TEL AVIV אוניברסיטת
UNIVERSITY תל אביב
7718-Lect 01

Welcome to

7718 semester 1 2022

Mixed Signal Electronic Circuits

Instructor: Dr. Miki Moyal

Lecture 01

1. Course Overview and Requirements

2. CMOS Transistor Basics

What will you get out of this course

1. Mixed Signal design **מעגלים של אותות מעורבים**

Part I: Emphasis on conversion from Digital to Analog and Analog to Digital domains, with detail on transistor operation

Part II: communications: Serial Links, PLL, SerDes

This includes:

2. Basic to detail of Analog circuit (transistor level) design of selected Analog blocks

Understanding of problem flavors and solution/s to mixed signal design

Course Overview

PART 1: ANALOG TO DIGITAL CONVERTERS AND CIRCUITS

Lecture 1: CMOS transistors: CMOS Transistor basics: I (Vgs), small signal, Gm, Gds, mismatch and noise

Lecture 2: ***Noise and Mismatches in Mixed Signal:*** Passive Silicon components R-C-L, Noise Sources, and Mis-match in CMOS, and sampling in-accuracy

Lecture 3 : ***Mixed Signal blocks, Comparators*** *transistor level*

Lecture 4 : ***Mixed Signal blocks, Track & Hold*** *transistor level*

Lecture 5: Converters Basic theory and definitions: Sampling Delta and Step functions. Definitions: SNR. Linearity: INL and DNL

Lecture 6: ADC Types- Flash converter: System and architecture, circuits: Flash-Architectures: Onestep flash, n- step sub-ranging, Charge base flash

Lecture 7 : ***Digital to analog converters :*** Transfer function, architectures types Voltage DAC, R-2R, current steering DACs

Lecture 8: SAR ADCs: The basic operation, SAR architecture and circuits

Course Overview

PART 2: ADVANCED HIGH SPEED SERIAL LINKS System and Circuits

Lecture 9: LC-PLLs Architecture: Loops, Transfer function, Noise transfer function, Jitter and phase noises in PLLs. LC PLLs.

Lecture 10: PLL Circuits: VCOs high frequency LC-VCOs. Phase detectors, charge pump, filters, dividers, and phase noise.

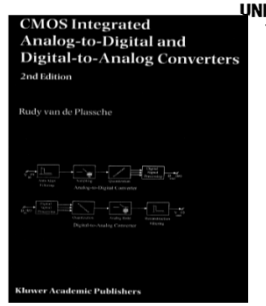
Lecture 11: High Speed SerDes *Basics:* Serial links, Wireline, optical links, transmission lines model, ISI Jitter, and cross talk

Lecture 12: SerDes Tx path: Architecture and circuits of P2S, Tx. FIR driver and terminations methods

Lecture 13: **SerDes *Rx path:*** Equalizer methods and circuits

Lecture 14: Advance Topics: CDR: Basics, architectures, types, and circuits

Books an References good to have



Perquisite:
Knowledge in Linear Circuits design and Feedbacks systems.

Book Listing: The link below lists the recommended textbooks for your course in the upcoming academic year.

1) CMOS Integrated Analog-to-Digital and Digital-to-Analog Converters by Rudy van de Plassche, 2nd Edition 2003 Kluwer Academic Publishers

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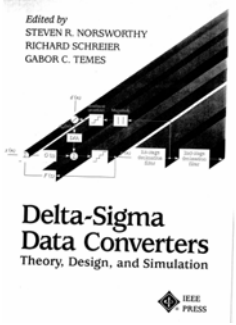
2) Oversampling Delta-Sigma Data Converters Theory Design and Simulations. James C. Candy and Gabor C. Temes, 1992 IEEE press Order num. PC0274-1

Book Listing - Option

Design of Analog Integrated Circuits and Systems, Kenner R. Laker and Willy M.C. Sansen, 1994 McGraw-Hill Series in Electrical and Computer Engineering

Recommended Supplemental Material:
IEEE Journal of Solid State Circuits and ISSCC from 1990-2020, and Lecture's notes.



Grading

Course Grading:

Project:	70%
Homework assignments	30 % 1 assignment/few lectures

Class Hours:

Tues. 18:00 – 20:00 10 min break/hr.

Lectures are placed in my site:
http://www.gigalogchip.com/lectures.html
My WhatsApp 0547885707
Email: miki@gigalogchip.com

TAU e mail- expect longer delay.
mikimoyal@tauex.tau.ac.il

Requirements: Project- design in mixes signal arena

I will choose 2 to 3 projects ideas for you to work on.
You may under special case bring your idea but it will need to be approved by me.

Topics Area Suggestions:
ADC (Flash, SAR. others)
Data Links: (CDR, PLL, SerDes)

Delivery :
Project:

I will Define spec: next lecture..

Project suggestions..

next lecture….

simulations tools

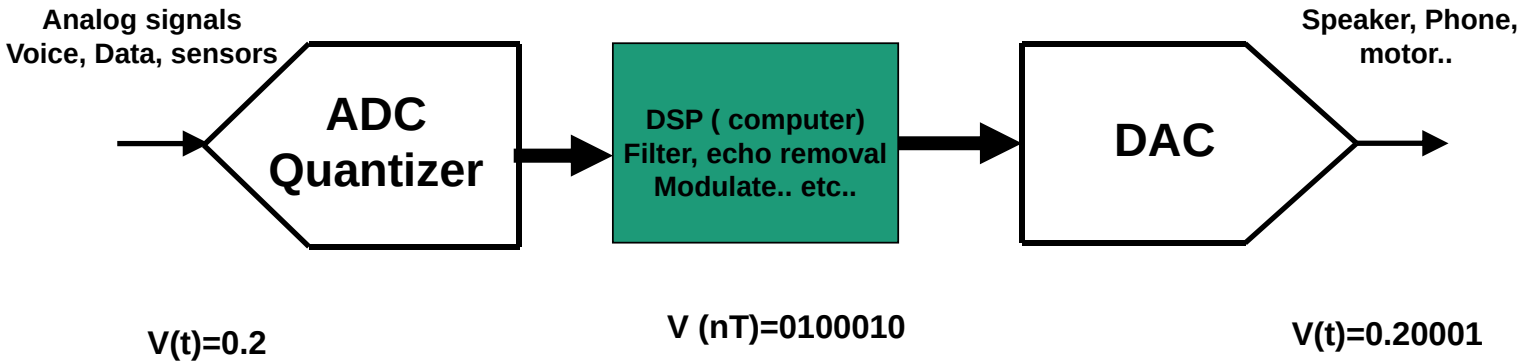
- At the university we have a workstation with Cadence and a general 90nm PDK.
- Can use MATLAB/Simulink for the project.
- Can use Cadence Analog-Lib, mixed with its libraries

Example of Mixed Signal systems

Review of CMOS Transistor Basics

Example of Mixed Signal Systems

Converters

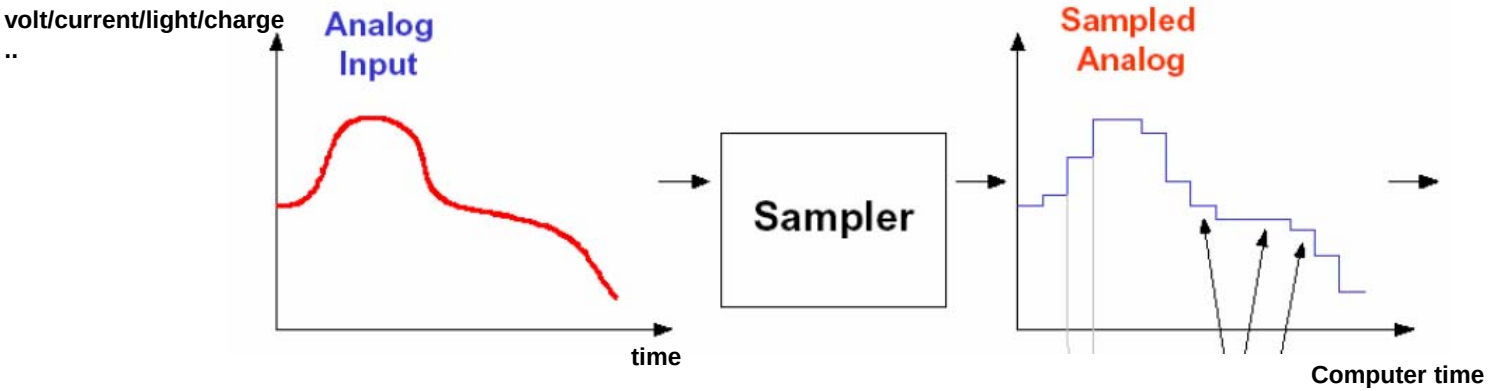


ADC –> DSP –> DAC

- It's a "Language" translator to do work. With fixed known boundary conditions **Vinmax/min clock rate, and maximum frequencies of throughput (BW)**
- The process burn power, produces inaccuracies, creates bad artifacts- Folding, distortions - but allow communications to exists and to be stored.

In this course we will learn how converters works and how those errors are generated. And more precisely why/when we can let the error exists.

ADC representation

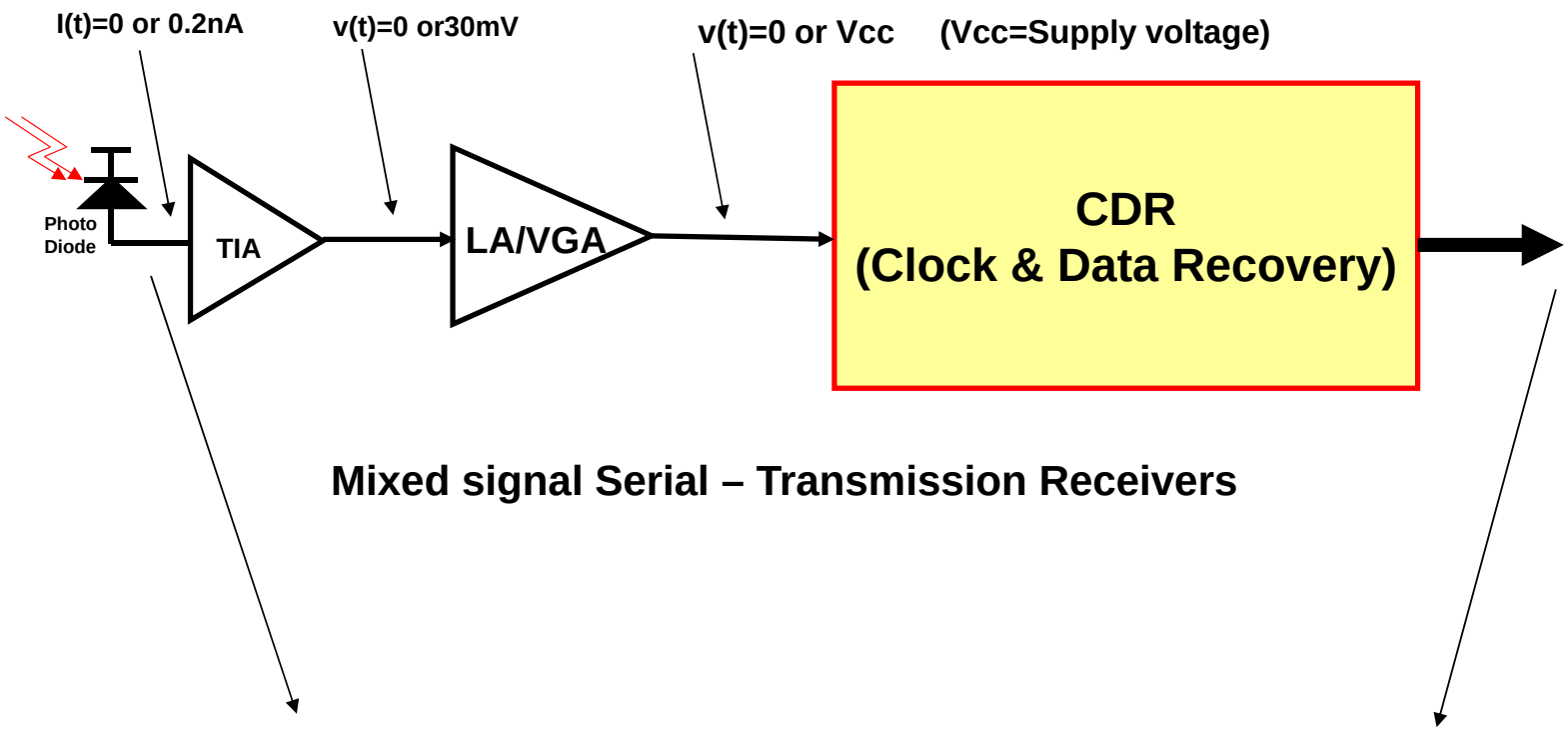


output is digital codes.

Sample at fixed time interval

Clock-with data Based Digitizing

Example of Mixed Signal systems



1. Review of Silicon based passives elements

2. Review of CMOS Transistor Basics

CMOS Transistors

Transistors : (CMOS in this example)

- 4 terminal device, mostly 3 terminals are used, the 4th is default connection - not always.
- CMOS works so nice because it is possible to build and repeat it: it is an efficient and dense element (~1.6million/mm^2 in 45nm tech.)
- Transistor can change its “function” and become R, C, or a voltage controlled current source(VCCS).
- Applying mostly the control voltage to the gate to source voltage.

Key is to understand which control does what!

$$i_{ds} = f(V_{gs}, V_{ds}, W, L, V_t, U, C_{ox})$$

CMOS Transistor Basics

Large Signal Equations for NMOS/PMOS transistor

Linear Region – A “resistors”

Strong Inversion – A current source (v-c-c-s)

Moderate Inversion – “transition region”

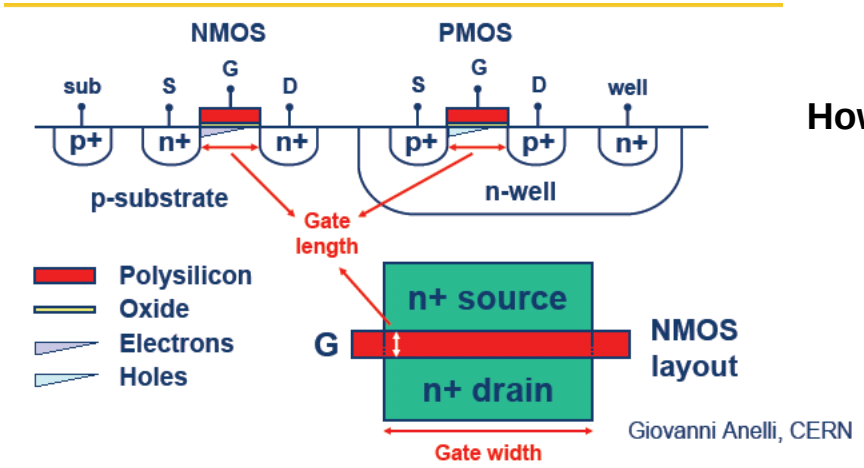
Weak Inversion – A “bipolar device” (Exponential i/v)

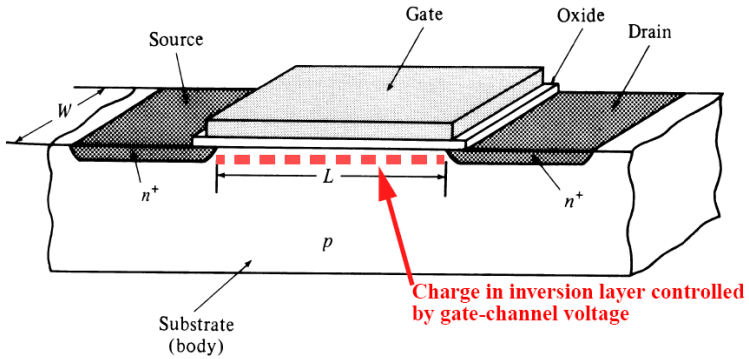
Off (Accumulation) – Open Switch

Velocity saturation, and Breakdown regions !
– important in sub um logic devices..!

A “digital cell” transistors could switch through all those regions

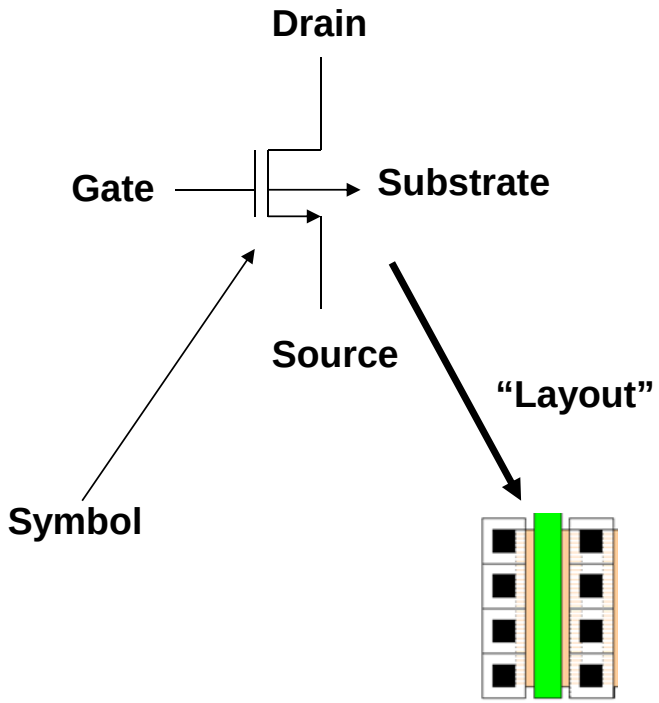
Physical Structure of NMOS / PMOS Transistor





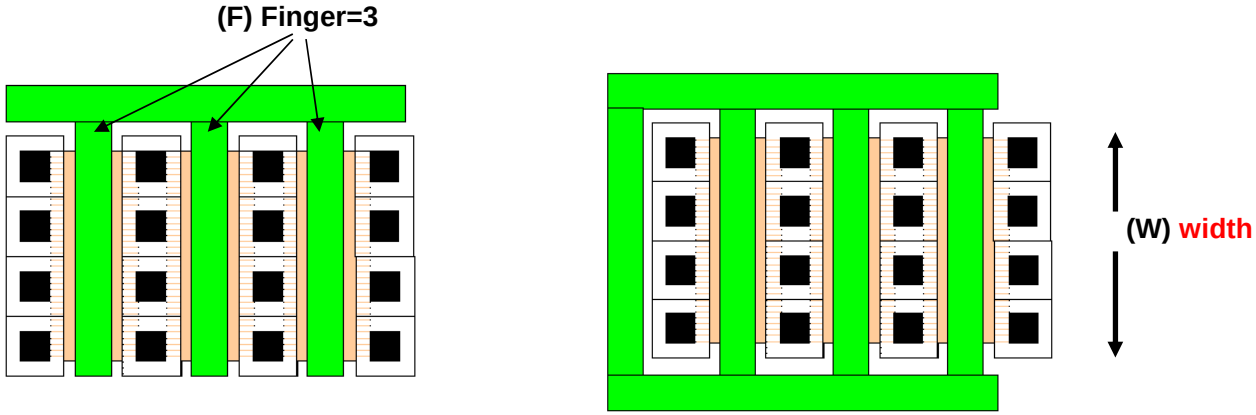
Source: IEEE & T.H. Lee.

How do we define W, L, Multiplier, Finger..?



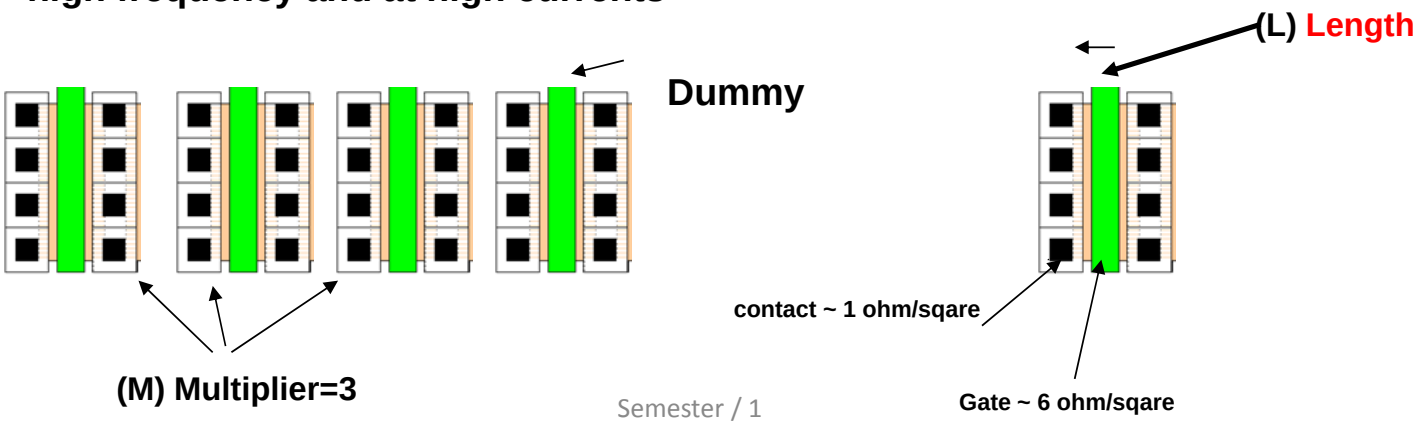
Transistor layout view

A very important part of Mixed Signal is placement and layout of the elements.



Now we have added errors:

Contacts resistance, metal routings and capacitance they can make difference at high frequency and at high currents



CMOS Transistor why we like them ?

- Technology Enhancement
  - Enhanced 28nm CMOS with 13 metal layers
  - 3 billion transistors on 588mm²

~ 5.million transistors /1mmsquare.

If you go to 16nmFF, can double it to 10Million/1mmsquare..

Leff = 3-4nm is the best people can do .. 2022..

Linear Region

- **Linear Region the Drain current is mobility time electric field (surface)**

$$I_D = W Q_n(y) \mu_n E$$

$$\int_0^L I_D dy = I_D L = \int_0^{V_{DS}} \mu_n C_{ox} W [V_{DS} - V(y) - V_t] dV$$

Source: IEEE & T.H. Lee.

$$I_{ds} = \mu C_{ox} \left(\frac{W}{L}\right) \left[(V_{gs} - V_{th}) \cdot V_{ds} - \frac{1}{2} {V_{ds}}^2\right] \quad V_{gs} - V_{th} > V_{ds}$$

- In this region electron are attached to the surface creating a conductive surface R which is Vds dependent (for small Vds)

- Mobility:
  how a charge carriers responds to an induced electric field, the mobility in Silicon MOSFET is roughly 400 cm^2/Vs

Saturation Region

If $V_{gs}-V_{th} < V_{ds}$ and $V_{gs}-V_{th} > \frac{3kT}{q} \sim 78mV$

Then: $$\boxed{I_D = \frac{\mu \cdot Cox}{2} \cdot \frac{W}{L}(V_{GS} - V_T)^2 = \frac{\beta}{2}(V_{GS} - V_T)^2}$$

transistor here is voltage controlled current source – too early yet to define

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Or we can define $V_{gs}-V_{th} \equiv Vsat$

- **Strong Inversion region**
  The inversion channel does not extend all the way to the end ”pinched off”

- **Strong Inversion, large Vds, transistor do not respond to drain movement – Great place to make a current element or to make an amplification… or an ADC, DACs**

Mobility in Silicon MOSFET is roughly 400 cm^2/Vs

In most design, to keep the transistor in saturation we always watch for Vdsat, and keep in mind that Vdsat (Vsat) is lower than Vds

My magic number is 150mV

$$V_{gs} - V_{th} \equiv Vsat$$

Weak Inversion (sub threshold) Region

IF $V_{gs} - V_{th} < \frac{3KT}{q} \sim 78mV$ $Vds > \frac{4KT}{q}$

Then : $Ids = Ido\left(\frac{W}{L}\right)e^{\frac{Vgs}{nKT/q}}$

The region is an interesting place to design- IOT, watches
But we getting in new set of problems (matching ?)

Keys:

- **Can happen at any Vds (above ~ 100mv)**
- **Transistor is Very large or has very small current!**
- **Slope: ~70mV per decade of current**

Where:

n (sometime k) is called Kappa around 0.7 and represents the coupling of gate to source potential

$$n = \frac{C_{ox}}{C_{ox} + C_{depl}}$$

Other Regions

Moderate Inversion – V_{gs}-V_{th} ~30-50mV
same as Sub threshold (transition place)

Off region – V_{gs}~0 leaky region I_{dss} and I_{gate}

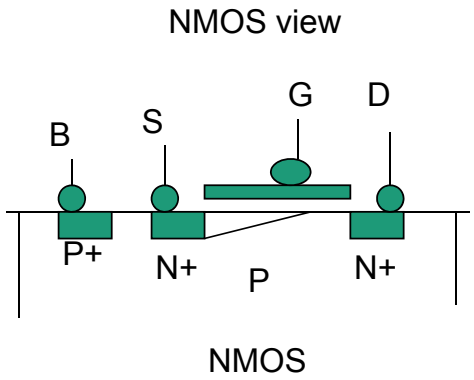
Mobility saturation – Large V_{gs} - V_{th} ~V supply or more.

Snap back – Very large V_{ds} exceed supply, a bipolar action

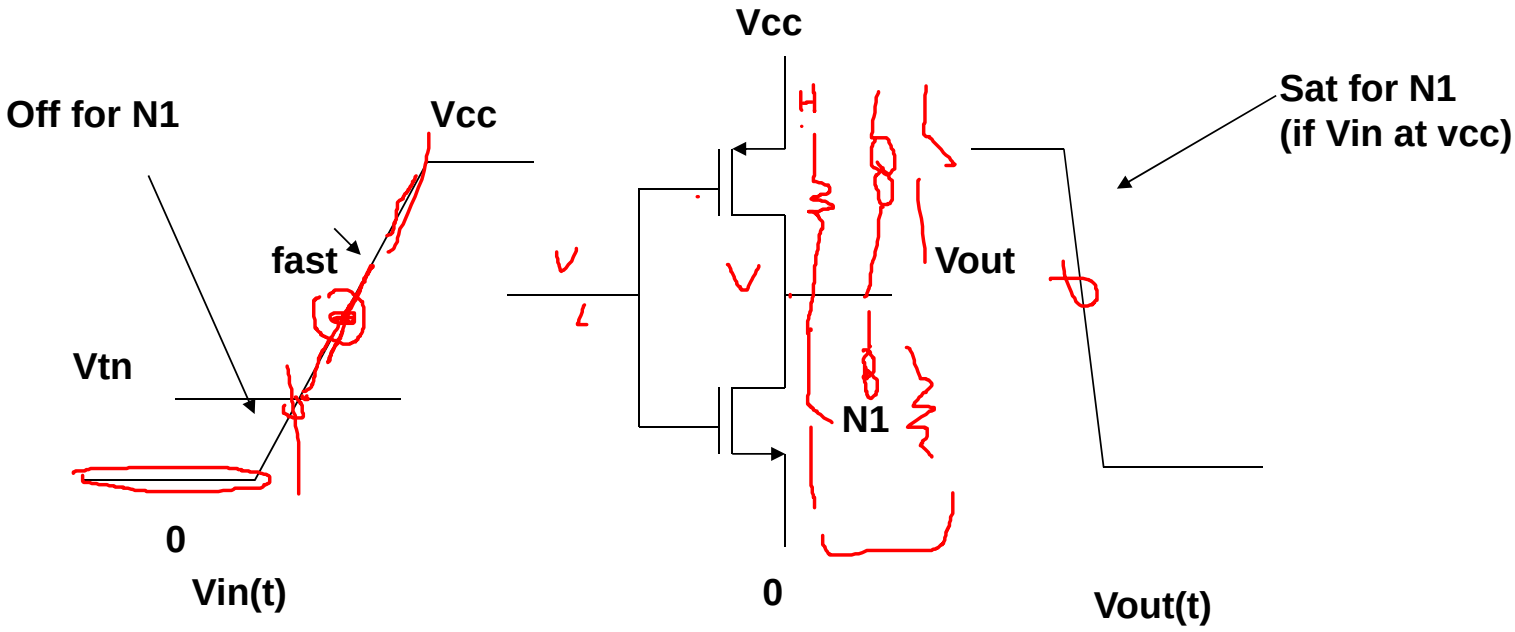
Off region is not so off Ido, diodes..- 10pA is possible to loose Remember 100 million elements..

it's a function of how big V_{th} is! and all leakages of all parasitic diodes

Source: IEEE & T.H. Lee.



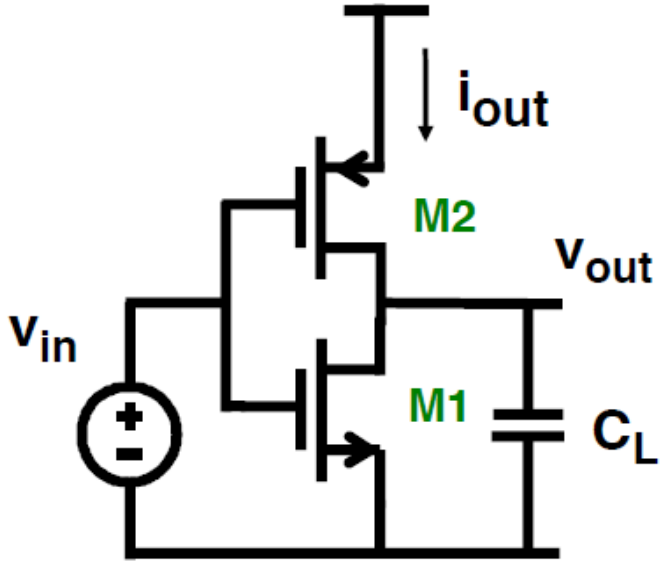
Inverter example- operate as a large Signal



Example: In class region analysis.
An inverter will switch through all those regions

But in most Analog/Mixed signals most transistors will stay in one region or will switch from Off to one of those region.

2nd Inverter example- operate as small signal=all in sat....



$$v_{out} = A_v\, v_{in}$$

Hold on. What is small signal ?

Class AB stage

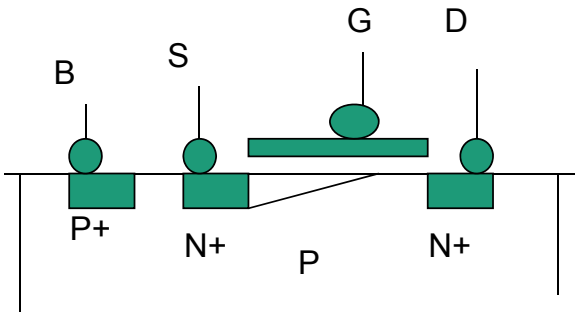
CMOS Small Signal Model

Key: now we get help from the mathematicians
… since I=a*V*V, the equation of current vs. Vgs is square or exponential (bipolar)

the way to linearized the system is ? **answer: Derivatives**

NMOS view

Than can we be free to use ohm law, Kirchhoff law.



Good (for better understand) to convert the transistor to passive and active elements.

Small Signal Transistor Parameters: g_m and G_{ds}

- Lets take the saturation region and assume the transistor V_{gs}-V_{th} does not change a lot. The current is set at DC but fluctuate as we 'slightly' (small signal), move the Gate voltage.

Its important because the "quality" of the transistor in term of amplifications and output impedance is measured. (ignoring g_{msb})

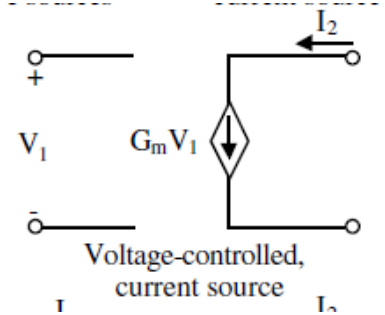
$$V_{gs} - V_{th} < V_{ds}$$

$$I_{ds} = \mu C_{ox}\left(\frac{W}{2L}\right)(V_{gs} - V_{th})^2$$

$$g_m = \frac{\partial I_{ds}}{\partial V_{gs}} = \mu C_{ox}\left(\frac{W}{L}\right)(V_{gs} - V_{th})$$

$$g_m = \sqrt{2\mu C_{ox}\left(\frac{W}{L}\right) I_{ds}}$$

$$\Delta I_{ds} = g_m \cdot \Delta V_{gs}$$



- **we want large gm but it cost:**
  - **Squaring the I_{ds}.**
  - **Large W and small L – can helps**

Tricky: what about V_t ?

Gds= Small signal transistor parameters: g_m and G_{ds}

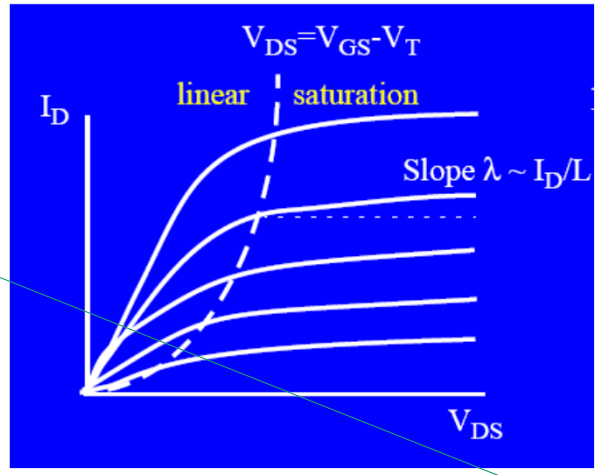
$$V_{gs} - V_{th} < V_{ds}$$

- At a fixed V_{gs}, I_{ds} is not constant in term of V_{ds} (replace sat current equation with- channel modulation)

$$I_{ds} = \mu C_{ox}\left(\frac{W}{2L}\right)(V_{gs} - V_{th})^2 + (1 + \lambda V_{ds})$$

$$g_{ds} = \frac{\partial I_{ds}}{\partial V_{ds}} \equiv \frac{1}{r_o}$$

$$g_{ds} = \lambda \cdot \mu C_{ox}\left(\frac{W}{2L}\right)(V_{gs} - V_{th})^2 = \lambda \cdot I_{ds}$$



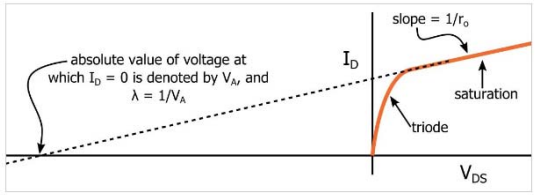
Typ. Lambda = 0.04/0.01 (1um/2um) 1/v

Keys:

- r_o is proportional to L! And $1/I_{ds}$
  Slope: $1/r_o$
- Make long L if you like large r_o!
- Don't use much current
- Large r_o means current is unaffected W. V_{ds} changes

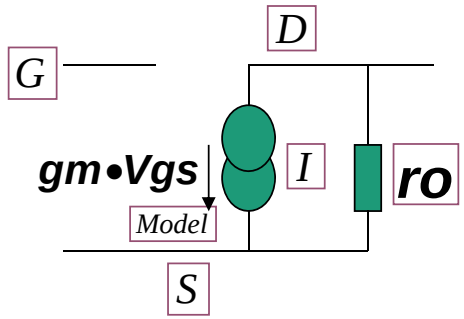
Channel length modulation

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2\left(1 + \frac{V_{DS}}{V_A}\right)$$



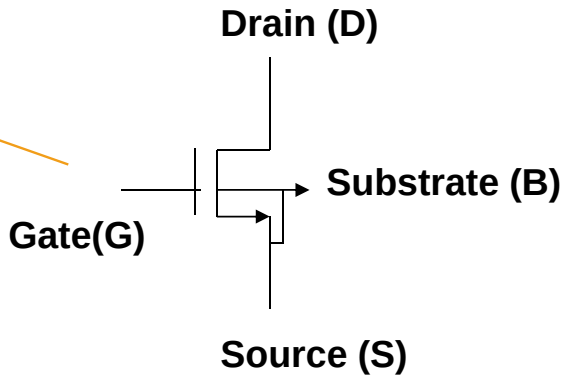
Gm= Model for Small Signal (no capacitors = DC)

Units =1/ohm, siemens



The **siemens** = electric conductance, electric admittance = the reciprocals of resistance, one siemens is one ohm (Ω^{-1}) = *mho*

in small signal model
Vgs, ids, ro, gm all are derivatives saturation

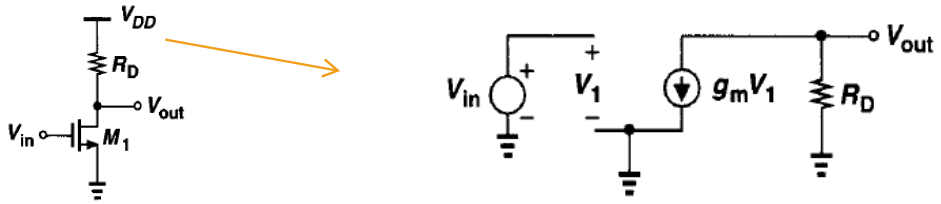


$$g_m \equiv \frac{\partial I_{ds}}{\partial V_{gs}} \qquad I_{ds} = g_m \cdot V_{gs}$$

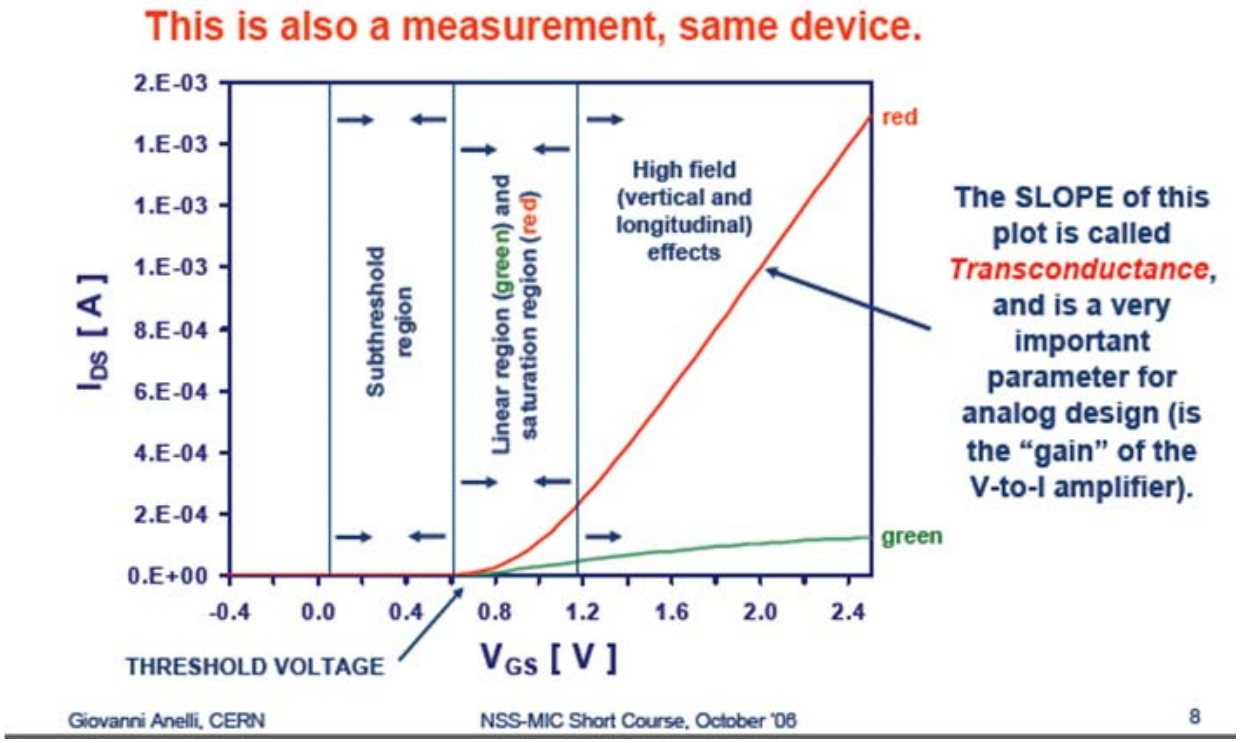
$$g_{ds} \equiv \frac{\partial I_{ds}}{\partial V_{ds}} \qquad r_o = \frac{1}{\lambda \cdot I_{ds}}$$

−gm•Vgs **For Pch**

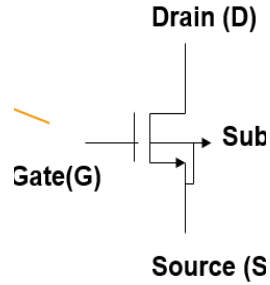
transistor here is voltage controlled current source



Graphical view: I_{DS} Vs. V_{GS}



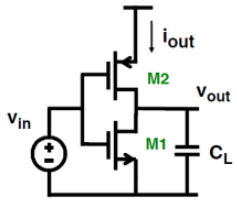
Force Vds =Vcc or high



gm~400e-6 is a typ number..

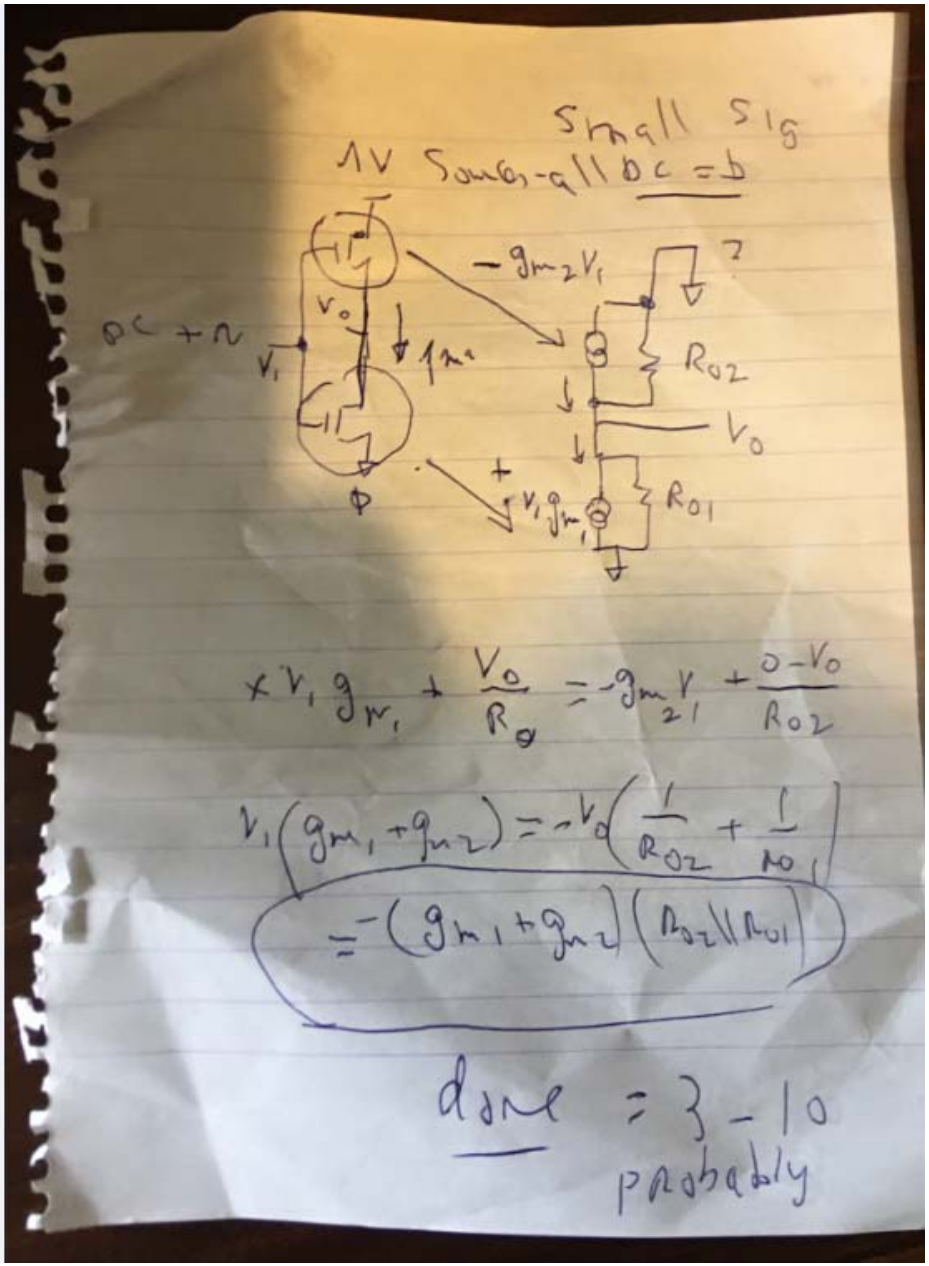
on class lecture 2 examples

on class lecture 2 examples: derive voltage gain and sat range, next page..



$v_{out} = A_v\, v_{in}$

Class AB stage


Small Sig
1V Source-all DC = 0
DC + N
V_i
V_o
1MΩ
$-g_{m2}V_i$
R_{O2}
V_o
R_{O1}
$V_i g_{m1}$
$V_i g_{m1} + \frac{V_o}{R_o} = -g_{m2} V_i + \frac{0 - V_o}{R_{O2}}$
$V_i (g_{m1} + g_{m2}) = -V_o \left(\frac{1}{R_{O2}} + \frac{1}{R_{O1}} \right)$
$= -(g_{m1} + g_{m2})(R_{O2} \| R_{O1})$
done = 3 - 10
probably

Small signal transistor parameters: g_{msb}

Influence of the Bulk Voltage on the Large Signal MOSFET Model - Continued

Bulk-Source (v_{BS}) influence on the transconductance characteristics-

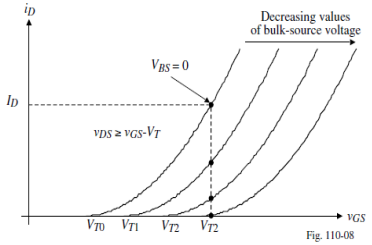


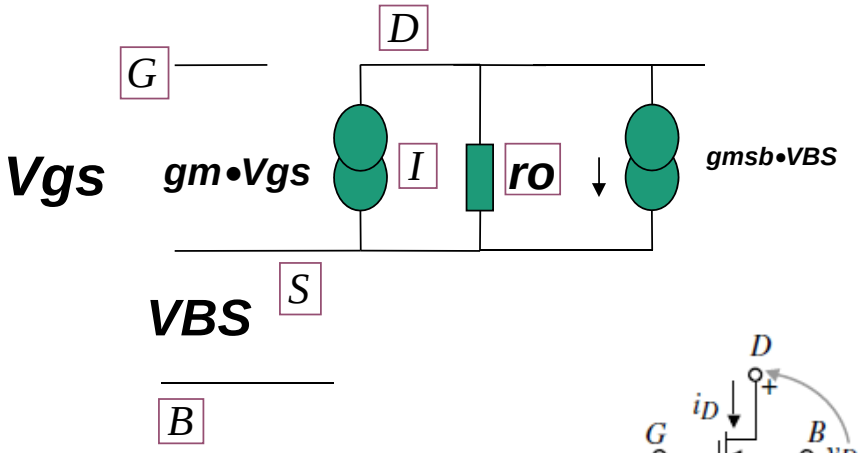
Fig. 110-08

In general, the simple model incorporates the bulk effect into V_T by the previously developed relationship:

$$V_T(v_{BS}) = V_{T0} + \gamma\sqrt{2|\phi_f| + |v_{BS}|} - \gamma\sqrt{2|\phi_f|}$$

$$V_t = V_{t0} + \gamma \cdot \left(\sqrt{2 \cdot \phi_f + V_{SB}} - \sqrt{2 \cdot \phi_f}\right)$$

$$\frac{gmb}{gm} = \frac{\gamma}{2 \cdot \sqrt{2 \cdot \phi_f + V_{SB}}} = \chi$$

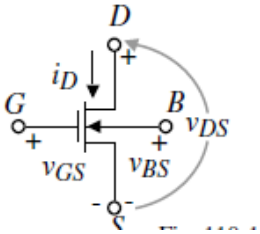


g_{msb} (an additional gain path)
Because V_t changes as a function of source to baulk:
(See V_{th} equation)

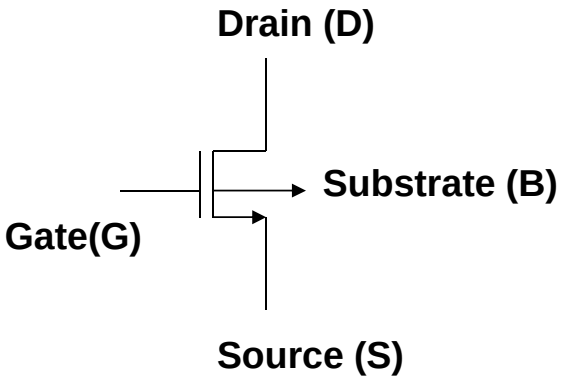
In many cases to avoid this gain path it is good to tie source to baulk !

$$g_{msb} \equiv \frac{\partial I_{ds}}{\partial V_{sb}} = \eta \cdot g_m$$

η is In the range of $0.2g_m$ (every technology has an η)



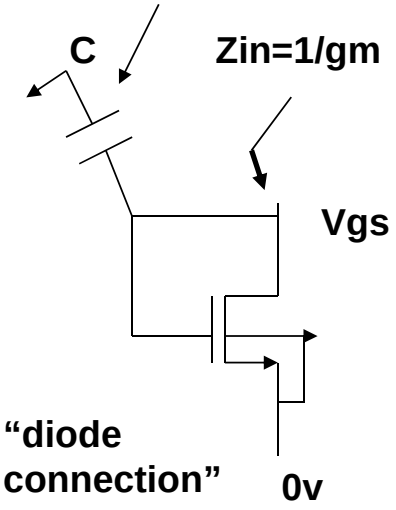
Model – with _ baulk



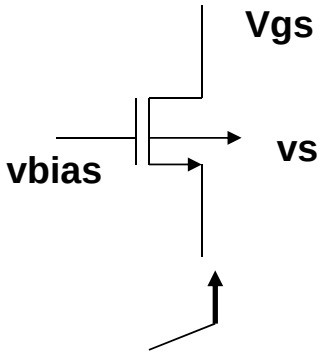
Convince yourself

- Use the small signal model derive the impedance of n channel transistors below.

And what about C



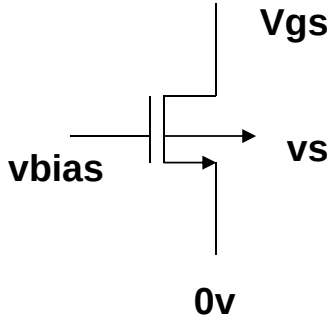
"low Z"

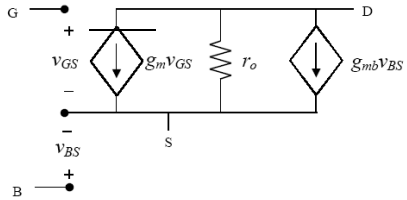


Zin=1/(gm+gmsb)

"high Z"

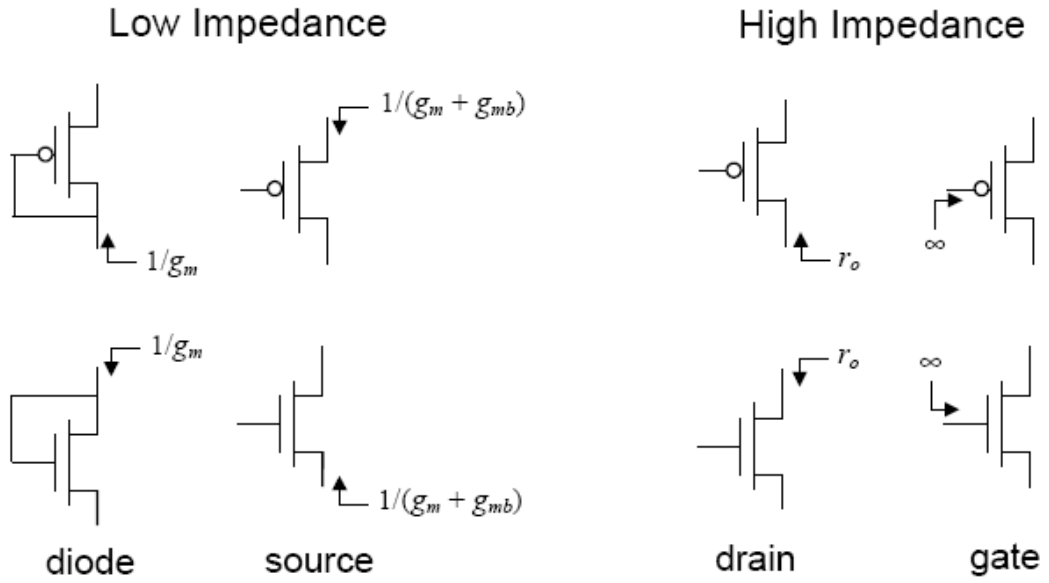
Zin=1/(gds)





An example of transistor impedances:

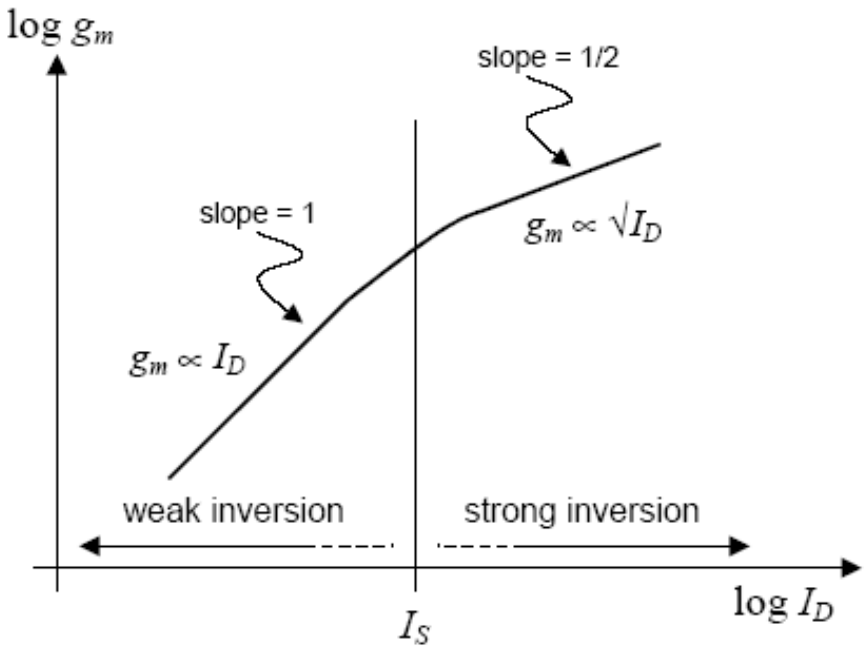
- MOS is a source device you move the drain nothing happen at the source but once you move the source the drain follow with gain!
- In NMOS source potential is lower than the drain and you can exchange source and drains- symmetrically.



Source: IEEE & T.H. Lee.

Gate impedance in thin gates is not infinite
Ig is becoming significant for L below ~ 65nm. (thin oxide) conventional CMOS

How g_m behaves with at different regions



Source: R Harrison, Uof Utah

Source: R. Harrison.

Keys:

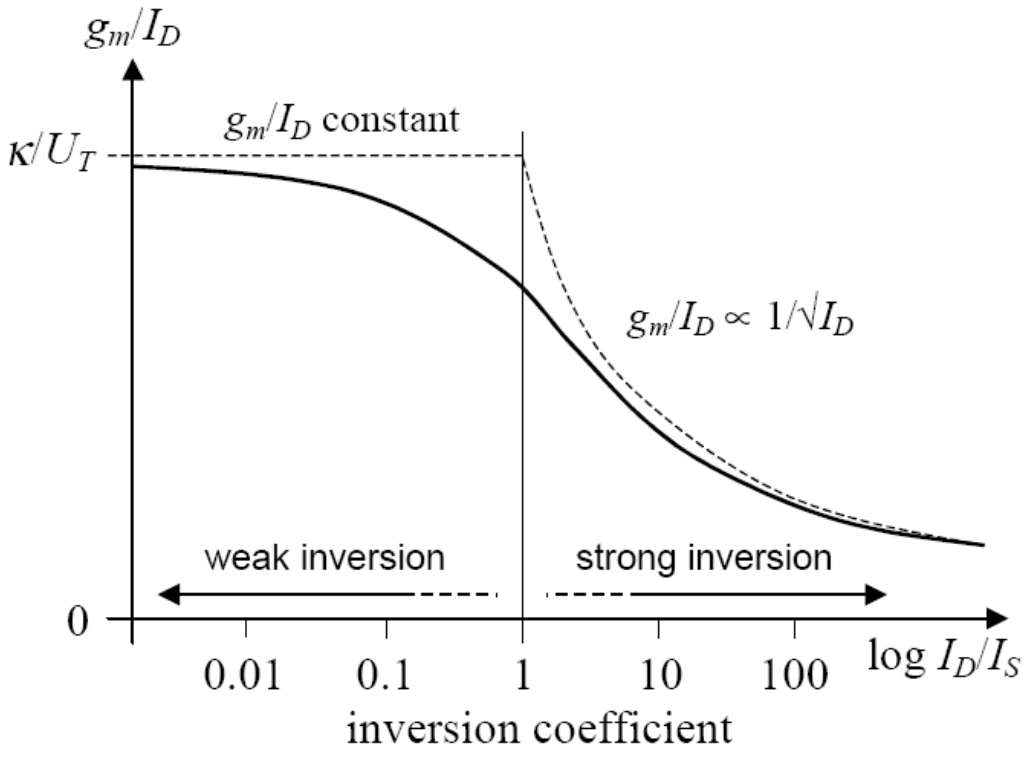
- g_m increases faster in weak inversion
- In moderate V_{ds}=30-80mv – g_m = ~ I_{ds}
- Small absolute g_m - slow device

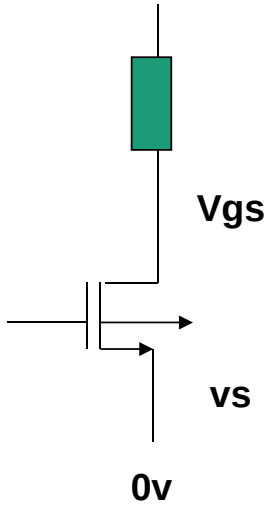
$$g_{msat} = \sqrt{2\mu C_{ox}\left(\frac{W}{L}\right) I_{ds}}$$

$$g_{mwk\_inv} = \frac{I_{ds}}{KT/q}$$

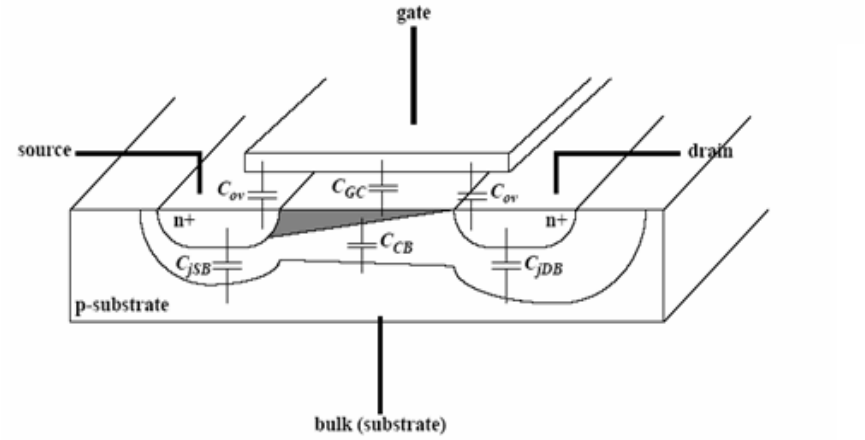
Gain => $-g_m \times r_o$

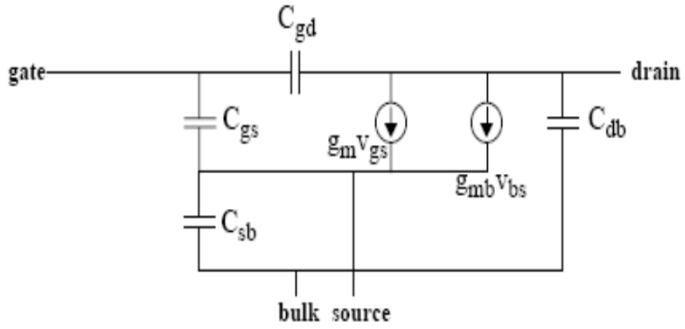
- **Another look** is relative g_m defined as g_m/I_{ds} (for low I design)
  But also the "gain" is
  $g_m\, r_o = \sim g_m/I_{ds}$





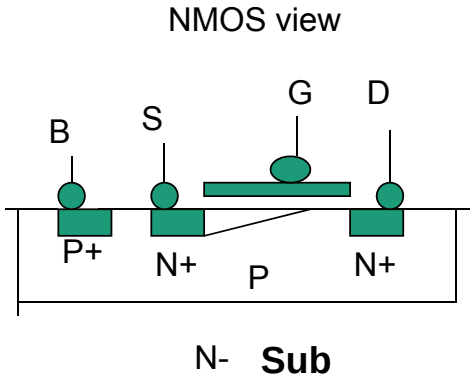
Capacitor of CMOS : small signal model with Cap.

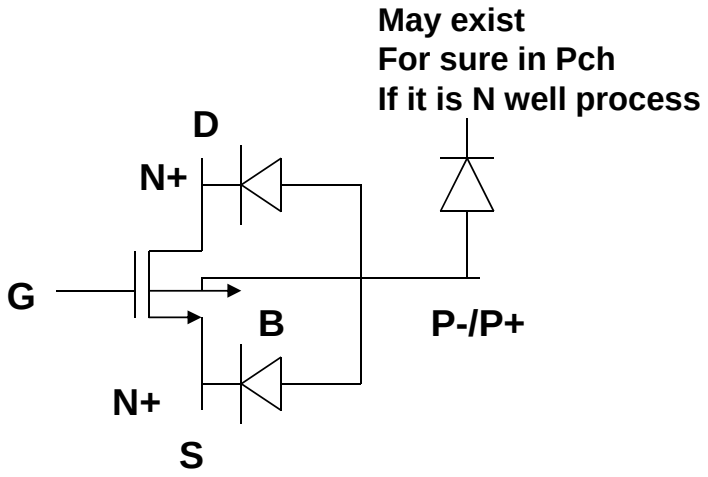


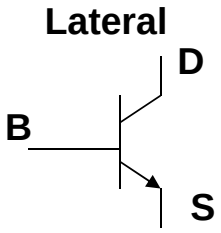


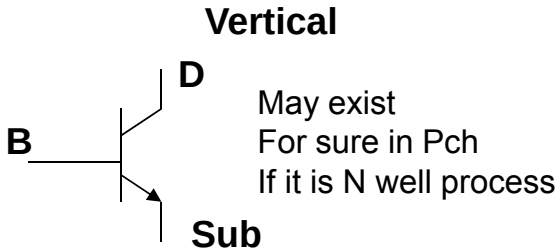
capacitors	Saturation	Linear	Off	
C gate to S	2/3Cox+Cov	1/2Cox+Cov	Cov	
C gate to D	Cov	1/2Cox+Cov	Cov	
C gate to B	0	0	Cox//Ccb+..	
C drain to B C source B	Cj(diode) CJ	Cj Cj	Cj CJ	Voltage dependance

❑ CMOS Model – Never forget the Parasitic Bipolar/diodes !

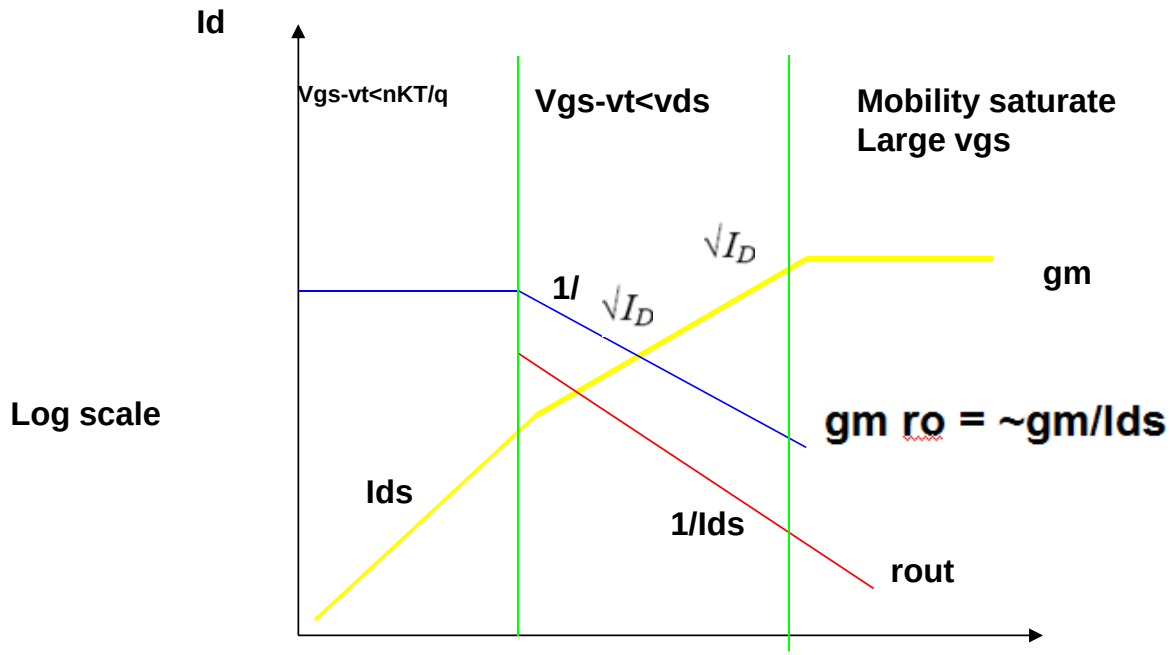








Summary



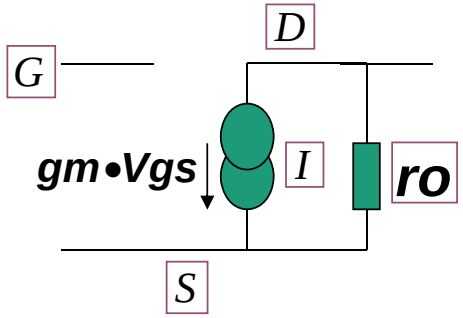
Region dependency on Ids

Source: R Harrison, Uof Utah

Summary

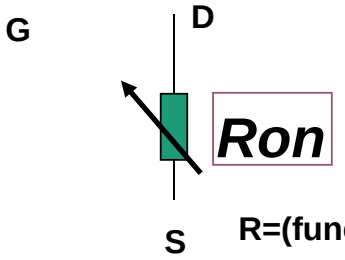
Saturation

$$I_{ds} = \mu C_{ox}\left(\frac{W}{2L}\right)(V_{gs} - V_{th})^2(1 + \lambda V_{ds})$$



Linear

$$I_{ds} = \mu C_{ox}\left(\frac{W}{L}\right)[(V_{gs} - V_{th}) \cdot V_{ds} - \frac{1}{2}{V_{ds}}^2 \qquad V_{gs} - V_{th} > V_{ds}$$



R=(function of vgs,vds)

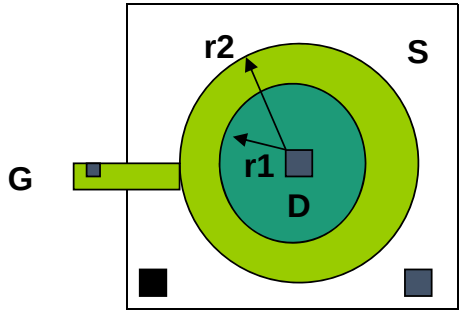
Sub Threshold

$$Ids = Ido\left(\frac{W}{L}\right)e^{\frac{Vgs}{nKT/q}}$$

“Rule of thumb” : 70mv/decade of I

Now add capacitance according to Mode of operation on table provided

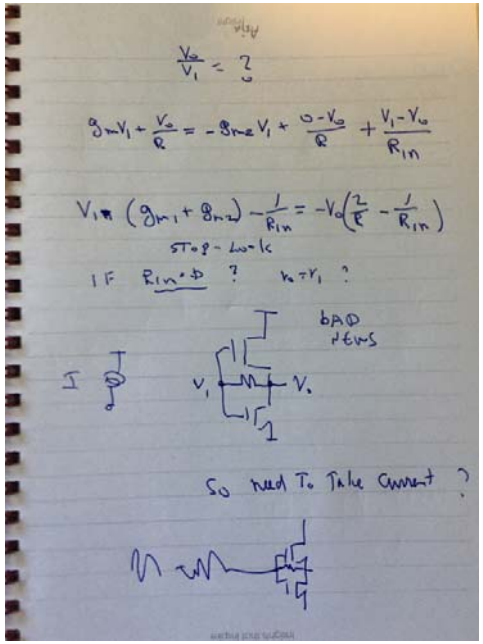
optional



1. What is W/L of a round donut shape transistor?
2. Can you derive it?
3. What is it good for?

---

not everything is voltage gain

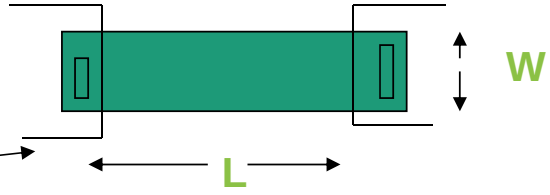


Si Passive Elements Used in Mixed Signal - more in mismatch (next lecture)

Silicon Resistors:

In Silicon **R =** Sheet resistance x Number of square. 6Ω -1KΩ /square

$$R = R_s \cdot squares(1 + \alpha T/T_0)$$

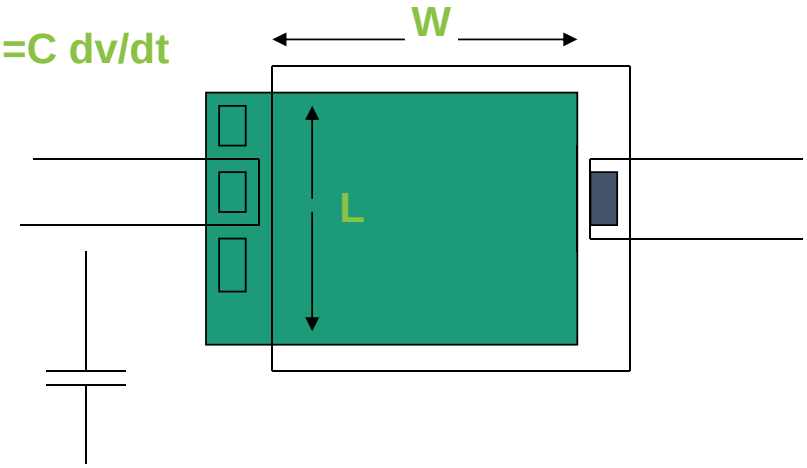


Si Top view

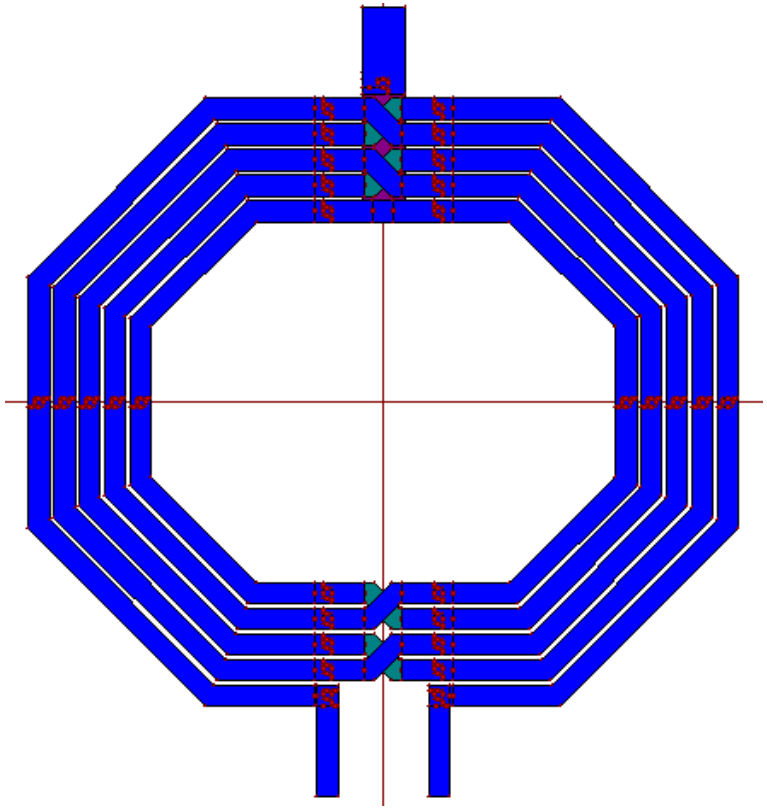
Capacitors

C= Ca x Area = Ca x W x L (W and L are dimension of plates)0.1-4 ff/uu

i=C dv/dt



Si Passive Elements Used in Mixed Signal - more in mismatch (lect4)



Inductors

Inductors are also becoming a common elements-

End lecture 01