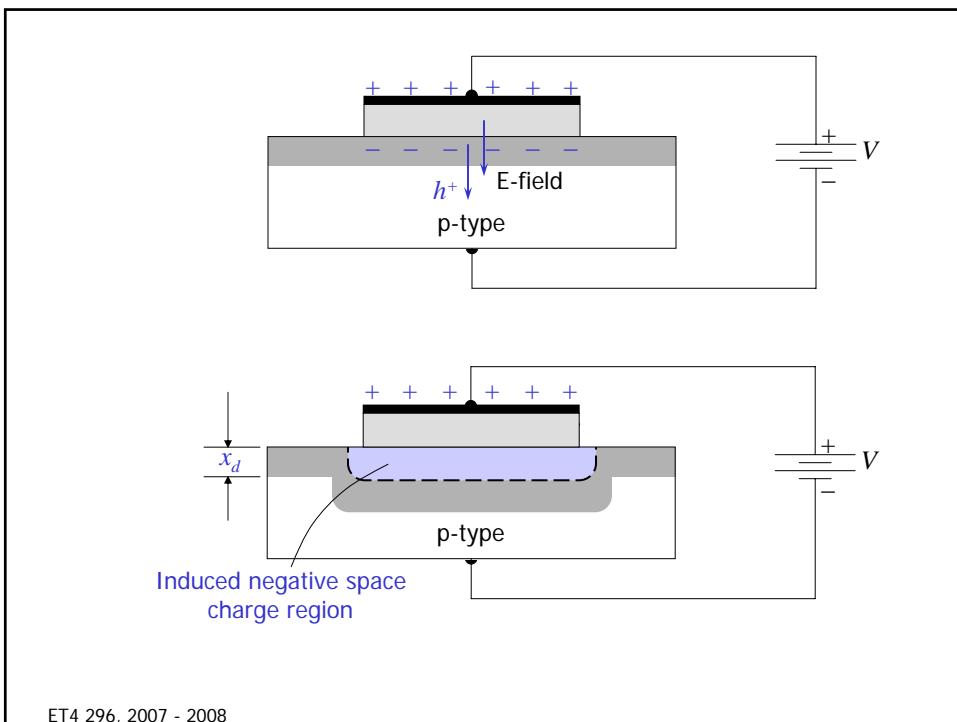
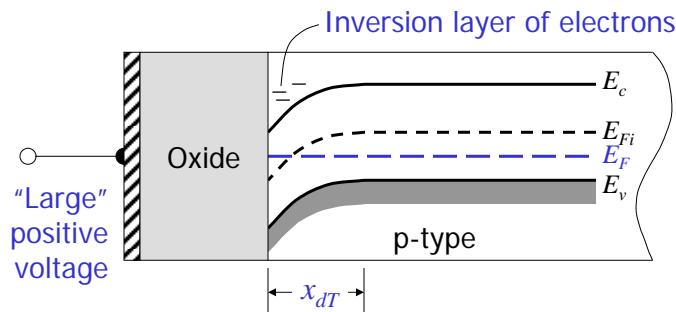


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Thickness of the depletion layer

Definition of the potential, ϕ_{fp} :
$$\phi_{fp} = \frac{E_{Fi} - E_F}{e} = \frac{kT}{e} \ln\left(\frac{N_a}{n_i}\right)$$

Start with the Poisson equation:
$$\frac{d^2\phi}{dx^2} = -\frac{dE}{dx} = -\frac{\rho}{\epsilon_s}$$

The electric field:

$$\frac{dE}{dx} = \frac{\rho}{\epsilon_s} \Rightarrow E(x) = \frac{\rho}{\epsilon_s} x + C_1$$

$$E(x_d) = 0 \Rightarrow C_1 = -\frac{\rho}{\epsilon_s} x_d$$

So:
$$E(x) = \frac{\rho}{\epsilon_s} (x - x_d)$$

The potential:

$$\frac{d\phi(x)}{dx} = -E(x) \Rightarrow \phi(x) = \frac{\rho}{\epsilon_s} x_d x - \frac{\rho}{2\epsilon_s} x^2 + C_2$$

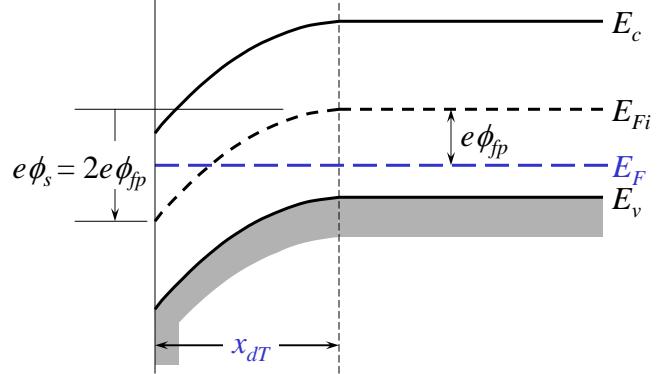
$$\phi(x_d) = 0 \Rightarrow C_2 = -\frac{\rho}{2\epsilon_s} x_d^2$$

Thus:
$$\phi(x) = -\frac{\rho}{2\epsilon_s} (x - x_d)^2$$

For ($\rho = -eN_a$) the surface potential, ϕ_s , becomes:

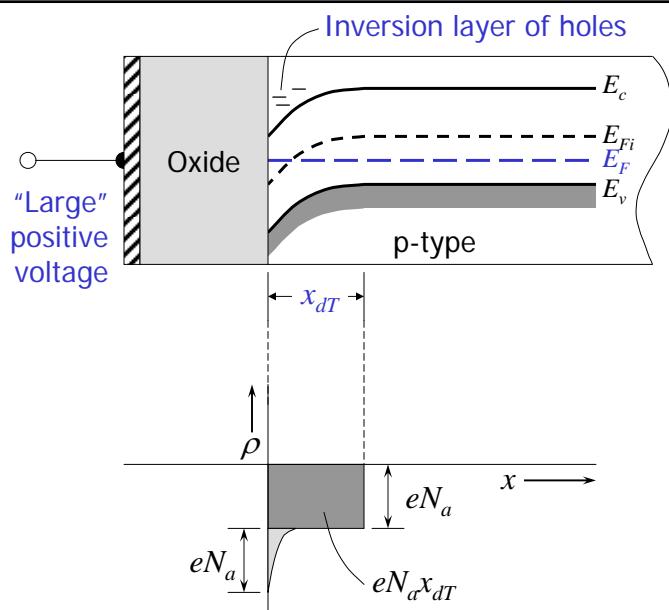
$$\phi_s = \phi(0) = \frac{eN_a x_d^2}{2\epsilon_s} \Rightarrow x_d = \sqrt{\frac{2\epsilon_s \phi_s}{eN_a}}$$

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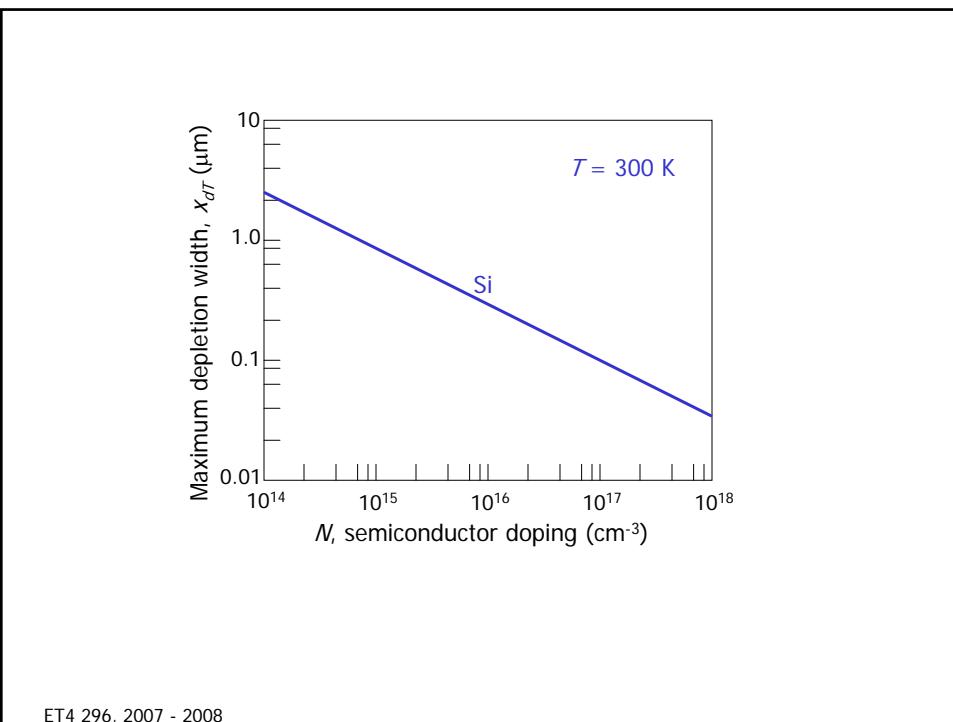


$$x_{dT} = \sqrt{\frac{4\epsilon_s\phi_{fp}}{eN_a}}$$

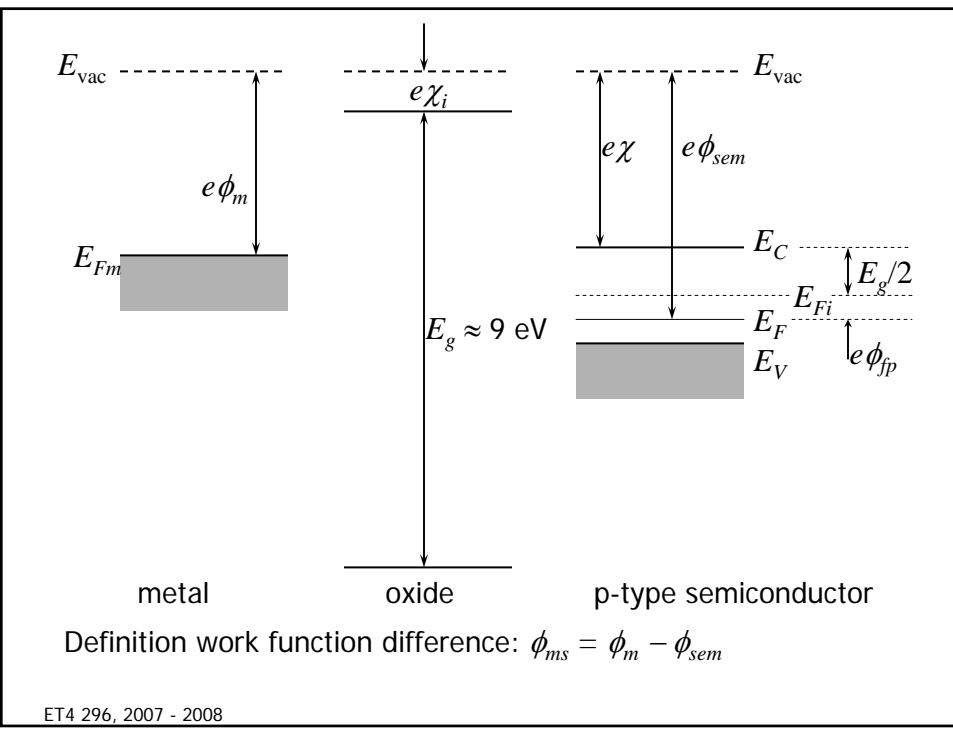
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Definition work function difference: $\phi_{ms} = \phi_m - \phi_{sem}$

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Work function difference

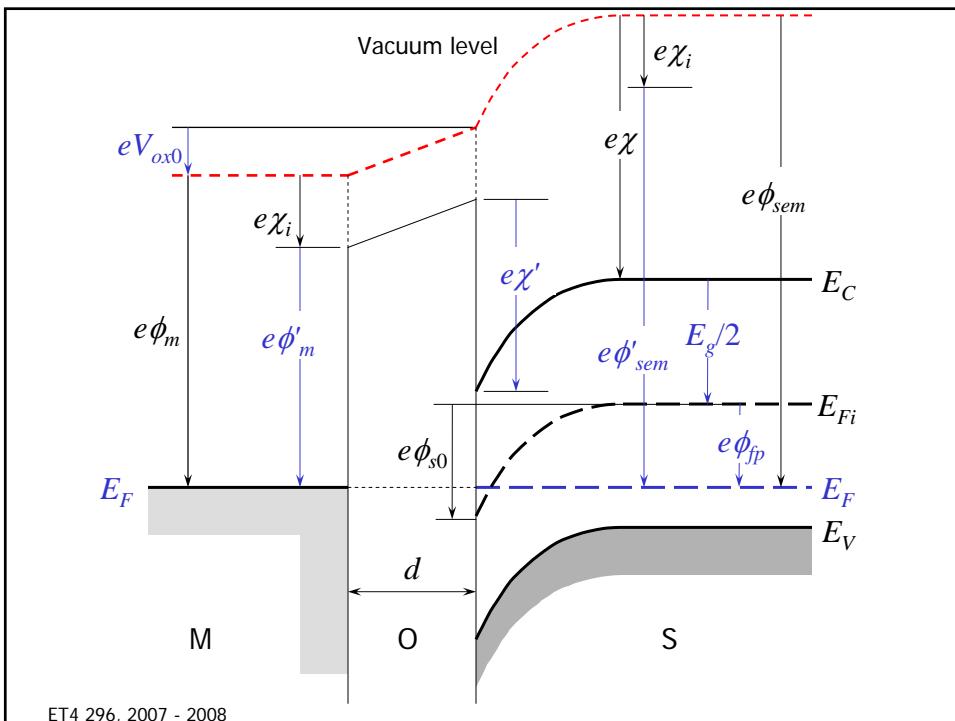
From previous figure follows: $\phi_{ms} = \phi_m - \phi_{sem} = \phi_m - \left(\chi + \frac{E_g}{2} + \phi_{fp} \right)$

In the book is defined that: $\phi'_m = \phi_m - \chi_i$
 $\chi' = \chi - \chi_i$

...and in that case the work function difference becomes:

$$\phi_{ms} = \phi'_m - \left(\chi' + \frac{E_g}{2} + \phi_{fp} \right)$$

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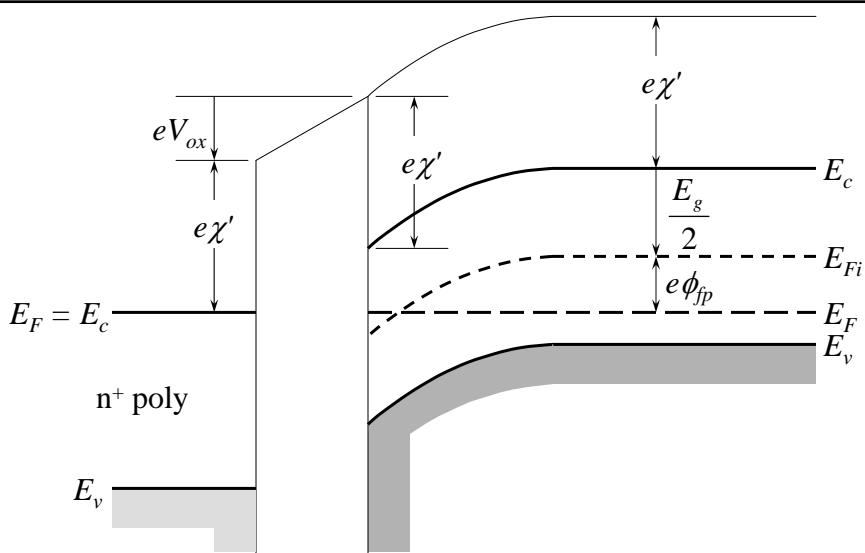
Work function difference

From the band diagram follows: $e\phi_m + V_{ox0} = e\chi + \frac{E_g}{2} + e\phi_{fp} - e\phi_{s0}$

Rewriting this gives: $V_{ox0} + \phi_{s0} = -\phi_{ms}$

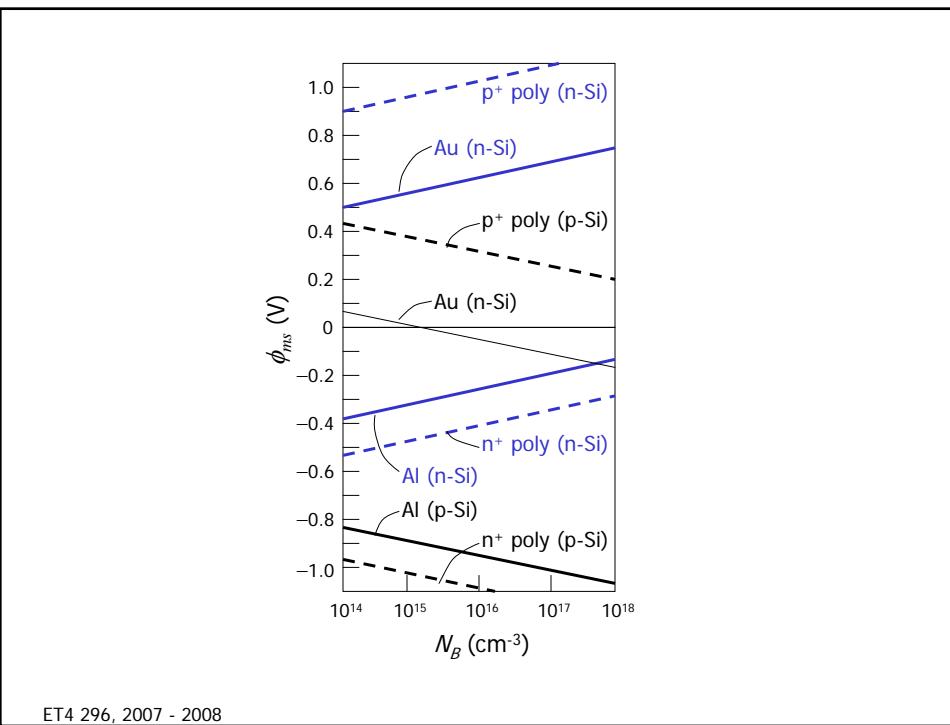
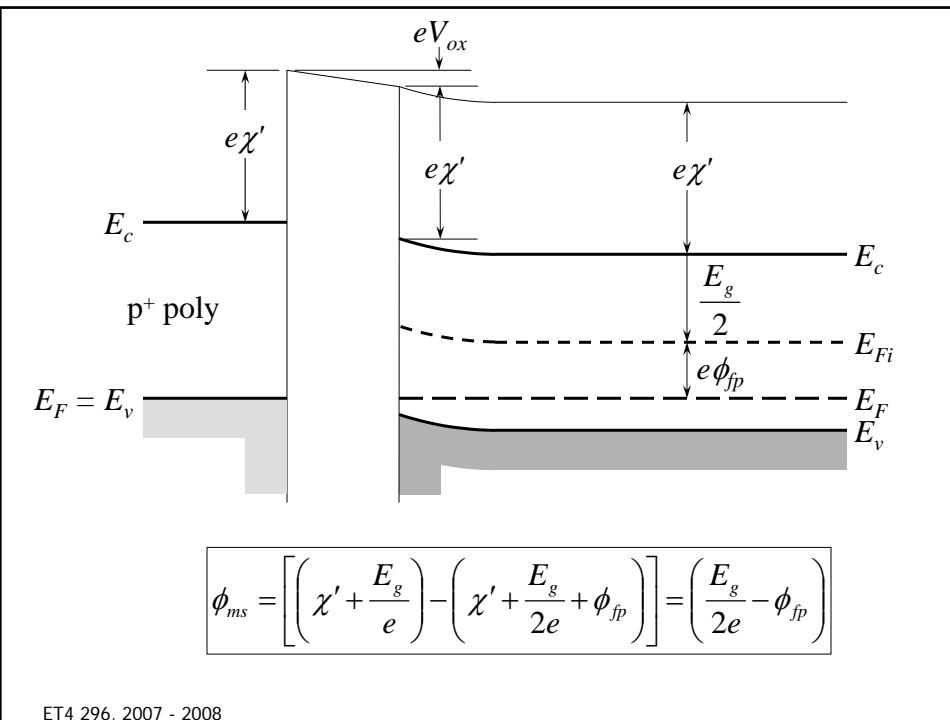
The same result is found using the definition for ϕ'_m and χ' in the book.

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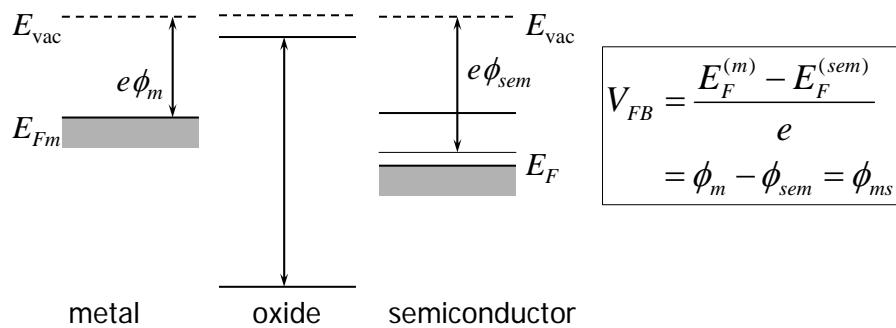
$$\phi_{ms} = \left[\chi' - \left(\chi' + \frac{E_g}{2e} + \phi_{fp} \right) \right] = -\left(\frac{E_g}{2e} + \phi_{fp} \right)$$

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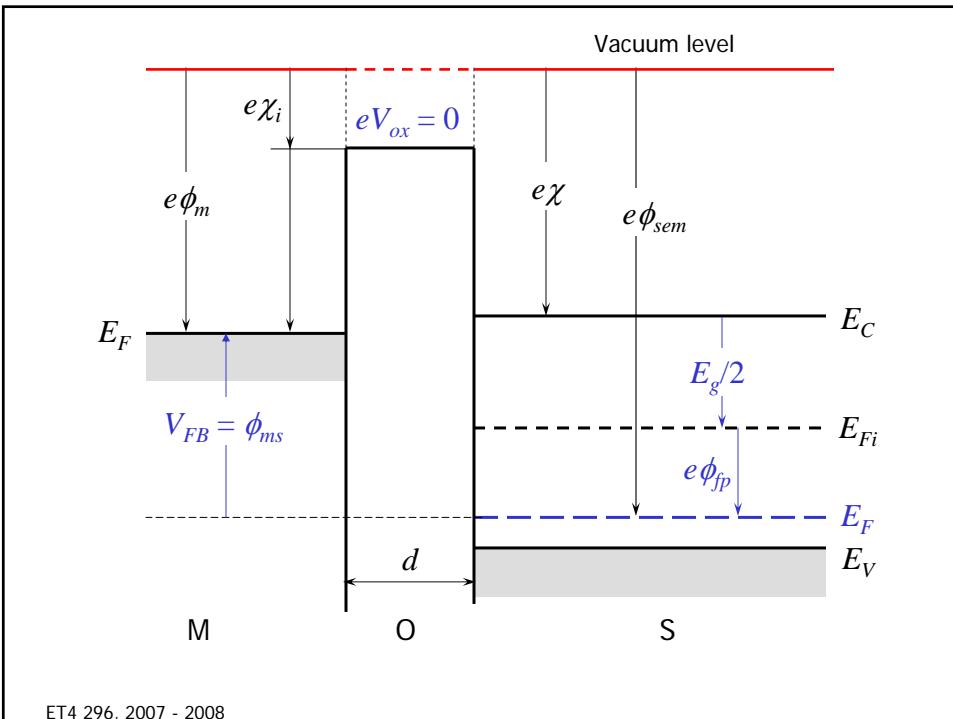


Flat-band voltage

- ⇒ That applied gate voltage at which the bands in the semiconductor are flat
- Seen before: accumulation, depletion, or inversion, dependent on the applied voltage.
- Flat band: in between.



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Applying a bias on a MOS-capacitor ...taking into account the voltage drop over the oxide...

In case no bias is applied: $V_{ox0} + \phi_{s0} = -\phi_{ms}$

We now apply a bias and compare the new situation with the situation in which no bias was applied:

$$\begin{aligned} V_G &= \Delta V_{ox} + \Delta \phi_s = (V_{ox} - V_{ox0}) + (\phi_s - \phi_{s0}) \\ &= V_{ox} + \phi_s + \phi_{ms} \end{aligned}$$

In the case of the flat-band condition the surface potential, ϕ_s , is equal to zero, so:

$$V_{FB} = V_G = V_{ox} + \phi_{ms}$$

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Charge in the oxide

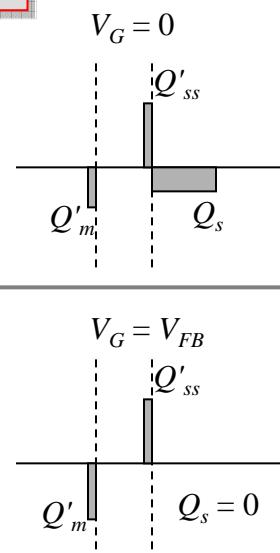
- Thus far it appeared that for flat-band condition the drop over the oxide was equal to zero.
- In practice on fixed charge (usually positive) is present on the semiconductor-oxide interface due to broken or dangling bonds.

Relation between V_{ox} and charge distribution: $V_{ox} = Q_m / C_{ox}$

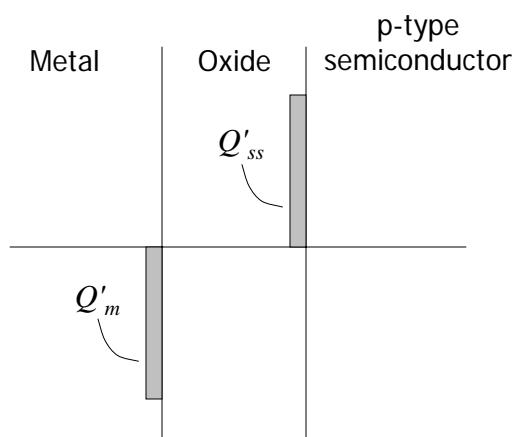
$$\text{For flat band: } V_{ox} = \frac{Q'_m}{C_{ox}} = -\frac{Q'_{ss}}{C_{ox}}$$

$$\dots \text{and so: } V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{ox}}$$

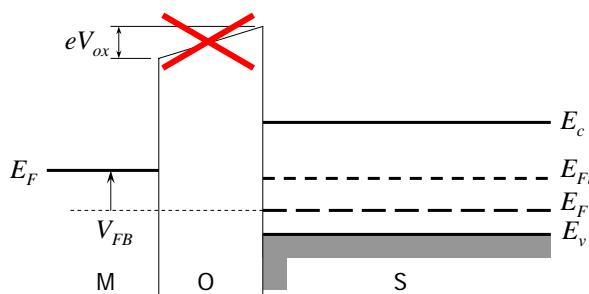
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Influence charge in oxide on V_{FB}



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$$V_{FB} = \phi_{ms} + V_{ox}$$

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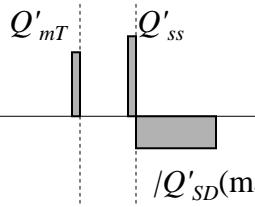
Threshold voltage

Definition threshold voltage: the bias required to get the MOS-capacitor in strong inversion, $\phi_s = 2\phi_{fp}$ for a p-type semiconductor.

Charge neutrality: $Q'_{mT} + Q'_{ss} = |Q'_{SD}(\max)|$

$$\text{Because: } \left. \begin{aligned} V_G &= V_{ox} + \phi_s + \phi_{ms} \\ \phi_s &= 2\phi_{fp} \end{aligned} \right\} \Rightarrow V_{TN} = V_{oxT} + 2\phi_{fp} + \phi_{ms}$$

$$\text{Further: } V_{oxT} = \frac{Q'_{mT}}{C_{ox}} = \frac{1}{C_{ox}} (|Q'_{SD}(\max)| - Q'_{ss})$$



$$\text{So: } V_{TN} = (|Q'_{SD}(\max)| - Q'_{ss}) \left(\frac{t_{ox}}{\epsilon_{ox}} \right) + \phi_{ms} + 2\phi_{fp}$$

$$|Q'_{SD}(\max)| = eN_a x_{dT}$$

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E_{vac}

$e\phi_{sem}$

$e\chi$

E_c

$e\chi_i$

$e\phi_m$

$e\phi_{fp}$

E_{Fi}

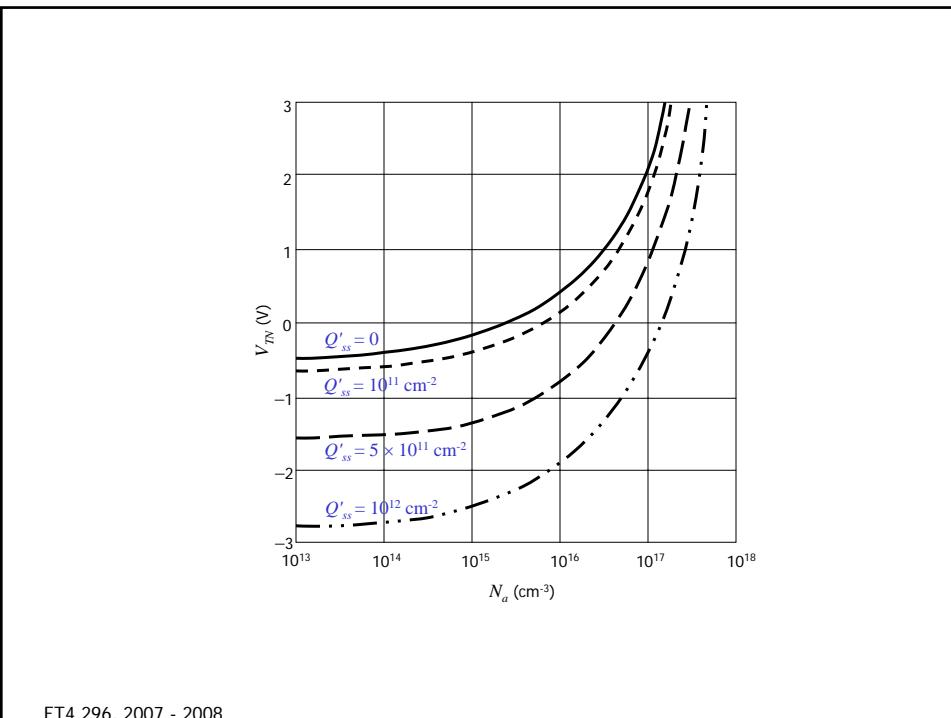
E_F

E_v

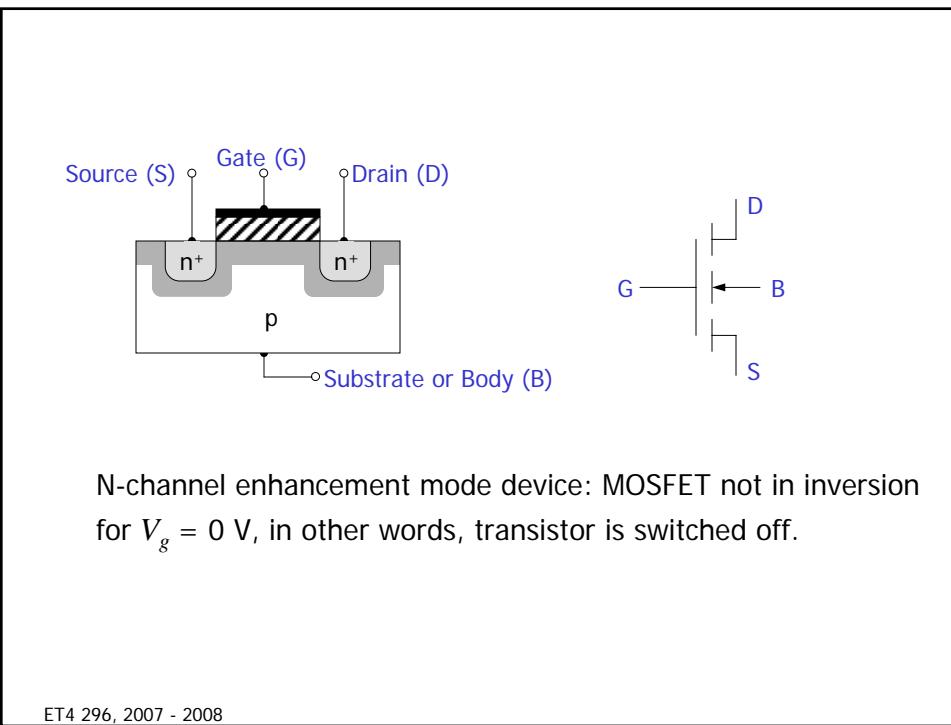
V_{TN}

$e\phi_s = 2e\phi_{fp}$

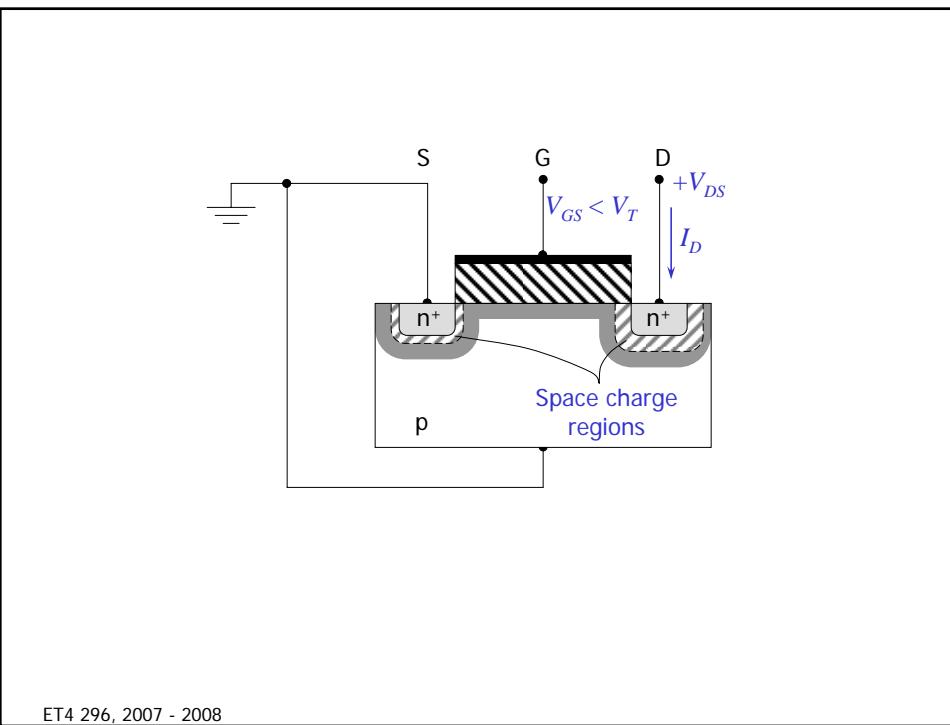
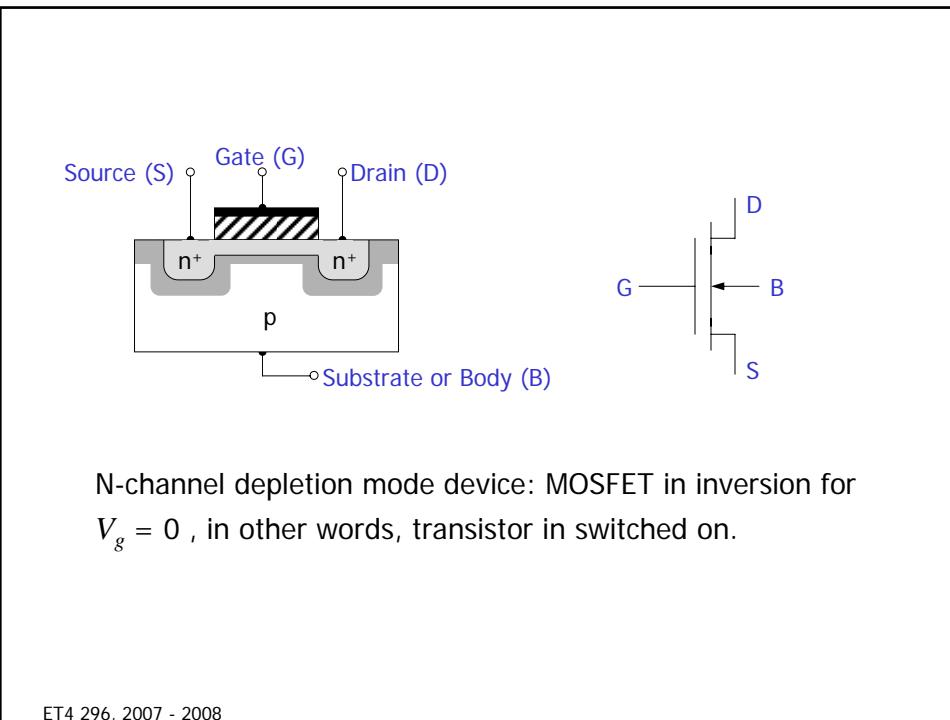
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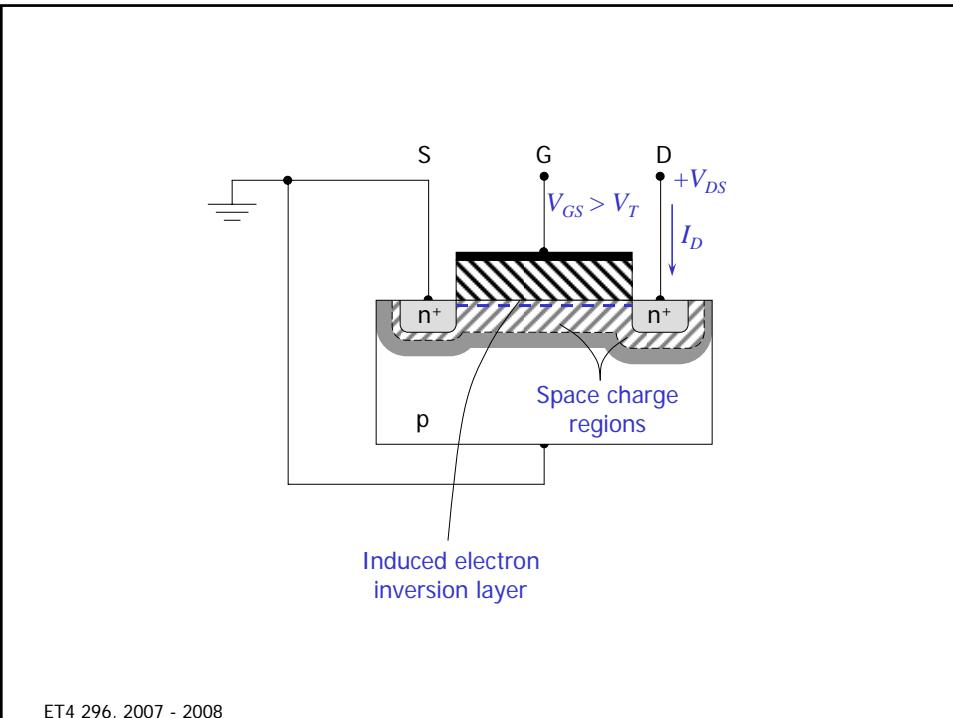


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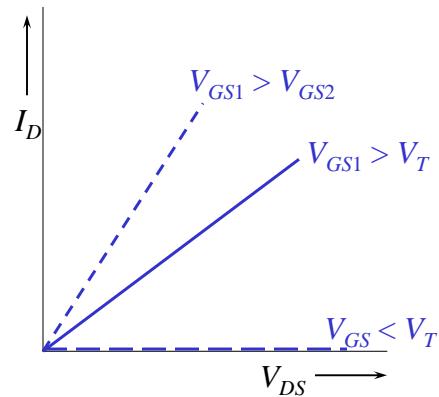
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Channel conductance, g_d

$$\begin{aligned}
 I_D &= env_n W \\
 &= en\mu_n E W \\
 &= |Q'_n| \mu_n \frac{V_{DS}}{L} W \\
 &= g_d V_{DS}
 \end{aligned}$$

Here, Q'_n is the surface charge density in the inversion layer

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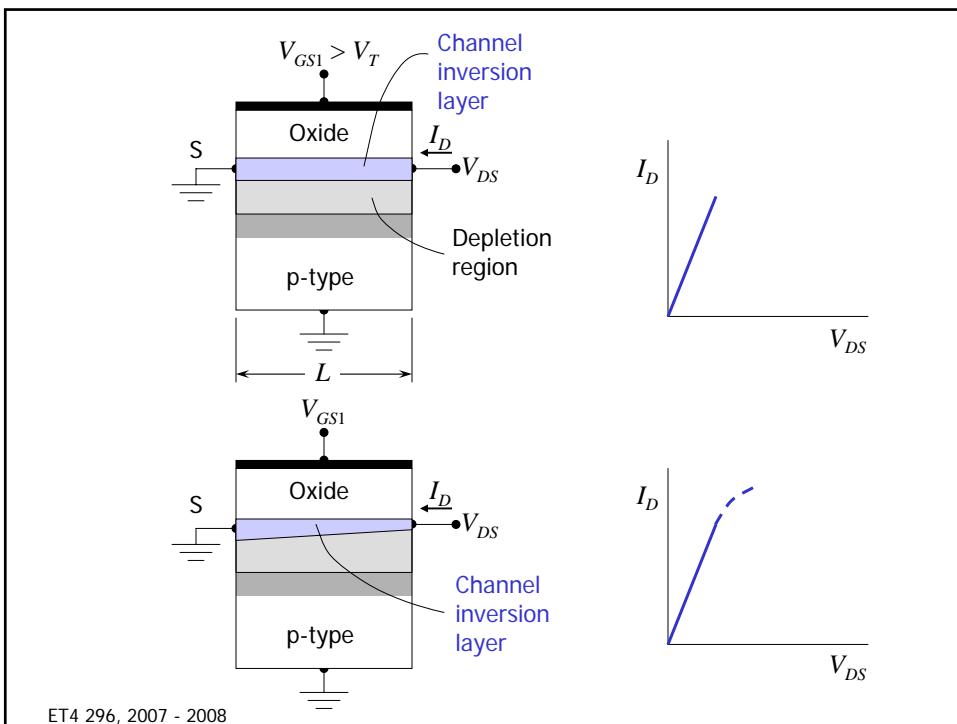
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Transconductance

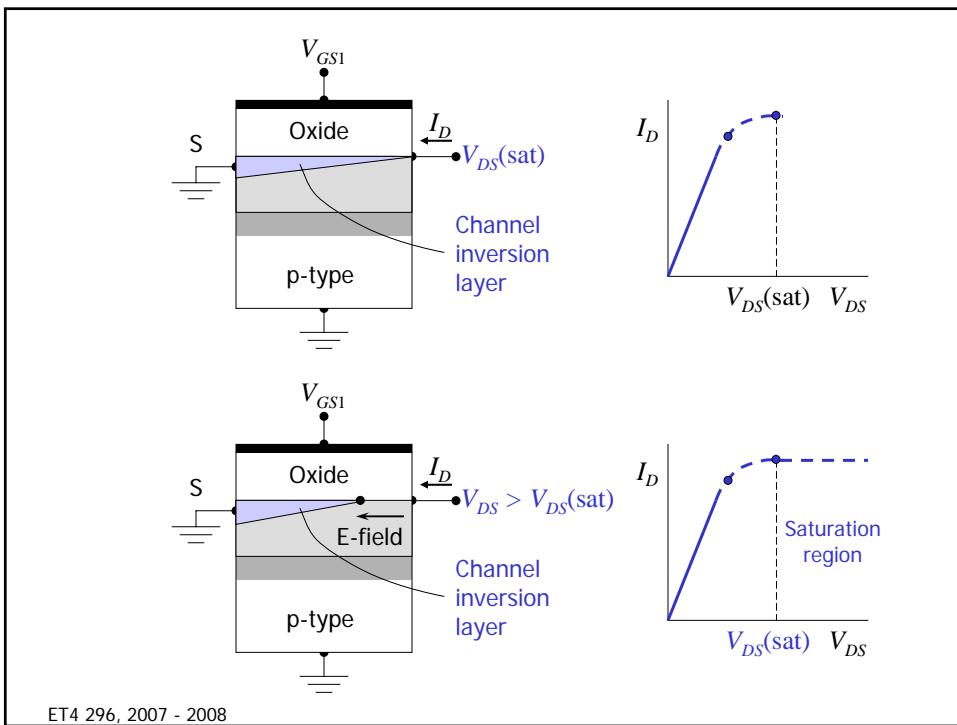
$$g_m = \frac{\partial I_D}{\partial V_{GS}} \Rightarrow \begin{cases} g_{mL} = \frac{W\mu_n C_{ox}}{L} \cdot V_{DS} \\ g_{ms} = \frac{\partial I_D(\text{sat})}{\partial V_{GS}} = \frac{W\mu_n C_{ox}}{L} (V_{GS} - V_T) \end{cases}$$

Note that the transconductance is dependent on the geometry of the device

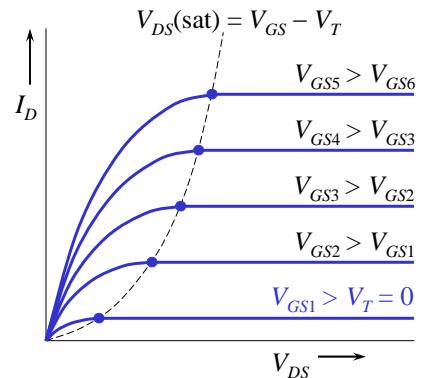
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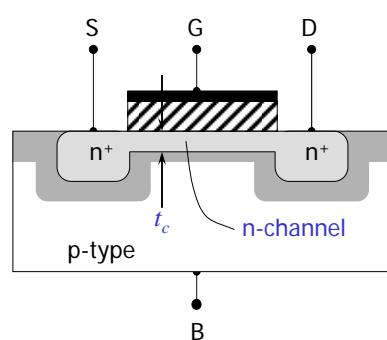
ET4 296, 2007 - 2008



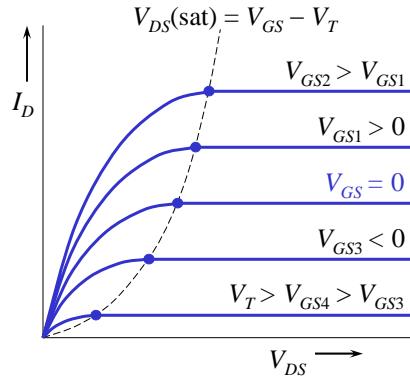
Non-saturated part: $I_D = \frac{W\mu_n C_{ox}}{2L} [2(V_{GS} - V_T)V_{DS} - V_{DS}^2]$

Saturated part: $I_D = \frac{W\mu_n C_{ox}}{2L} (V_{GS} - V_T)^2$

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Bias on the substrate

- Note that the source-body junction is reverse biased, thus that $V_{SB} = V_S - V_B$ is positive!!! (with respect to the n-type region).
- A large reverse bias across the source-body junction induces a larger depletion region (compare with a one-sided diode).

The charge difference, $\Delta Q'_{SD}$, to achieve inversion becomes:

$$\begin{aligned} Q'_{SD}(\max) &= -eN_a x_{dT} = -\sqrt{2e\varepsilon_s N_a (2\phi_{fp})} \\ Q'_{SD} &= -eN_a x_d = -\sqrt{2e\varepsilon_s N_a (2\phi_{fp} + V_{SB})} \\ \Delta Q'_{SD} &= -\sqrt{2e\varepsilon_s N_a} \left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}} \right] \end{aligned}$$

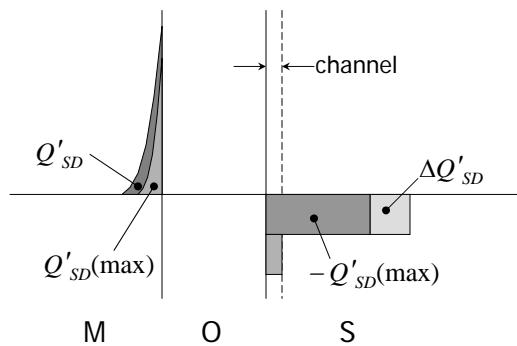
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The threshold voltage becomes:

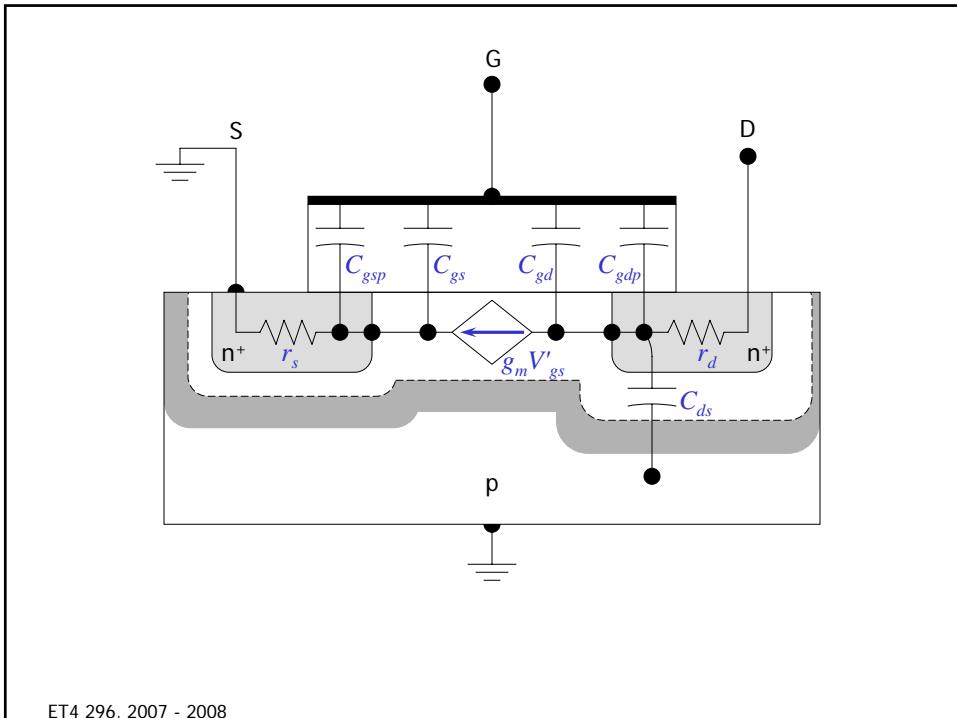
$$\Delta V_T = -\frac{\Delta Q'_{SD}}{C_{ox}} = \frac{\sqrt{2e\varepsilon_s N_a}}{C_{ox}} \left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}} \right]$$

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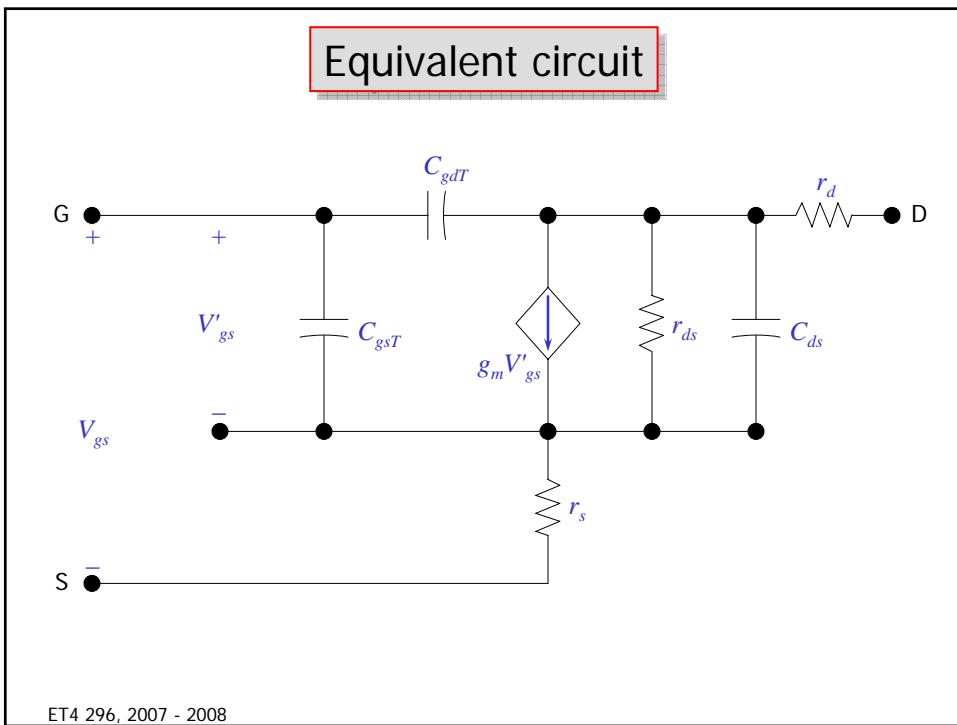
Charge distribution with a bias on the substrate



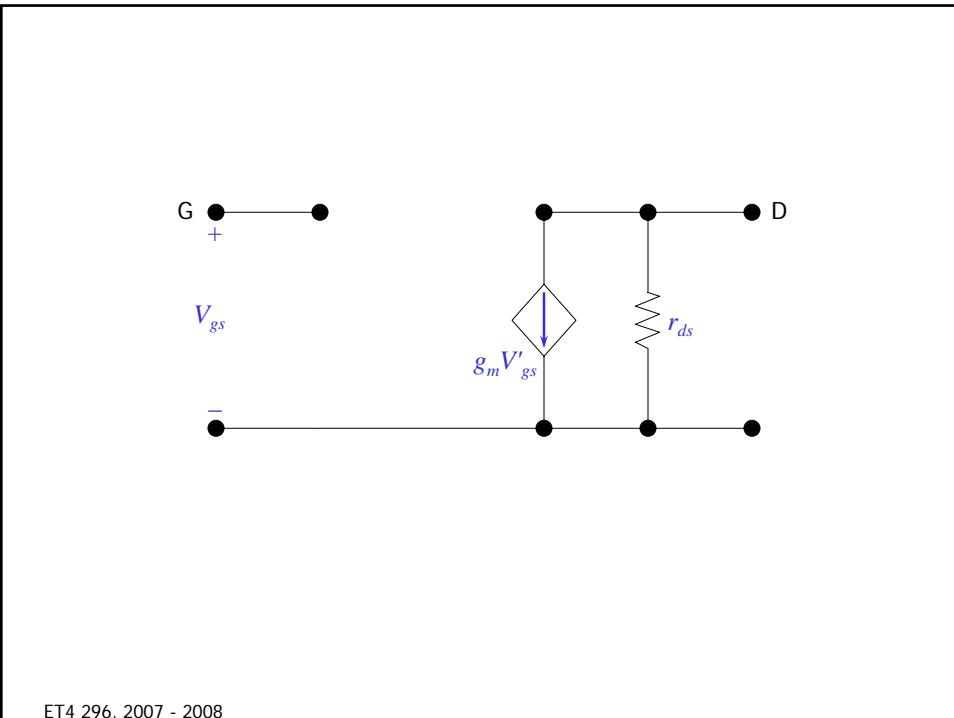
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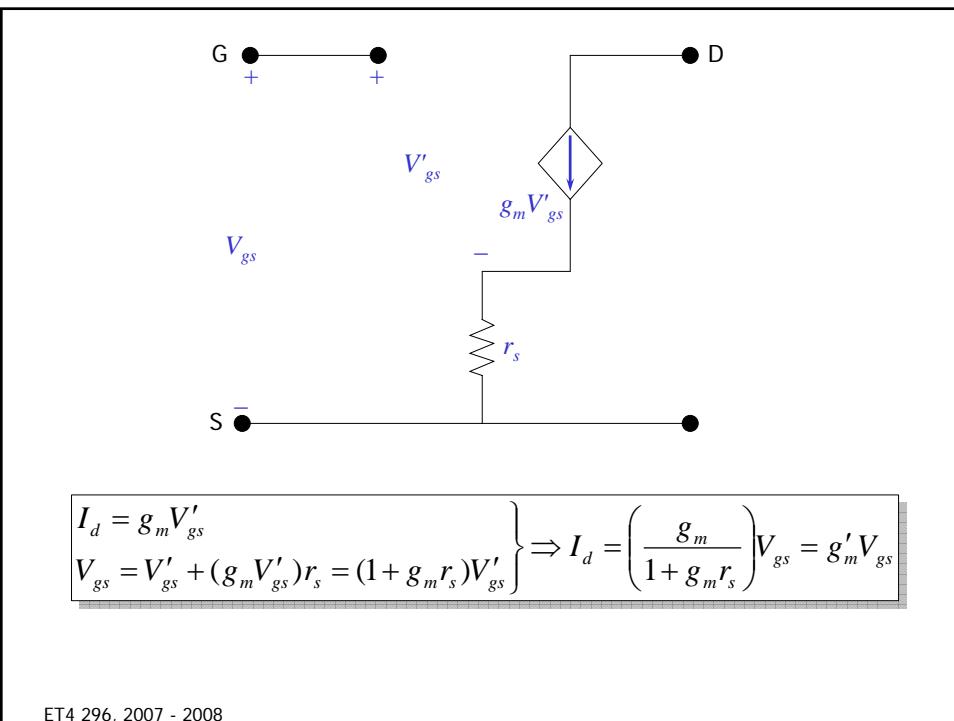
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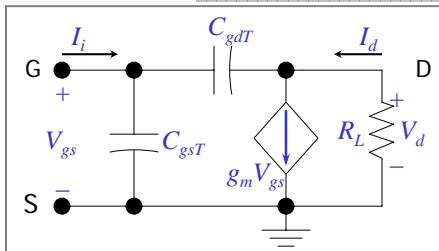
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Frequency limiting factors

- Transit time: time required to drift across the channel.
This time is determined by the saturation drift velocity and this is not the limiting process.
- Charging time of the gate.

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Charging time of the gate



$$I_i = j\omega C_{gsT} V_{gs} + j\omega C_{gdT} (V_{gs} - V_d)$$

$$\frac{V_d}{R_L} + g_m V_{gs} + j\omega C_{gdT} (V_d - V_{gs}) = 0$$

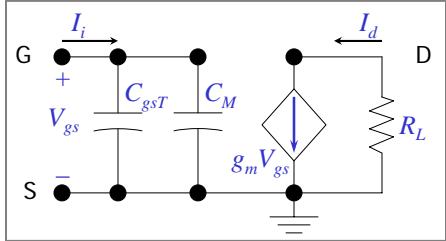
$$\text{Eliminate } V_d: \quad I_i = j\omega \left\{ C_{gsT} + C_{gdT} \left[\frac{1 + g_m R_L}{1 + j\omega R_L C_{gdT}} \right] \right\} V_{gs}$$

$$\dots \text{and because } j\omega R_L C_{gdT} \ll 1: \quad I_i = j\omega [C_{gsT} + \underbrace{C_{gdT}(1 + g_m R_L)}_{C_M}] V_{gs}$$

In saturation $C_{gd} = 0$ (channel near the drain) and the capacitance (and thus the frequency response of the device) is determined by the overlap capacitance C_{gdp} .

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Cut-off frequency



Cut-off frequency defined by $|I_d/I_i| = 1$, so:

$$\left| \frac{I_d}{I_i} \right| = \frac{g_m}{2\pi f(C_{gsT} + C_M)} \Rightarrow f_T = \frac{g_m}{2\pi(C_{gsT} + C_M)} = \frac{g_m}{2\pi C_G}$$

In case the MOSFET is in saturation and there are no overlap capacitances, then: $C_M = 0$ and $C_{gsT} = C_{ox}WL$ and thus:

$$f_T = \frac{\mu_n(V_{GS} - V_T)}{2\pi L^2}$$

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