ECE 5205 Spring 2014

MOSFET OPERATION Part 1

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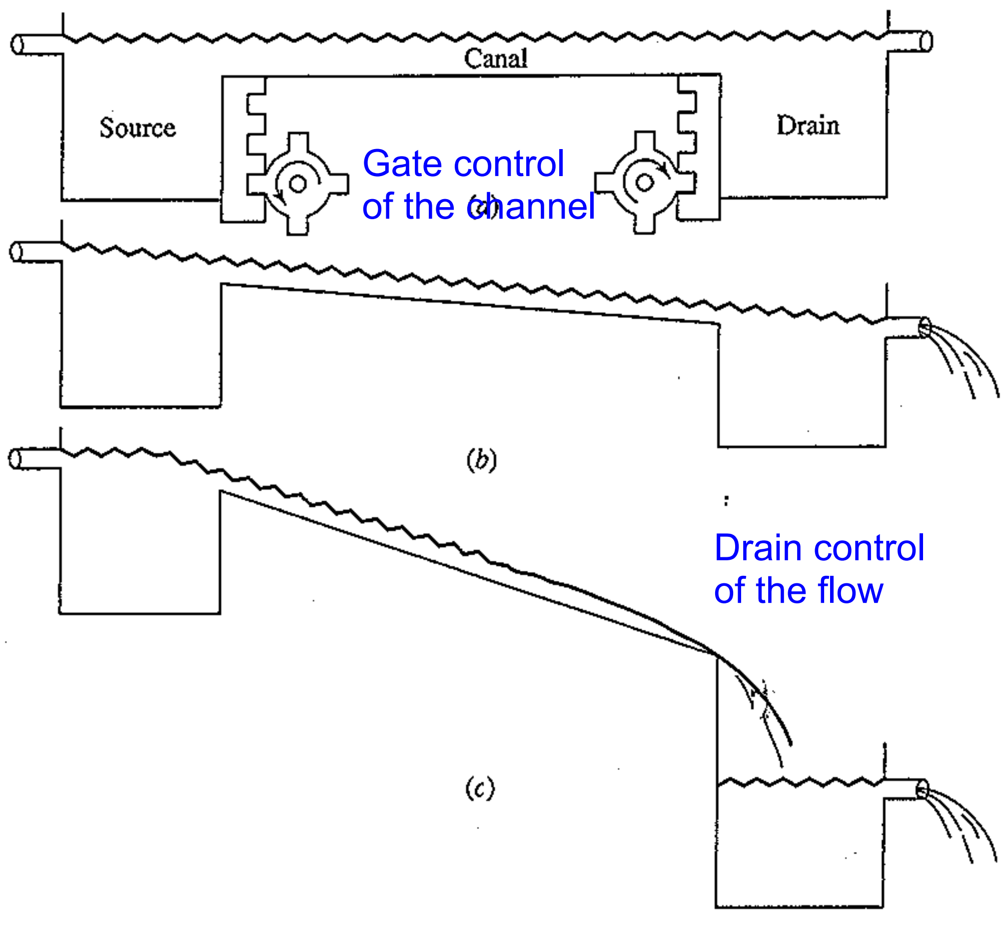
Fluid Analogy to MOSFET Operation



- When the source and drain are level, there is no flow V_{DS}=0
- Whatever depth in the canal can be varied by the gear and track (V_{GS})
- When the drain is lower than the source, water flows along the canal
- The flow is limited by the channel capacity, lowering the drain further only increases the height of the waterfall at its edge

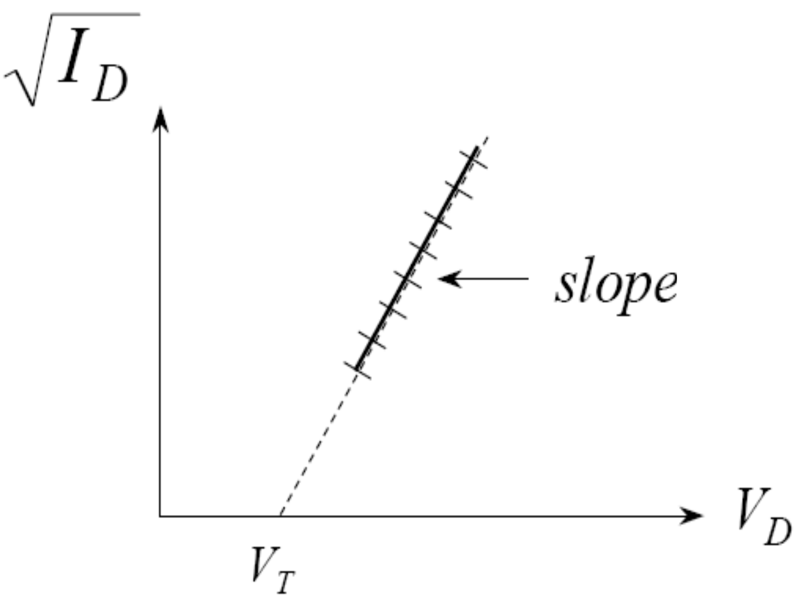
MOSFET Operation
Contents Part 1

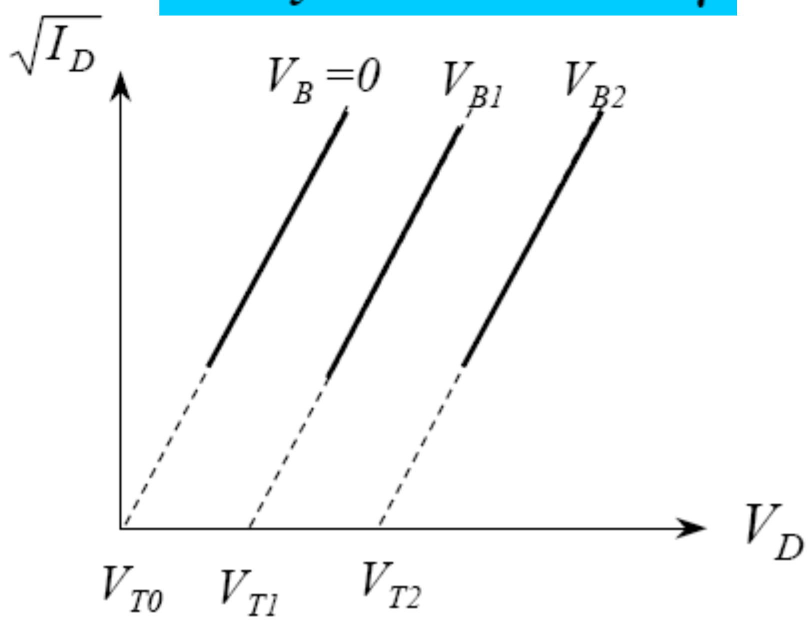
- Overview (MOSFET Current Regimes)
- Inversion charge in a MOSFET
- Pao-Sah Double Integral Model
- Gradual channel approximation
- Charge-Sheet Approximation
- MOSFET I-V Characteristics
- Subthreshold Current
- Subthreshold Swing – a critical issue today

Threshold Voltage Extraction from linear region as a function of Substrate Bias

$$I_{ds} = \mu_{eff} C_{ox} \frac{W}{L} [V_g - V_T(V_B)] V_{ds}$$

Body Coefficient γ





Subthreshold Characteristics

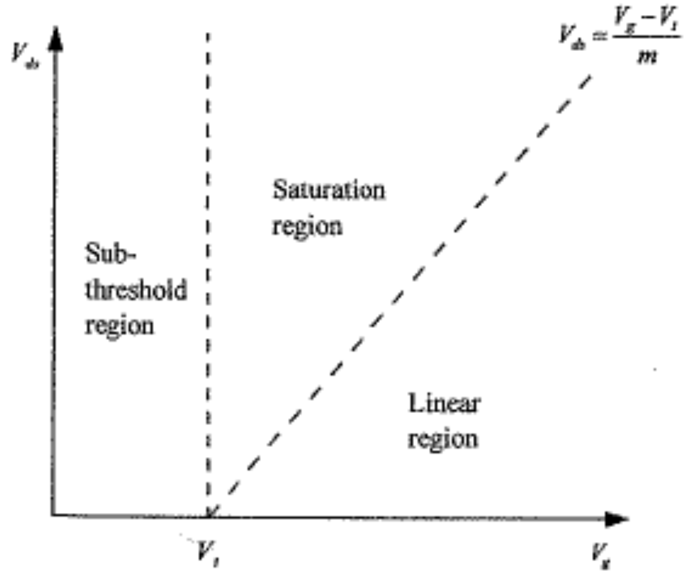


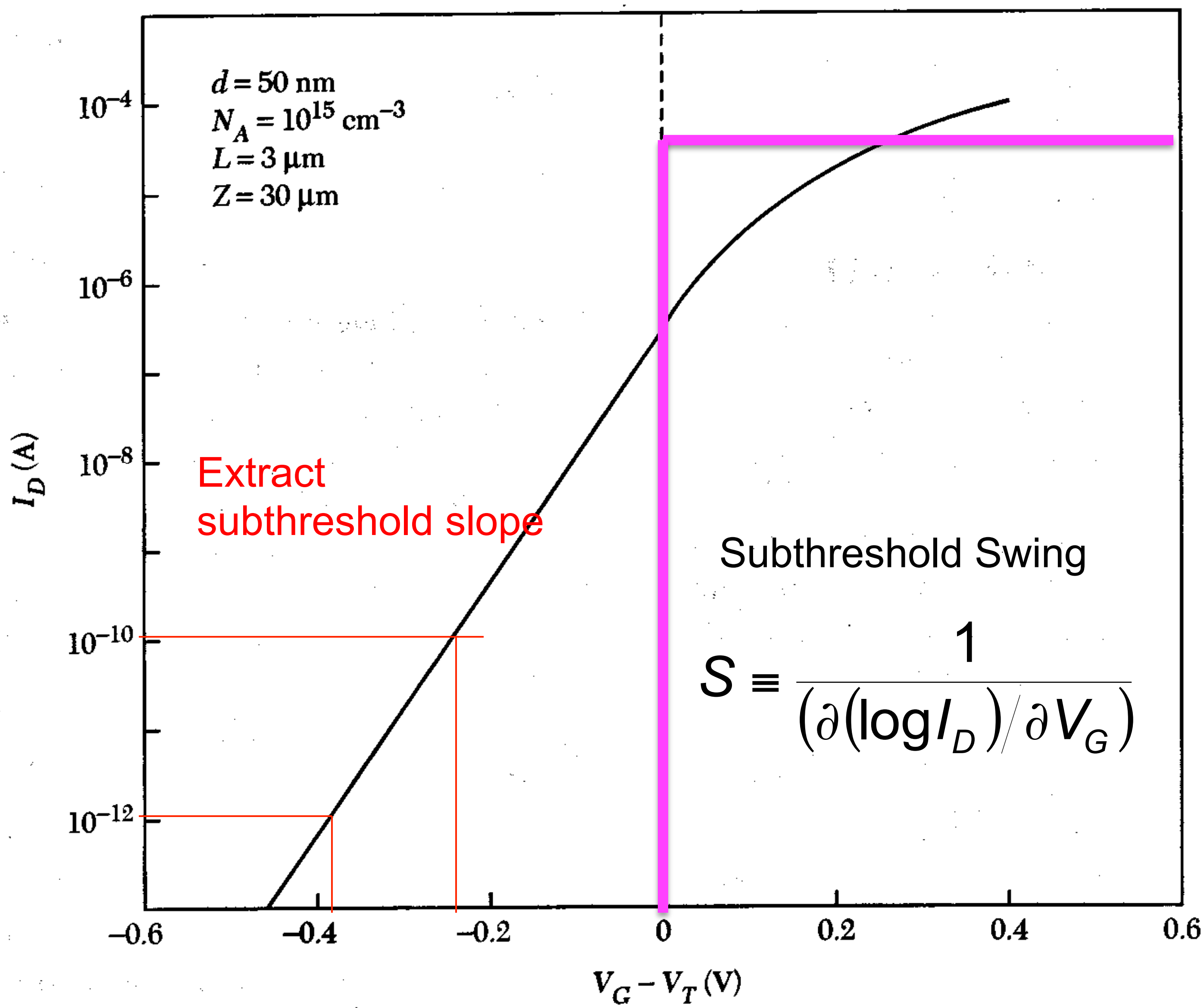
FIGURE 3.9. Three regions of MOSFET operation in the V_{ds}–V_g plane.

On linear scale, the off-current is negligible. However, on a logarithmic scale, the drain current remains at non-negligible levels for several tenths of a volt below V_T.

This is because the inversion charge density does not drop to zero abruptly. Rather, it follows an exponential dependence on ψ_s or V_g.

$$n(x, y) = n(\psi, V) = \frac{n_i^2}{N_A} \exp(\beta[\psi - V])$$

Subthreshold Slope or Swing



$$S \equiv \frac{1}{\left(\partial\left(\log I_D\right)/\partial V_G\right)}$$

Ideal MOSFET turn-off characteristics

Subthreshold Current

Leakage current issues

- Leakage vs. performance trade-off:
  - For high-speed, need small V_T and L
  - For low leakage, need high V_T and large L (to reduce DIBL and V_T roll-off)
- Process scaling
  - V_T reduces with each new process (historically)
  - Leakage increases ~10X!
- One solution: dual-V_T process
  - Low-V_T transistors: use in critical paths for high speed
  - High-V_T transistors: use to reduce power

Subthreshold Characteristics

Subthreshold behavior is of particular importance in low-voltage, low-power applications. The subthreshold is the region immediately below V_T.

($\psi_B < \psi_s < 2\,\psi_B$) is called the WEAK INVERSION region and has received a lot of attention in the last 15 years.

[Comment: Swiss watch industry, integrated circuits for watches, Prof. Eric Vittoz, University of Lausanne.]

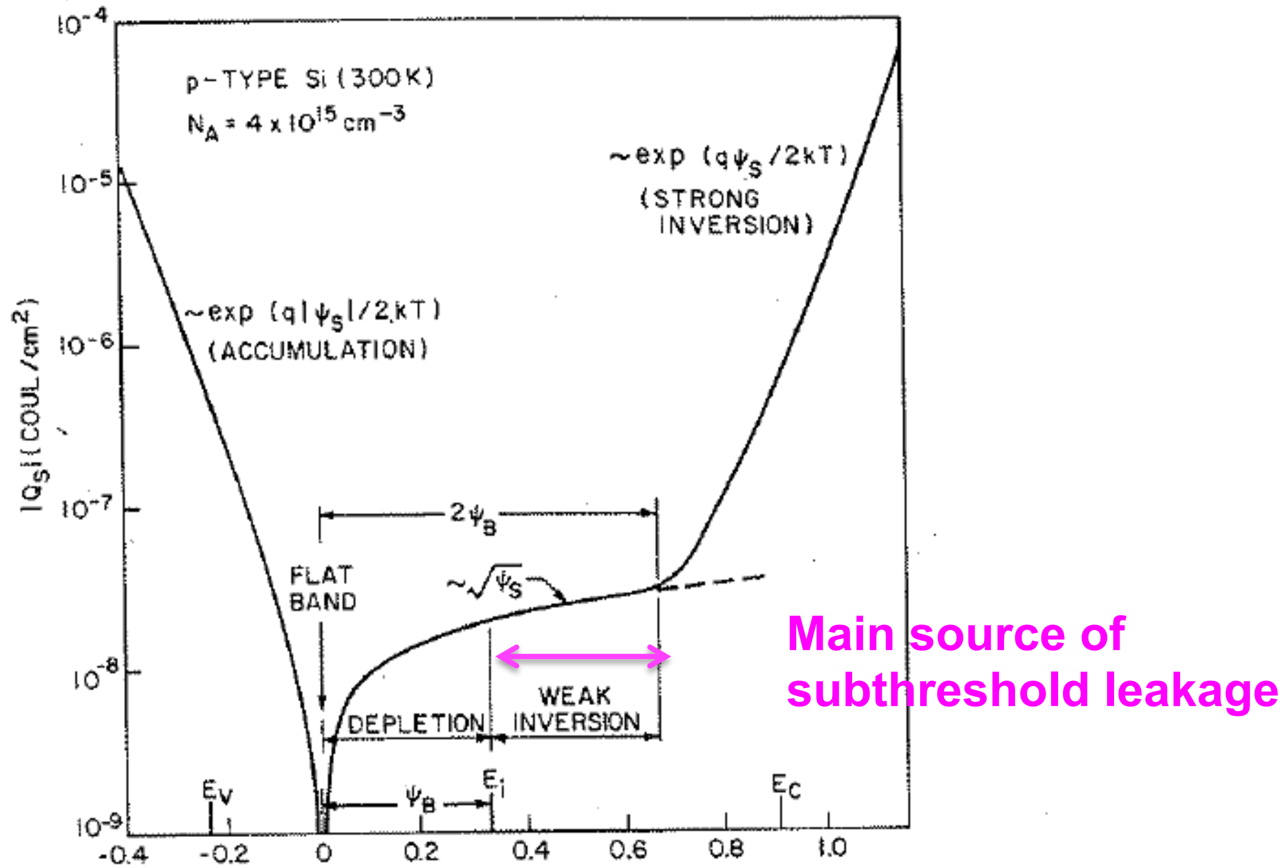
We know already the exact relation between surface potential and electric field at the semiconductor surface valid for any band bending.

$$E_s^2 =$$

$$= (\frac{2kTN_A}{\varepsilon_s})[(\exp(-\beta\psi)+\beta\psi-1)+\frac{n_i^2}{N_A}(\exp(-\beta V\ )\exp(\beta\psi)-\beta\psi-1)]\}^{1/2}$$

Subthreshold Characteristics

recall



$$E_s^2 =$$

$$= (\frac{2kTN_A}{\varepsilon_s})[(\exp(-\beta\psi) + \beta\psi - 1) + \frac{n_i^2}{N_A}(\exp(-\beta V)\exp(\beta\psi) - \beta\psi - 1)]\}^{1/2}$$

Subthreshold Characteristics

Drift and Diffusion Components of the Current

Unlike the strong inversion region, in which the drift current dominates, subthreshold conduction is dominated by the diffusion current. Both components are included in the Pao-Sah double-integral formula. In general, current continuity applies to the total current, NOT to its components. In other words, the ratio between drift and diffusion may vary from one point of the channel to another.

At low drain bias it is possible to separate drift and diffusion components using ψ_s (V) relation. When qV/kT<<1, only the first terms of the expansion in V need to be kept.

$$I_{ds}(y) = -\mu_{eff} W \frac{dV(y)}{dy} Q_n(V) \approx -\mu_{eff} W \frac{dV(y)}{dy} Q_n(0)$$

Since the total current is proportional to dV/dy, the drift fraction of the current is given by the change of surface potential (band bending) with respect to the quasi-Fermi potential, i.e. $d\psi_s$ /dV.

Subthreshold Characteristics

Drift and Diffusion Components of the Current

This can be evaluated from eq.:

$$V_g = V_{FB} + \psi_s + \frac{\sqrt{2\varepsilon_s kTN_A}}{C_{ox}}\left[\frac{q\psi_s}{kT} + \frac{n_i^2}{N_A}\exp[\beta(\psi_s - V_D)]\right]$$

In the limit for small V we obtain;

$$\frac{d\psi_s}{dV_D} = \frac{\frac{n_i^2}{N_A^2}\exp[\beta\psi_s]}{1 + \frac{n_i^2}{N_A}\exp[\beta(\psi_s - V_D)] + \frac{C_{ox}^2}{\varepsilon_s qN_A}\frac{|Q_s|}{C_{ox}}}$$

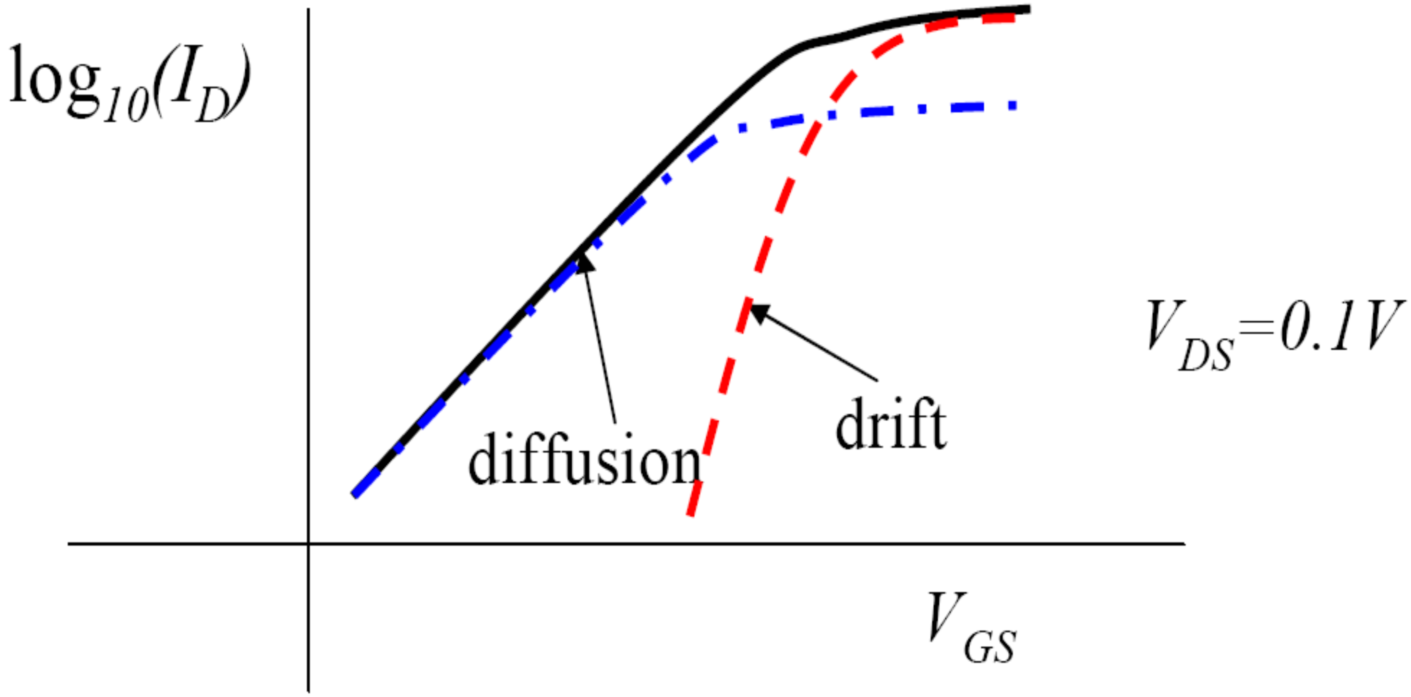
<< 0 for ($\psi_B < \psi_s < 2\,\psi_B$)

In the weak inversion where ($\psi_B < \psi_s < 2\,\psi_B$), the numerator is much smaller than 1 and the diffusion current dominates.

Conversely, beyond strong inversion, $d\psi_s/dV \approx 1$ and the drift current dominates. This is shown in Figure on next page.

Subthreshold Characteristics

Drift and Diffusion Components of the Drain Current



Derivation of Subthreshold Current

$$E_s^2 =$$

$$= (\frac{2kTN_A}{\varepsilon_s})[(\exp(-\beta\psi) + \beta\psi - 1) + \frac{n_i^2}{N_A}(\exp(-\beta V)\exp(\beta\psi) - \beta\psi - 1)]\}^{1/2}$$

From E_s we can calculate Q_s and we keep only the two significant terms in the weak inversion region

$$-Q_s = \varepsilon_s E_s = \sqrt{2\varepsilon_s kTN_A}\left[\frac{q\psi_s}{kT} + \frac{n_i^2}{N_A^2}\exp[q(\psi_s - V)/kT]\right]^{1/2}$$

$$Q_d = -qNAWd = -\sqrt{2\varepsilon_s qN_A\psi_s}$$

Of course the first term is the depletion charge density (we know this from our threshold voltage formula) and the second term gives the (weak) inversion charge density, after expanding into a power series and identifying the zeroth-order term as Q_d, one obtains:

$$-Q_n = \sqrt{2\varepsilon_s qN_A/(2\psi_s)}\frac{kT}{q}\frac{n_i^2}{N_A^2}\exp[q(\psi_s - V)/kT]$$

Derivation of Subthreshold Current

$$-Q_n = \sqrt{2\varepsilon_s kTN_A/(2\psi_s)}\left[\frac{kT}{q}\frac{n_i^2}{N_A^2}\exp[q(\psi_s - V)/kT]\right]$$

Substituting Q_n in $$I_{ds} = \mu_{eff} W \int_0^{V_{ds}} [-Q_n(V)]dV$$

We obtain

$$I_{ds} = \mu_{eff}\frac{W}{L}\sqrt{2\varepsilon_s kTN_A/(2\psi_s)}\left(\frac{kT}{q}\frac{n_i}{N_A}\right)^2 \exp(q\psi_s/kT)[1-\exp(-qV_{ds}/kT)]$$

With $$V_g = V_{FB} + \psi_s + \frac{\sqrt{2\varepsilon_s qN_A\psi_s}}{C_{ox}}$$

The last equation can be solved for ψ_s . After few more transformations we can eliminate ψ_s from the drain current formula and replace it by an expression with V_g.

Derivation of Subthreshold Current

We obtain the final formula for the subthreshold current:

$$I_{ds} = \mu_{eff} C_{ox} \frac{W}{L}(m-1)\left(\frac{kT}{q}\right)^2 \exp(q(V_g - V_T)/kT)[1-\exp(-qV_{ds}/kT)]$$

Note that the subthreshold current depends exponentially on both the gate and drain bias.

The subthreshold current is however independent of V_{ds} once V_{ds} is larger than a few kT/q as we would expect for diffusion-dominated current transport.

The dependence on the gate voltage is exponential and is called *subthreshold slope.*

Subthreshold Slope and Swing

We define the subthreshold **slope** as

$$\ln 10 = 2.3$$

$$S = \left(\frac{d(\log_{10} I_{ds})}{dV_g} \right)^{-1} = \frac{mkT}{q} \ln 10 = 2.3 \frac{kT}{q} \left(1 + \frac{C_d}{C_{ox}} \right)$$

Which is typically for bulk transistors 70-100 mV/decade. Here $m=1+C_d/C_{ox}$.

Subthreshold slope gives the gate voltage decrease to reduce the current by one decade.

Note that subthreshold slope decreases with smaller depletion capacitance (lighter p-substrate doping → larger depletion width). This runs counter to the scaling trends of the MOSFETs. (Solution: Fully depleted SOI transitors)

Note that the term in parenthesis is the inverse capacitive divider ratio $(C_{ox}+C_d)/C_{ox}$.

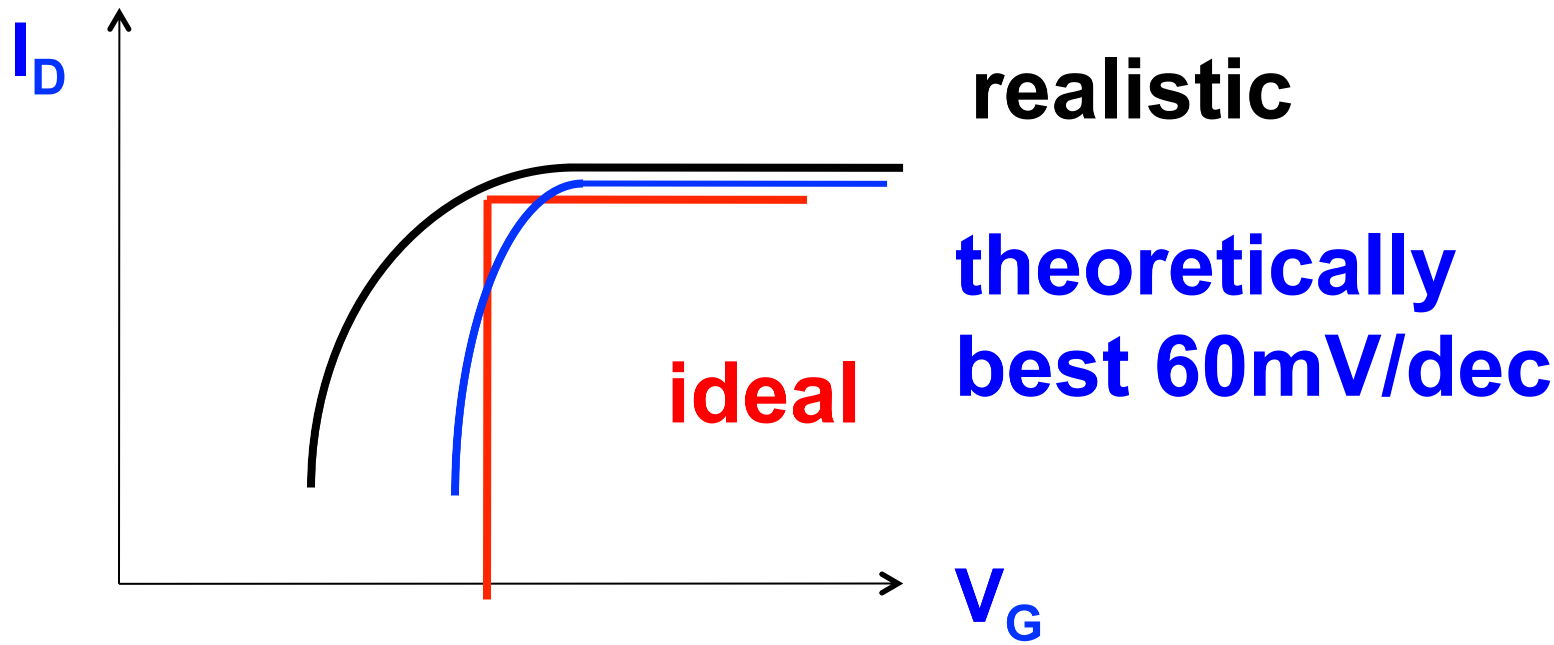
Subthreshold is mainly a thermal issue !!!

Theoretical Limit of Subthreshold Slope

$$S = 2.3\frac{kT}{q}\left(1+\frac{C_d}{C_{ox}}\right) \rightarrow 2.3\frac{kT}{q}$$

$$\xrightarrow{300K} \quad 2.3 \times 0.0259 = 60mV/dec$$

Best possible subthreshold slope for the current MOSFET architecture



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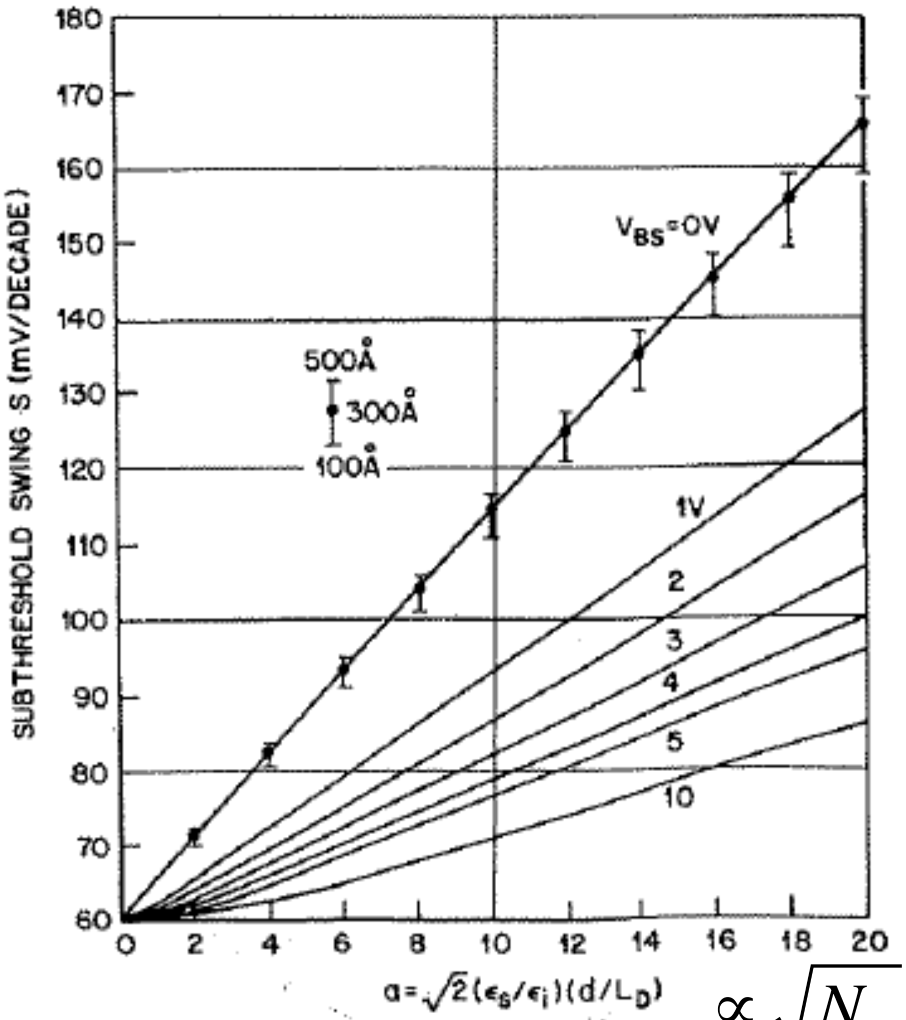
$$\xrightarrow{300K} \quad 2.3 \times 0.0259 = 60mV/dec$$

$(1+C_d/C_{ox})$ depends on the oxide thickness d (C_{ox}) and on the maximum depletion width W_d (C_d). The maximum depletion width depends in turn on the substrate doping (assuming uniform substrate doping N_A) and substrate doping can be characterized by the Debey length $L_D(N_A)$. Therefore the factor is often characterized in terms of parameter *a* defined as:

$$a = \sqrt{2}(\varepsilon_s / L_D)/C_{ox} = \sqrt{2}(\varepsilon_s / \varepsilon_{ox})(d_{ox} / L_D)$$

Subthreshold Slope and Substrate Bias

Subthrehold swing versus substrate doping and versus substrate reverse bias.



$\propto \sqrt{N_A}$

$$a = \sqrt{2}(\varepsilon_s / L_D)/C_{ox}$$

Essentially ratio between flat band capacitance and gate oxide capacitance

Subthreshold Slope and Oxide damage

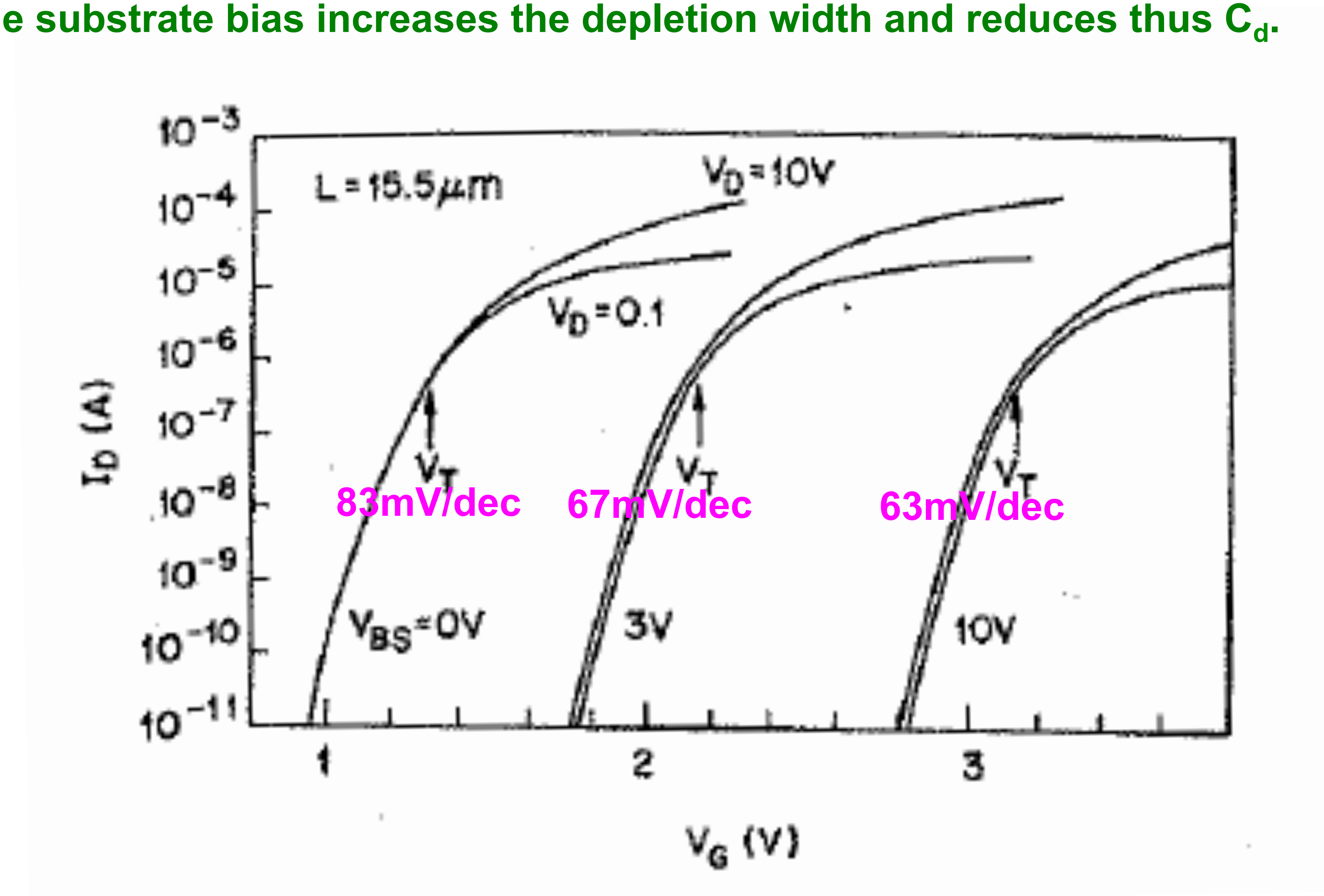
If there is a significant interface-trap density, the capacity C_{it} associated with the interface traps is in parallel with the depletion layer capacitance C_d. So we have to substitute (C_d+C_{it}) for C_d and obtain

$$S = 2.3\frac{kT}{q}\left(1+\frac{C_d}{C_{ox}}\right)\times\frac{1+(C_d+C_{it})/C_{ox}}{1+C_d/C_{ox}}$$

The extra factor is larger than one and degrades the subthreshold slope.

Subthreshold Slope and Substrate Bias

Subthreshold slope can be improved by applying substrate bias because the substrate bias increases the depletion width and reduces thus C_d.



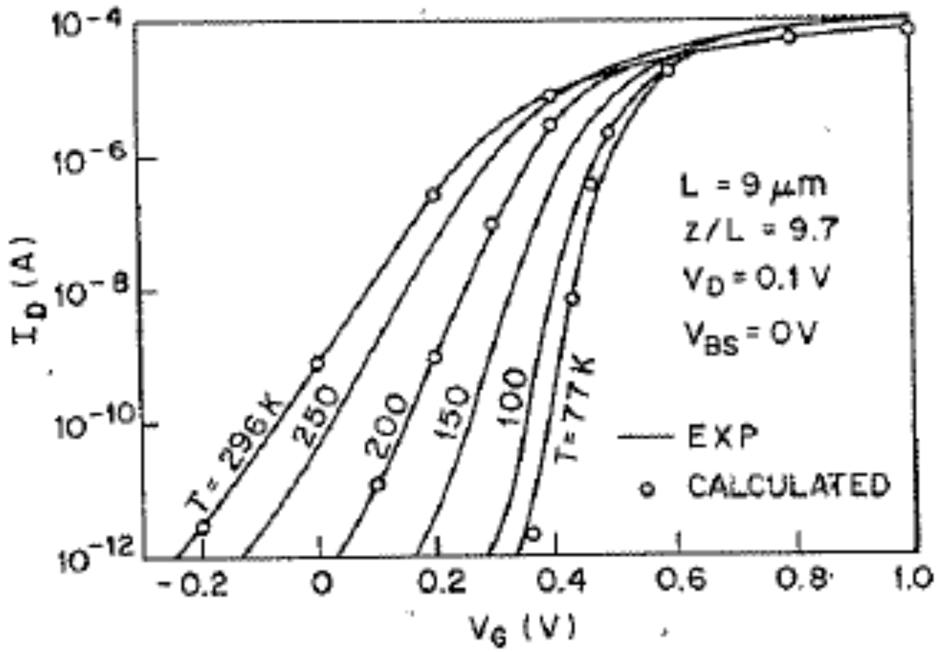
Subthreshold swing versus substrate doping and versus substrate reverse bias.

Subthreshold Slope and Temperature

$$S = \ln 10 \times \frac{kT}{q}\left(1 + \frac{C_d}{C_{ox}}\right)$$

$$S_{\min} = \ln 10 \times \frac{kT}{q} = 60mV/dec$$

$$@\ \ T = 300K$$



As T decreases, the switching properties of a MOSFET improve. As T decreases from 296K to 77K, the V_T increases from 0.25V to about 0.5V. The most important improvement is the reduction of subthreshold swing from 80mV/dec at 296K to 22mV/decade (a dream for CMOS circuit designers for room temperature applications) at 77K – thus an improvement of almost factor of 4. Of course this improvement is coming mainly from the kT/q term.
Other improvements of low temperature operation include higher mobility, lower leakage current and lower metal resistance.

However MOSFET would have to be immersed in liquid nitrogen (not a very practical proposition).

Alternative (More Intuitive) Derivation of Subthreshold Current

We already know that in a weak inversion the current is dominated by diffusion and can be derived in the same way as in pn junction or in the bipolar transistor. Considering the MOSFET as an n-p-n back-to-back junctions, we have

$$I_d = -qAD_n \frac{dn}{dy} \approx -qAD_n \frac{n(0) - n(L)}{L}$$

But

$$n(0) = n_{p0} \exp(\beta \psi_s)$$

$$n(L) = n_{p0} \exp[\beta(\psi_s - V_D)]$$

We have to determine A. A is product of the width W of the device times the thickness of the channel x_j. Because of the exponential dependence of electron density on the potential ψ_s, the effective channel thickness corresponds to the distance in which ψ_s decreases by kT/q. Therefore, the effective channel thickness is kT/qE_s where E_s is the weak-inversion surface field

$$x_i = \frac{kT}{q} \cdot \frac{1}{E_s} \qquad E_s = -Q_B / \varepsilon_s = \sqrt{2qN_A \psi_s / \varepsilon_s}$$

Alternative (Intuitive) Derivation of Subthreshold Current

$$n(0) = n_{p0}\exp(\beta\psi_s)$$

$$n(L) = n_{p0}\exp[\beta(\psi_s - V_D)]$$

$$E_s = -Q_B / \varepsilon_s = \sqrt{2qN_A\psi_s / \varepsilon_s}$$

$$x_i = kT / \varepsilon_s E_s$$

Here we make the assumption from the beginning that subthreshold current is due to diffusion.

$$I_d = -qAD_n\frac{dn}{dy} = qAD_n\frac{n(0)-n(L)}{L}$$

Substituting the two first equation in the third one, we obtain:

$$I_d = \mu_n\left(\frac{W}{L}\right)\frac{aC_{ox}}{2\beta^2}\left(\frac{n_i}{N_A}\right)^2(1-\exp(-\beta V_d)\exp(-\beta\psi_s)(\beta\psi_s)^{1/2}$$

$$\psi_s = (V_g - V_{FB}) - \frac{a^2}{2\beta}\left\{\left[1+\frac{4}{a^2}(\beta V_g - \beta V_{FB} - 1\right]^{1/2} - 1\right\}$$

$$a = \sqrt{2}(\varepsilon_s / L_D)/C_{ox}$$

From this the subthreshold swing can be found in the same way as previously.

More complete model – sub-threshold to saturation

- Must include diffusion and drift currents
- Still use gradual channel approximation
- Yields sub-threshold and saturation behavior for long channel MOSFETS
- Exact Charge Model – numerical integration (Pao-Sah Model)

$$I_D = \frac{Z}{L}\frac{\varepsilon_s \mu_n}{L_D}\int_0^{V_D}\int_{\psi_B}^{\psi_s}\frac{e^{\beta\psi-\beta V}}{F\left(\beta\psi, V, \frac{n_{p0}}{p_{p0}}\right)}$$