ECE606: Solid State Devices
Lecture 23
MOSFET I-V Characteristics
MOSFET non-idealities

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Outline

1) Square law/ simplified bulk charge theory
2) Velocity saturation in simplified theory
3) Few comments about bulk charge theory, small transistors
4) Flat band voltage - What is it and how to measure it?
5) Threshold voltage shift due to trapped charges
6) Conclusion

Ref: Sec. 16.4 of SDF Chapter 18, SDF

Post-Threshold MOS Current ($V_G>V_{th}$)

$$I_D = -\frac{W}{L_{ch}}\mu_{eff}\int_0^{V_{DS}} Q_i(V)\,dV$$

Formula overview – derivation to follow

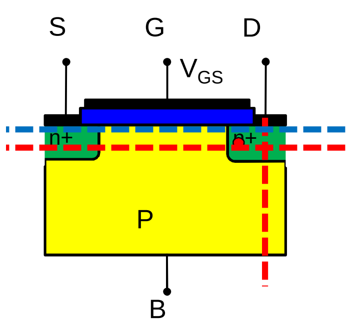
1) Square Law $\quad Q_i(V) = -C_G\left[V_G - V_T - V\right]$

2) Bulk Charge $\quad Q_i(V) = -C_G\left(V_G - V_{FB} - 2\psi_B - V - \frac{\sqrt{2q\varepsilon_{Si}N_A(2\phi_B + V)}}{C_O}\right)$

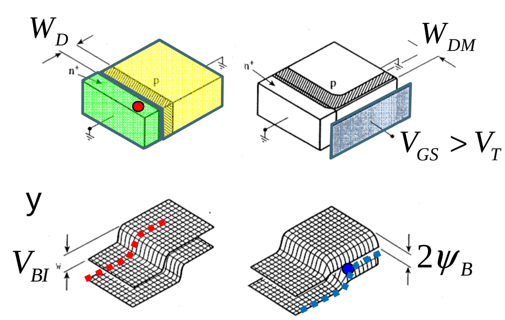
3) Simplified Bulk Charge $\quad Q_i(V) = -C_G\left[V_G - V_T - mV\right]$

4) “Exact” (Pao-Sah or Pierret-Shields)

Effect of Gate Bias



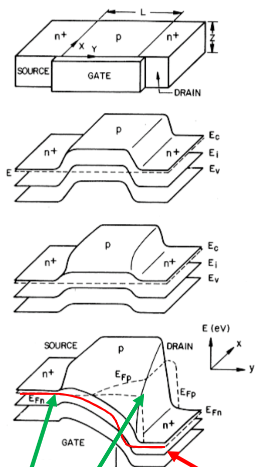
No source-drain bias



Gated doped or p-MOS with adjacent n^+ region
a) gate biased at flat-band
b) gate biased in inversion
A. Grove, *Physics of Semiconductor Devices*, 1967.

The Effect of Drain Bias

2D band diagram for an n-MOSFET



a) device

b) equilibrium (flat band)

c) equilibrium ($\psi_S > 0$)

d) non-equilibrium with V_G and V_D >0 applied

SM. Sze, *Physics of Semiconductor Devices*, 1981

Pao and Sah.

Depletion very different in source and drain side

F_N

Gate voltage must ensure channel formation=> LARGE

Effect of a Reverse Bias at Drain

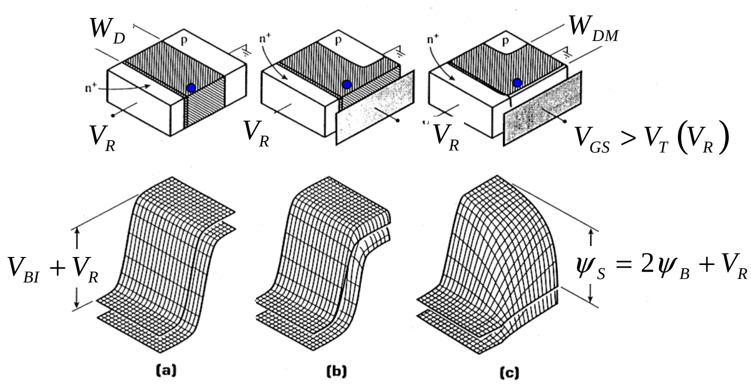


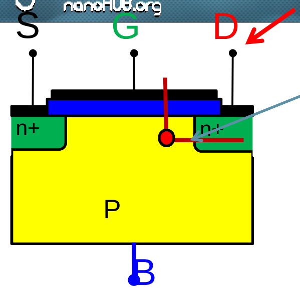
FIGURE 2.34. Gated diode or p-type MOS with adjacent n^+ region under nonequilibrium (reverse

Gated doped or p-MOS with adjacent, reverse-biased n^+ region

a) gate biased at flat-band
b) gate biased in depletion
c) gate biased in inversion

A. Grove, *Physics of Semiconductor Devices*, 1967.

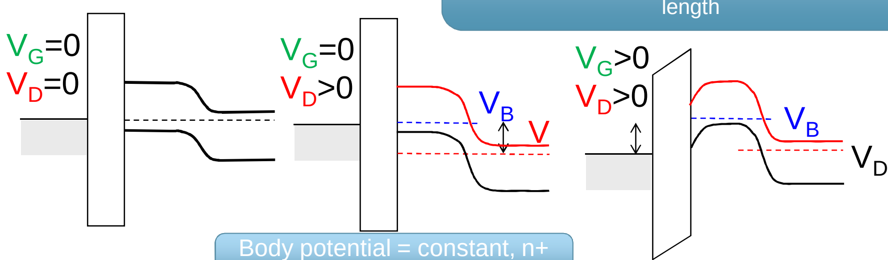
Inversion Charge in the Channel



Band diagrams (Gate – Channel - Drain)

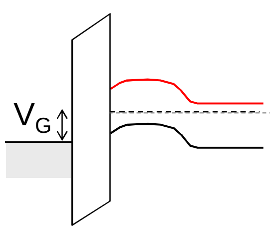
$$Q_i = -C_{ox}(V_G - V_{th} - V)$$
$$+ qN_A(W_T(V) - W_T(V=0))$$

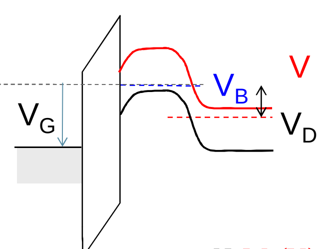
Due to drain bias, additional gate voltage (as compared to threshold in MOSCAP) is now needed to invert the channel throughout its length



Body potential = constant, n+ region potential lowered

Inversion Charge at one point in Channel





$$V_{th} = 2\phi_F - \frac{qN_A W_T(V=0)}{C_{ox}}$$

$$V_{th}^* = (2\phi_F + V) - \frac{qN_A W_T(V)}{C_{ox}}$$

$$V_{th}^* = V_{th} + V - \frac{qN_A\left(W_T(V) - W_T(V=0)\right)}{C_{ox}}$$

$$Q_i = -C_{ox}(V_G - V_{th}^*)$$

Threshold voltage in the presence of drain bias

Approximations for Inversion Charge

$$Q_i = -C_O(V_G - V_{th} - V) + qN_A\left(W_T(V) - W_T(V=0)\right)$$

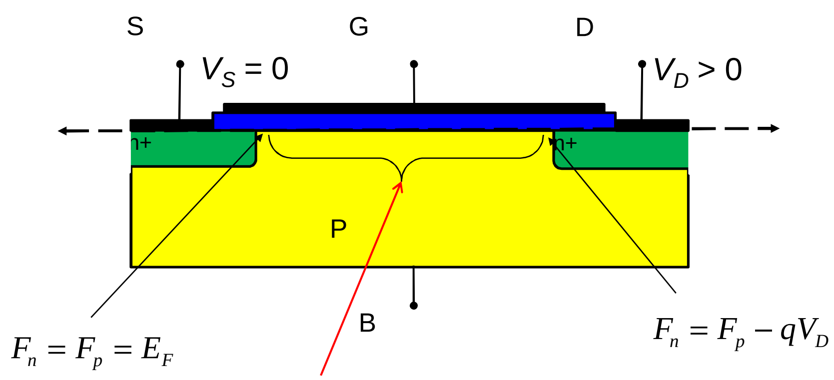
$$= -C_O(V_G - V_{th} - V) + \left[\sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B + V\right)} - \sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B\right)}\right]$$

Approximations:

$Q_i \approx -C_{ox}(V_G - V_{th} - V)$ Square law approximation …

$Q_i \approx -C_{ox}(V_G - V_{th} - mV)$ Simplified bulk charge approximation …

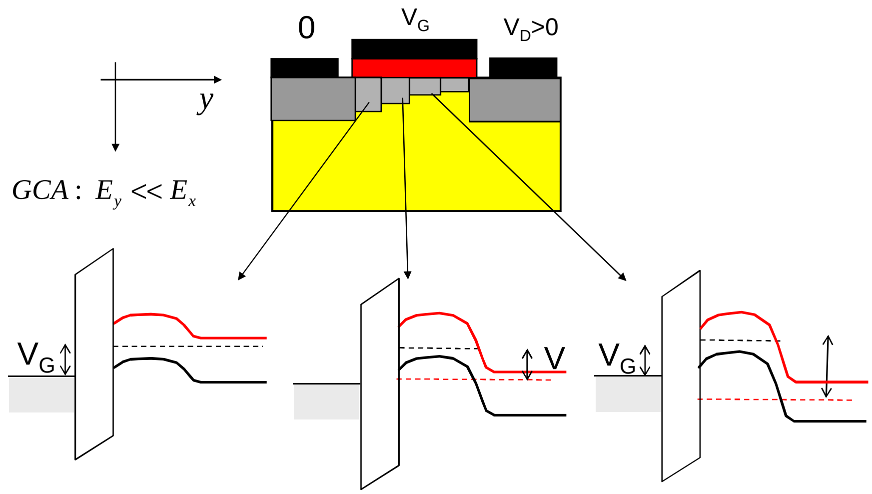
The MOSFET



F_n increasingly negative from source to drain (reverse bias increases from source to drain)

Elements of Square-law Theory

Voltage and hence inversion charge vary spatially

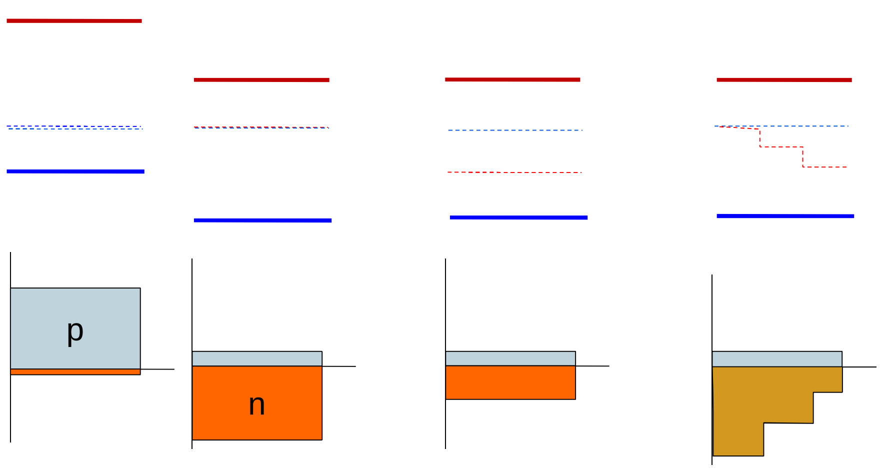


$GCA: \ E_y << E_x$

$$Q_i(y) = -C_{ox}\left[V_G - V_{th} - mV(y)\right]$$

Charge along the channel ....

$$n = N_C e^{-(E_C - F_n)\beta} \qquad p = N_C e^{(E_V - F_p)\beta}$$



Charge along the channel …

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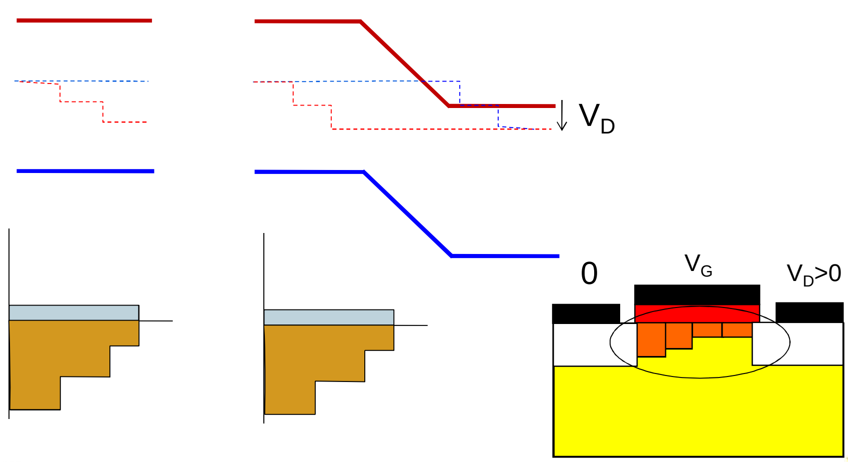
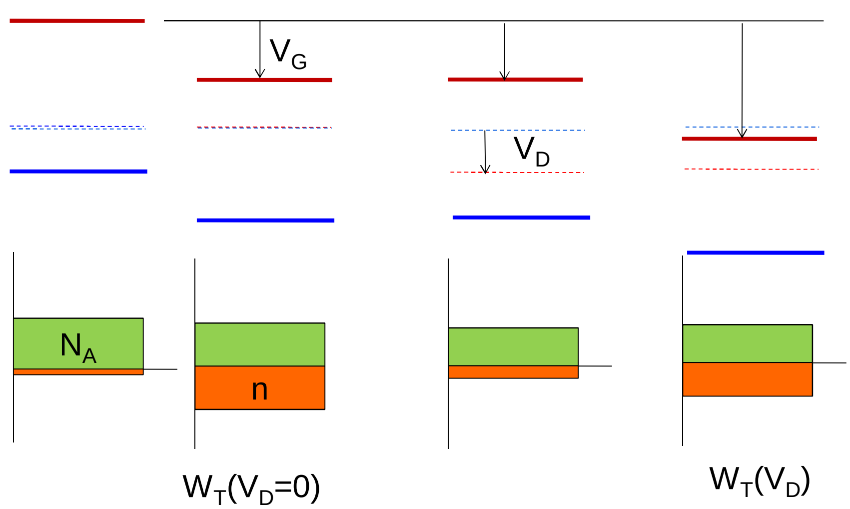
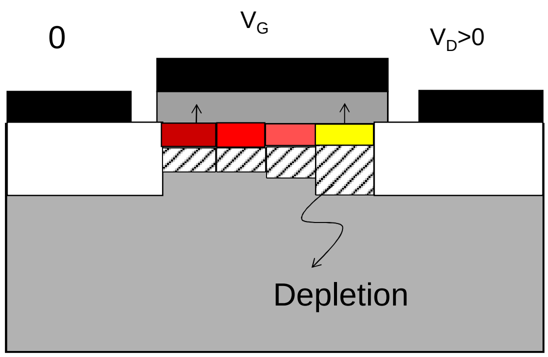


Depletion into the channel ….

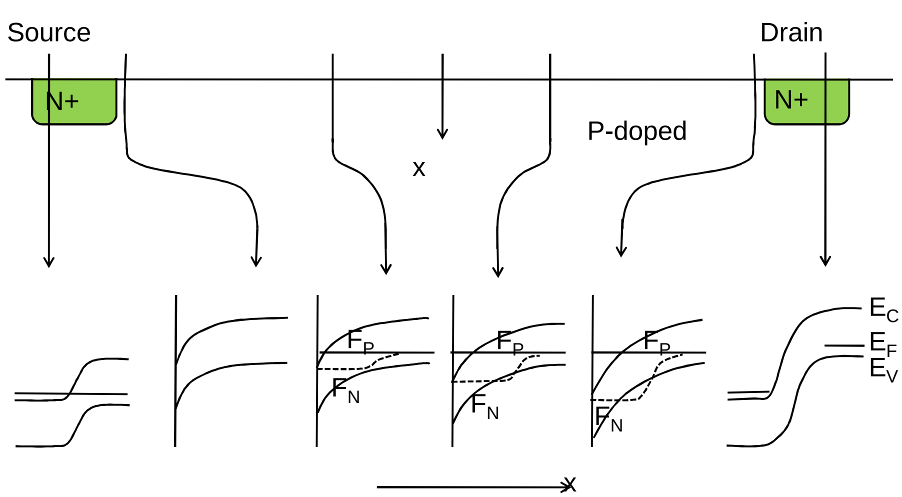
$$n = N_C e^{-(E_C - F_n)\beta} \qquad p = N_C e^{(E_V - F_p)\beta}$$



Depletion into the channel …



Another view of Channel Potential



Square Law Theory

$$J_1 = Q_1 \mu \mathcal{E}_1 = Q_1 \mu \left.\frac{dV}{dy}\right|_1$$

$$J_2 = Q_2 \mu \mathcal{E}_2 = Q_2 \mu \left.\frac{dV}{dy}\right|_2$$

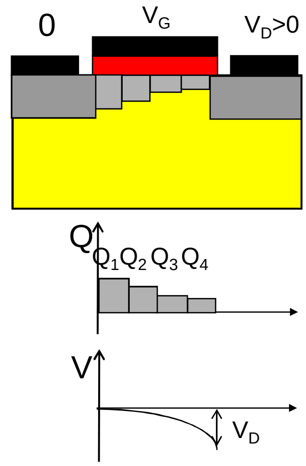
$$J_3 = Q_3 \mu \mathcal{E}_3 = Q_3 \mu \left.\frac{dV}{dy}\right|_3$$

$$J_4 = Q_4 \mu \mathcal{E}_4 = Q_4 \mu \left.\frac{dV}{dy}\right|_4$$

$$\sum_{i=1,N} \frac{J_i dy}{\mu} = \sum_{i=1,N} Q_i \, dV$$

$$\frac{J_D}{\mu} \sum_{i=1,N} dy = \int_0^{V_D} C_{ox}(V_G - V_{th} - mV)dV$$

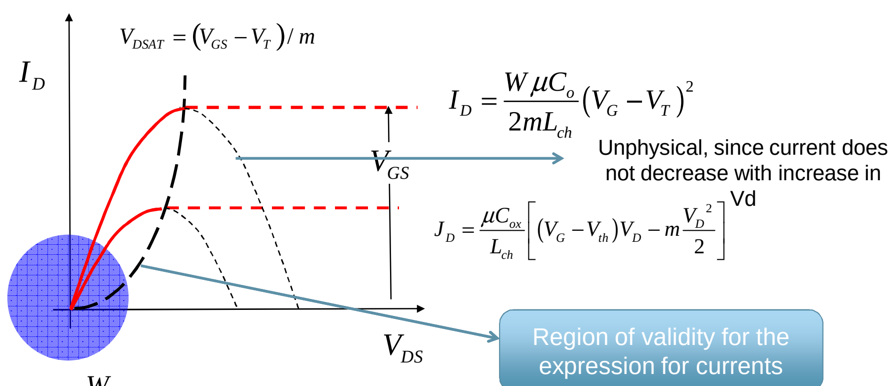
$$J_D = \frac{\mu C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - m\frac{V_D^{\ 2}}{2}\right]$$



Square Law or Simplified Bulk Charge Theory

$$I_D = W\frac{\mu C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - m\frac{V_D^{\ 2}}{2}\right]$$

$$\frac{dI_D}{dV} = 0 = (V_G - V_{th}) - mV_D \Rightarrow V_{D,sat} = \left(V_G^{\ *} - V_{th}\right)/m$$

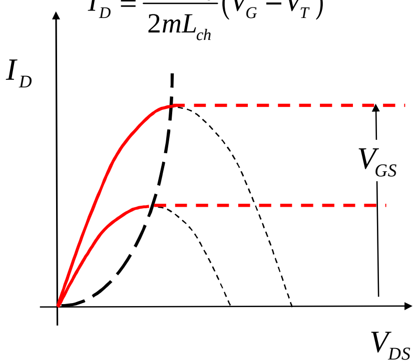


$$I_D = \mu C_o \frac{W}{L}(V_G - V_T)V_D$$

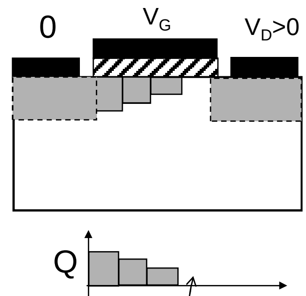
Why square law? And why does it become invalid

$$V_{DSAT} = (V_{GS} - V_T)/m$$

$$I_D = \frac{W\mu C_o}{2mL_{ch}}(V_G - V_T)^2$$



$$Q_i \approx -C_{ox}(V_G - V_{th} - mV)$$

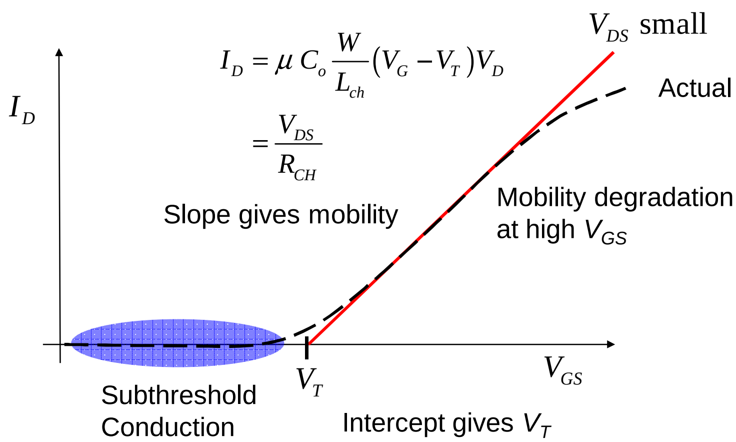


This situation doesn't arise since electrons travelling from left to right are swept into the drain under the effect of the reverse bias applied

Linear Region (Low V_{DS})

$$I_D = W\frac{\mu C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - m\frac{V_D^2}{2}\right]$$

$$I_D = \mu C_o \frac{W}{L_{ch}}(V_G - V_T)V_D = \frac{V_{DS}}{R_{CH}}$$



Can get V_T also from C-V

Outline

1) Square law/ simplified bulk charge theory
2) **Velocity saturation in simplified theory**
3) Few comments about bulk charge theory, small transistors
4) Flat band voltage - What is it and how to measure it?
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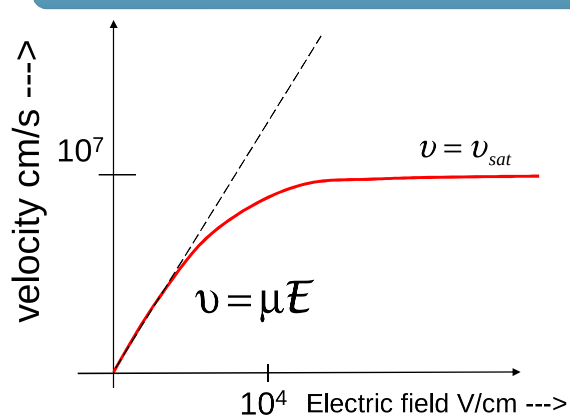
Ref: Sec. 16.4 of SDF   Chapter 18, SDF

Velocity vs. Field Characteristic (electrons)

Velocity saturates at high fields because of scattering



$$\upsilon_d = \frac{-\mu\mathcal{E}}{\left[1+(\mathcal{E}/\mathcal{E}_c)^2\right]^{1/2}}$$

$$\upsilon_d = \frac{-\mu\mathcal{E}}{1+(|\mathcal{E}|/\mathcal{E}_c)}$$

$$\upsilon_{d,sat} = \mu\mathcal{E}_c$$

This expression can be used to re-derive the expression for current since since mobility is now, in principle, a function of distance

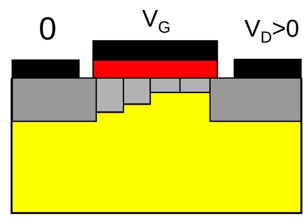
Recap - derivation for MOSFET current

$$J_1 = Q_1 \mu_1 \mathcal{E}_1 = Q_1 \mu_1 \left.\frac{dV}{dy}\right|_1$$

$$J_2 = Q_2 \mu_2 \mathcal{E}_2 = Q_2 \mu_2 \left.\frac{dV}{dy}\right|_2$$

$$J_3 = Q_3 \mu_3 \mathcal{E}_3 = Q_3 \mu_3 \left.\frac{dV}{dy}\right|_3$$

$$J_4 = Q_4 \mu_4 \mathcal{E}_4 = Q_4 \mu_4 \left.\frac{dV}{dy}\right|_4$$



$$\Rightarrow \sum_{i=1,N} \frac{J_i dy}{\mu(y)} = \sum_{i=1,N} Q_i\, dV$$

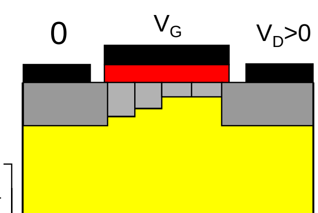
Velocity Saturation

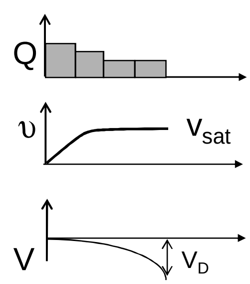
$$J_D \sum_{i=1,N} \frac{dy}{\mu_0 \Big/ \left[1 + \frac{|\mathcal{E}|}{\mathcal{E}_c}\right]} = \int_0^{V_D} C_{ox}(V_G - V_{th} - mV)dV$$

$$\frac{J_D}{\mu_0} \int_0^{L_{ch}} dy \left[1 + \frac{1}{\mathcal{E}_c}\frac{dV}{dy}\right] = C_{ox}\left[(V_G - V_{th})V_D - \frac{mV_D{}^2}{2}\right]$$

$$\int_0^{L_{ch}} J_D dy + \int_0^{V_{DS}} \frac{J_D}{E_c} dV = C_{ox}\left[(V_G - V_{th})V_D - \frac{mV_D{}^2}{2}\right]$$

$$J_D = \frac{\mu_0 C_{ox}}{L_{ch} + \frac{V_D}{\mathcal{E}_c}}\left[(V_G - V_{th})V_D - \frac{mV_D{}^2}{2}\right]$$





Significance of the new expression

$$J_D = \frac{\mu_0 C_{ox}}{L_{ch} + \frac{V_D}{\mathcal{E}_c}} \left[(V_G - V_{th}) V_D - \frac{m V_D^{\ 2}}{2} \right]$$

- At very small channel lengths and high drain biases, the current expression becomes independent of the channel length
- In the linear region in the I-V_d characteristics, you have a resistance that doesn't depend on the length of the channel

Calculating V_{DSAT}

$$\frac{dI_D}{dV_{DS}} = 0$$

$$\frac{I_D}{W} = \frac{\mu_o C_{ox}}{L_{ch} + \frac{V_D}{\mathcal{E}_c}} \left[(V_G - V_{th}) V_D - m \frac{V_D^2}{2} \right]$$

Take log on both sides and then set the derivative to zero ….

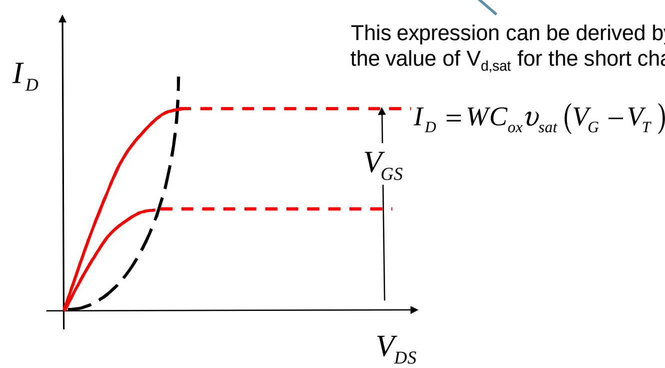
$$V_{DSAT} = \frac{2\left(V_G - V_{th}\right)/m}{1 + \sqrt{1 + 2\mu_o \left(V_G - V_{th}\right) / m \upsilon_{sat} L_{ch}}} < \frac{\left(V_{GS} - V_T\right)}{m}$$

Velocity Saturation in short channel devices

$$J_{D,sat} = \frac{\mu_0 C_{ox}}{L_{ch} + \frac{V_{D,sat}}{\mathcal{E}_C}} \left[(V_G - V_{th}) V_{D,sat} - \frac{m V_{D,sat}^{\,2}}{2} \right]$$

$$\sim \frac{\mu_0 \boldsymbol{E}_C C_{ox}}{V_{D,sat}} \left[(V_G - V_{th}) V_{D,sat} - \frac{m V_{D,sat}^2}{2} \right] \sim \upsilon_{sat} C_{ox} (V_G - V_{th})$$

This expression can be derived by plugging in the value of $V_{d,sat}$ for the short channel regime



'Linear Law' Expression at the limit of L --> 0

$$V_{DSAT} = \frac{2(V_G - V_{th})/m}{1 + \sqrt{1 + 2\mu_0 (V_G - V_{th}) / m \upsilon_{sat} L_{ch}}}$$

$$V_{DSAT} \rightarrow \sqrt{2 \upsilon_{sat} L_{ch} (V_G - V_{th}) / m \mu_0}$$

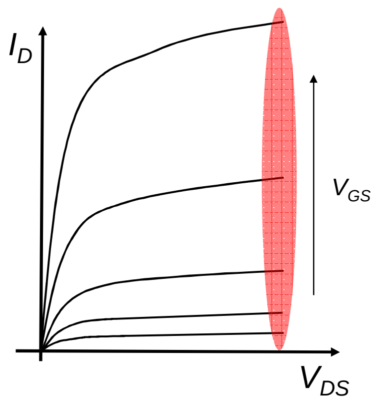
$$I_{DSAT} = W C_{ox} \upsilon_{sat} (V_G - V_{th}) \frac{\sqrt{1 + 2\mu_0 (V_G - V_{th}) / m \upsilon_{sat} L_{ch}} - 1}{\sqrt{1 + 2\mu_0 (V_G - V_{th}) / m \upsilon_{sat} L_{ch}} + 1}$$

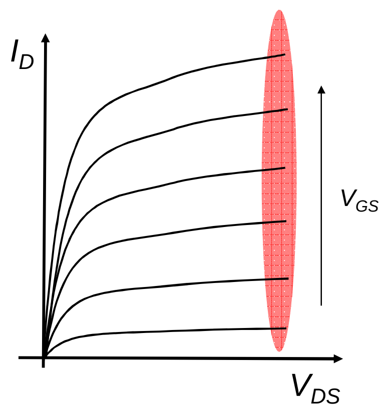
$$I_{DSAT} = W C_{ox} \upsilon_{sat} (V_G - V_{th})$$

Complete velocity saturation

Current independent of *L*

'Signature' of Velocity Saturation



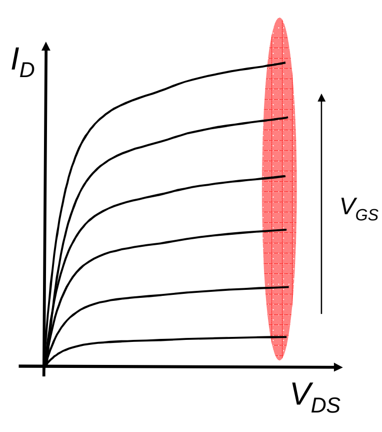


$$I_D = \frac{W}{2L_{ch}} \mu_0 C_{ox} \frac{(V_G - V_{th})^2}{m}$$

$$I_D = W \upsilon_{sat} C_{ox} (V_G - V_{th})$$

Can pull out oxide thickness from experimental curves… How?

I_D and (V_{GS} - V_T): In practice …..



$$I_D(V_D = V_{DD}) \sim (V_G - V_{th})^{\alpha}$$

$$1 < \alpha < 2$$

Complete velocity saturation

Long channel

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6) Conclusion

Ref: Sec. 16.4 of SDF Chapter 18, SDF

Approximations for Inversion Charge

$$Q_i = -C_O(V_G - V_{th} - V) + qN_A\left(W_T(V) - W_T(V=0)\right)$$

$$= -C_O(V_G - V_{th} - V) + \sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B + V\right)} - \sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B\right)}$$

Approximations:

$Q_i \approx -C_{ox}(V_G - V_{th} - V)$ Square law approximation …

$Q_i \approx -C_{ox}(V_G - V_{th} - mV)$ Simplified bulk charge approximation …

One could substitute the expression for Q_i above explicitly instead of using m to simplify the equation, resulting in a more complete bulk charge expression

Complete Bulk-charge Theory

Additional V dependent terms abstracted into m previously

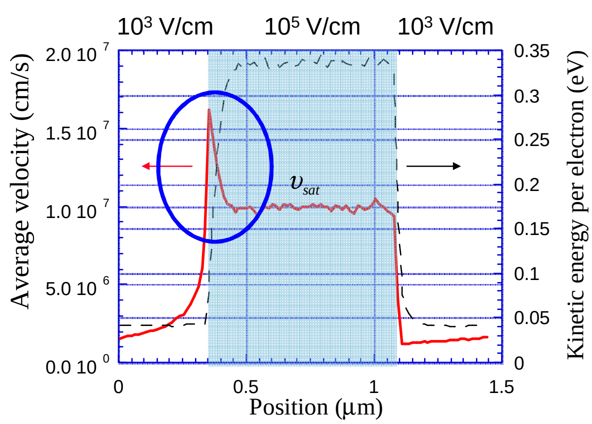
$$\frac{J_D}{\mu_0}\sum_{i=1,N} dy = \int_0^{V_D} C_O(V_G - V_{th} - V)dV + \int_0^{V_D} [..........]dV$$

$$\frac{J_D}{\mu_0}\int_0^{L_{ch}} dy = \int_0^{V_D} C_O(V_G - V_{th} - V)dV + \int_0^{V_D} [..........]dV$$

$$J_D = \frac{\mu_0 C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - \frac{V_D^{\,2}}{2} - \frac{4}{3}\frac{qN_A W_T}{C_O}\phi_F\left\{\left(1+\frac{V_D}{2\phi_F}\right)^{3/2} - \left(1+\frac{3V_D}{4\phi_F}\right)\right\}\right]$$

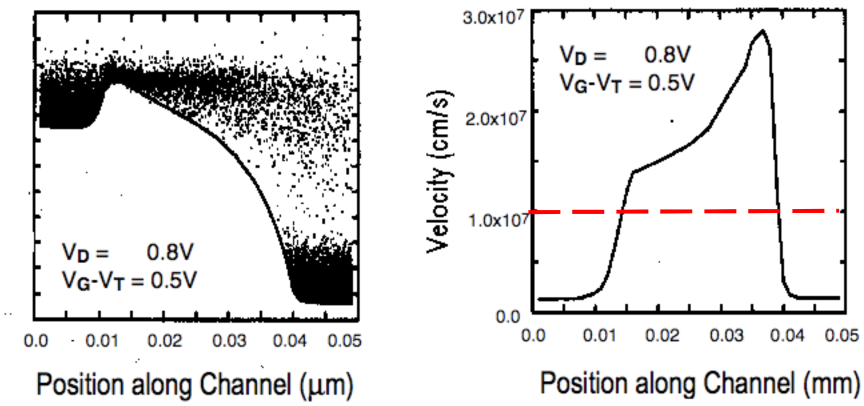
(Eq. 17.28 in SDF) .... Explicit dependence on bulk doping

Velocity Overshoot



$\upsilon \neq \mu_n(E)E$ → Valid for bulk semiconductors, not valid at top of the barrier

Velocity Overshoot in a MOSFET



Frank, Laux, and Fischetti, IEDM Tech. Dig., p. 553, 1992

Intermediate Summary

1) Velocity saturation is an important consideration for short channel transistors (e.g., V_D=1V, L_{ch}=20nm). Therefore, $\alpha \sim 1$ for most modern transistors.
2) Bulk charge theory explains why MOSFET current depends on substrate (bulk) doping. In the simplified bulk charge theory, doping dependence is encapsulated in ***m***.
3) Additional considerations of velocity overshoot could complicate calculation of current.
4) Good news is that for very short channel transistors, electrons travel from source to drain without scattering. A considerably simpler 'Lundstrom theory of MOSFET' applies.

Outline

1) Square law/ simplified bulk charge theory
2) Velocity saturation in simplified theory
3) Few comments about bulk charge theory, small transistors
4) **Flat band voltage - What is it and how to measure it?**
5) Threshold voltage shift due to trapped charges
6) Conclusion

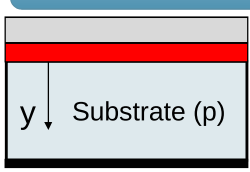
$$I_D(V_D = V_{DD}) \sim (V_G - V_{th})^{\alpha}$$
$$1 < \alpha < 2$$

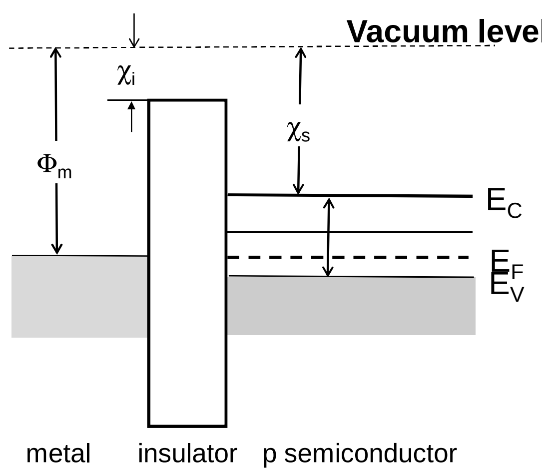
Ref: Sec. 16.4 of SDF Chapter 18, SDF

$$V_{th} = V_{th,ideal} + \phi_{MS} - \frac{\gamma_M Q_M}{C_O} - \frac{Q_F}{C_O} - \frac{Q_{IT}(\phi_s)}{C_O}$$

(1) Idealized MOS Capacitor

In the idealized MOS capacitor, the Fermi Levels in metal and semiconductor align perfectly so that at zero applied bias, the energy bands are flat



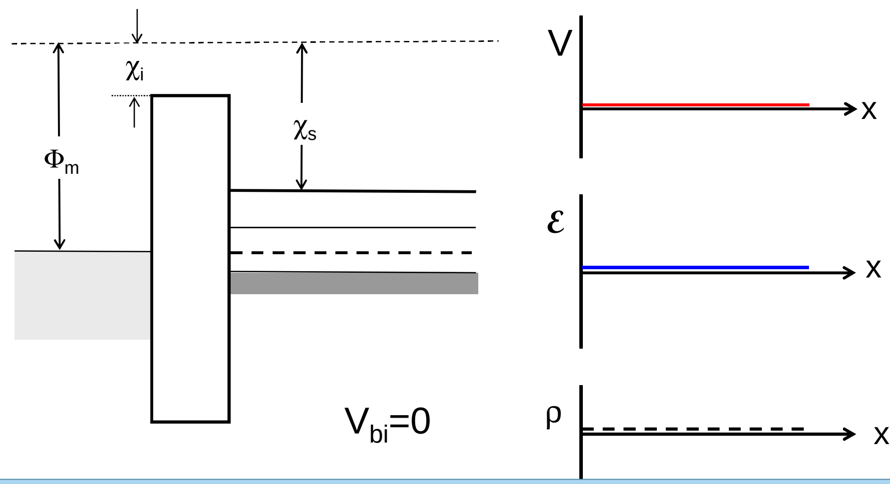


Recall that

$$Q_i = C_{ox}(V_G - V_{th,ideal})$$

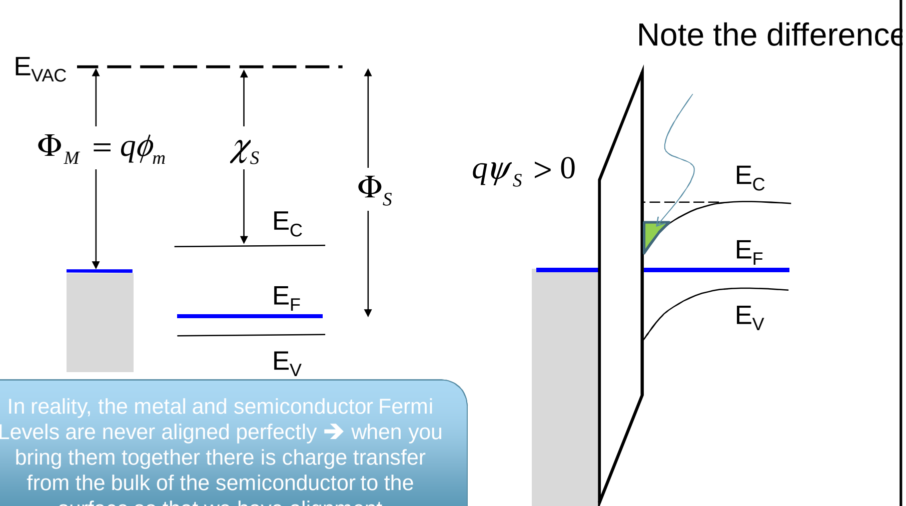
$$V_{th,ideal} = \psi_s - \left.\frac{Q_B}{C_{ox}}\right|_{\psi_s = 2\phi_F}$$

Potential, Field, Charges



No built in potential, fields or charges at zero applied bias in the idealized MOS structure

Real MOS Capacitor with $\Phi_M < \Phi_S$



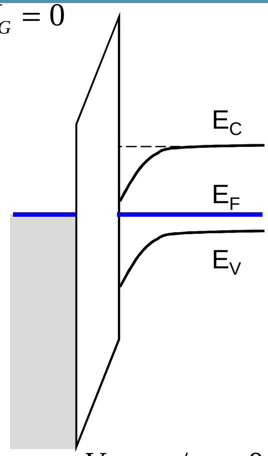
In reality, the metal and semiconductor Fermi Levels are never aligned perfectly ➔ when you bring them together there is charge transfer from the bulk of the semiconductor to the surface so that we have alignment

Do we need to apply less or more V_G to invert the channel ?

Physical Interpretation of Flatband Voltage

The Flatband Voltage is the voltage applied to the gate that gives zero-band bending in the MOS structure. Applying this voltage nullifies the effect of the built-in potential. This voltage needs to be incorporated into the idealized MOS analysis while calculating threshold voltage

$V_G = 0$

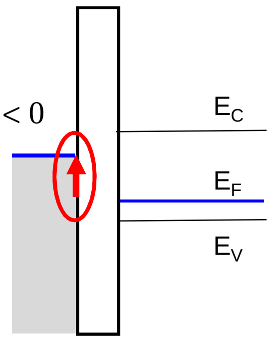


$V_{bi} = -\phi_{ms} > 0$

$+ \leftarrow -$

$V_{FB} = \phi_{ms} = -V_{bi} < 0$

$V_G = V_{FB} < 0$



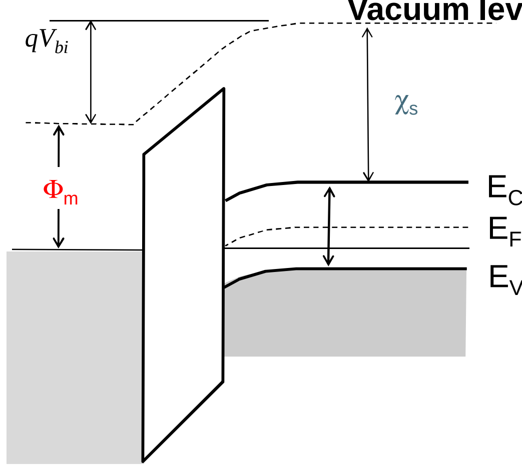
$\psi_S = 0$ flat band

How to Calculate Built-in or Flat-band Voltage

The presence of a flatband voltage lowers or raises the threshold voltage of a MOS structure. Engineering question ➔ Is it desirable to have a metal having a work function greater or less than the electron affinity+(Ec-Ef) in the semiconductor?

$$qV_{bi} = \left(\chi_s + E_g - \Delta_p\right) - \Phi_M$$

$$= qV_{FB} \equiv \phi_{MS}$$



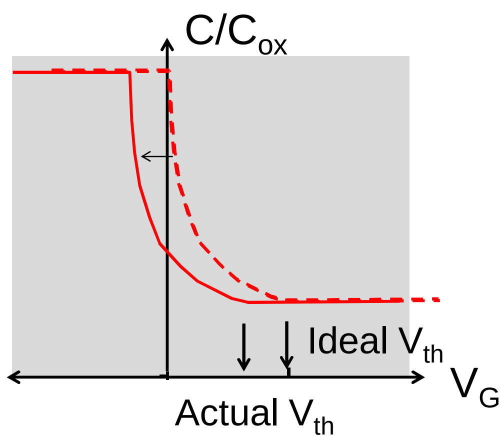
Therefore,

$$Q_i = C_{ox}(V_G - V_{th})$$

$$V_{th} = \left(2\phi_F - \frac{Q_B}{C_{ox}}\right) - V_{FB}$$

Measure of Flat-band shift from C-V Characteristics

The transition point between accumulation and depletion in a non-ideal MOS structure is shifted to the left when the metal work function is smaller that the electron affinity +(Ec-Ef). At **zero applied bias the semiconductor is already depleted** so that a very small positive bias inverts the channel. The flatband voltage is the amount of voltage required to shift the curve such that the transition point is at zero bias.



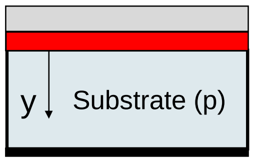
Outline

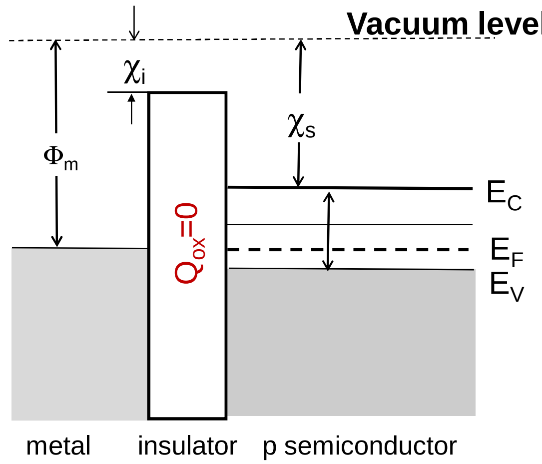
1) Square law/ simplified bulk charge theory
2) Velocity saturation in simplified theory
3) Few comments about bulk charge theory, small transistors
4) Flat band voltage - What is it and how to measure it?
5) Threshold voltage shift due to trapped charges
6) Conclusion

Ref: Sec. 16.4 of SDF Chapter 18, SDF

$$V_{th} = V_{th,ideal} + \phi_{MS} - \frac{\gamma_M Q_M}{C_{ox}} - \frac{Q_F}{C_{ox}} - \frac{Q_{IT}(\phi_s)}{C_{ox}}$$

(2) Idealized MOS Capacitor



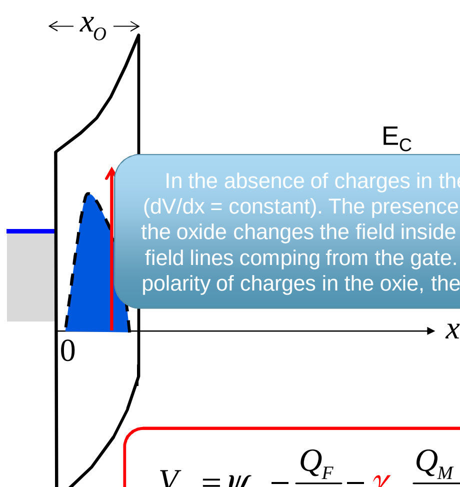


Recall that

$$Q_i = C_{ox}(V_G - V_{th,ideal})$$

$$V_{th,ideal} = \psi_s - \left.\frac{Q_B}{C_{ox}}\right|_{\psi_s = 2\phi_F}$$

Distributed Trapped charge in the Oxide



In the absence of charges in the oxide, the field is constant (dV/dx = constant). The presence of a charge distribution inside the oxide changes the field inside the oxide and effectively traps field lines comping from the gate. As a result, depending on the polarity of charges in the oxie, the threshold voltage is modified.

$$Q_M = \int_0^{x_O} \rho_{ox}(x)dx$$

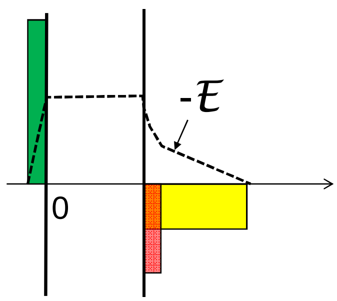
$$\gamma_M \ldots (x)dx \;/\; x_0 \int_0^{x_0} \rho_{ox}(x)dx$$

$$V_{th} = \psi_S - \frac{Q_F}{C_{ox}} - \gamma_M \frac{Q_M}{C_{ox}}$$

x_m represents the centroid of the charge distribution – one can think of this as replacing the entire distribution with a delta charge at this point

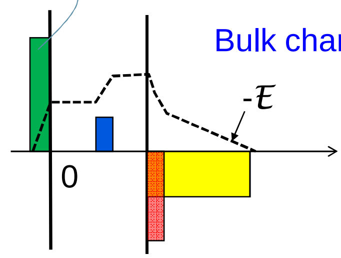
An Intuitive View

Ideal charge-free oxide

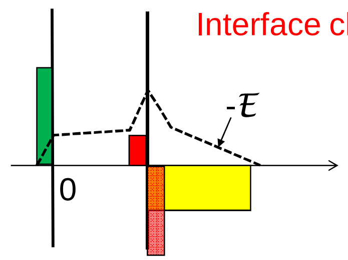


Reduced gate charge

Bulk charge



Interface charge



Gate Voltage and Oxide Charge

$$V_G = V_{ox} + \psi_s$$

Kirchoff's Law – balancing voltages

$$-\frac{d^2V_{ox}}{dx^2} = \frac{d\mathcal{E}_{ox}}{dx} = \frac{\rho_{ox}(x)}{\kappa_{ox}\varepsilon_0}$$

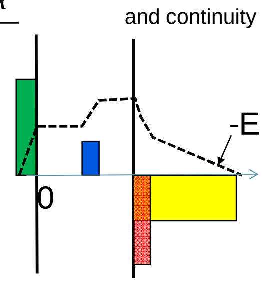
$$\int_{\mathcal{E}(x)}^{\mathcal{E}(x_0)} d\mathcal{E}_{ox} = \int_{x}^{x_0} \frac{\rho_{ox}(x')dx'}{\kappa_{ox}\varepsilon_0}$$

$$-\frac{dV_{ox}}{dx} = \mathcal{E}_{ox}(x_0) - \mathcal{E}_{ox}(x) = \mathcal{E}_{ox}(x_0) - \int_{0}^{x} \frac{\rho_{ox}(x')dx'}{\kappa_{ox}\varepsilon_0}$$

Known from boundary conditions in semiconductor and continuity of E

$$V_{ox} = \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \int_0^{x_0} dx \int_0^{x_0} \frac{\rho_{ox}(x')dx'}{\kappa_{ox}\varepsilon_0}$$

$$= \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \int_0^{x_0} \frac{x\rho_{ox}(x)dx}{\kappa_{ox}\varepsilon_0}$$



Gate Voltage and Oxide Charge

$$\Delta V_{ox} = \frac{\kappa_S}{\kappa_o} x_0 \mathcal{E}_S(x_0) - \int_0^{x_0} \frac{x\rho_{ox}(x)dx}{\left(\frac{\kappa_{ox}\varepsilon_0}{x_0}\right)x_0}$$

$$= \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \frac{1}{C_{ox}x_0}\int_0^{x_0} x\rho_{ox}(x)dx$$

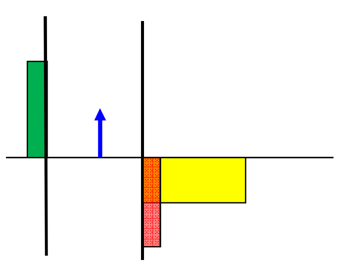
$$V_{th} = \psi_s(=2\phi_F) + \Delta V_{ox}$$

$$= \psi_s(=2\phi_F) + \frac{\kappa_S}{\kappa_{ox}} x_0 \mathcal{E}_S(x_0) - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)dx$$

$$= V_{th,ideal} - \frac{1}{C_{ox}x_0}\int_0^{x_0} x\rho_{ox}(x)dx$$

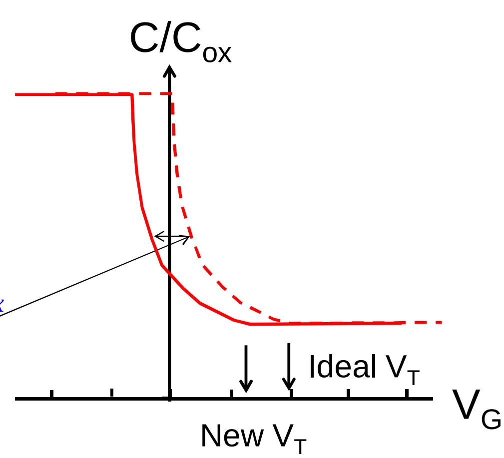
$$= V_{th,ideal} - \frac{Q_M}{C_{ox}}\gamma_M$$

Interpretation for Bulk Charge

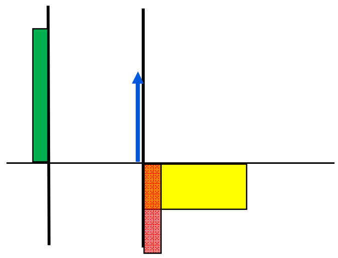


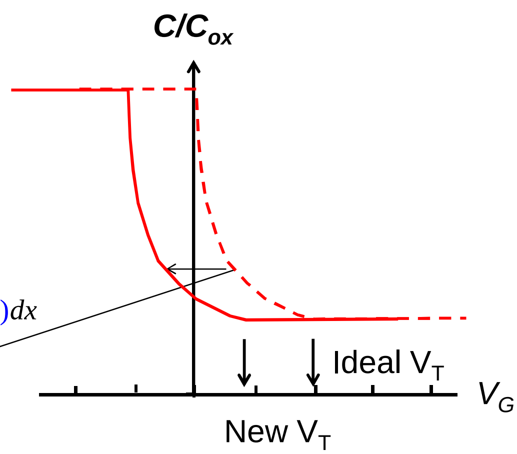
$$V_{th} = V_{th,ideal} - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x-x_1)dx$$

$$= V_{th,ideal} - \frac{x_1}{x_0}\frac{Q_M(x_1)}{C_o}$$



Interpretation for Interface Charge

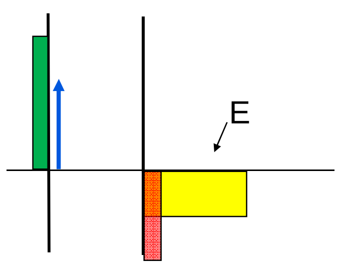


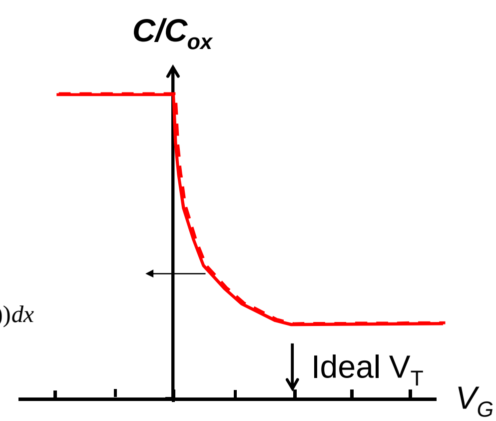


$$V_{th} = V_{th}^{*} - \frac{1}{C_o x_0}\int_0^{x_0} x\rho_{ox}(x)\delta(x - x_o)dx$$

$$= V_{th}^{*} - \frac{Q_F}{C_o}$$

Time-dependent shift of Trapped Charge



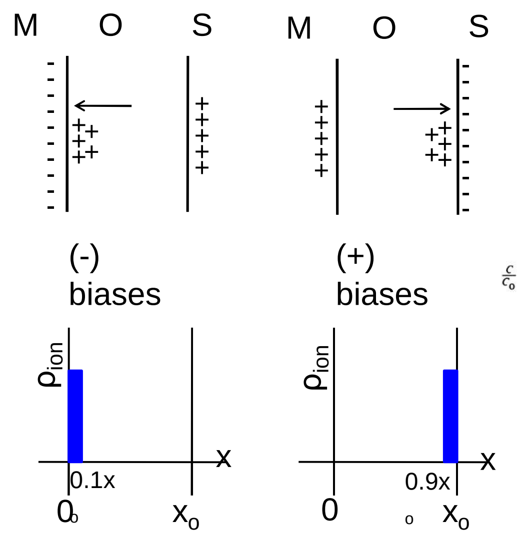


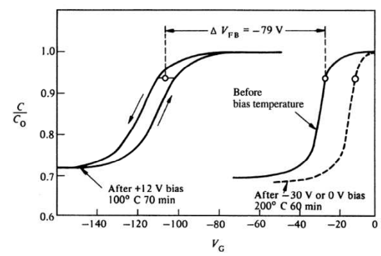
$$V_{th} = V_{th,ideal} - \frac{1}{C_{ox} x_0}\int_0^{x_0} xQ_{ox}(x)\times\delta(x - x_1(t))dx$$

$$= V_{th,ideal} - \frac{x_1(t)}{x_0}\times\frac{Q_{ox}(x)}{C_{ox}}$$

Sodium related bias temperature instability (BTI) issue

Bias Temperature Instability (Experiment)





Conclusion

1) Non-ideal threshold characteristics are important consideration of MOSFET design.
2) The non-idealities arise from differences in gate and substrate work function, trapped charges, interface states.
3) Although nonindeal effects often arise from transistor degradation, there are many cases where these effects can be used to enhance desirable characteristics.