EE 330

Lecture 35

Telescopic Cascode OpAmp

Amplifier Biasing

Other Amplifier Structures

Frequency-Dependent Performance of Amplifiers

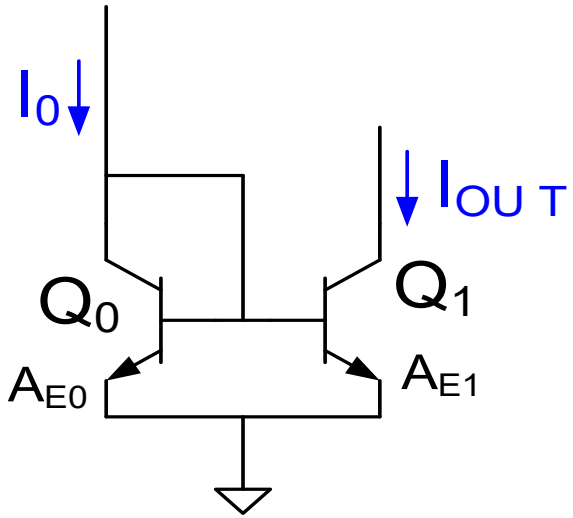
Parasitic Capacitances in MOS Devices

Fall 2023 Exam Schedule

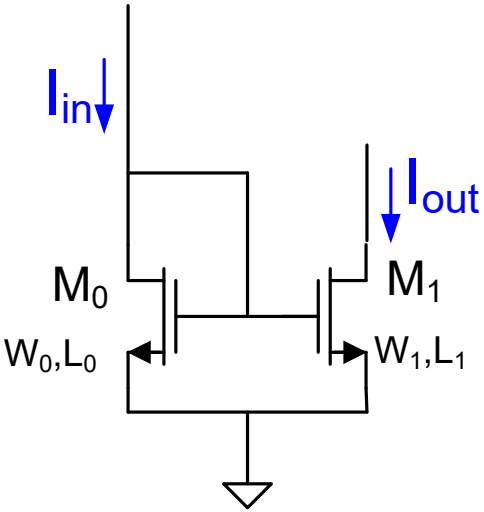
Exam 1	Friday Sept 22	
Exam 2	Friday Oct 20	
Exam 3	Friday Nov. 17	
Final	Monday Dec 11	12:00 – 2:00 p.m.

Review From Previous Lecture

Current Sources/Mirrors Summary



npn Current Mirror



n-channel Current Mirror

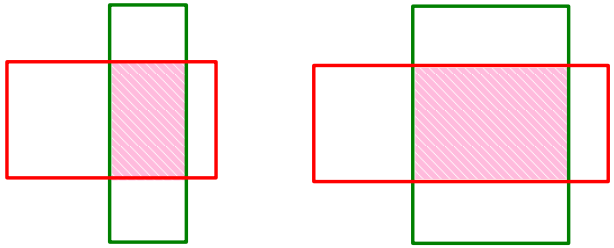
$$I_{out} = \left[\frac{A_{E1}}{A_{E0}} \right] I_{in}$$

$$I_{out} = \left[\frac{W_1}{W_0} \frac{L_0}{L_1} \right] I_{in}$$

- Current mirror gain can be accurately controlled !
- Layout is important to get accurate gain (for both MOS and BJT)

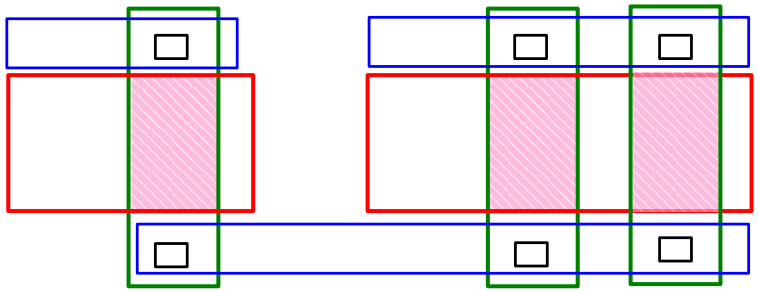
Layout of Current Mirrors

Example with M = 2



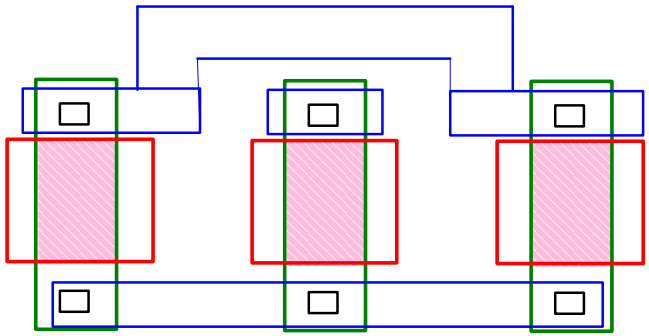
Standard layout

$$M=\left[\frac{W_2}{W_1}\frac{L_1}{L_2}\right]$$



Better Layout

$$M=\left[\frac{2W_1+4\Delta W}{W_1+2\Delta W}\bullet\frac{L_1+2\Delta L}{L_1+2\Delta L}\right]=2$$



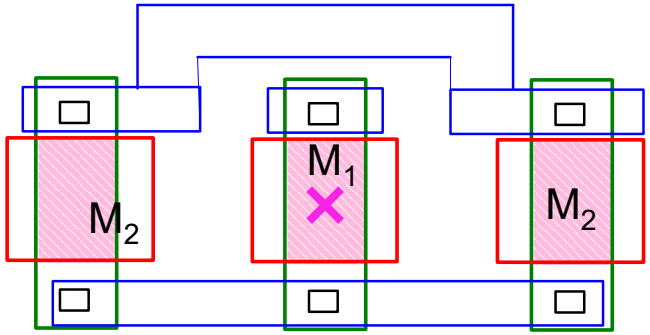
Even Better Layout

$$M=\left[\frac{2W_1+4\Delta W}{W_1+2\Delta W}\bullet\frac{L_1+2\Delta L}{L_1+2\Delta L}\right]=2$$

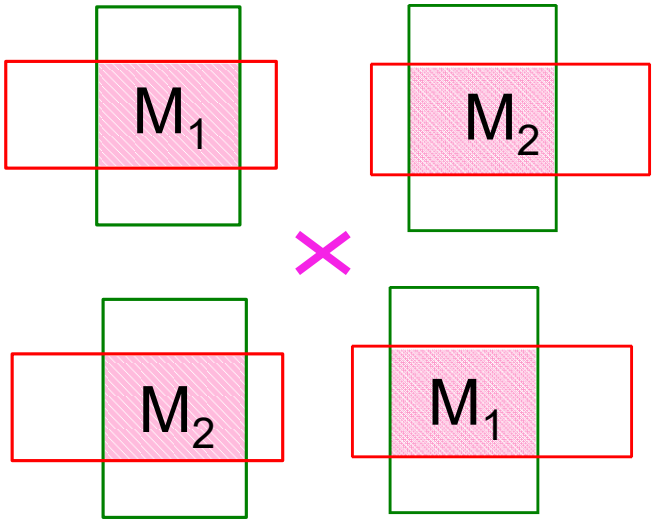
- **This is termed a common-centroid layout**
- **Linear gradient mismatch eliminated with common-centroid layout !**

Review From Previous Lecture

Common-Centroid Layouts



$$M=\left[\frac{2W_1}{W_1}\bullet\frac{L_1}{L_1}\right]=2$$



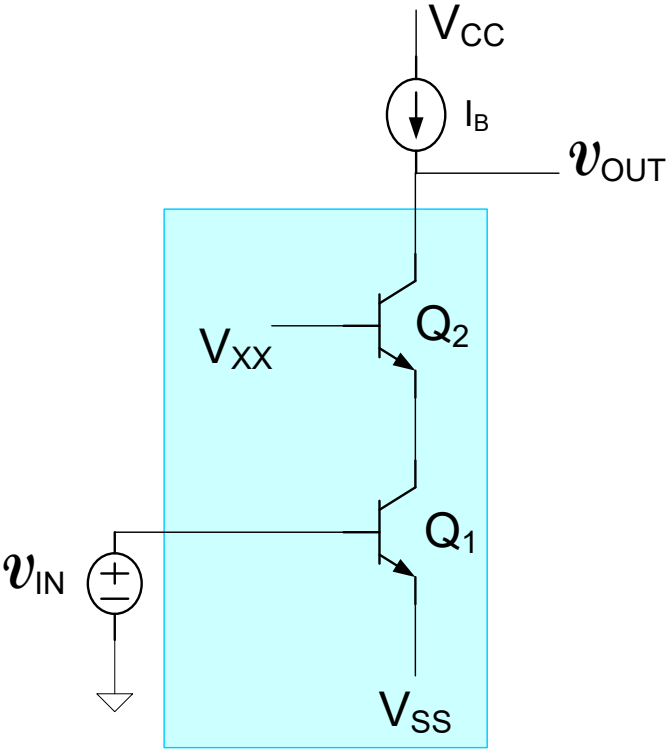
$$M=\left[\frac{2W_1}{2W_1}\bullet\frac{L_1}{L_1}\right]=1$$

- Individual transistors often decomposed into parallel multiple unary devices connected in parallel
- Common-Centroid layout approach widely used to minimize (ideally cancel) gradient effects in matching-critical circuits
- Applications extend well beyond current mirrors
- More than 2 devices can share a common centroid

Review From Previous Lecture

Cascode Configuration

Discuss



$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{02}}\beta\right] \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

$$g_{0CC} \cong \frac{g_{02}}{\beta}$$

$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta = \left[\frac{2V_{AF}}{V_t}\right]\beta = [-8000]100$$

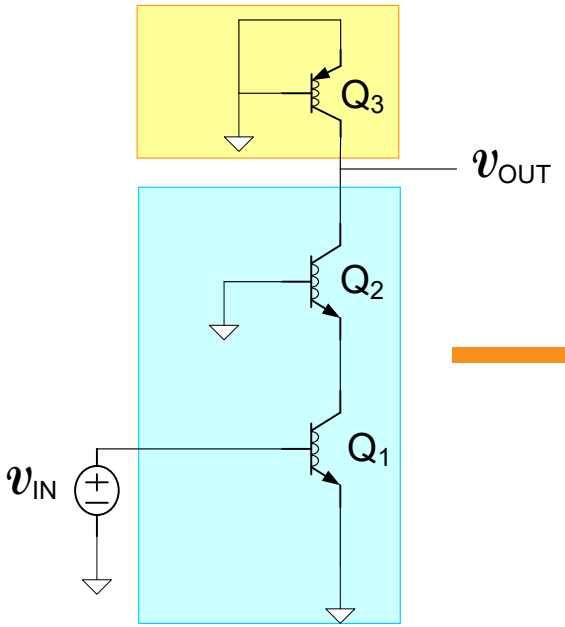
$$A_{VCC} \cong -800{,}000$$

This gain is very large and only requires two transistors!

What happens to the gain if a transistor-level current source is used for I_B?

Review From Previous Lecture

Cascode Configuration



$$A_V \cong A_{VCC}\left[\frac{g_{0CC}}{g_{03}}\right] \cong \frac{A_{VCC}}{\beta}$$

But recall

$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

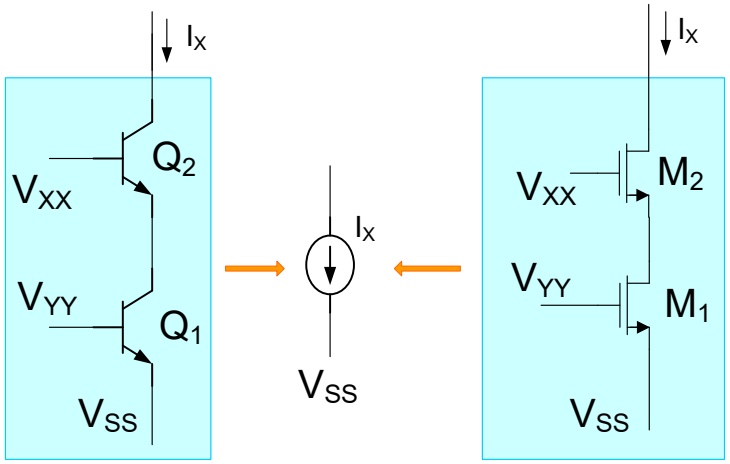
Thus

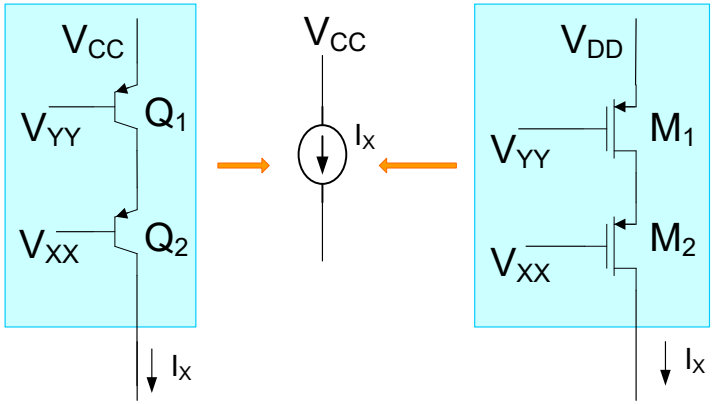
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

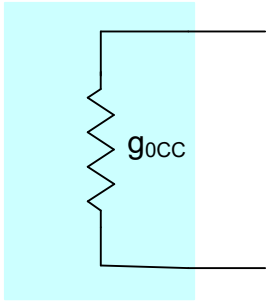
$$A_V \cong -\left[\frac{I_{CQ}/V_t}{I_{CQ}/V_{AF}}\right] = -\left[\frac{V_{AF}}{V_t}\right] \cong -8000$$

- **This is still a factor of 2 better than that of the CE amplifier with transistor current source** $\left(A_{VCE} \cong -\left[\frac{g_{m1}}{2g_{01}}\right]\right)$
- **It only requires one additional transistor**
- **But its not nearly as good as the gain the cascode circuit seemed to provide**

Cascode current sources







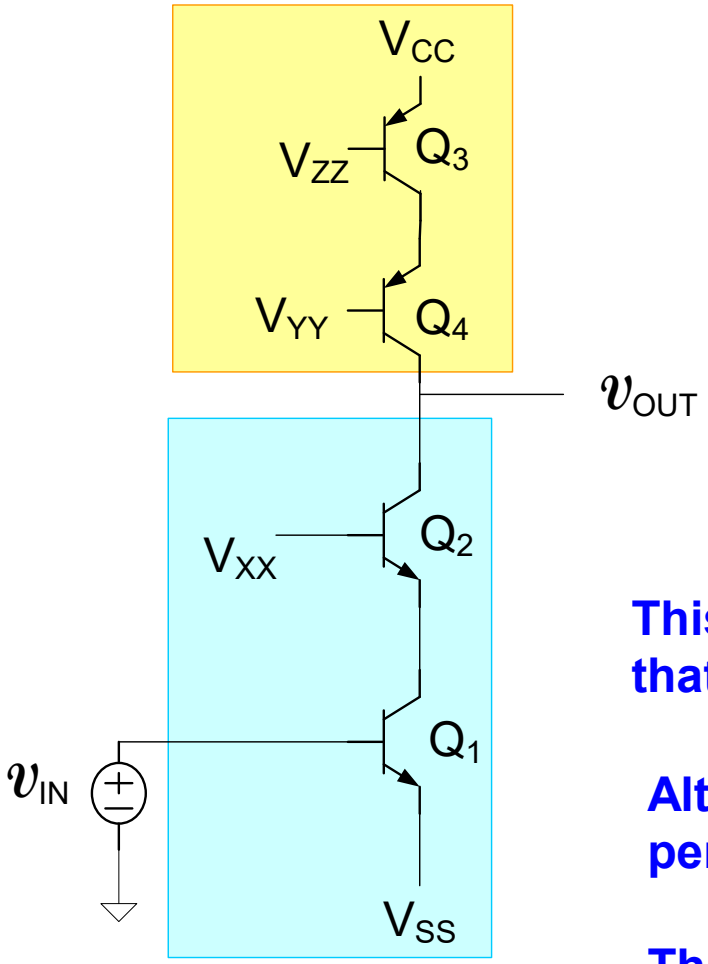
All have the same small-signal model

$$g_{0CC} = \left[\frac{g_{02}\left(g_{01}+g_{\pi 2}\right)}{g_{01}+g_{02}+g_{\pi 2}+g_{m2}} \right]$$

Review From Previous Lecture

Cascode Configuration

Discuss



$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

$$A_V = -[8000]\frac{100}{2} \cong -400{,}000$$

This gain is very large and is a factor of 2 below that obtained with an ideal current source biasing

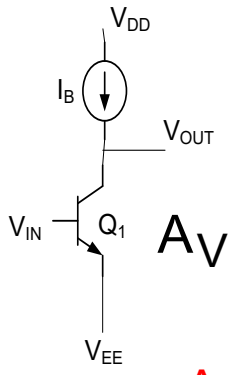
Although the factor of 2 is not desired, the performance of this circuit is still very good

This factor of 2 gain reduction is that same as was observed for the CE amplifier when a transistor-level current source was used

Review From Previous Lecture

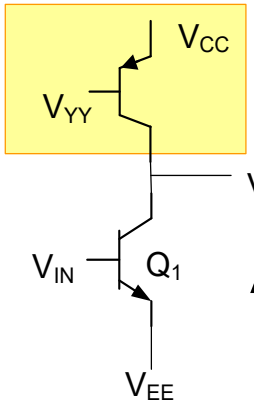
Cascode Configuration Comparisons

Discuss



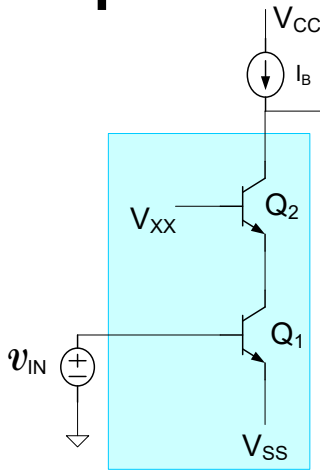
$$A_V = \frac{-g_m}{g_0}$$

A_V= -8,000



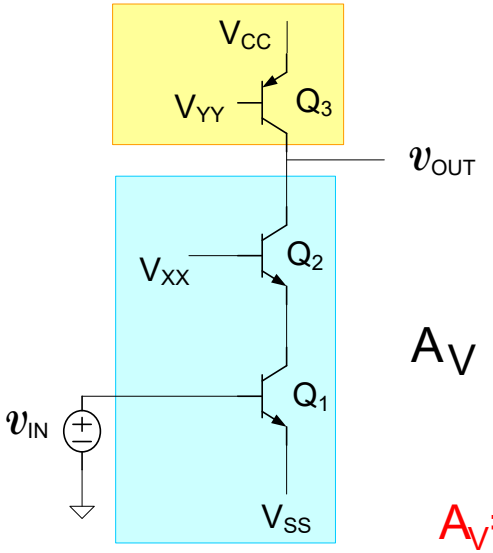
$$A_V \cong \frac{-g_{m1}}{2g_{01}}$$

A_V= -4,000



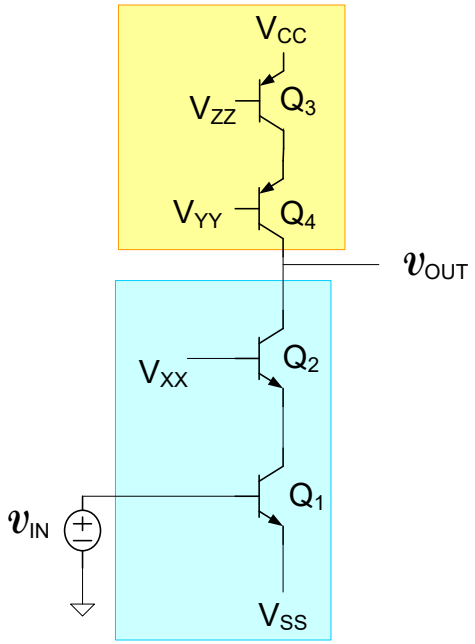
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$

A_V= -800,000



$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

A_V= -8,000

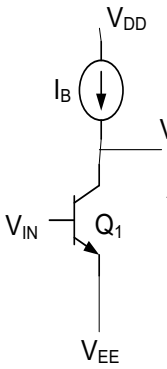


$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

A_V= -400,000

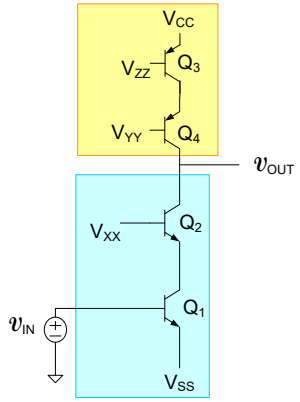
Can we use more cascoding to further increase the gain?

High Gain Amplifiers Seldom Used Open Loop



$$A_V = \frac{-g_m}{g_0}$$

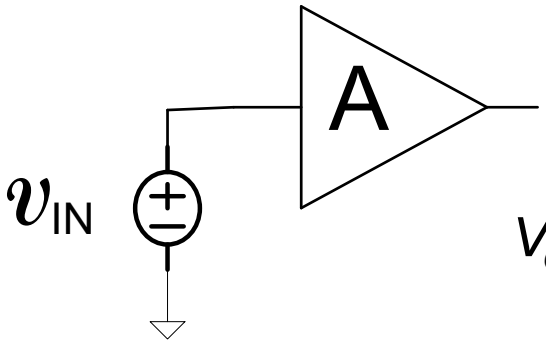
A_V= -8,000



Discuss

$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

A_V= -400,000



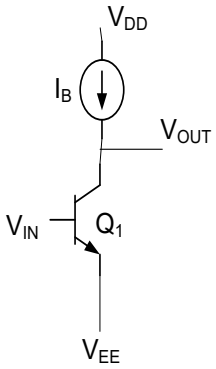
$$V_{OUT} = A\,v_{IN} + V_{OUTQ}$$

If A_V=-400,000 and V_{IN} increases by 1mV, what would happen at the output?

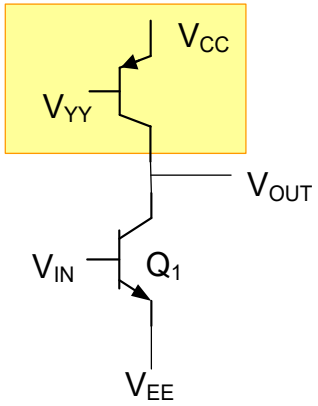
V_{OUT} would decrease by 400,000 x 1mV=-400V

Review From Previous Lecture

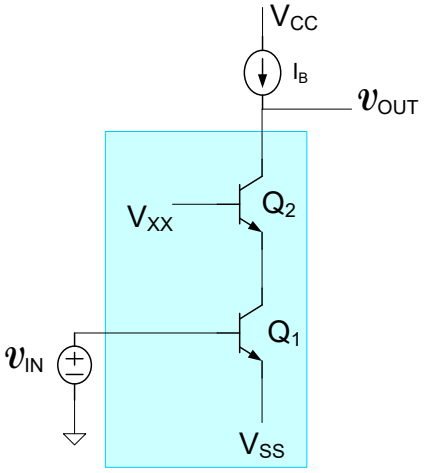
High Gain Amplifier Comparisons (BJT)



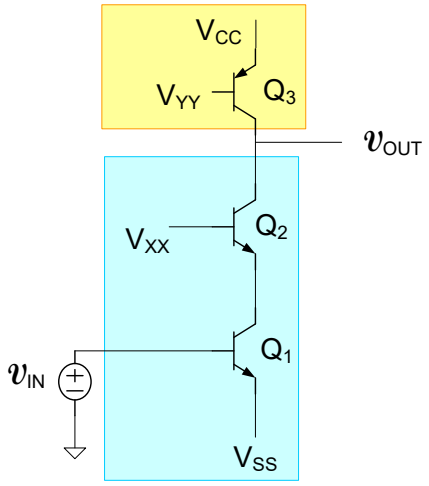
$$A_V = \frac{-g_m}{g_0}$$



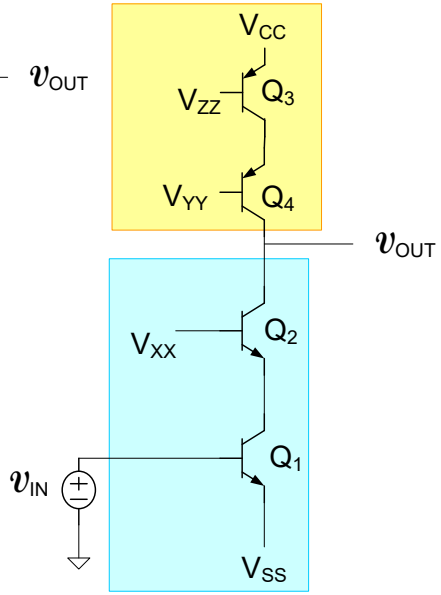
$$A_V \cong -\frac{1}{2}\frac{g_{m1}}{g_{01}}$$



$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]\beta$$



$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$

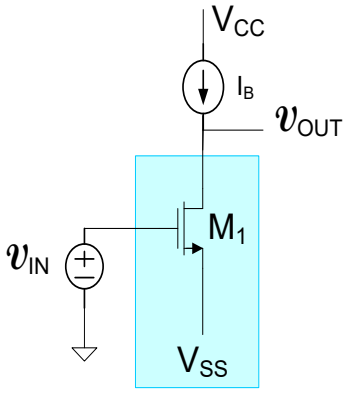


$$A_V = -\left[\frac{g_{m1}}{g_{01}}\right]\frac{\beta}{2}$$

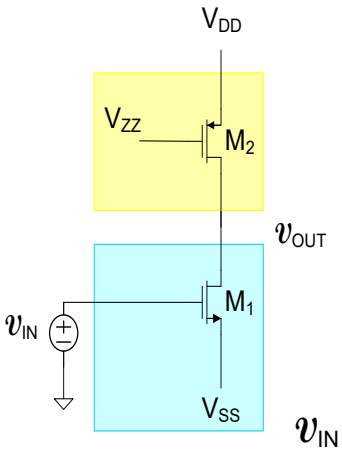
- Single-ended high-gain amplifiers inherently difficult to bias (because of the high gain)
- Biasing becomes practical when used in differential applications
- These structures are widely used but usually with differential inputs

Review From Previous Lecture

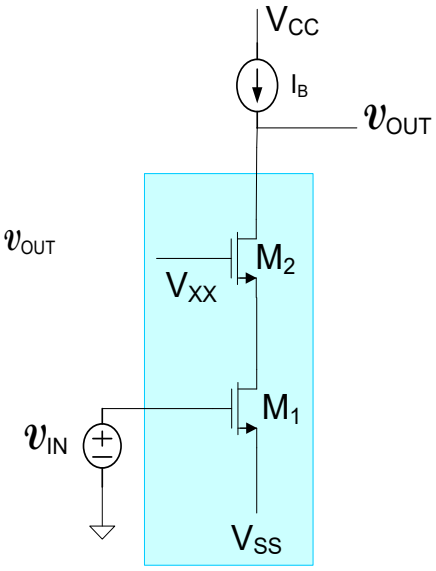
High Gain Amplifier Comparisons (n-ch MOS)



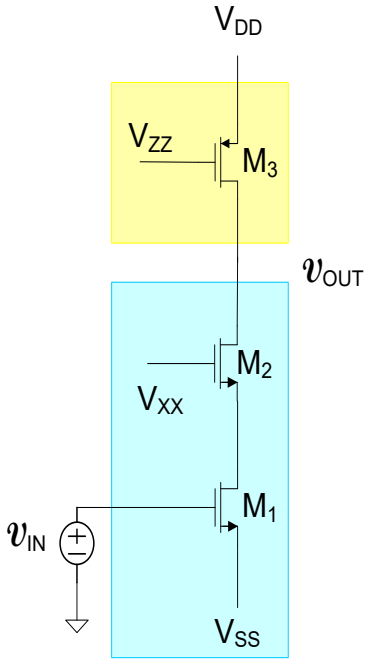
$$A_V \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$



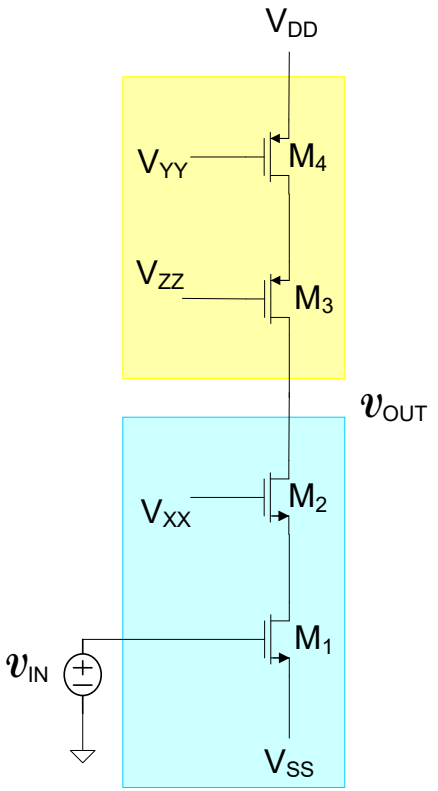
$$A_V \cong -\frac{1}{2}\left[\frac{g_{m1}}{g_{01}}\right]$$



$$A_{VCC} \cong -\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$



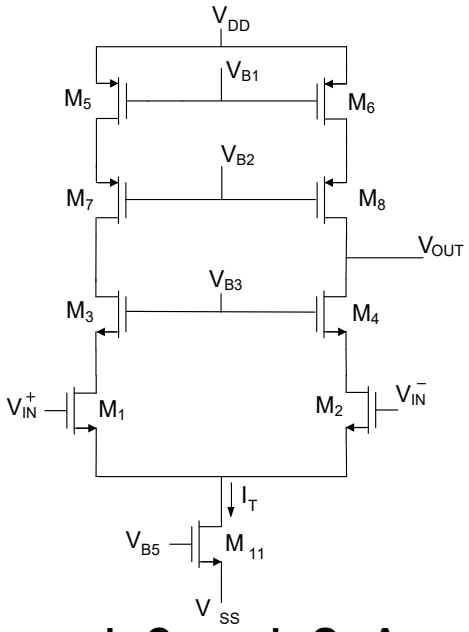
$$A_{VCC} \cong -\left[\frac{g_{m1}}{g_{01}}\right]$$



$$A_{VCC} \cong -\frac{1}{2}\left[\frac{g_{m1}g_{m2}}{g_{01}g_{02}}\right]$$

The Cascode Amplifier

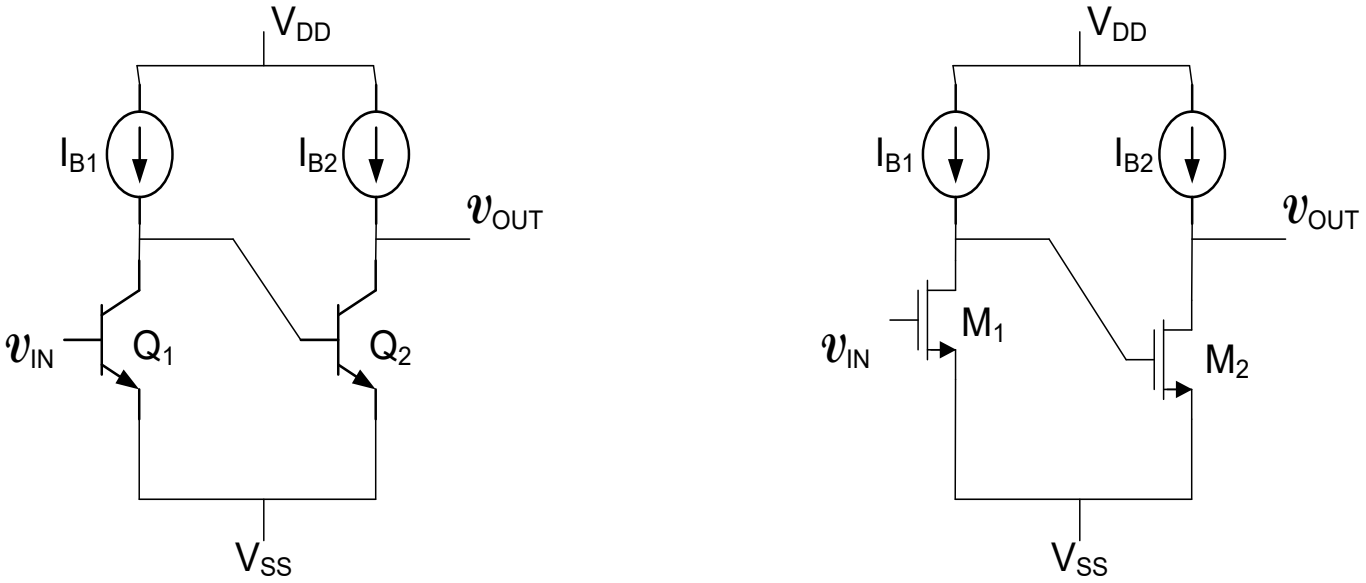
- Operational amplifiers often built with basic cascode configuration
- CMFB used to address the biasing problem
- Usually configured as a differential structure when building op amps
- Have high output impedance (but can be bufferred)
- Terms “telescopic cascode”, “folded-cascode”, and “regulated cascode” often refer to op amps based upon the cascode configuration



Telescopic Cascode Op Amp

(CMFB feedback biasing not shown)

Cascade Configurations

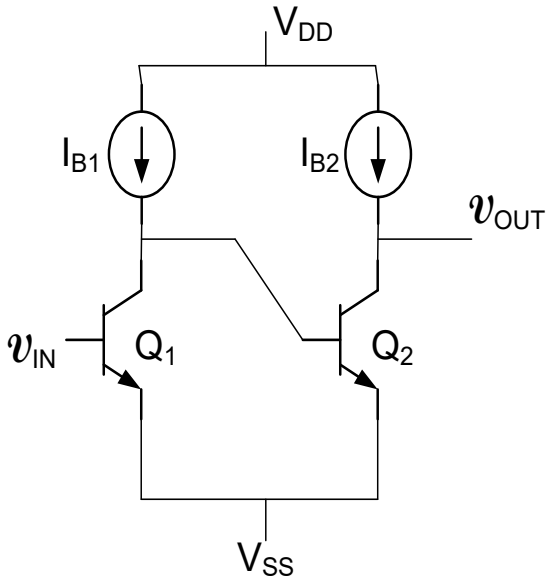


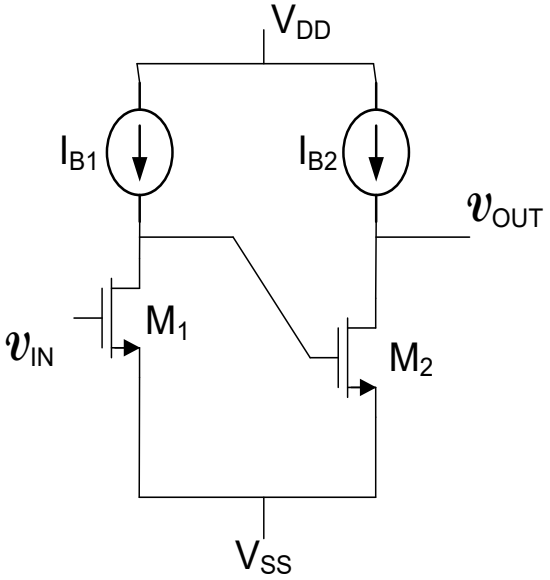
Two-stage CE:CE or CS:CS Cascade

$$A_{VCB} = ?$$

$$A_{VCM} = ?$$

Cascade Configurations





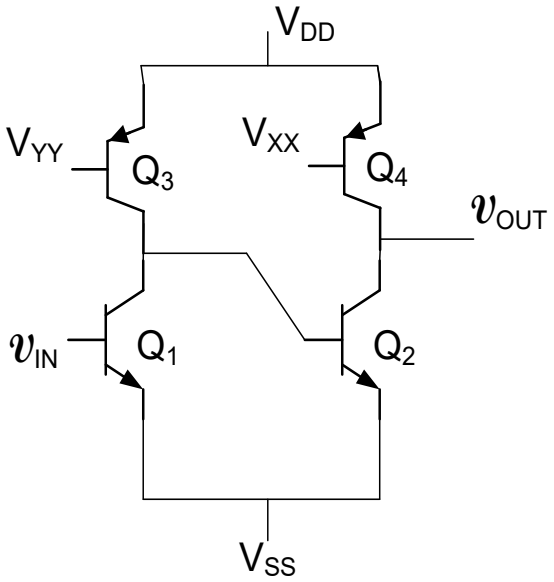
Two-stage CE:CE or CS:CS Cascade

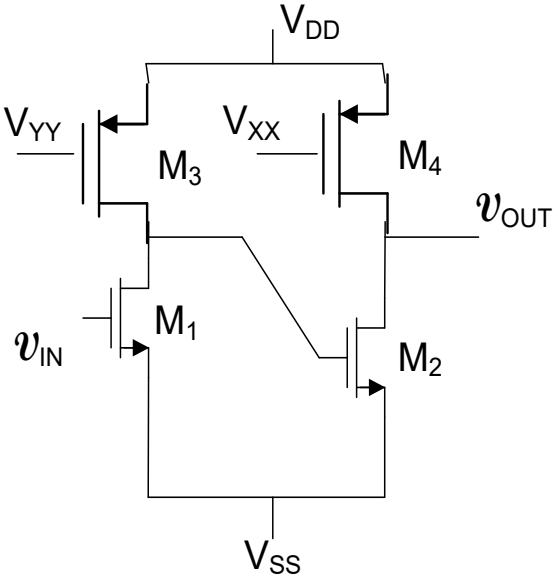
$$A_{VCB} \cong \left[\frac{-g_{m1}}{g_{01}+g_{\pi 2}}\right]\left[\frac{-g_{m2}}{g_{02}}\right] \cong \frac{g_{m1}g_{m2}}{g_{\pi 2}g_{02}} = \beta\frac{g_{m1}}{g_{02}}$$

$$A_{VCM} = \left[\frac{-g_{m1}}{g_{01}}\right]\left[\frac{-g_{m2}}{g_{02}}\right] = \frac{g_{m1}g_{m2}}{g_{01}g_{02}}$$

- **Significant increase in gain**
- **Gain is noninverting**
- **Comparable to that obtained with the cascode but noninverting**

Cascade Configurations





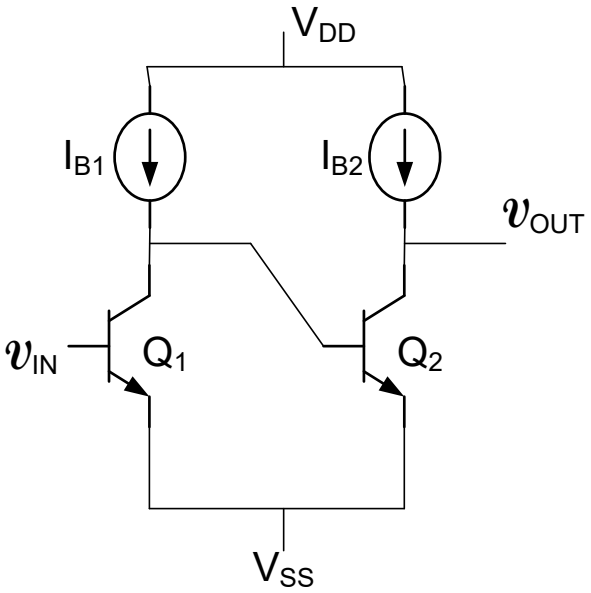
Two-stage CE:CE or CS:CS Cascade

$$A_{VCB} \cong \left[\frac{-g_{m1}}{g_{01}+g_{03}+g_{\pi 2}}\right]\left[\frac{-g_{m2}}{g_{02}+g_{04}}\right] \cong \frac{g_{m1}g_{m2}}{2g_{\pi 2}g_{02}} = \beta\frac{g_{m1}}{2g_{02}}$$

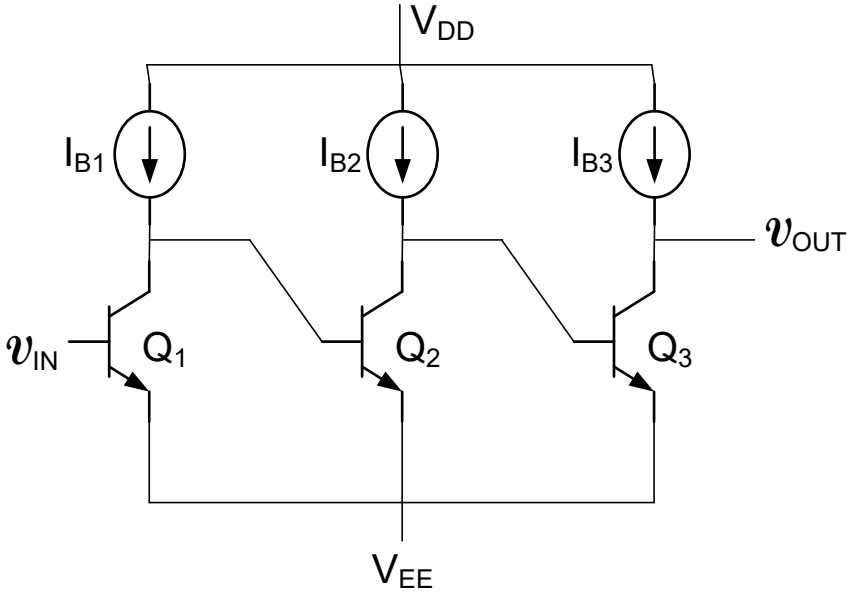
$$A_{VCM} = \left[\frac{-g_{m1}}{g_{01}+g_{03}}\right]\left[\frac{-g_{m2}}{g_{02}+g_{04}}\right] = \frac{g_{m1}g_{m2}}{4g_{01}g_{02}}$$

Note factor or 2 and 4 reduction in gain due to actual current source bias

Cascade Configurations



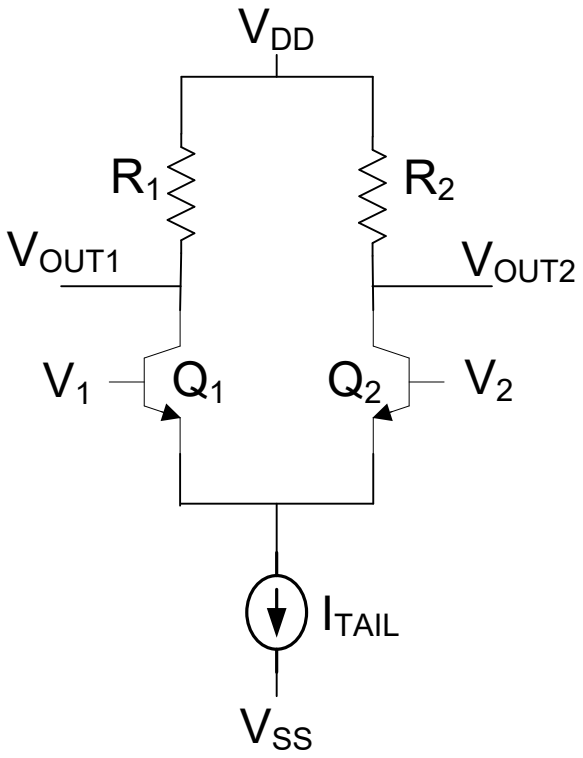
Two-stage CE Cascade



Three-stage CE Cascade

- **Large gains can be obtained by cascading**
- **Gains are multiplicative (when loading is included)**
- **Large gains used to build "Op Amps" and feedback used to control gain value**
- **Some attention is needed for biasing but it is manageable**
- **Minor variant of the two-stage cascade often used to build Op Amps**
- **Compensation of two-stage cascade needed if feedback is applied to maintain stability**
- **For many years three or more stages were seldom cascaded because of challenges in compensation to maintain stability though recently some industrial adoptions**

Differential Amplifiers



Basic operational amplifier circuit

Amplifier Biasing

Amplifier biasing is that part of the design of a circuit that establishes the desired operating point (or Q-point)

Goal is to invariably minimize the impact the biasing circuit has on the small-signal performance of a circuit

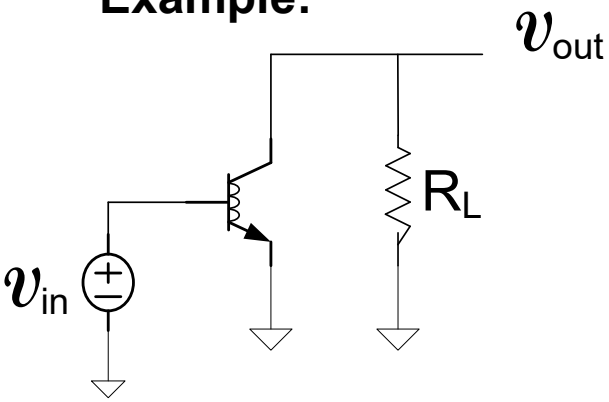
Usually at most 2 dc power supplies are available and these are often fixed in value by system requirements – this restriction is cost driven

Discrete amplifiers invariable involve adding biasing resistors and use capacitor coupling and bypassing

Integrated amplifiers often use current sources which can be used in very large numbers and are very inexpensive

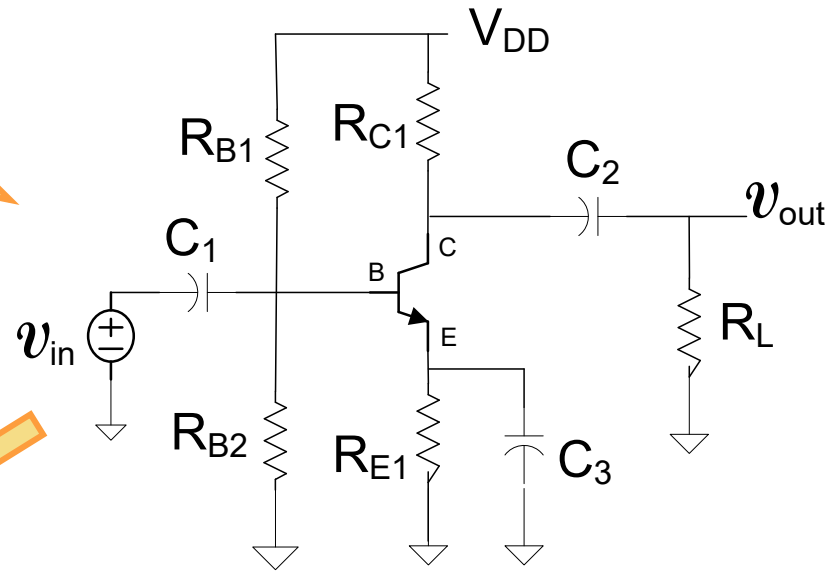
Amplifier Biasing

Example:

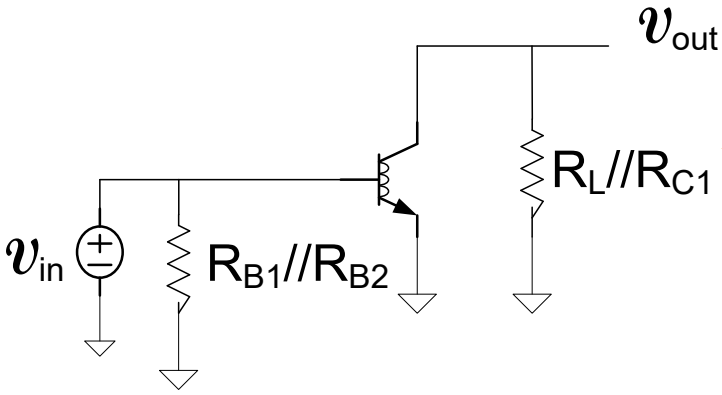


$$A_V = -g_m R_L$$

Desired small-signal circuit
Common Emitter Amplifier



Biased circuit

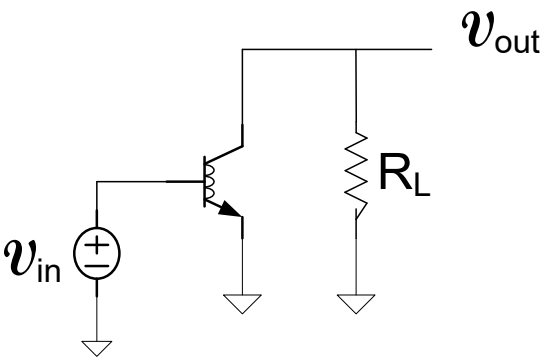


Actual small-signal circuit

$$A_V = -g_m \left(R_L // R_{C1} \right)$$

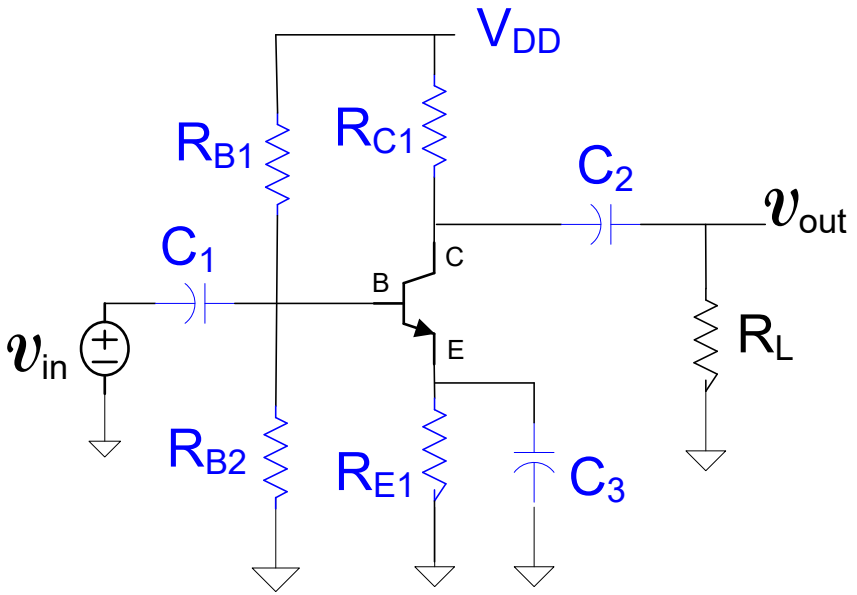
Amplifier Biasing

Example:



Desired small-signal circuit
Common Emitter Amplifier

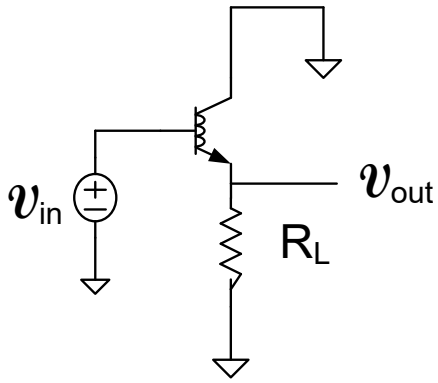
Biasing components shown in blue



Biased small-signal circuit

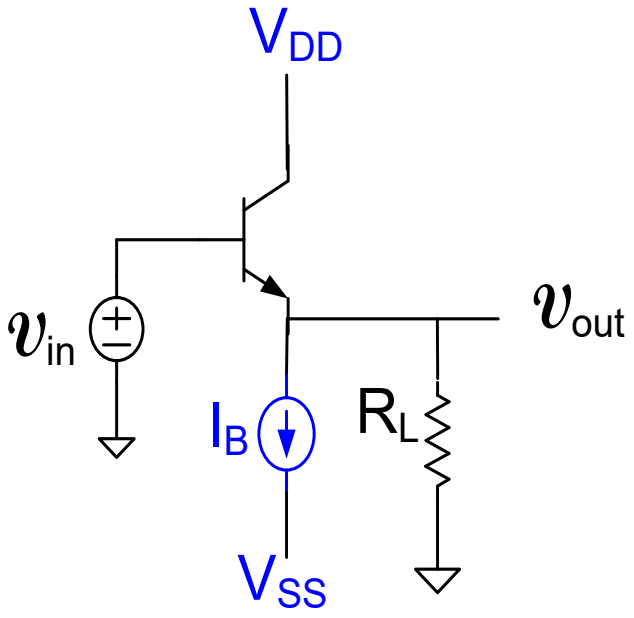
Amplifier Biasing

Example:



Desired small-signal circuit
Common Collector Amplifier

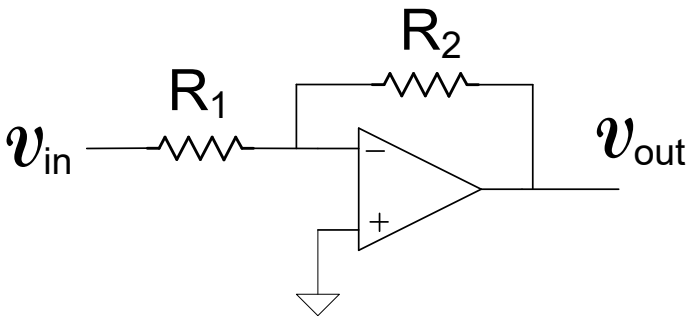
Biasing components shown in blue



Biased circuit

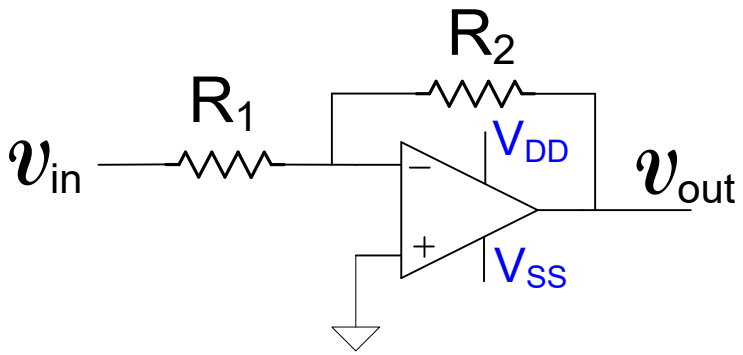
Amplifier Biasing

Example:



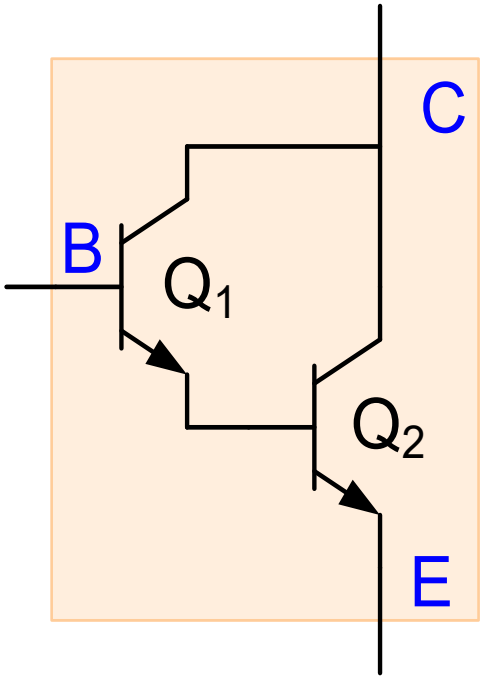
Desired small-signal circuit
Inverting Feedback Amplifier

Biasing components shown in blue

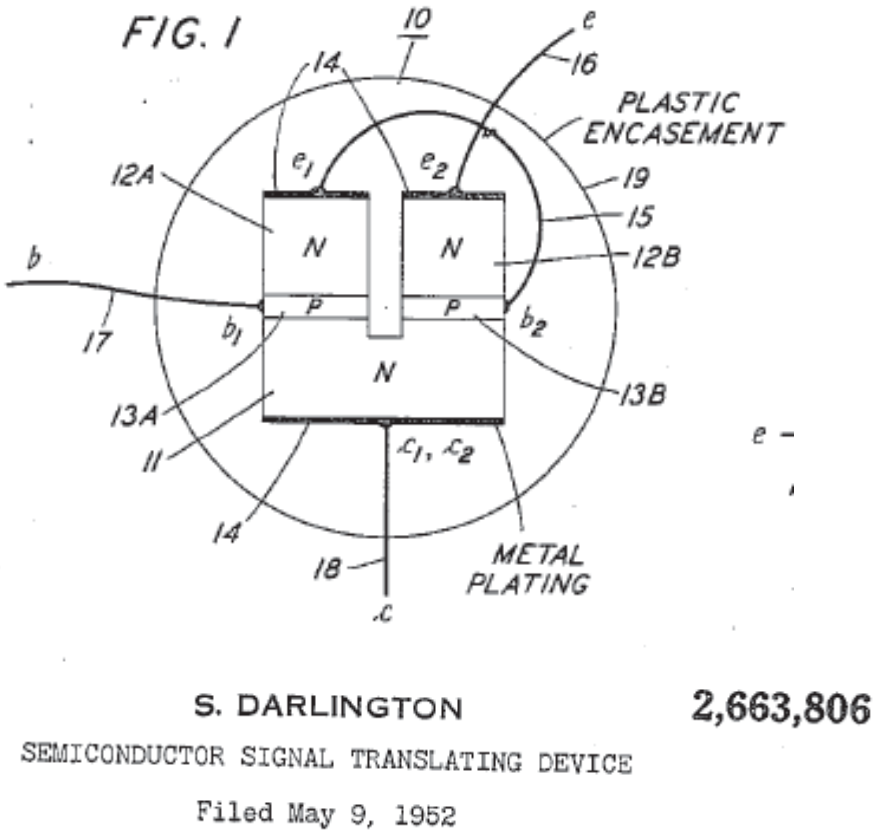


Biased circuit

Other Basic Configurations

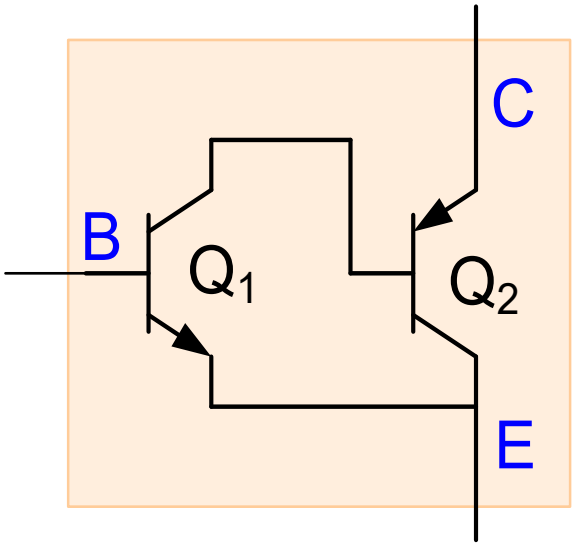


Darlington Configuration



- **Current gain is approximately β^2**
- **Two diode drop between B_{eff} and E_{eff}**

Other Basic Configurations



Sziklai Pair

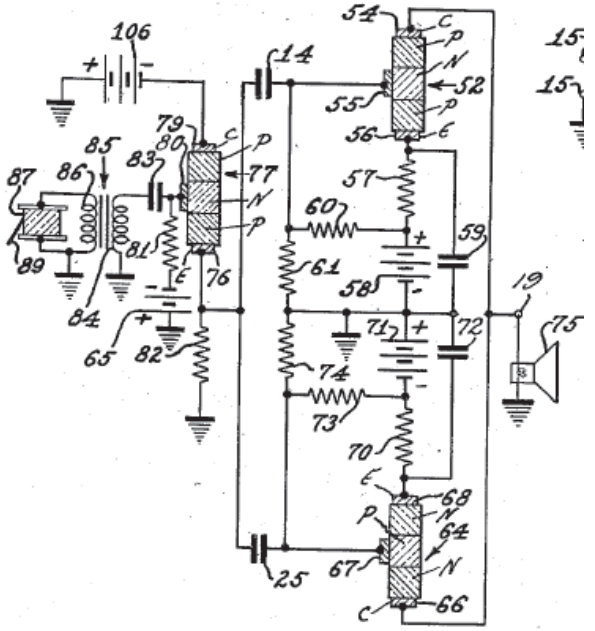


FIG. 3.

May 7, 1957 G. C. SZIKLAI 2,791,644

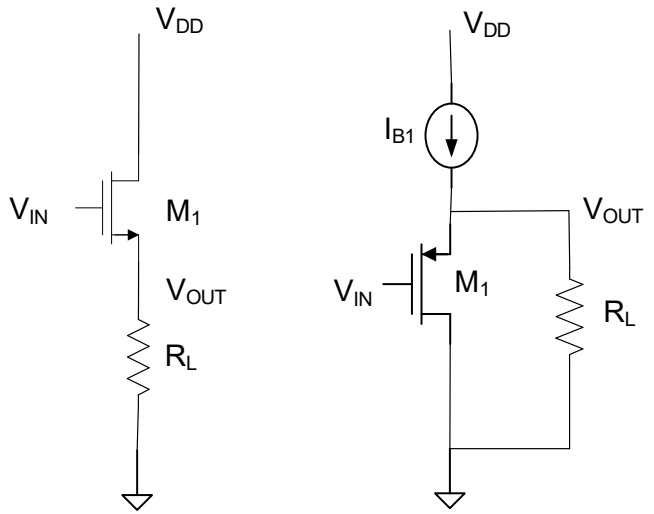
PUSH-PULL AMPLIFIER WITH COMPLEMENTARY TYPE TRANSISTORS

Filed Nov. 7, 1952

- **Gain similar to that of Darlington Pair**
- **Current gain is approximately $\beta_n \beta_p$**
- **Current gain will not be as large when $\beta_p < \beta_n$**
- **Only one diode drop between B_{eff} and E_{eff}**

Other Basic Configurations

Buffer



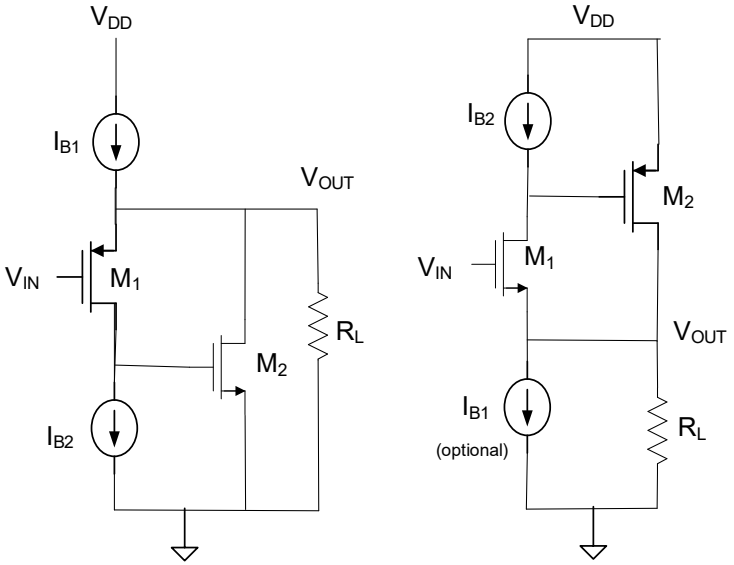
Ideally $V_{OUT}=V_{IN}$

Assume load terminated on gnd

Current through M_1 changes with V_{IN}

Voltage shift varies with V_{IN} in buffer

Super Buffer



Ideally $V_{OUT}=V_{IN}$

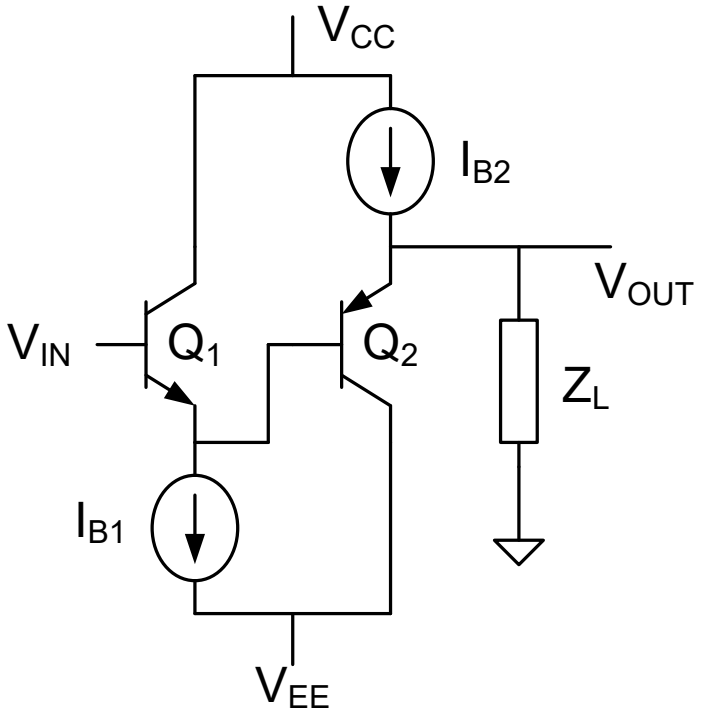
Assume load terminated on gnd

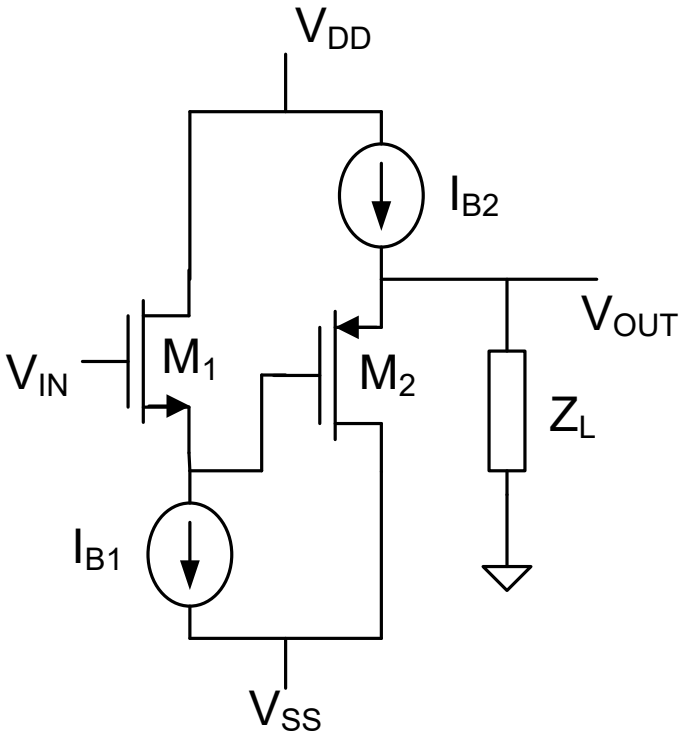
Current through shift transistor is constant for Super Buffer as V_{IN} changes so voltage shift does not change with V_{IN}

Same nominal voltage shift as buffer

Other Basic Configurations

Low offset buffers

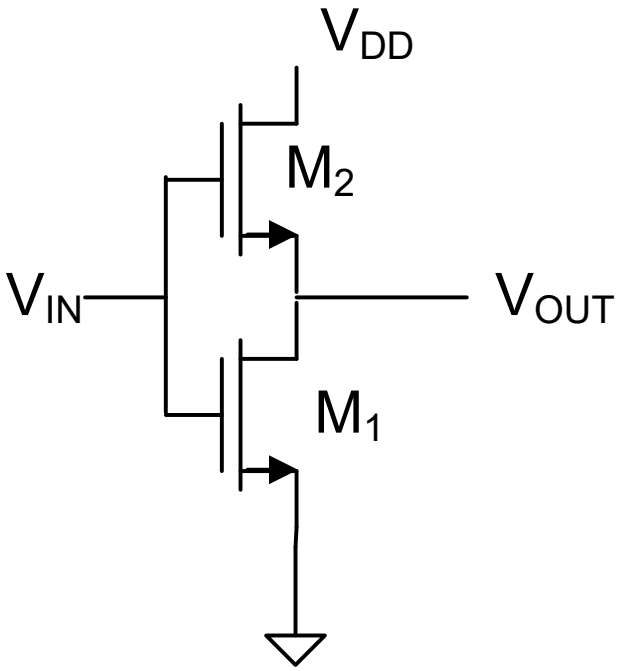


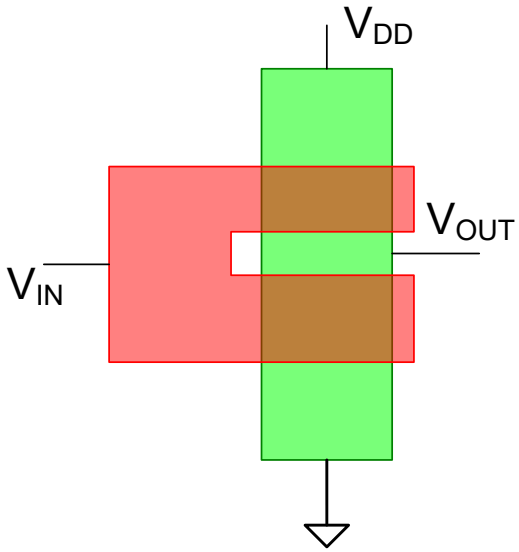


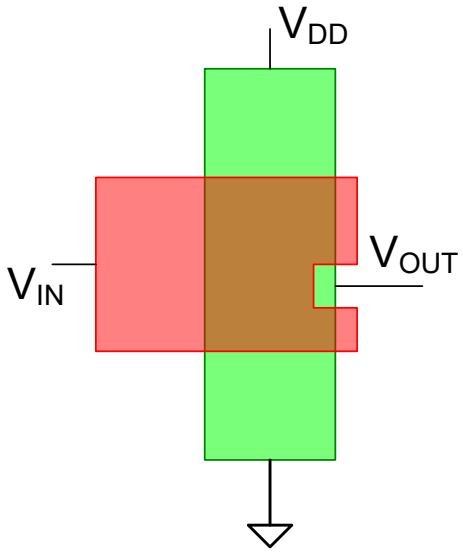
- **Actually a CC-CC or a CD-CD cascade**
- **Significant drop in offset between input and output**
- **Biasing with DC current sources**
- **Can Add Super Buffer to Output**

Other Basic Configurations

Voltage Attenuator



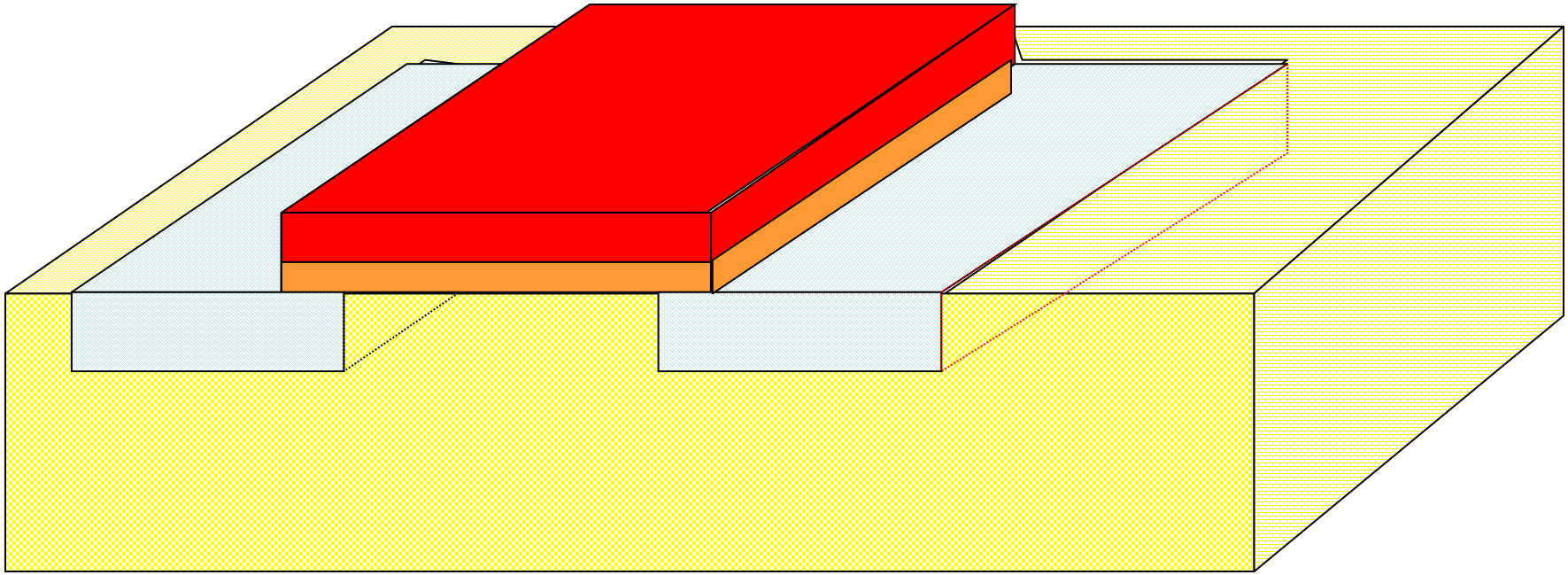




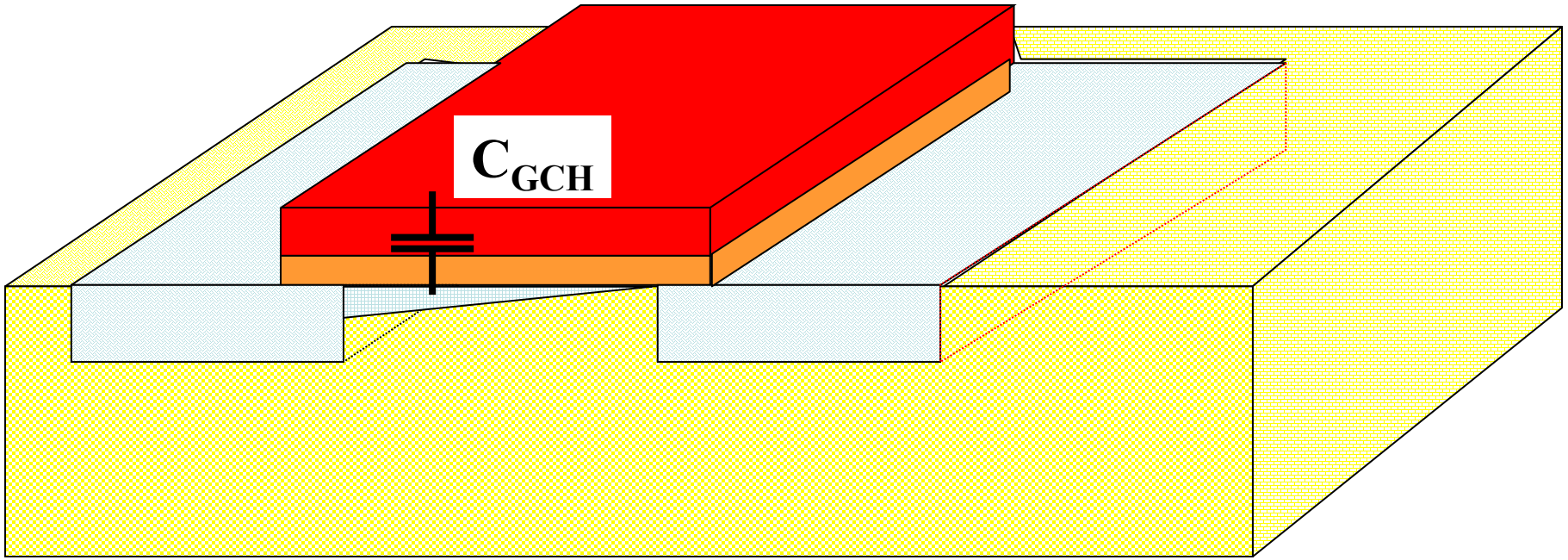
- **Attenuation factor is quite accurate (Determined by geometry)**
- **Infinite input impedance**
- **M_1 in triode, M_2 in saturation**
- **Actually can be a channel-tapped structure**

Frequency-Dependent Performance of Amplifiers

Parasitic Capacitors in MOSFET

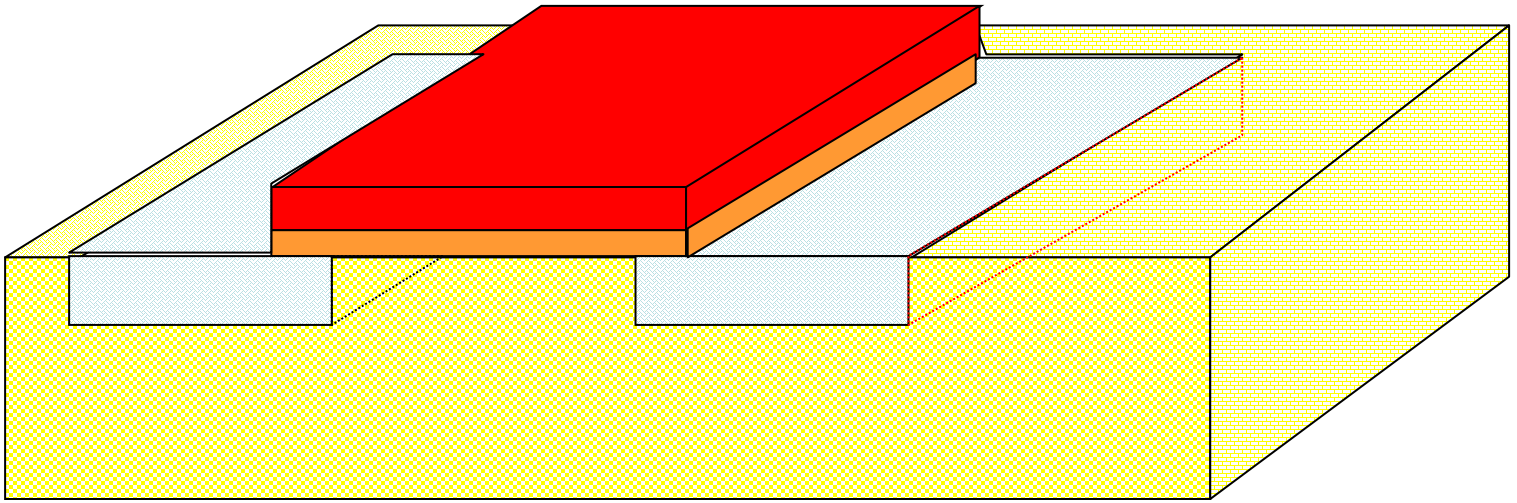


Parasitic Capacitors in MOSFET

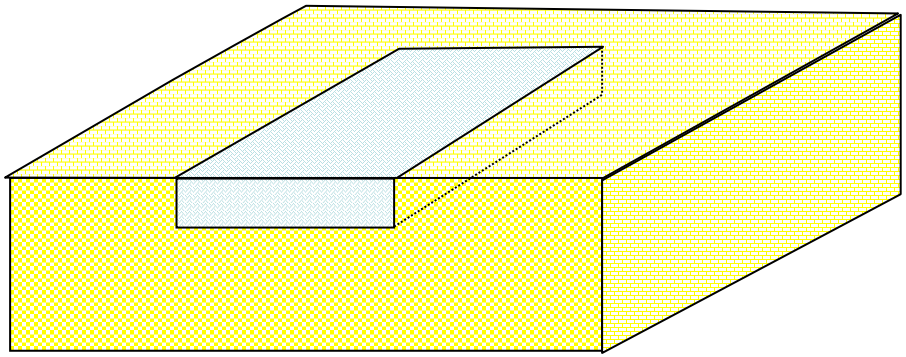


- This capacitance was modeled previously and exists when the transistor is operating in triode or saturation
- But there are others that also affect high-frequency or high-speed operation

Parasitic Capacitors in MOSFET

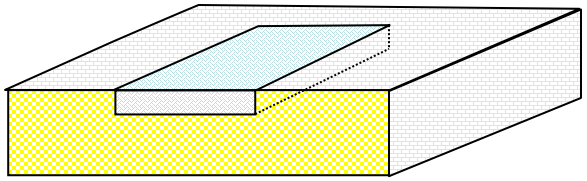


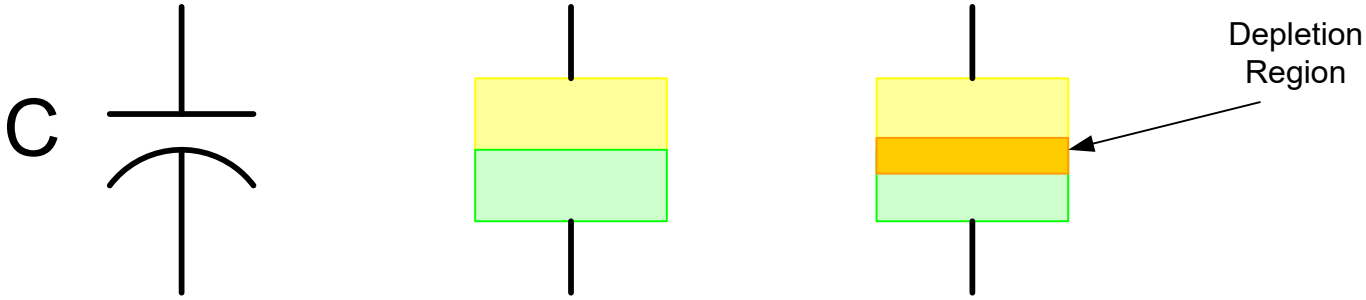
Recall that pn junctions have a depletion region!



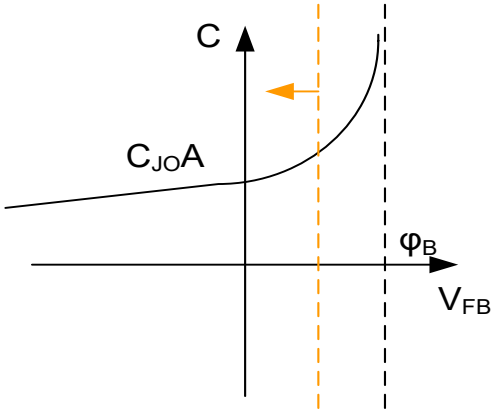
Parasitic Capacitors in MOSFET

pn junction capacitance





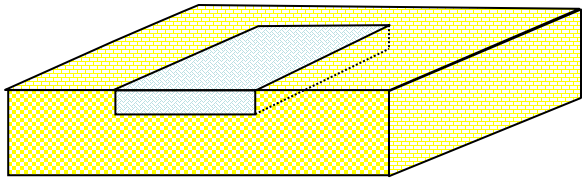
For $V_{FB}<\varphi_B/2$



$$C = \frac{C_{J0}A}{\left(1-\frac{V_{FB}}{\varphi_B}\right)^m}$$

Parasitic Capacitors in MOSFET

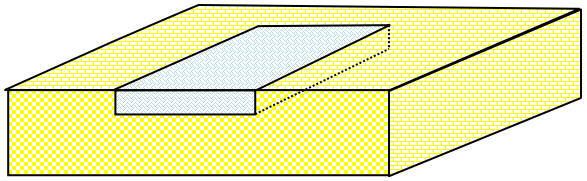
pn junction capacitance

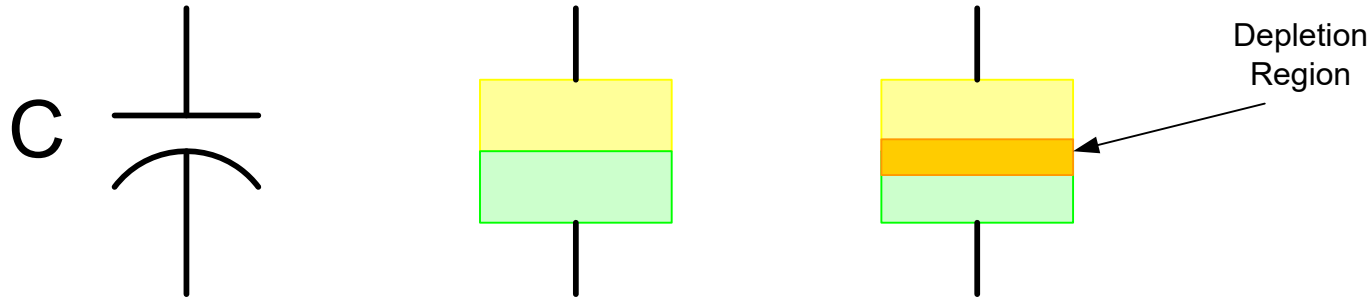


The bottom and the sidewall:

Parasitic Capacitors in MOSFET

pn junction capacitance





For a pn junction capacitor

$$C_J = C_{BOT} A + C_{SW} P$$

$$C_{BOT} = \frac{C_{BOT0}}{\left(1 - \frac{V_{FB}}{\varphi_B}\right)^m} \qquad C_{SW} = \frac{C_{SW0}}{\left(1 - \frac{V_{FB}}{\varphi_B}\right)^m}$$

A : Junction Area
P: Junction Perimeter
V_{FB}: forward bias on junction

Model Parameters:

$\{C_{BOT0}, C_{SW0}, \varphi_B, m\}$

C_{BOT} and C_{SW} are capacitance densities

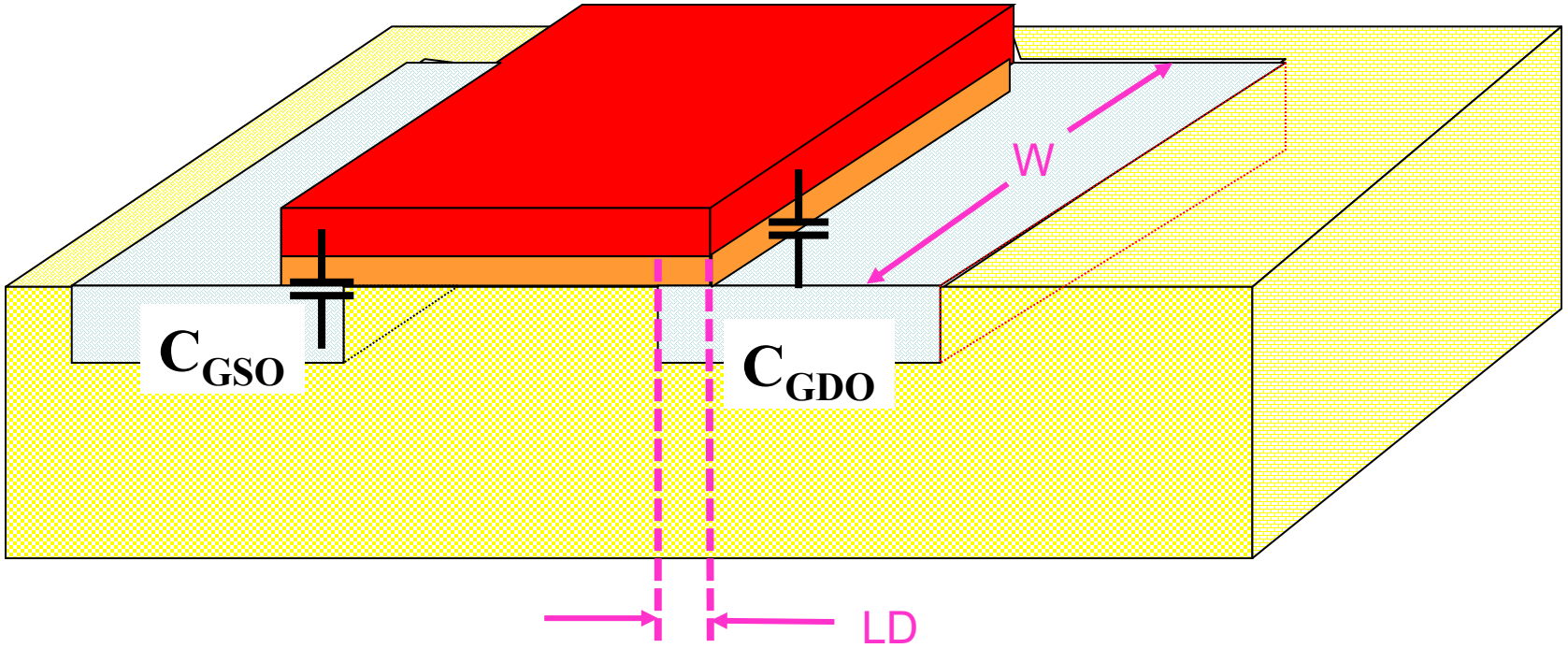
Types of Capacitors in MOSFETs

1. Fixed Capacitors
   a. Fixed Geometry
   b. Junction

2. Operating Region Dependent

Parasitic Capacitors in MOSFET

Fixed Capacitors – Fixed Geometry

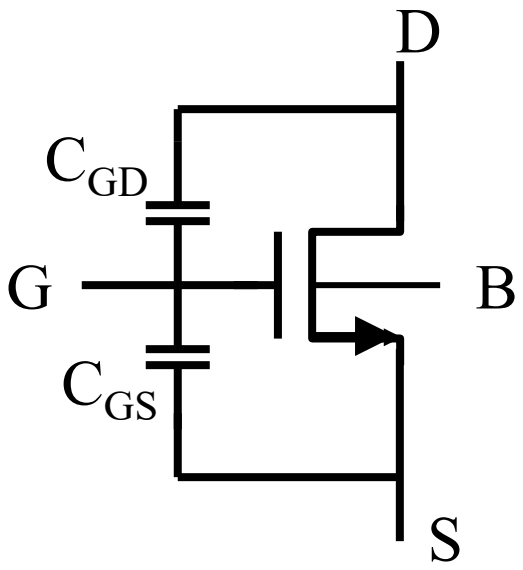


Overlap Capacitors: C_{GDO}, C_{GSO}

L_D: lateral diffusion

Cap Density: C_{OX}

Parasitic Capacitance Summary (partial)



	Cutoff	Ohmic	Saturation
C_{GSO}	$CoxWL_D$	$CoxWL_D$	$CoxWL_D$
C_{GDO}	$CoxWL_D$	$CoxWL_D$	$CoxWL_D$

L_D is a model parameter

Overlap Capacitance Model Parameters

CAPACITANCE PARAMETERS	N+	P+	POLY	M1	M2	M3	M4	M5	M6	R_W	D_N_W	M5P	N_W	UNITS
Area (substrate)	942	1163	106	34	14	9	6	5	3		123		125	aF/um^2
Area (N+active)			8484	55	20	13	11	9	8					aF/um^2
Area (P+active)			8232											aF/um^2
Area (poly)				66	17	10	7	5	4					aF/um^2
Area (metal1)					37	14	9	6	5					aF/um^2
Area (metal2)						35	14	9	6					aF/um^2
Area (metal3)							37	14	9					aF/um^2
Area (metal4)								36	14					aF/um^2
Area (metal5)									34				984	aF/um^2
Area (r well)	920													aF/um^2
Area (d well)										582				aF/um^2
Area (no well)	137													aF/um^2
Fringe (substrate)	212	235		41	35	29	21	14						aF/um
Fringe (poly)				70	39	29	23	20	17					aF/um
Fringe (metal1)					52	34		22	19					aF/um
Fringe (metal2)						48	35	27	22					aF/um
Fringe (metal3)							53	34	27					aF/um
Fringe (metal4)								58	35					aF/um
Fringe (metal5)									55					aF/um
Overlap (N+active)			895											aF/um
Overlap (P+active)			737											aF/um

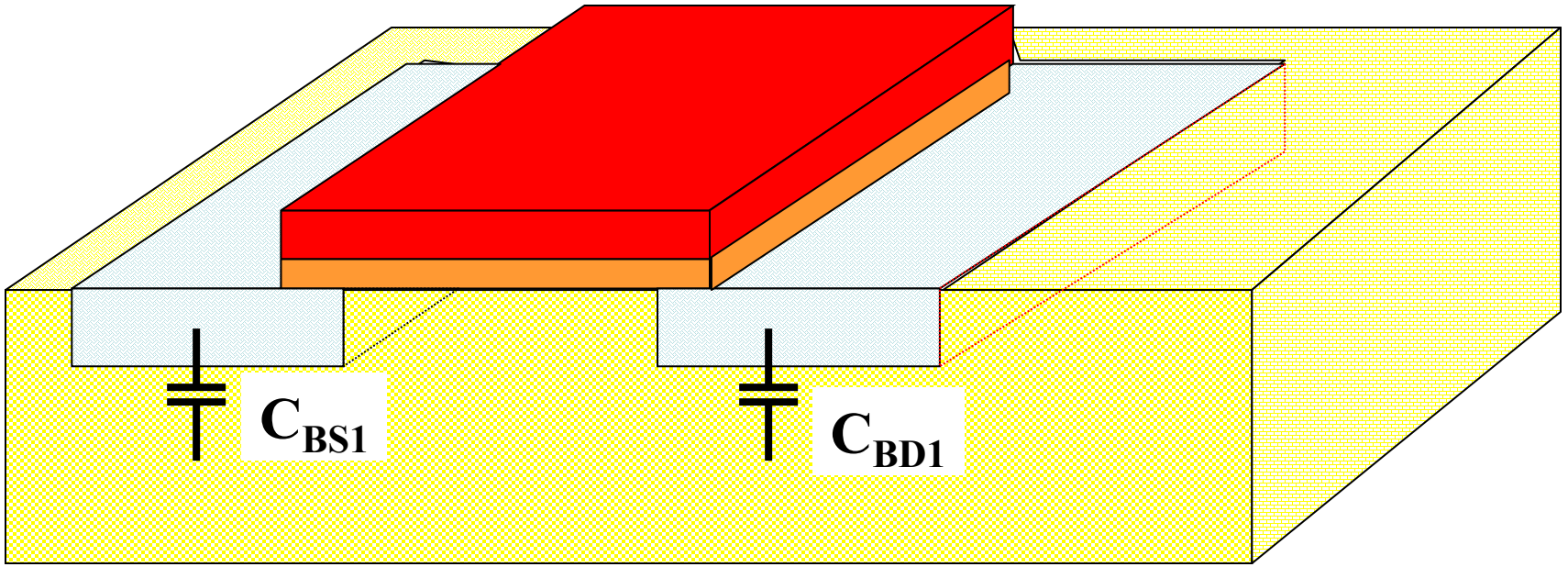
Types of Capacitors in MOSFETs

1. Fixed Capacitors
   a. Fixed Geometry
   b. Junction

2. Operating Region Dependent

Parasitic Capacitors in MOSFET

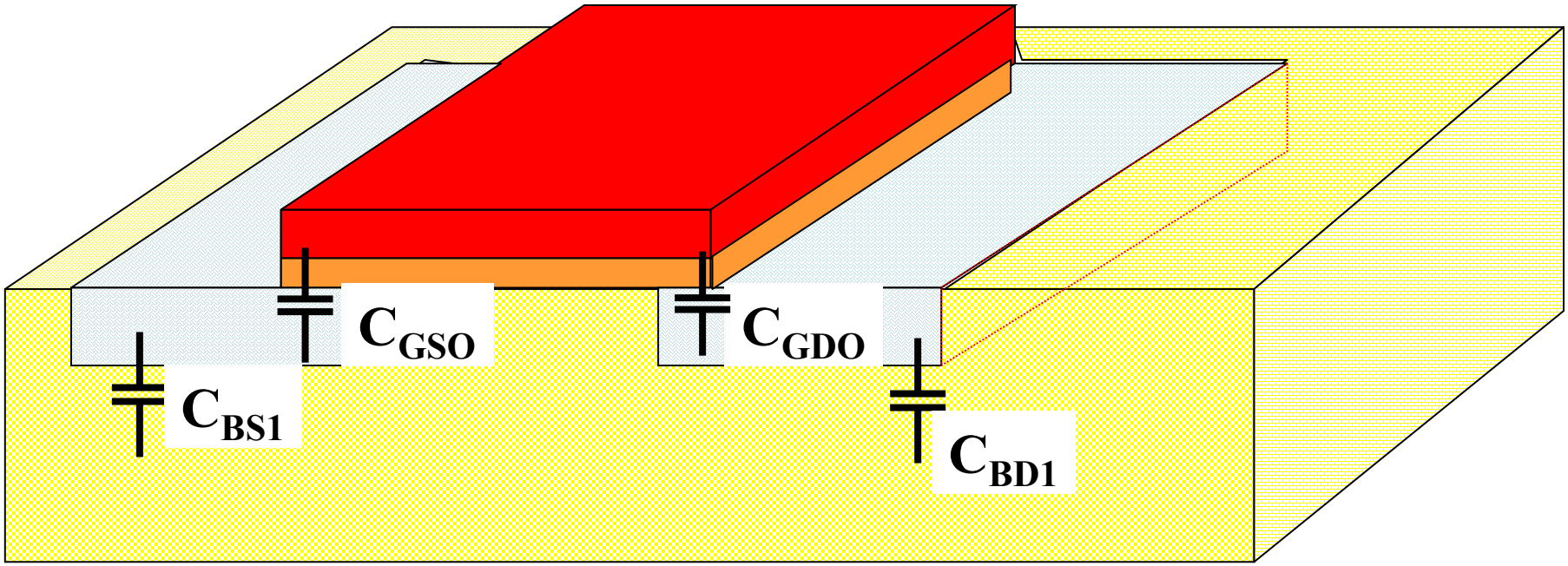
Fixed Capacitors- Junction



Junction Capacitors: C_{BS1}, C_{BD1}

Parasitic Capacitors in MOSFET

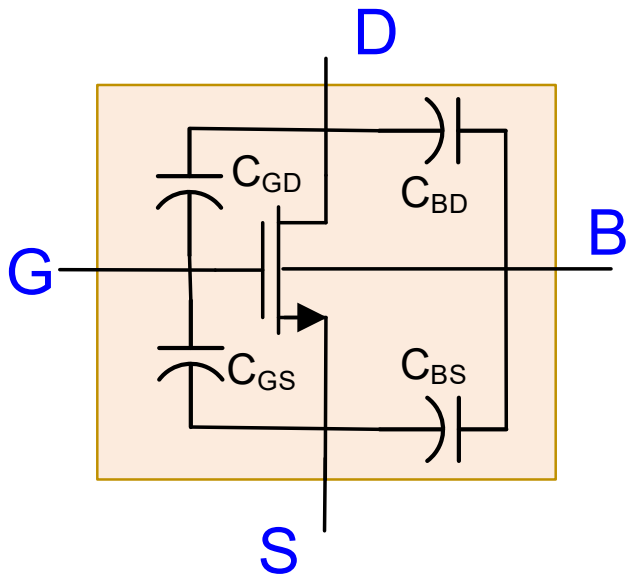
- Fixed Capacitors



Overlap Capacitors: C_{GDO}, C_{GSO}

Junction Capacitors: C_{BS1}, C_{BD1}

Fixed Parasitic Capacitance Summary



C_{BOT} and C_{SW} are model parameters

	Cutoff	Ohmic	Saturation
C_{GSO}	$CoxWL_D$	$CoxWL_D$	$CoxWL_D$
C_{GDO}	$CoxWL_D$	$CoxWL_D$	$CoxWL_D$
C_{BG}			
C_{BS}	$C_{BS1} = C_{BOT}A_S+C_{SW}P_S$	$C_{BS1} = C_{BOT}A_S+C_{SW}P_S$	$C_{BS1} = C_{BOT}A_S+C_{SW}P_S$
C_{BD}	$C_{BD1} = C_{BOT}A_D+C_{SW}P_D$	$C_{BD1} = C_{BOT}A_D+C_{SW}P_D$	$C_{BD1} = C_{BOT}A_D+C_{SW}P_D$

C_{BOT} and C_{SW} model parameters

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Area (substrate)	942	1163	106	34	14	9	6	5	3		123		125	aF/um^2
Area (N+active)			8484	55	20	13	11	9	8					aF/um^2
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Area (poly)				66	17	10	7	5	4					aF/um^2
Area (metal1)					37	14	9	6	5					aF/um^2
Area (metal2)						35	14	9	6					aF/um^2
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Area (metal4)								36	14					aF/um^2
Area (metal5)									34				984	aF/um^2
Area (r well)	920													aF/um^2
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Overlap (N+active)			895											aF/um
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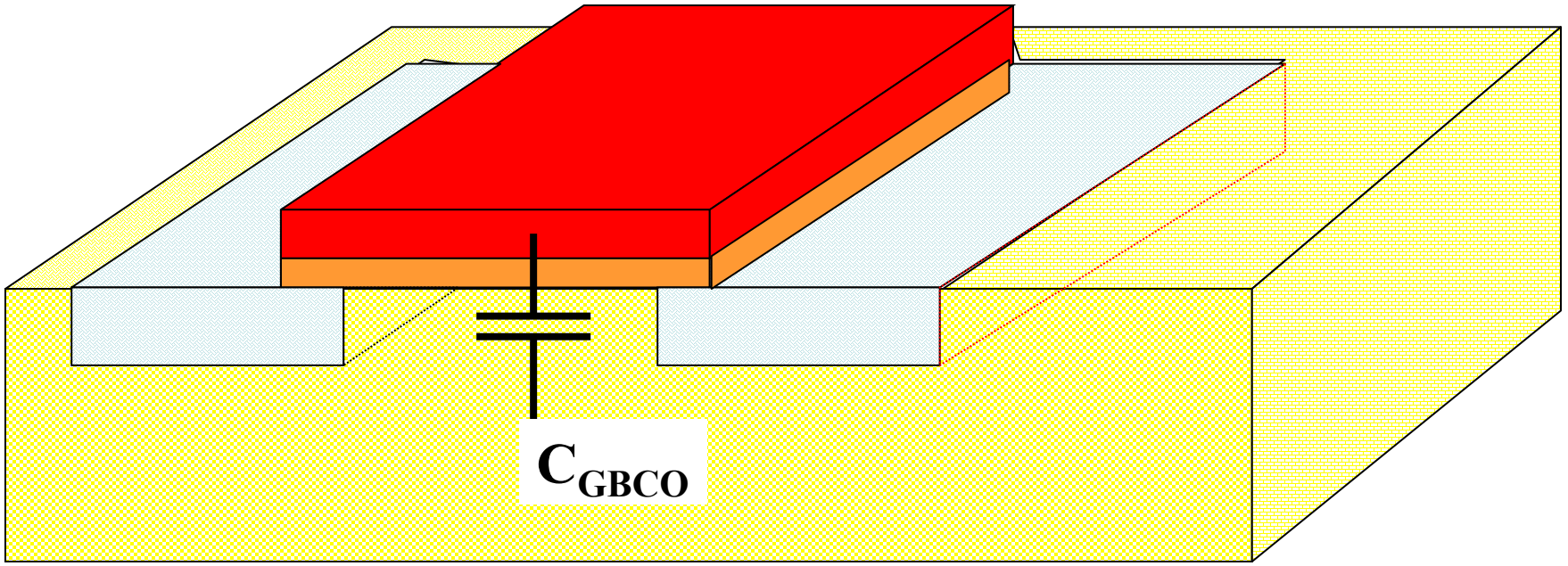
Types of Capacitors in MOSFETs

1. Fixed Capacitors
   a. Fixed Geometry
   b. Junction

2. Operating Region Dependent

Parasitic Capacitors in MOSFET

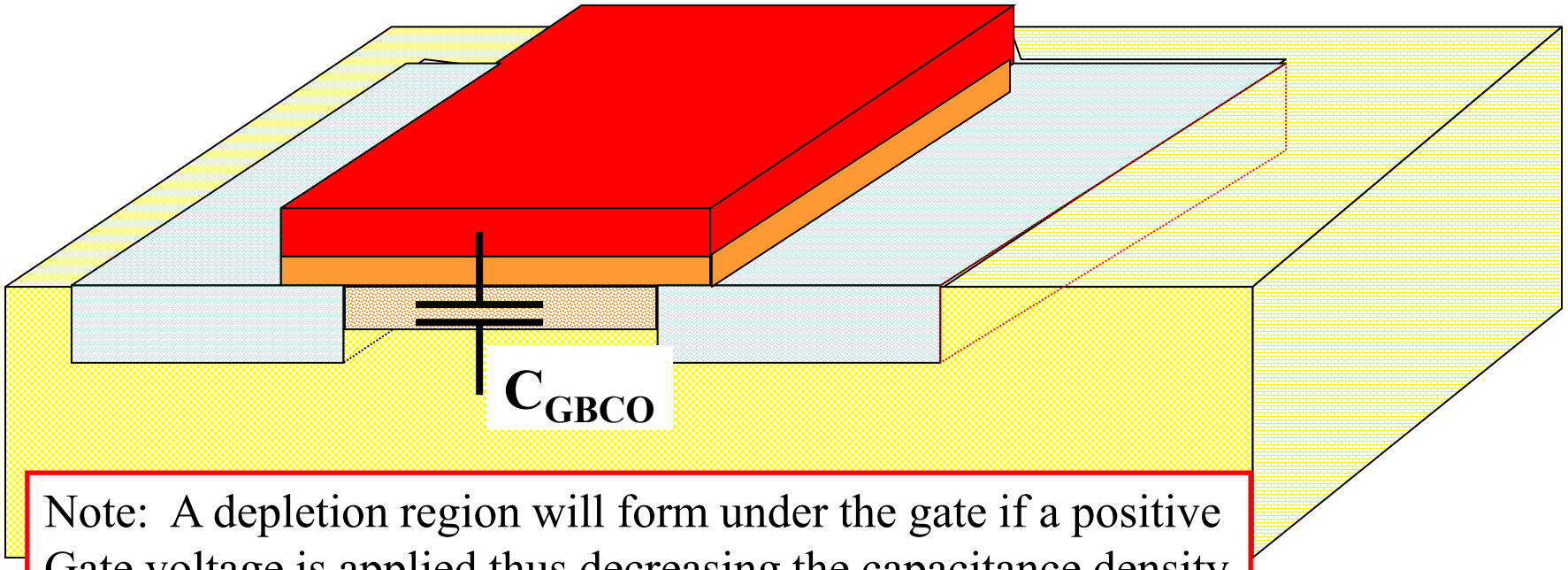
Operation Region Dependent -- Cutoff



Cutoff Capacitor: C_{GBCO}

Parasitic Capacitors in MOSFET

Operation Region Dependent -- Cutoff

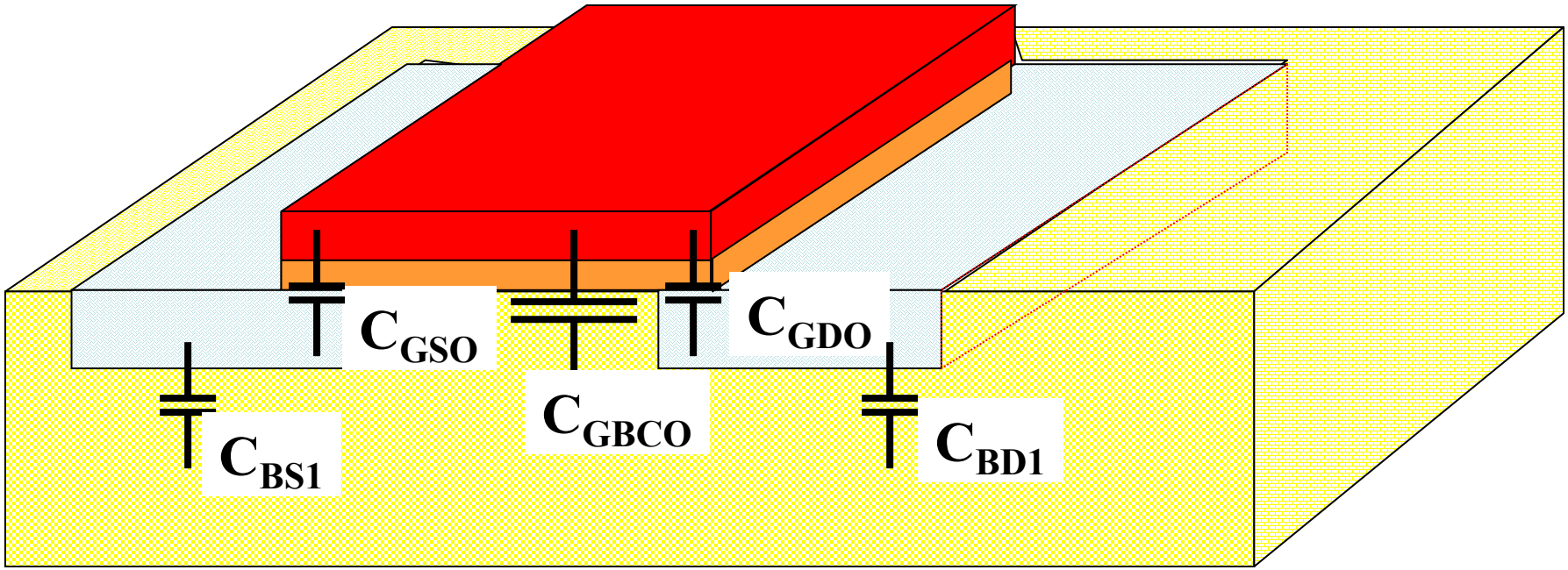


Note: A depletion region will form under the gate if a positive Gate voltage is applied thus decreasing the capacitance density

Cutoff Capacitor: C_{GBCO}

Parasitic Capacitors in MOSFET

Operation Region Dependent and Fixed -- Cutoff

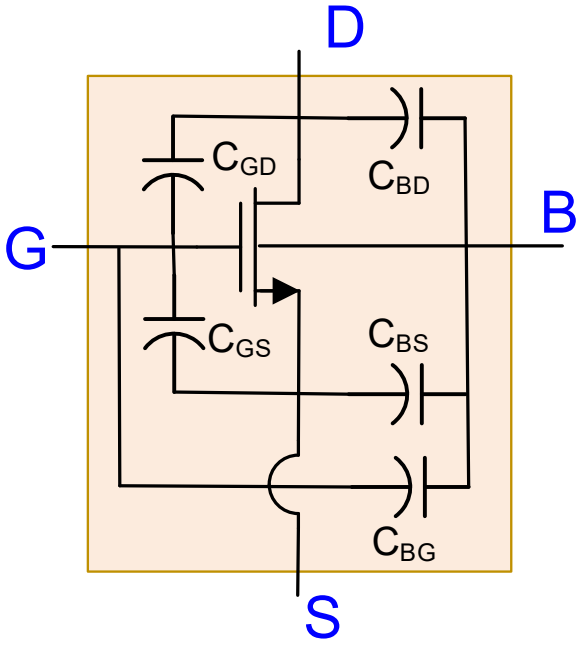


Overlap Capacitors: C_{GDO}, C_{GSO}

Junction Capacitors: C_{BS1}, C_{BD1}

Cutoff Capacitor: C_{GBCO}

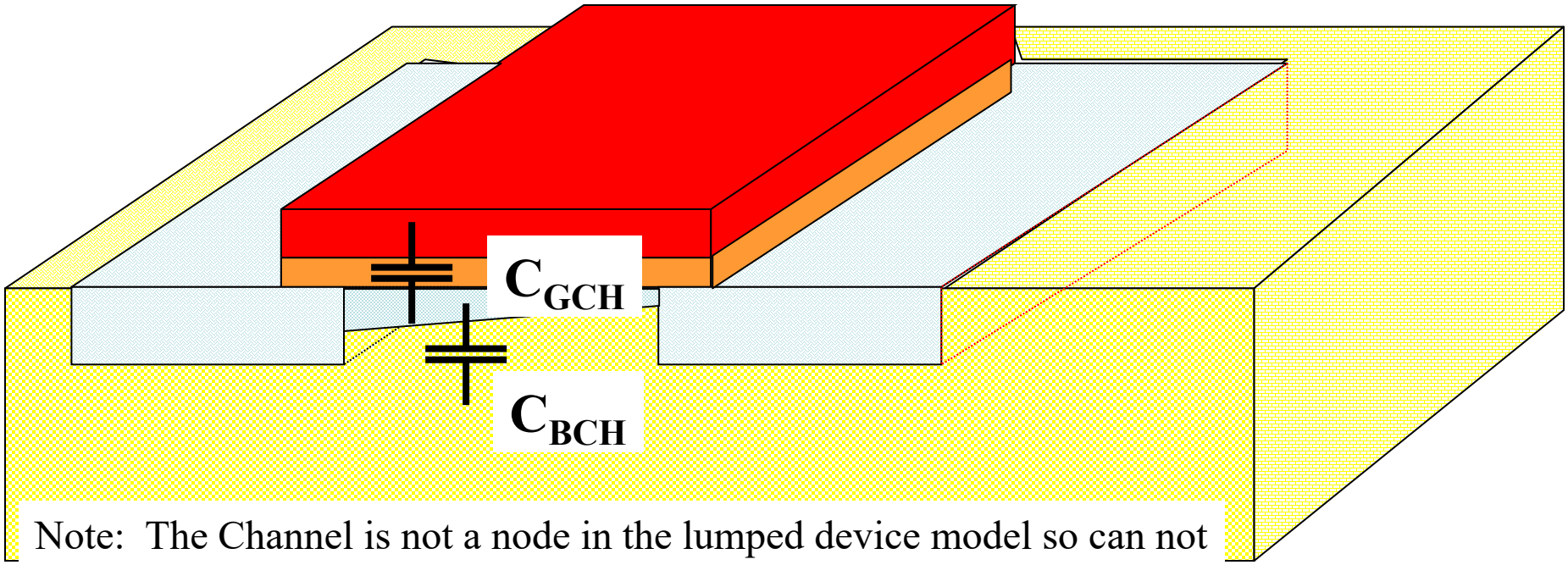
Parasitic Capacitance Summary



	Cutoff	Ohmic	Saturation
C_{GSO}	$CoxWL_D$		
C_{GDO}	$CoxWL_D$		
C_{BG}	CoxWL (or less)		
C_{BS}	$C_{BOT}A_S+C_{SW}P_S$		
C_{BD}	$C_{BOT}A_D+C_{SW}P_D$		

Parasitic Capacitors in MOSFET

Operation Region Dependent -- Ohmic



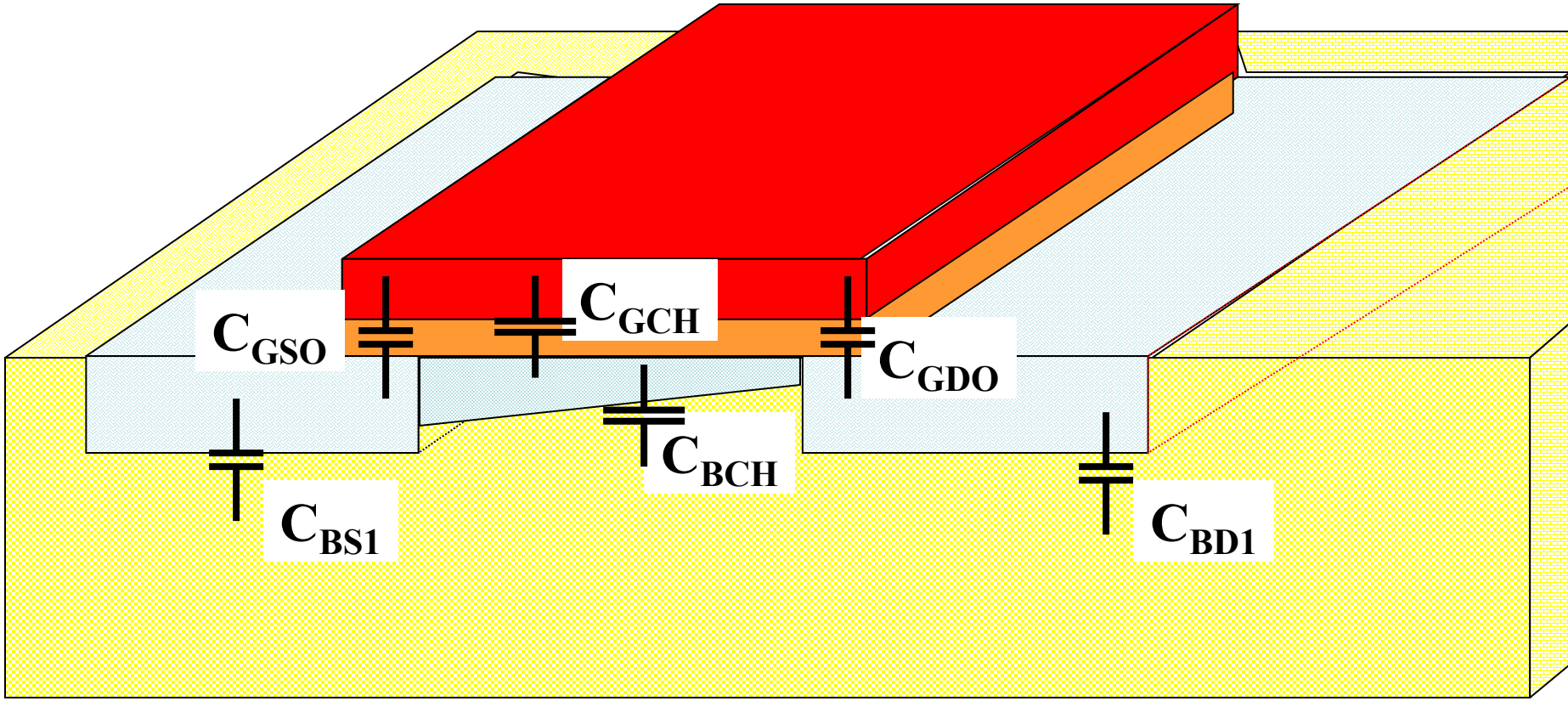
Note: The Channel is not a node in the lumped device model so can not directly include this distributed capacitance in existing models

Note: The distributed channel capacitance is usually lumped and split evenly between the source and drain nodes

Ohmic Capacitor: C_{GCH} , C_{BCH}

Parasitic Capacitors in MOSFET

Operation Region Dependent and Fixed -- Ohmic

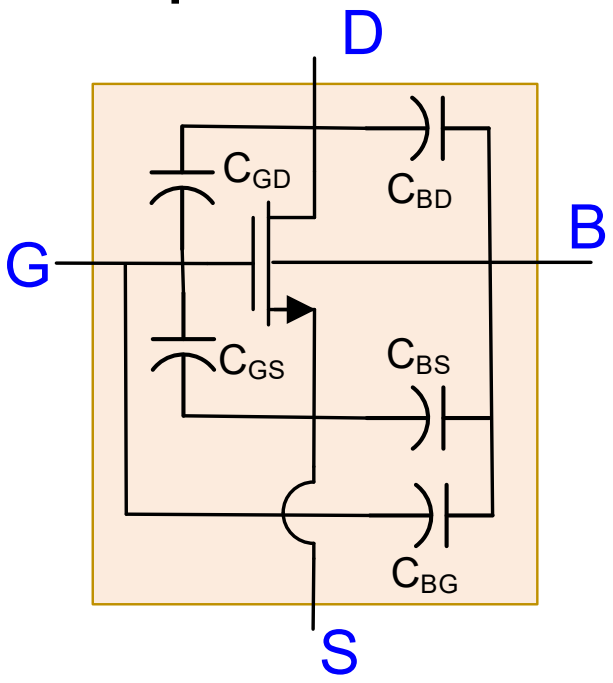


Overlap Capacitors: C_{GDO}, C_{GSO}

Junction Capacitors: C_{BS1}, C_{BD1}

Ohmic Capacitor: C_{GCH} , C_{BCH}

Parasitic Capacitance Summary

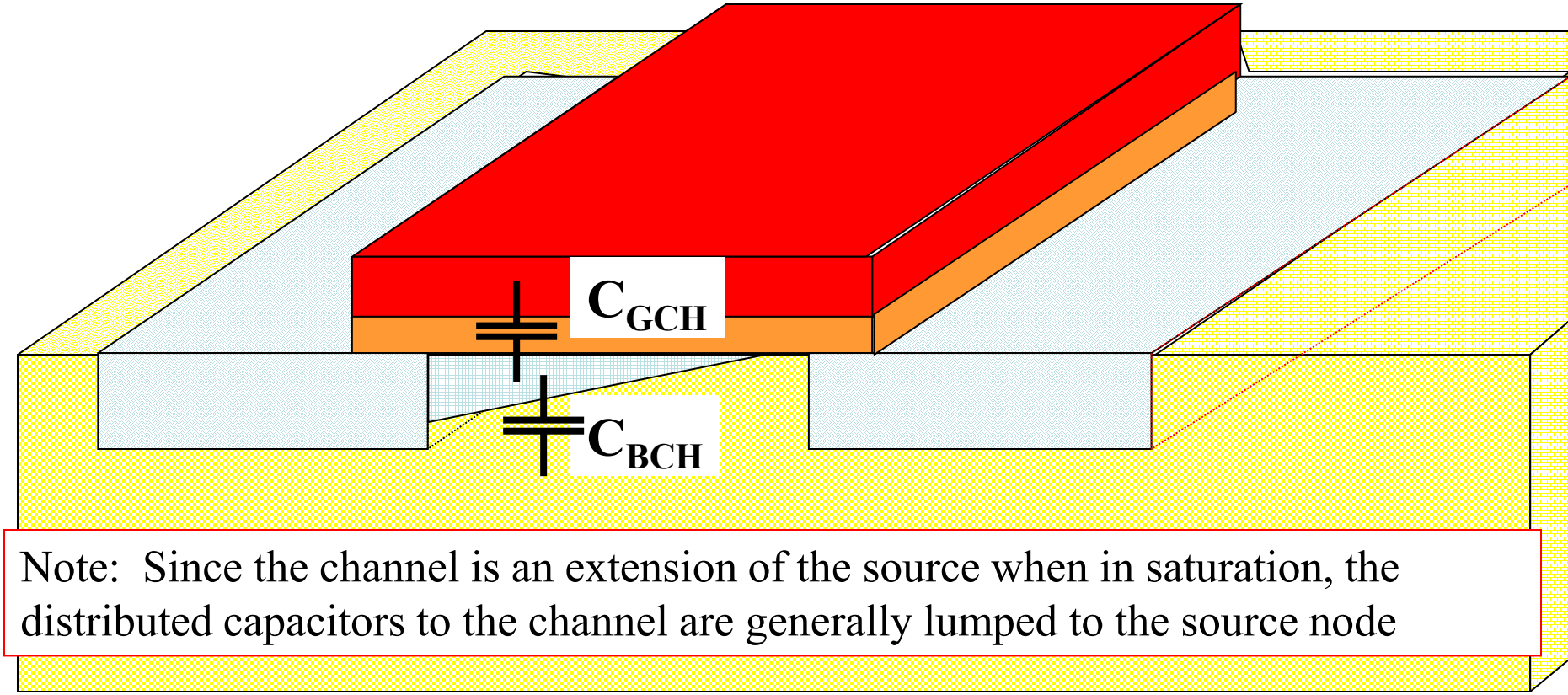


Lumped C_{GC} and C_{BC} to analytically avoid dealing with distributed capacitance

	Cutoff	Ohmic	Saturation
C_{GS}	$CoxWL_D$	$0.5CoxWL$	
C_{GD}	$CoxWL_D$	$0.5CoxWL$	
C_{BG}	CoxWL (or less)	0	
C_{BS}	$C_{BOT}A_S+C_{SW}P_S$	$C_{BOT}A_S+C_{SW}P_S+0.5WLC_{BOTCH}$	
C_{BD}	$C_{BOT}A_D+C_{SW}P_D$	$C_{BOT}A_D+C_{SW}P_D+0.5WLC_{BOTCH}$	

Parasitic Capacitors in MOSFET

Operation Region Dependent -- Saturation

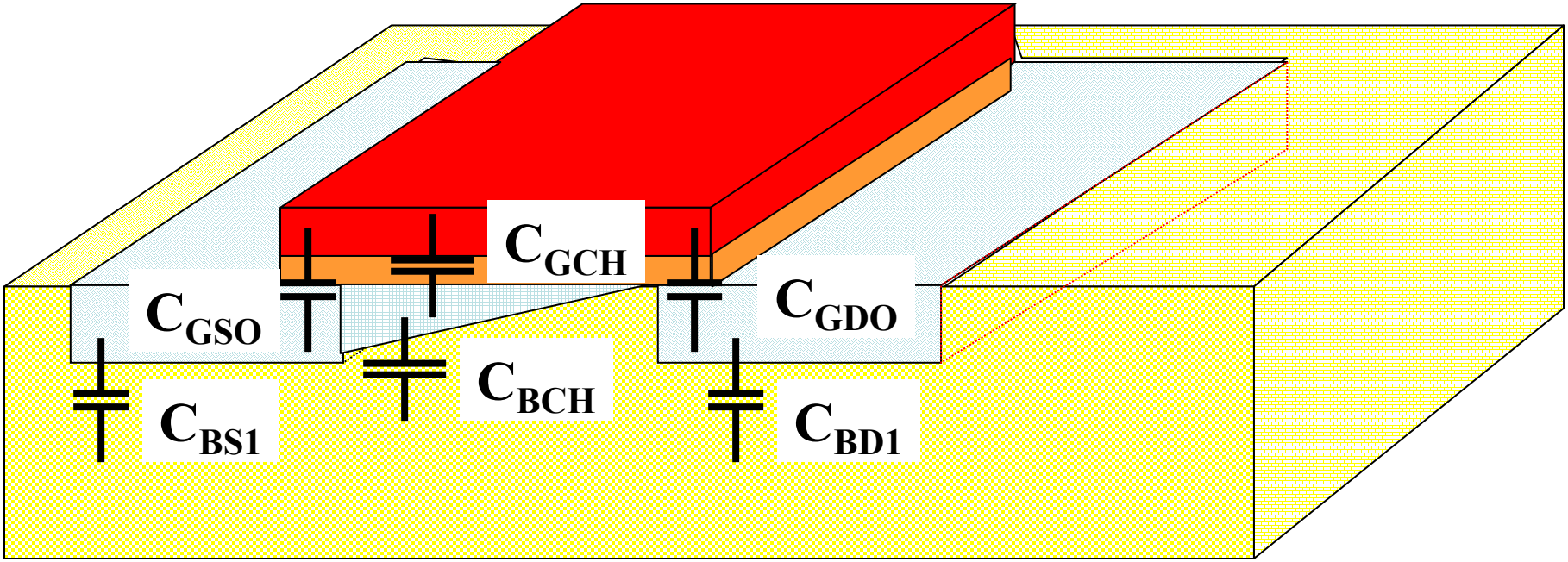


Note: Since the channel is an extension of the source when in saturation, the distributed capacitors to the channel are generally lumped to the source node

Saturation Capacitors: C_{GCH} , C_{BCH}

Parasitic Capacitors in MOSFET

Operation Region Dependent and Fixed --Saturation



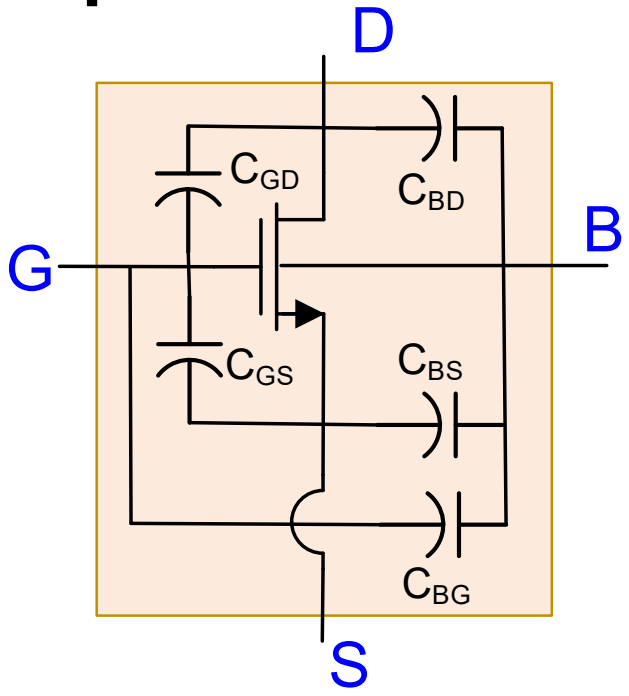
Overlap Capacitors: C_{GDO}, C_{GSO}

Junction Capacitors: C_{BS1}, C_{BD1}

Saturation Capacitors: C_{GCH} , C_{BCH}

- 2/3 $C_{OX}WL$ is often attributed to C_{GCH} to account for LD and saturation
- This approximation is reasonable for minimum-length devices but not so good for longer devices

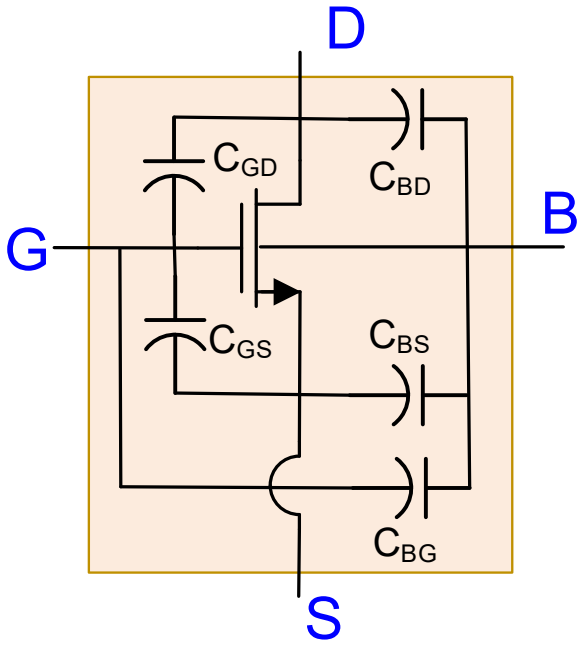
Parasitic Capacitance Summary



Lumped C_{GC} and C_{BC} to analytically avoid dealing with distributed capacitance

	Cutoff	Ohmic	Saturation
C_{GS}	$CoxWL_D$	$0.5C_{OX}WL$	$CoxWL_D+(2/3)C_{OX}WL$
C_{GD}	$CoxWL_D$	$0.5C_{OX}WL$	$CoxWL_D$
C_{BG}	CoxWL (or less)	0	0
C_{BS}	$C_{BOT}A_S+C_{SW}P_S$	$C_{BOT}A_S+C_{SW}P_S+0.5WLC_{BOTCH}$	$C_{BOT}A_S+C_{SW}P_S+(2/3)WLC_{BOTCH}$
C_{BD}	$C_{BOT}A_D+C_{SW}P_D$	$C_{BOT}A_D+C_{SW}P_D+0.5WLC_{BOTCH}$	$C_{BOT}A_D+C_{SW}P_D$

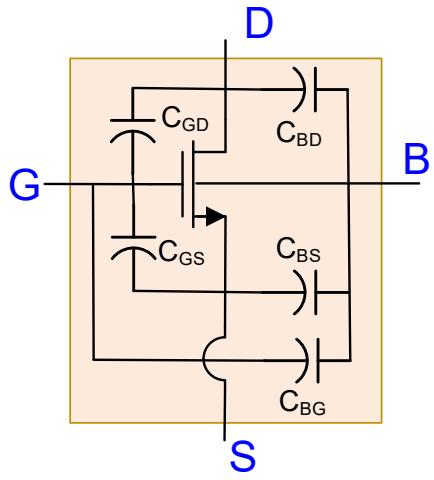
Parasitic Capacitance Summary



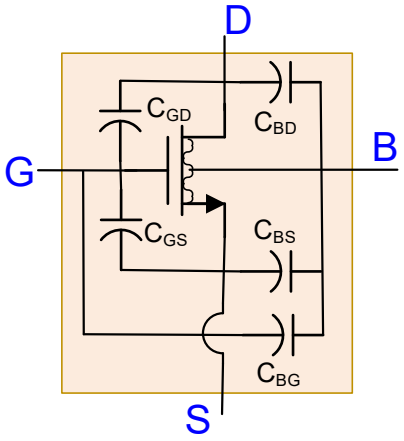
	Cutoff	Ohmic	Saturation
C_{GS}	$CoxWL_D$	$0.5C_{OX}WL$	$CoxWL_D+(2/3)C_{OX}WL$
C_{GD}	$CoxWL_D$	$0.5C_{OX}WL$	$CoxWL_D$
C_{BG}	CoxWL (or less)	0	0
C_{BS}	$C_{BOT}A_S+C_{SW}P_S$	$C_{BOT}A_S+C_{SW}P_S+0.5WLC_{BOTCH}$	$C_{BOT}A_S+C_{SW}P_S+(2/3)WLC_{BOTCH}$
C_{BD}	$C_{BOT}A_D+C_{SW}P_D$	$C_{BOT}A_D+C_{SW}P_D+0.5WLC_{BOTCH}$	$C_{BOT}A_D+C_{SW}P_D$

Observe there is no C_{DS} in this model because does not physically exist

Parasitic Capacitance Summary

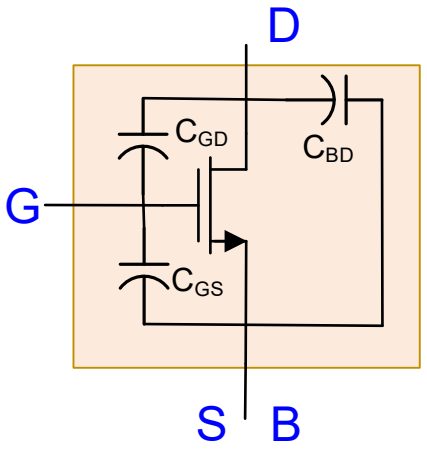


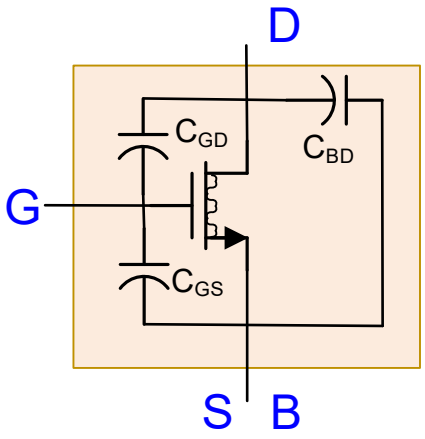
High Frequency Large Signal Model



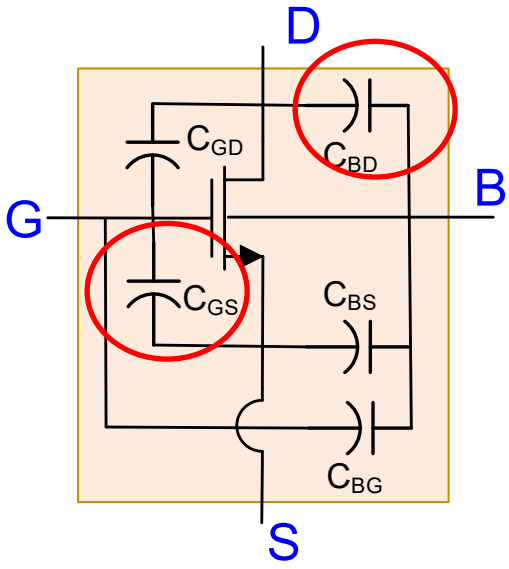
High Frequency Small Signal Model

Often V_{BS}=0 and C_{BG}=0, so simplifies to





Parasitic Capacitance Implications



The parasitic capacitances inherently introduce an upper limit on how fast either digital circuits or analog circuits can operate in a given process

Two parameters, f_{MAX} and f_T, (not defined yet) are two metric that are used to specify the fundamental speed limit in a semiconductor process

The dominant parasitic capacitances for most circuits are C_{GS} and C_{BD}

Stay Safe and Stay Healthy !

End of Lecture 35