ECE 4813

Semiconductor Device and Material Characterization

Dr. Alan Doolittle

School of Electrical and Computer Engineering

Georgia Institute of Technology

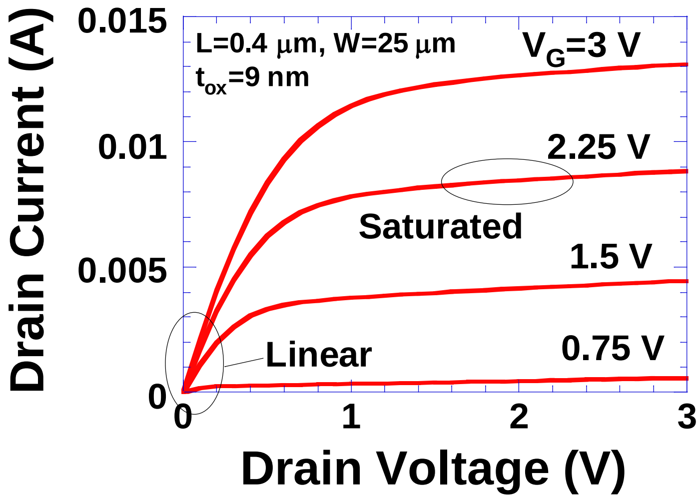
As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. ***Every serious microelectronics student should have a copy of this book!***

MOSFETs

Effective Channel Length
Threshold Voltage

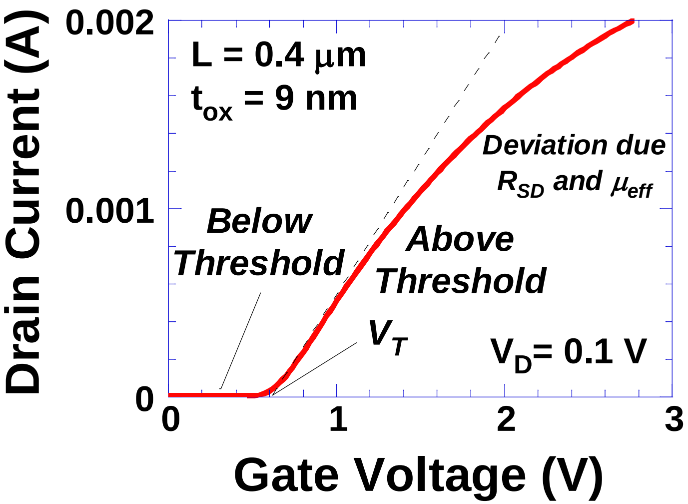
Drain Current – Drain Voltage

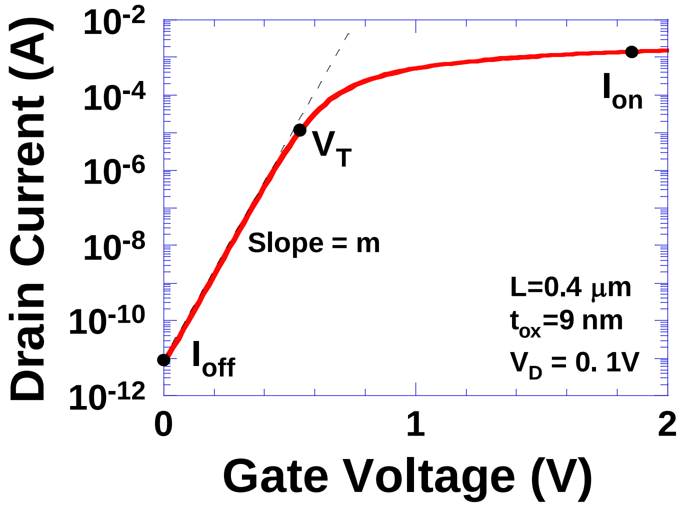
- **Linear at low V_D**
- **Saturated at high V_D**
- **Device parameters determined at low V_D**
  - **Drain conductance g_d**
  - **Effective channel length L_{eff}**
  - **Effective channel width W_{eff}**
  - **Source/drain resistance R_{SD}**
  - **Effective mobility μ_{eff}**



Drain Current – Gate Voltage

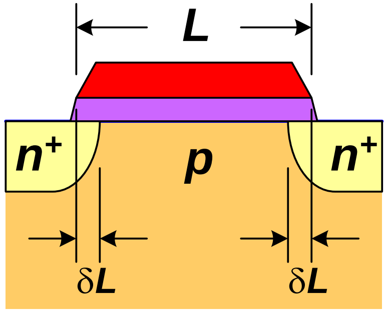
- Linear at low V_D low V_G (V_D = 0.1 V)
- Nonlinear at higher V_G
- Two regions
  - Above threshold voltage
  - Below threshold voltage (subthreshold)
- Device parameters
  - Threshold voltage V_T
  - Transconductance g_m
  - Field-effect mobility μ_{FE}



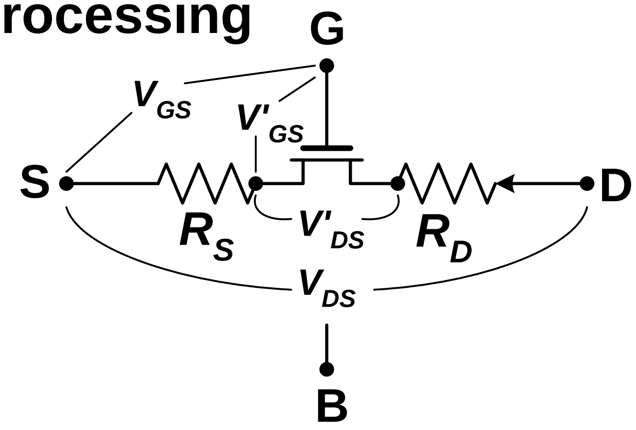


MOSFET Current-Voltage

- Series resistance degrades the MOSFET current
- δL results from self aligned processing



$\Delta L = 2\delta L$



$$I_D = k\left(V_{GS}^{'} - V_T - 0.5V_{DS}^{'}\right)V_{DS}^{'}$$

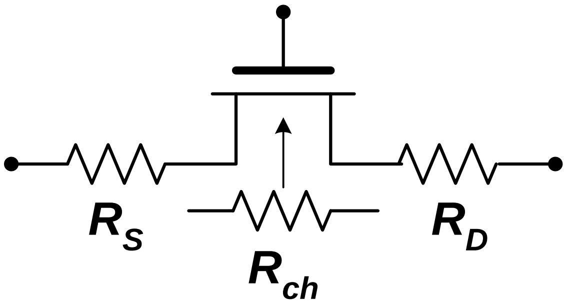
$$I_D = k\left[\left(V_{GS} - I_D R_S\right) - V_T - 0.5\left(V_{DS} - I_D R_{SD}\right)\right]\left(V_{DS} - I_D R_{SD}\right)$$
$$= k\left(V_{GS} - V_T - 0.5V_{DS}\right)\left(V_{DS} - I_D R_{SD}\right)$$

For $(V_{GS}-V_T)>>0.5V_{DS}$,

$$I_D = \frac{W_{eff}\mu_{eff}C_{ox}\left(V_{GS} - V_T\right)V_{DS}}{\left(L - \Delta L\right) + W_{eff}\mu_{eff}C_{ox}\left(V_{GS} - V_T\right)R_{SD}}$$

MOSFET Resistance

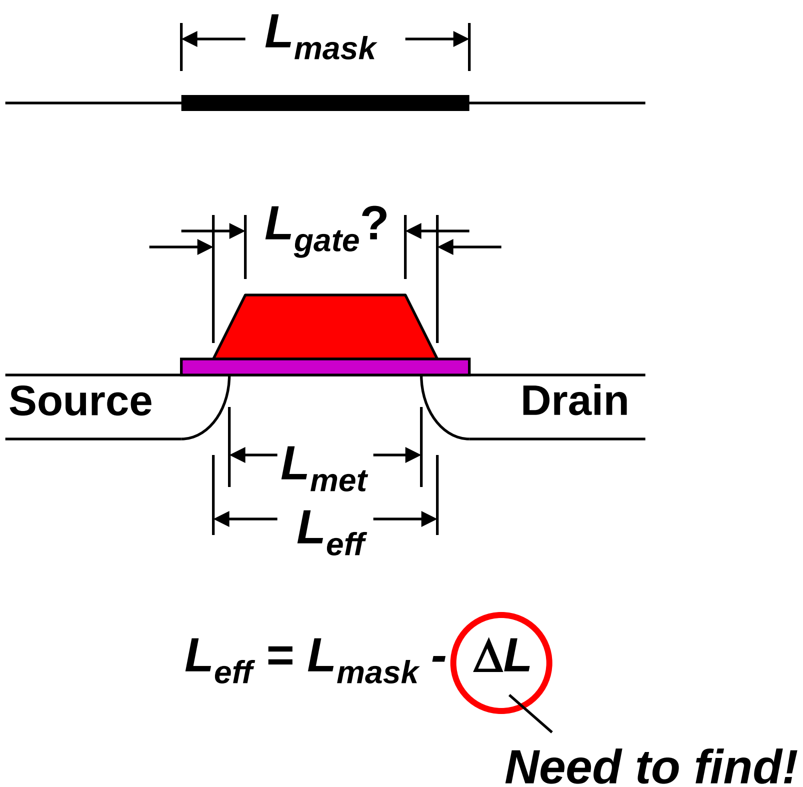
- **The MOSFET resistance is due to the channel resistance, R_{ch}, and the source/drain resistance, $R_{SD} = R_S + R_D$**



$$R_m = R_{ch} + R_{SD} = \frac{L - \Delta L}{W_{eff}\mu_{eff}C_{ox}\left(V_{GS} - V_T\right)} + R_{SD}$$

Channel Length

- **What is channel length?**



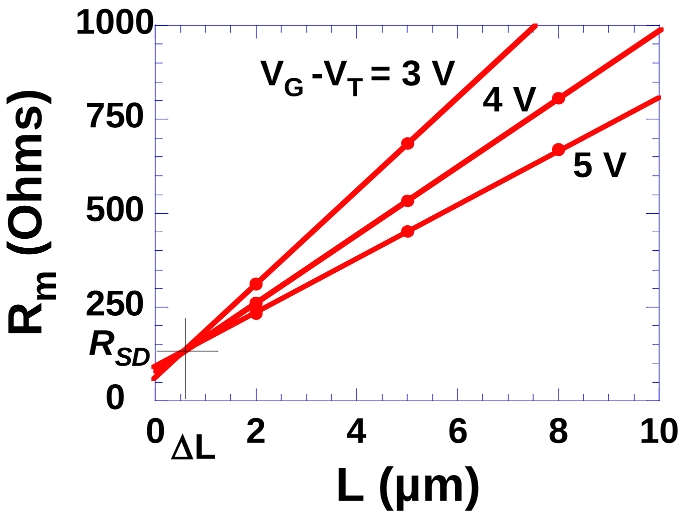
- **L_{mask}: design length on mask**
  - **(well known)**
- **L_{gate}: actual gate length**
  - **(measured by *e.g.*, SEM)**
- **L_{met}: distance between metallurgical junctions (difficult to measure)**
- **L_{eff}: not well defined; result of an electrical measurement (important for modeling purposes)**

Effective Channel Length

- Need several MOSFETs with different channel lengths
- Plot R_M versus L
- L is mask-defined channel length

$$R_m = \frac{L - \Delta L}{W_{eff}\mu_{eff}C_{ox}(V_G - V_T)} + R_{SD}$$

Equation converges to R_{SD} when numerator is zero →results in ΔL determined at RSD



Important Note: you need to measure V_T of each device separately, since MOSFETs with different channel lengths have different threshold voltages!

Effective Channel Length

$$R_m = \frac{L-\Delta L}{W_{eff}\,\mu_{eff}\,C_{ox}(V_G - V_T)} + R_{SD}$$

$$R_m(V_G - V_T) = \frac{L-\Delta L}{W_{eff}\,\mu_{eff}\,C_{ox}} + R_{SD}(V_G - V_T)$$

$$R_m(V_G - V_T) = \frac{L-\Delta L}{W_{eff}\left(\frac{\mu_o}{1+\theta(V_{GS}-V_T)}\right)C_{ox}} + R_{SD}(V_G - V_T)$$

$$R_m(V_G - V_T) = \frac{(L-\Delta L)(1+\theta(V_{GS}-V_T))}{W_{eff}\,\mu_o C_{ox}} + R_{SD}(V_G - V_T)$$

$$R_m(V_G - V_T) = \left[\frac{(L-\Delta L)}{W_{eff}\,\mu_o C_{ox}}\theta + R_{SD}\right](V_{GS} - V_T) + \left\{\frac{(L-\Delta L)}{W_{eff}\,\mu_o C_{ox}}\right\}$$

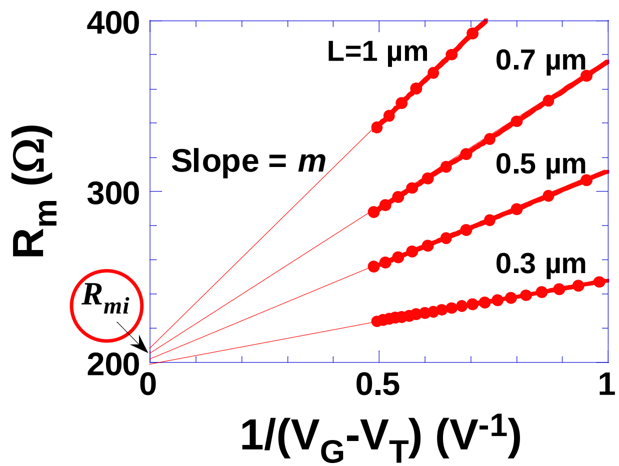
- **Allows ΔL, R_{SD}, μ_o, and θ to be determined…**

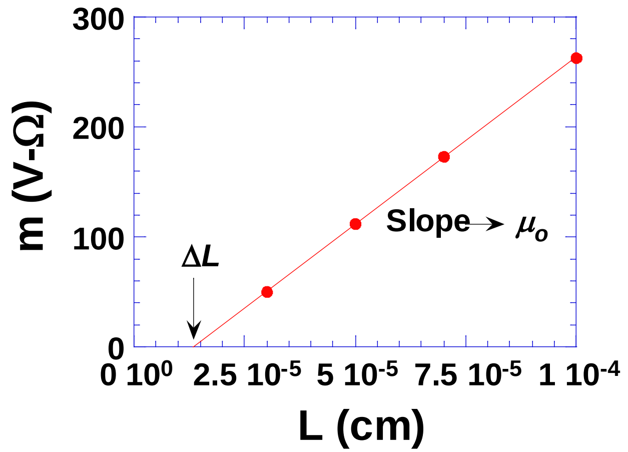
$$R_m = \left[\frac{(L-\Delta L)}{W_{eff}\,\mu_o C_{ox}}\theta + R_{SD}\right] + \left\{\frac{(L-\Delta L)}{W_{eff}\,\mu_o C_{ox}}\right\}\frac{1}{(V_{GS} - V_T)}$$

Effective Channel Length

- Allows ΔL, R_{SD}, μ_o, and θ to be determined
- A) Plot R_m vs $1/(V_{GS}-V_T)$
- Determine slope, m, and intercept R_{mi}
- B) Plot $m = 1/(W_{eff}\mu_o C_{ox})$ vs L→gives μ_o and ΔL
- ....

$$R_m = \frac{L-\Delta L}{W_{eff}\,\mu_o C_{ox}(V_G - V_T)} + \frac{\theta(L-\Delta L)}{W_{eff}\,\mu_o C_{ox}} + R_{SD}$$



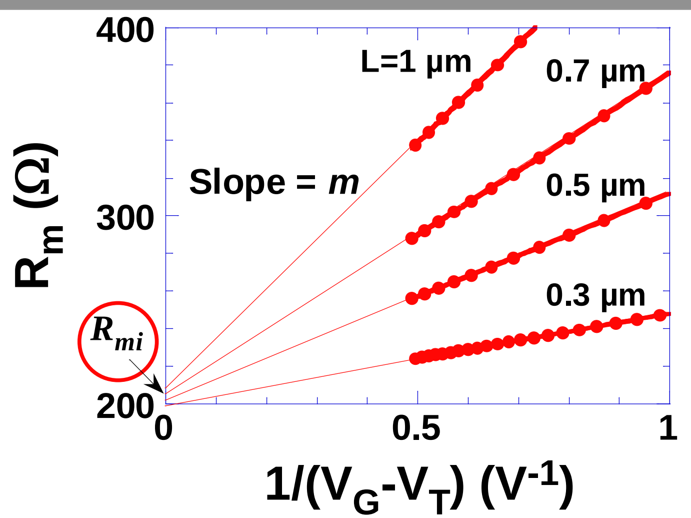


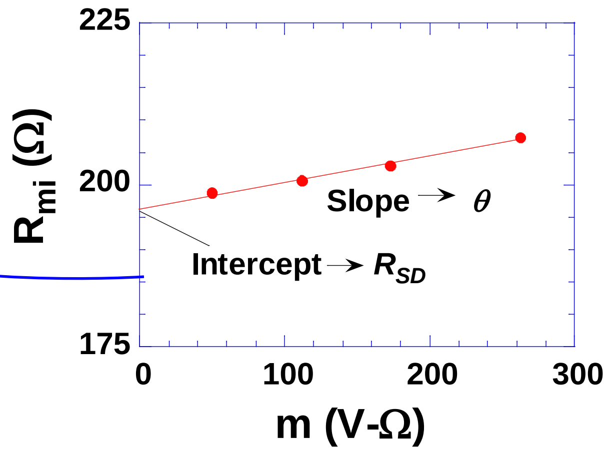
F.H. de la Moneda et al. "Measurement of MOSFET Constants," *IEEE Electron Dev. Lett.* **EDL-3**, 10-12, Jan. 1982.

Effective Channel Length

- **Allows ΔL, R_{SD}, μ_o, and θ to be determined**
- **A) Plot R_m vs $1/(V_{GS}-V_T)$**
- **Determine intercept R_{mi}**
- **…**
- **C) Plot R_{mi} vs $m = 1/(W_{eff}\mu_o C_{ox})$ → gives θ and R_{SD}**

$$R_m = \frac{L-\Delta L}{W_{eff}\mu_o C_{ox}(V_G - V_T)} + \frac{\theta(L-\Delta L)}{W_{eff}\mu_o C_{ox}} + R_{SD}$$





Shift and Ratio Method

- Uses one large and several variable-*L* devices

$$R_m = \frac{L - \Delta L}{W_{eff}\mu_{eff}C_{ox}(V_G - V_T)} + R_{SD}$$

- Measure resistance R_m

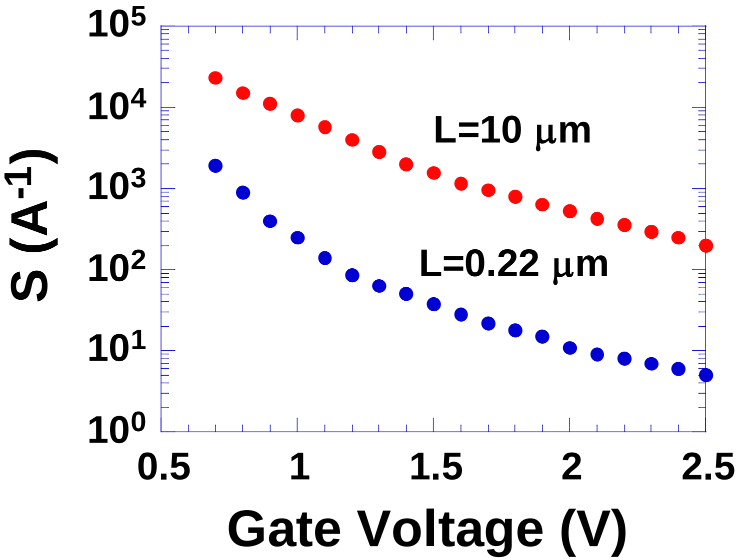
$$R_m = R_{SD} + L_{eff} f(V_G - V_T)$$

f is a general function of gate overdrive, V_G-V_T

$$S = \frac{dR_m}{dV_G} = L_{eff}\frac{d[f(V_G - V_T)]}{dV_G}$$

- Plot *S* versus V_G for large and one small device
- Determine ratio *r*

$$\frac{S_{Long}(V_G)}{S_{Short}(V_G + \Delta V_T)} = \frac{L_{Long} - \Delta L}{L_{Short} - \Delta L} = r$$



Ratio is not constant with gate voltage ONLY due to differences in threshold voltage.

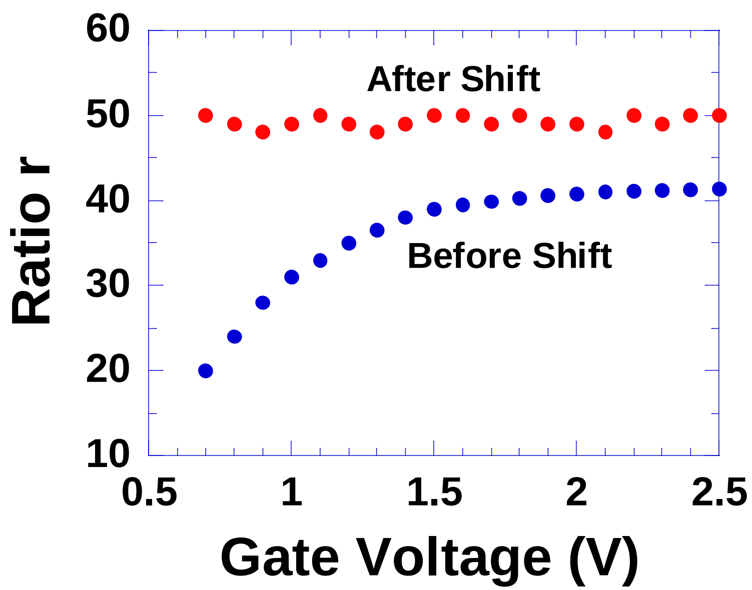
Shift and Ratio Method

- Shift one curve horizontally by ΔV_T (threshold voltage difference between the two devices) until r becomes constant
- The key is to find ΔV_T for which r is constant
- Determine ΔL and L_{eff}

$$\Delta L = \frac{L_{Long} - rL_{Short}}{r - 1}$$

- ***Once ΔL is found, RSD can be found from:***

$$R_m = \frac{L - \Delta L}{W_{eff}\mu_{eff}C_{ox}(V_G - V_T)} + R_{SD}$$



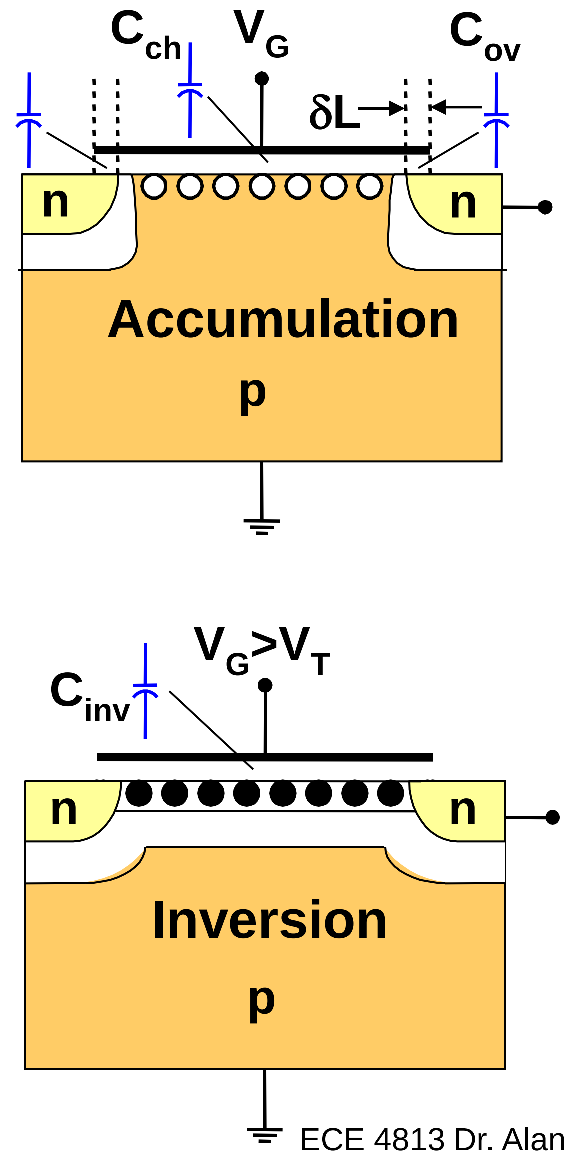
Capacitance Effective Channel Length

- **Capacitance measured between *G* and *S*/*D***
- **Step A) MOSFET biased into accumulation; source connected to drain**
- **Measure $C = 2C_{ov}$; $C_{ch} \sim 0$ (shunted to ground)**
- **Step B) MOSFET biased into inversion; source connected to drain**
- **Measure $C_{inv} = 2C_{ov}+C_{ch}$**

$$C_{inv} = \frac{K_{ox}\varepsilon_0 LW}{t_{ox}}; \quad C_{ov} = \frac{K_{ox}\varepsilon_0 \delta LW}{t_{ox}}$$

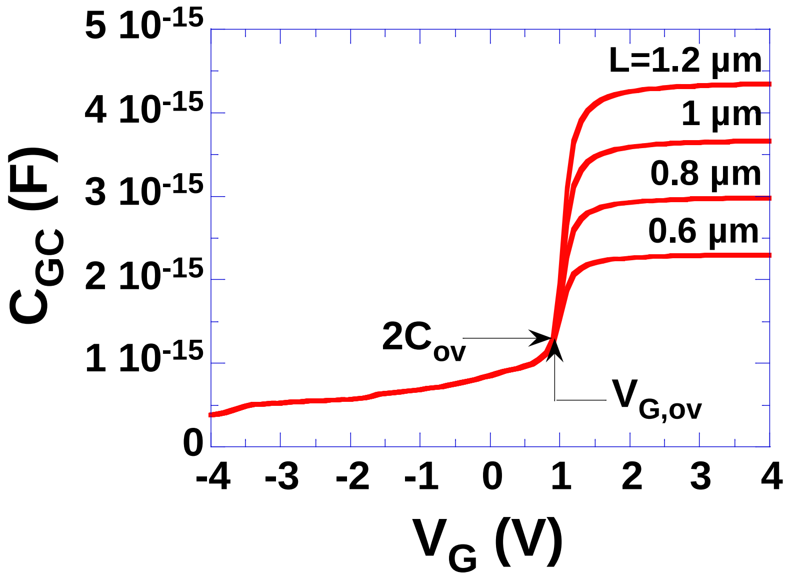
$$L_{met} = L\left(1 - \frac{2C_{ov}}{C_{inv}}\right)$$

Note missing factor of 2 in text.



Capacitance Effective Channel Length

- Due to extremely small device size, in modern MOSFETs, you need many device connected in parallel
- Not influenced by series resistance



Threshold Voltage

- Threshold voltage is an important MOSFET parameter

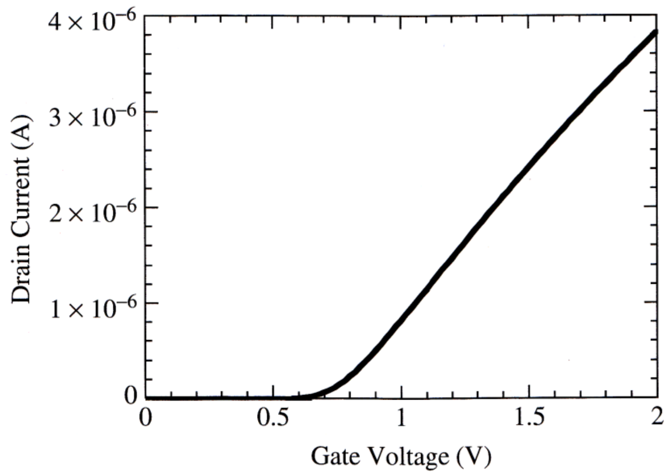
$$V_T = V_{FB} + 2\phi_F + \frac{\sqrt{2qK_s\varepsilon_0 N_A\left(2\phi_F - V_{BS}\right)}}{C_{ox}}$$

$$V_{FB} = \phi_{MS} - \frac{Q_f}{C_{ox}} - \gamma\frac{Q_m}{C_{ox}} - \gamma\frac{Q_{ot}}{C_{ox}} - \frac{Q_{it}\left(\phi_S\right)}{C_{ox}}$$

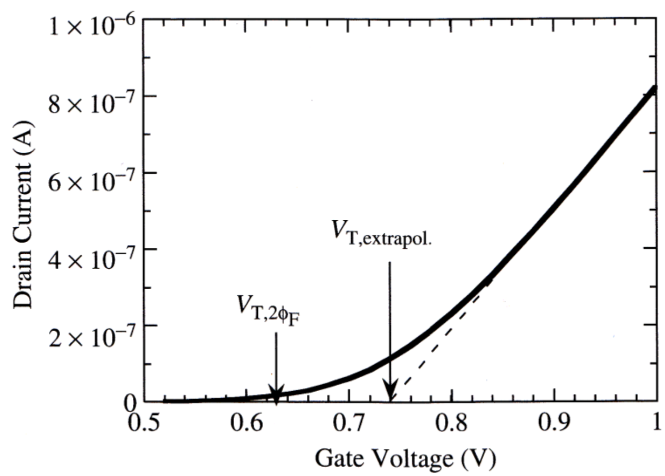
- V_T depends on
  - Oxide thickness
  - Doping density
  - Work function difference
  - Oxide charge
  - Interface trap charge
  - Substrate voltage

Threshold Voltage

- **There is no unique definition of the threshold voltage**



(a)



(b)

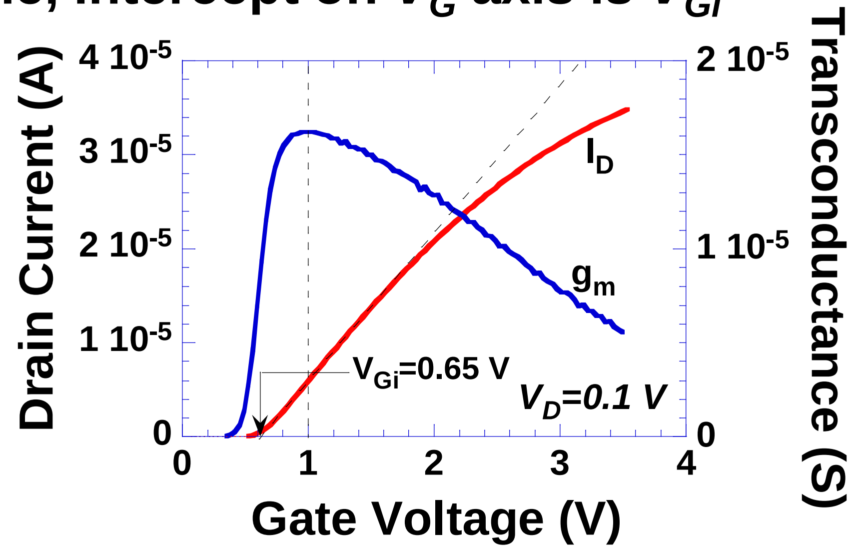
$$V_{T,2\phi_F} = V_{FB} + 2\phi_F + \frac{\sqrt{2qK_s\varepsilon_0 N_A\left(2\phi_F - V_{BS}\right)}}{C_{ox}}$$

$$V_{FB} = \phi_{MS} - \frac{Q_f}{C_{ox}} - \gamma\frac{Q_m}{C_{ox}} - \gamma\frac{Q_{ot}}{C_{ox}} - \frac{Q_{it}\left(\phi_S\right)}{C_{ox}}$$

$$\phi_{Surface} = 2\phi_F = \frac{2kT}{q}\ln\left(\frac{p}{n_i}\right) \approx \frac{2kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

Threshold Voltage: Linear Extrapolation

- Since the drain current is not actually equal zero below threshold, there is no "threshold voltage" where the Drain current =0. Otherwise, ID would =0 at V_T=V_{GS}+0.5V_{DS}
- Solution: Use asymptotic $V_{GS(intercept)}$
- Measure I_D-V_G; find point of maximum slope ($g_{m,max}$); fit straight line, intercept on V_G axis is V_{Gi}

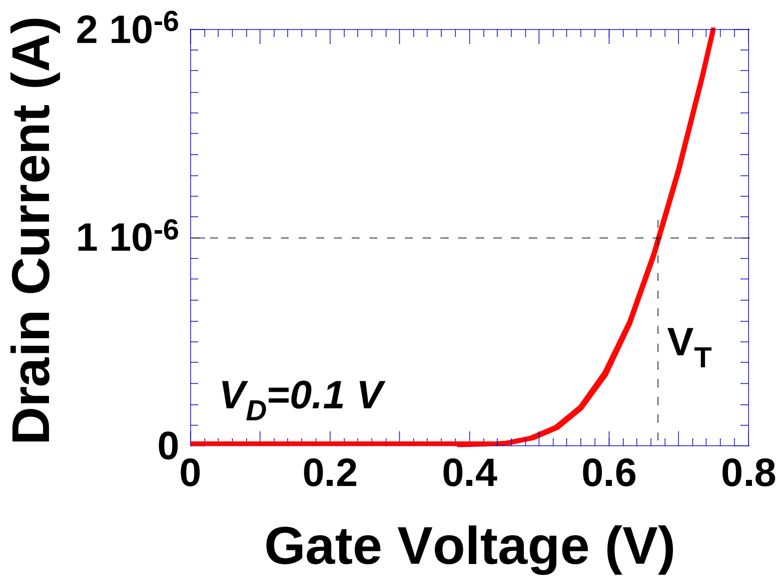


$$I_D = \frac{W_{eff}\mu_{eff}C_{ox}}{L_{eff}}(V_G - V_T - V_D/2)V_D; \qquad g_m = \frac{\partial I_D}{\partial V_G}\Big|_{V_D=\text{constant}}$$

$$V_T = V_{Gi} - V_D/2$$

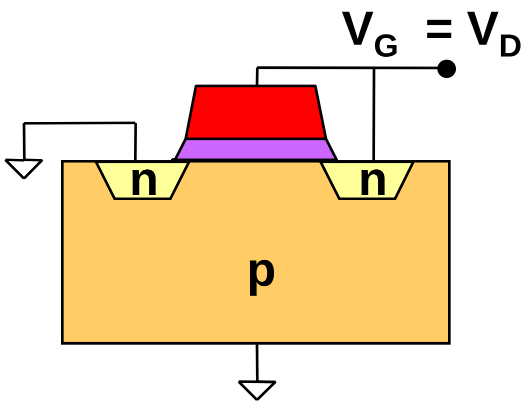
Threshold Voltage: Constant Normalized Drain Current

- I_D extrapolation is time consuming; faster method is to measure V_G at "some" low I_D *where* I_D *Is normalized to the device geometry*
- $V_T = V_G$ at $I_T = I_{D0}/(W/L)$ with $I_{D0} \approx$ 50-100 nA

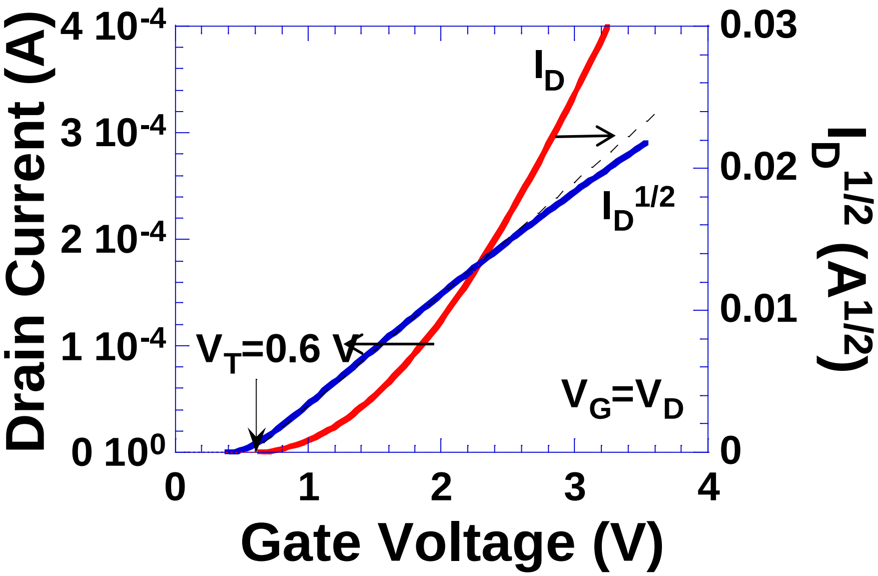


Threshold Voltage: Saturation

- Measure I_D - V_G; plot $I_D^{1/2}$ - V_G , extrapolated intercept is V_G



$$V_T = V_{Gi}$$

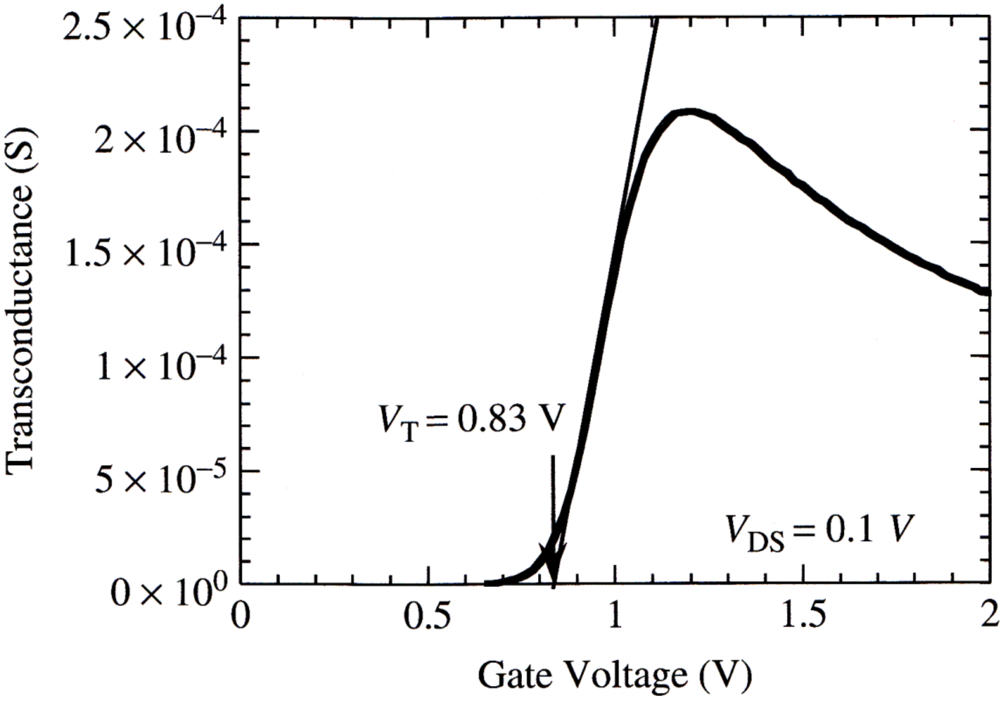


$$I_D = \frac{W_{eff}\mu_{eff}C_{ox}}{2L_{eff}}(V_G - V_T)^2$$

$$\sqrt{I_D} = \sqrt{\frac{W_{eff}\mu_{eff}C_{ox}}{2L_{eff}}}(V_G - V_T)$$

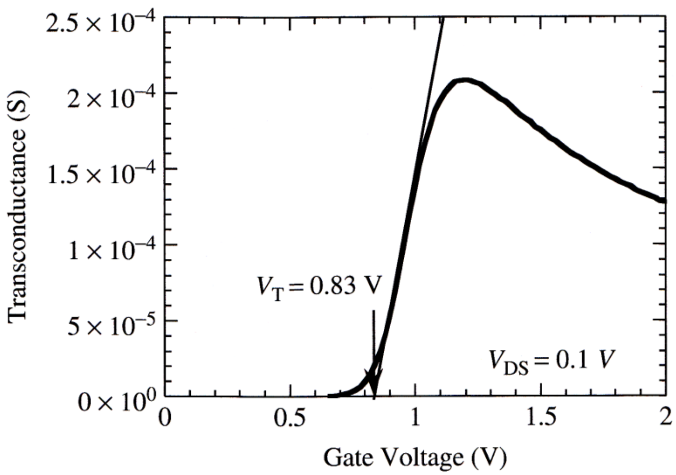
Threshold Voltage: Transconductance Slope

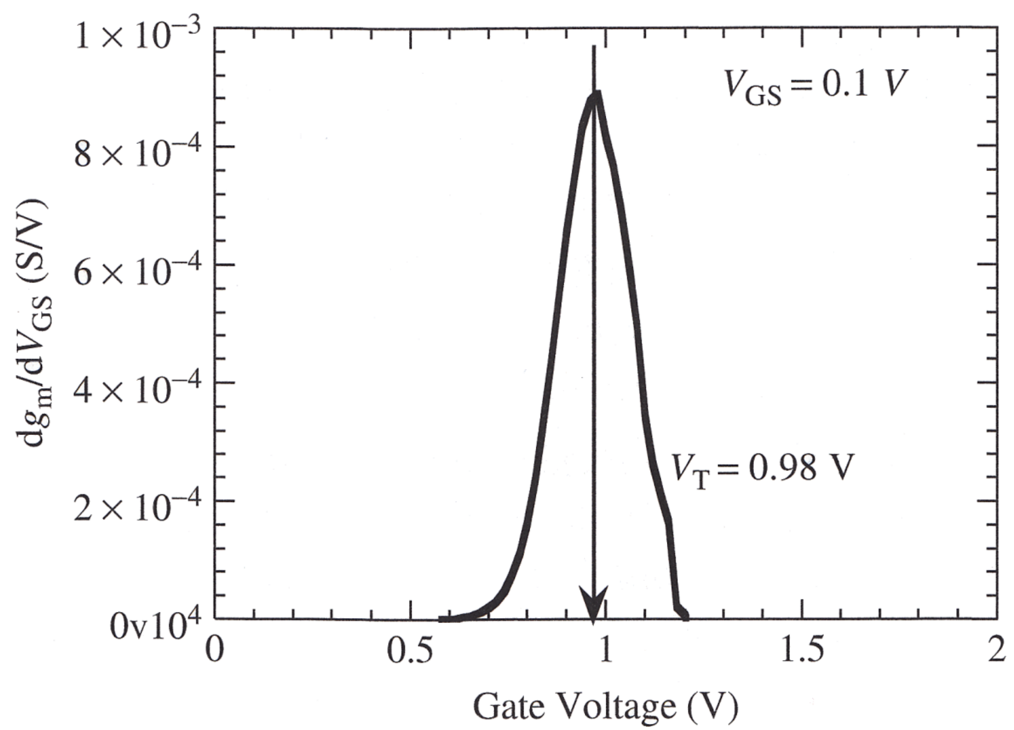
- Measure g_m - V_G
- V_T , is the intercept extrapolated from the maximum slope (1st derivative)



Threshold Voltage: Transconductance Derivative

- **Commonly used in RF devices (and others) since small signal parameters are often measured**
- **Measure g_m - V_G**
- ***Plot dg_m/dV_{GS} and V_T* is the maximum of the (1st derivative)**





Review Questions

- How is the threshold voltage measured?
- Name three device/material parameters that influence V_T.
- Why does the effective channel length differ from the physical gate length?
- What is an advantage of the capacitance technique over current-voltage techniques for effective channel length determination?