ENEE 303 Recitation 08

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All pictures are from Microelectronic Circuits, Sedra and Smith, 6th and 7th edition.

Week Notes

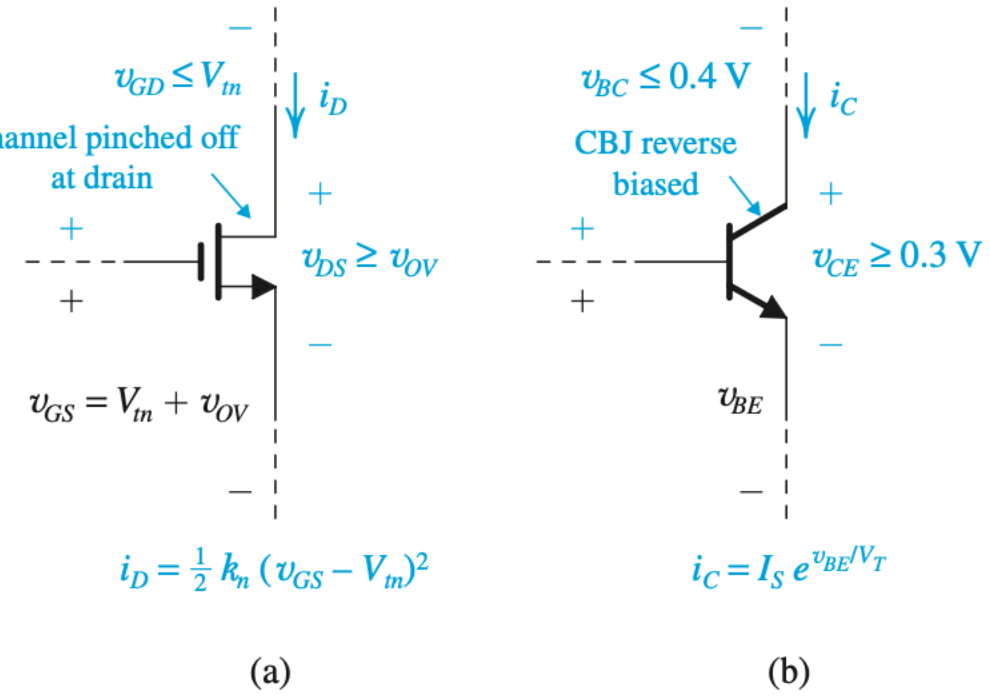
- Transistor amplifiers
  - Review for MOSFET and BJT
- Voltage transfer characteristics
- Small signal voltage gain
- Small signal operation and models
- 3 example problems

Week Notes

- To build a voltage amplifier with the transistor, MOSFET or BJT
- To obtain a linear amplifier from the nonlinear transistors
- To model the transistor operation so that we can analyze and design transistor amplifiers

Basic principles

- Recall the current equations for MOSFET and BJT



MOSFET: $i_D = \frac{1}{2} k_n (v_{GS} - V_{tn})^2$

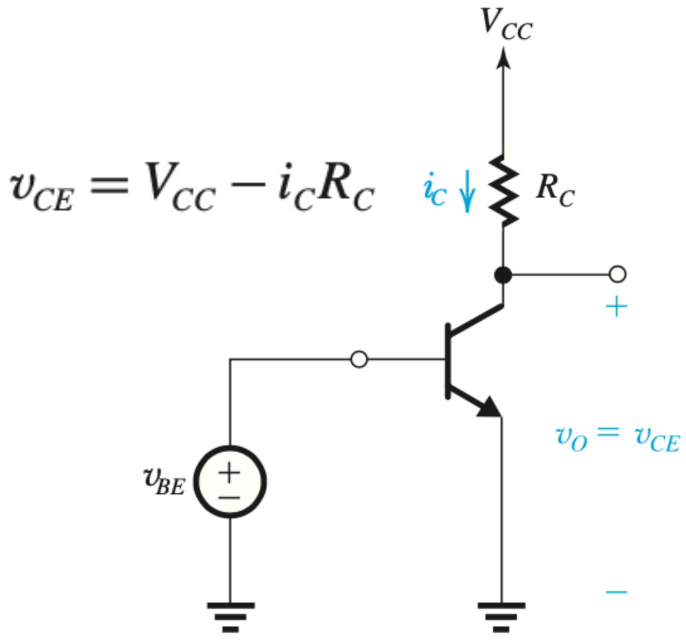
BJT: $i_C = I_S e^{v_{BE}/V_T}$

Transistors are basically transconductance amplifiers

Figure 7.1 Operating (**a**) an NMOS transistor and (**b**) an *npn* transistor in the active mode. Note that $v_{GS} = V_{tn} + v_{OV}$ and $v_{DS} \ge v_{OV}$; thus $v_{GD} \le V_{tn}$, which ensures channel pinch-off at the drain end. Similarly, $v_{BE} \simeq 0.7$ V, and $v_{CE} \ge 0.3$ V results in $v_{BC} \le 0.4$ V, which is sufficient to keep the CBJ from conducting.

Voltage transfer characteristics

- To use transistor to build a voltage amplifier, we need a load resistance



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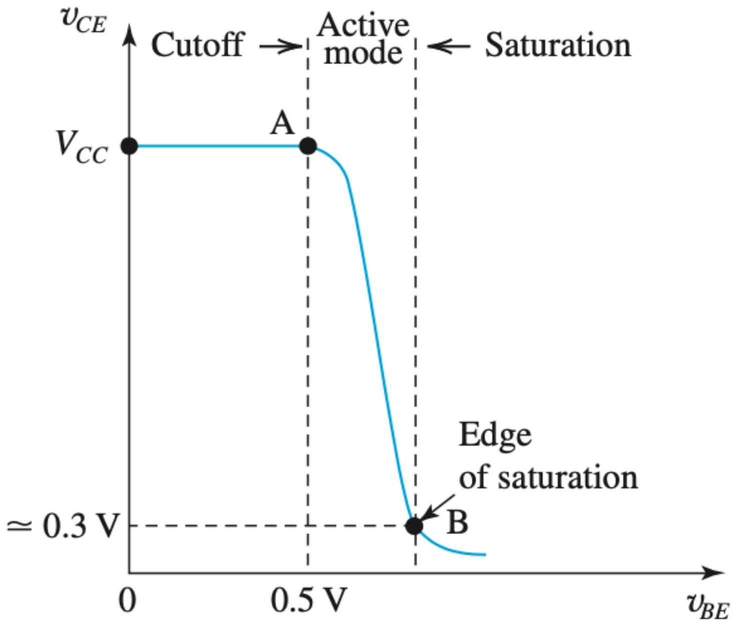
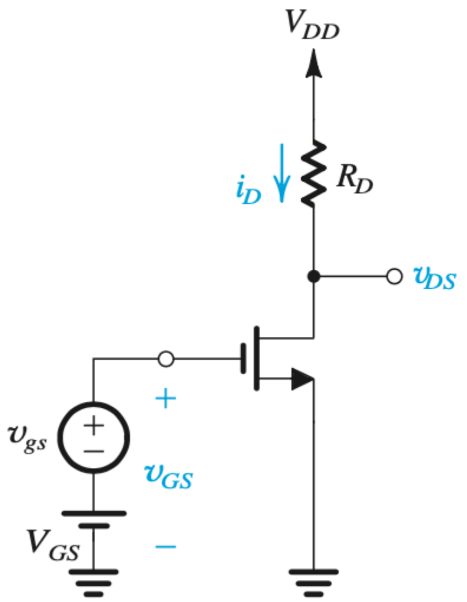


(d)

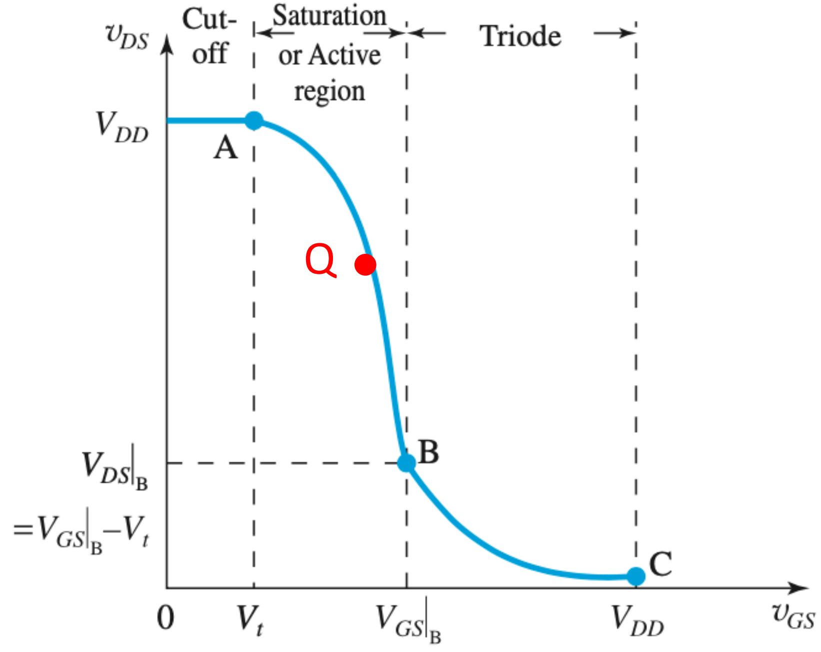
Voltage transfer characteristics

Linear amp by biasing MOSFET to operate in the active region and by keeping the input signal small

$$V_{GS}\big|_{B} = V_t + \frac{\sqrt{2k_n R_D V_{DD} + 1} - 1}{k_n R_D}$$



$$v_{DS} = V_{DD} - i_D R_D$$



(b)

Small signal voltage gain

- MOSFET case

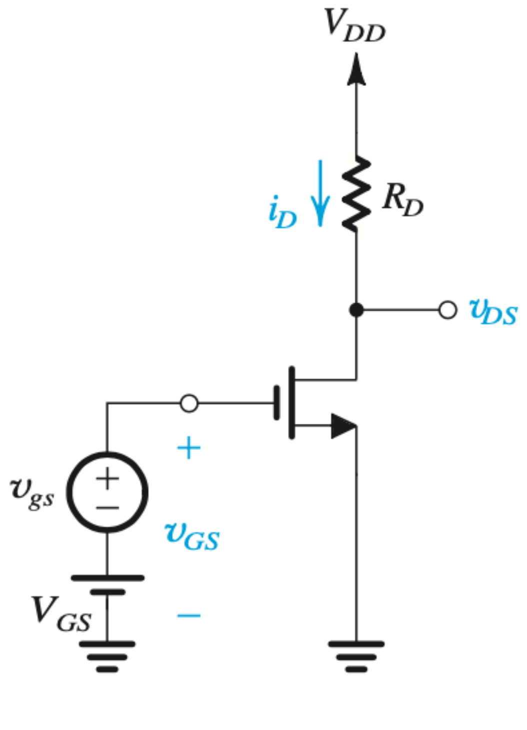
$$v_{DS} = V_{DD} - \frac{1}{2}k_n R_D (v_{GS} - V_t)^2$$

$$A_v = \left.\frac{dv_{DS}}{dv_{GS}}\right|_{v_{GS}=V_{GS}} = -k_n V_{OV} R_D$$

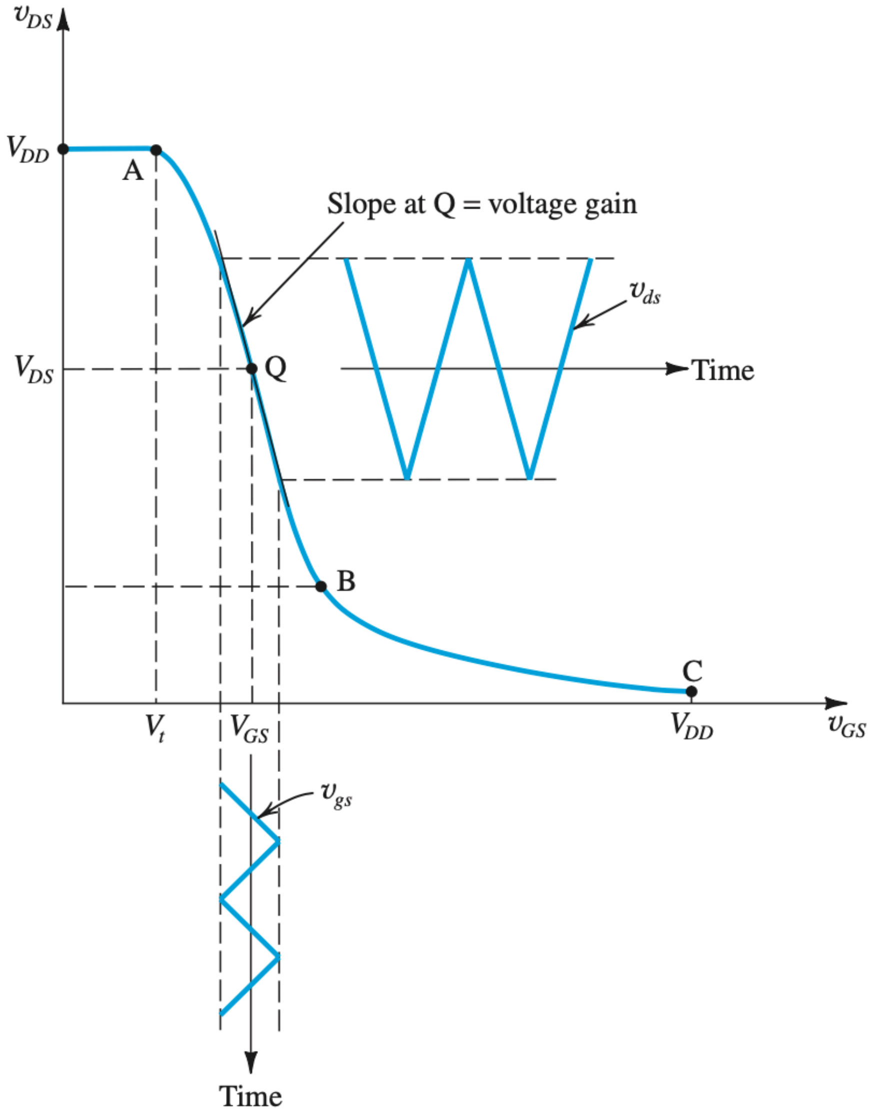
$$I_D = \frac{1}{2}k_n V_{OV}^2$$

$$A_v = -\frac{I_D R_D}{V_{OV}/2} = -\frac{V_{DD} - V_{DS}}{V_{OV}/2}$$

$$|A_{v\max}| = \frac{V_{DD} - V_{DS}|_B}{V_{OV}|_B/2} = \frac{V_{DD} - V_{OV}|_B}{V_{OV}|_B/2}$$



(a)



Small signal voltage gain

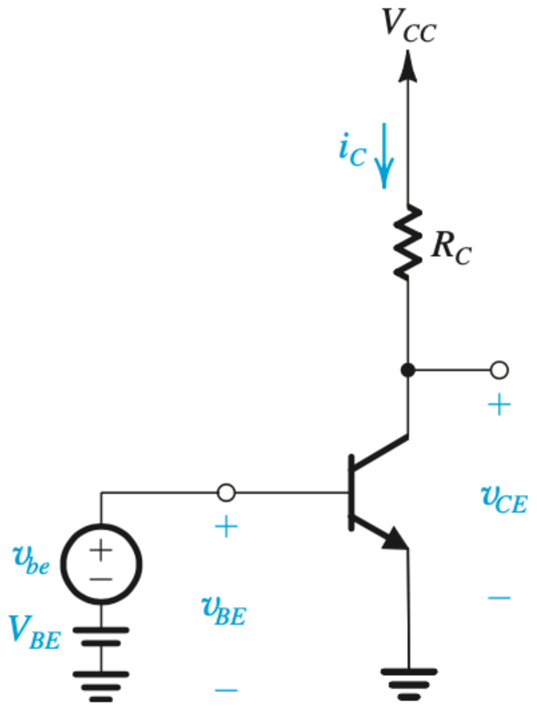
- BJT case

$$v_{CE} = V_{CC} - I_C R_C = V_{CC} - I_S e^{\frac{v_{BE}}{V_T}} R_C$$

$$A_v = \left.\frac{dv_{CE}}{dv_{BE}}\right|_{v_{BE}=V_{BE}} = -\left(\frac{I_C}{V_T}\right) R_C$$

$$A_v = -\frac{V_{CC} - V_{CE}}{V_T}$$

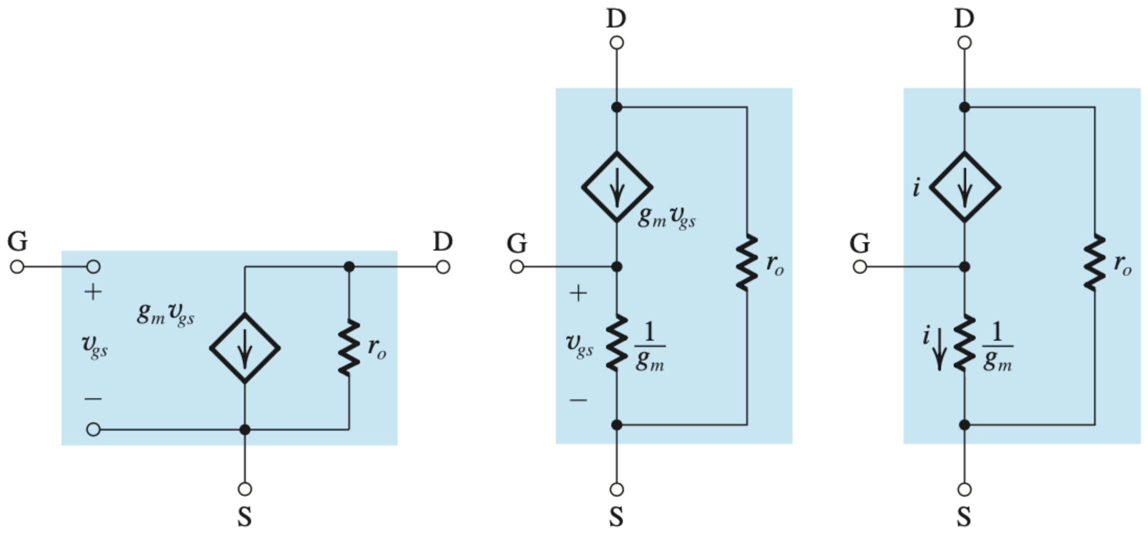
$$|A_{v\max}| = \frac{V_{CC} - 0.3}{V_T}$$



Small signal models

MOSFET

Small-Signal, Equivalent-Circuit Models



Hybrid-π model

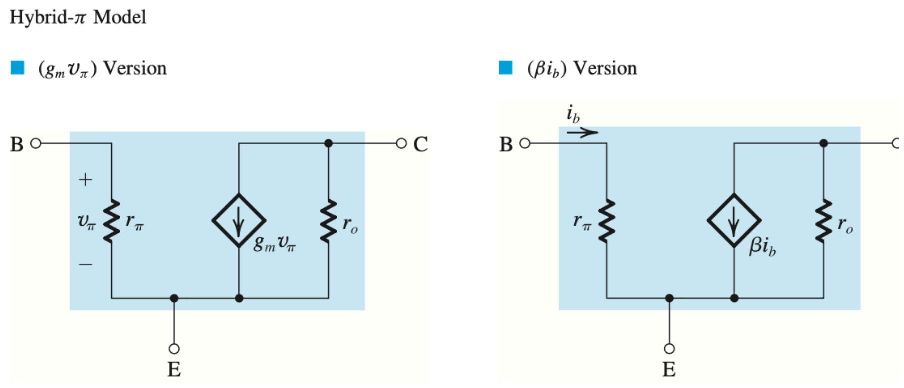
T models

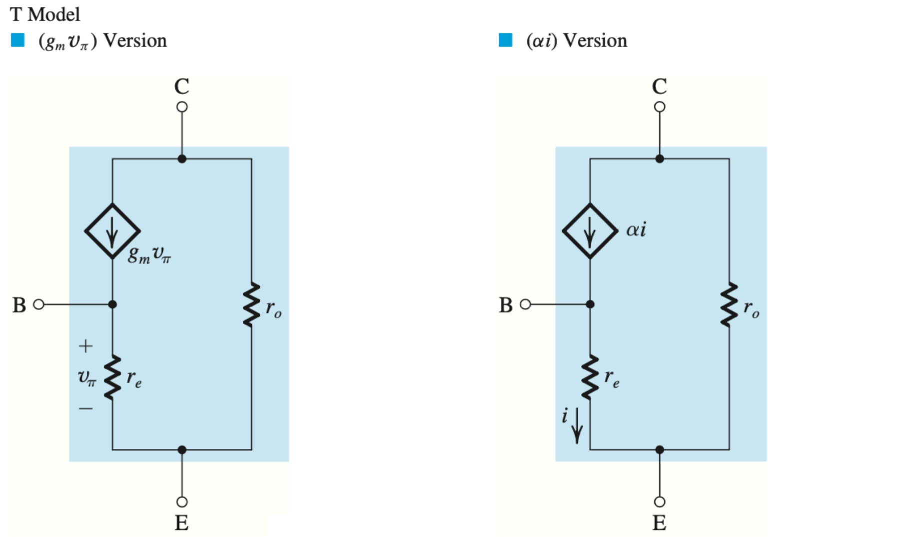
Small signal condition: $v_{gs} \ll 2(V_{GS} - V_t)$

$$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}} = k_n(V_{GS} - V_t)$$

$$A_v \equiv \frac{v_{ds}}{v_{gs}} = -g_m R_D$$

BJT





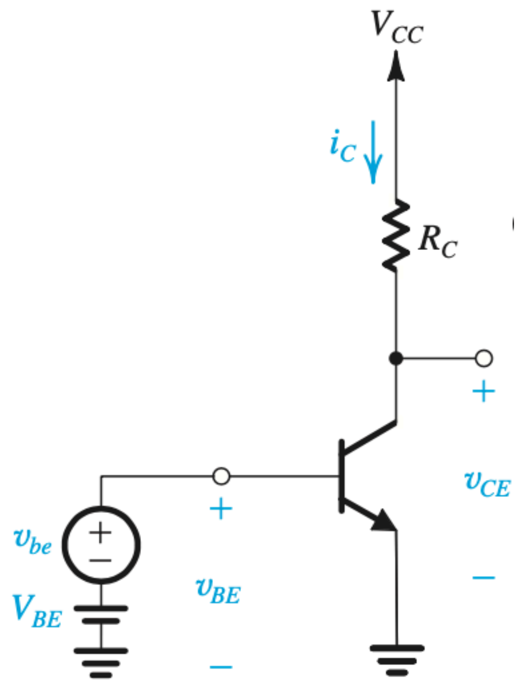
$$v_{be} \ll V_T$$

$$g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C=I_C} = \frac{I_C}{V_T} \qquad r_\pi = \frac{\beta}{g_m}$$

$$A_v \equiv \frac{v_{ce}}{v_{be}} = -g_m R_C$$

Example Problem 1

- Consider a BJT amplifier circuit having $I_s = 10^{-15}\ A$, a collector resistance $R_C = 6.8\ k\Omega$, and a power supply $V_{CC} = 10\ V$.
  - (a) what is I_C and V_{BE} when $V_{CE} = 3.2\ V$?
  - (b) what is voltage gain A_V?
  - (c) keeping I_C unchanged, find R_C that results in a voltage gain of -320 V/V
  - (d) What is the largest negative signal swing allowed at the output? Assuming $v_{CE} \geq 0.3\ V$
  - (e) what is the corresponding v_{BE}?



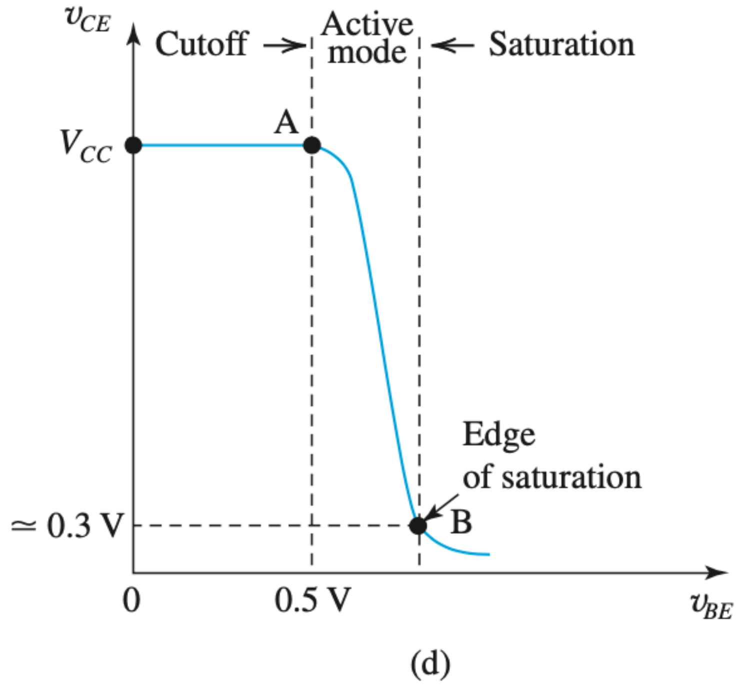
Example problem 1 continued

(a) $V_{CC} - I_C R_C = V_{CE}$

$$\boxed{I_C = 1\ mA}$$

$$I_C = I_S e^{\frac{V_{BE}}{V_T}} \qquad \boxed{V_{BE} = 690\ mV}$$

(b) $$\boxed{A_V = -\frac{I_C R_C}{V_T} = -272\ V/V}$$



(c) To keep I_C unchanged and $A_V = -\frac{I_C R_C}{V_T}$

$$\boxed{R_C = -\frac{A_V V_T}{I_C} = 8.28\ k\Omega}$$

(d) $V_{CE} = V_{CC} - I_C R_C = 1.72\ V$

Since $v_{CE} \geq 0.3\ V$, the largest allowable negative signal is $\boxed{1.72 - 0.3 = 1.42\ V}$

(e) $A_V = -320\ V/V$

$$\boxed{v_{BE} = \frac{v_{CE}}{A_V} = 4.4\ mV}$$

Example problem 2

Design the circuit of Fig. 5.52(e) to operate at a dc drain current of 0.5 mA and $V_D = +2$ V. Let $V_t = 1$ V, $k_n' W/L = 1$ mA/V^2, $\lambda = 0$, $V_{DD} = V_{SS} = 5$ V. Use standard 5% resistor values (see Appendix G), and give the resulting values of I_D, V_D, and V_S.

$$I_D = \frac{1}{2}(k_n' W/L)V_{OV}^2 \qquad V_{OV} = V_{GS} - V_t = 1\ V$$

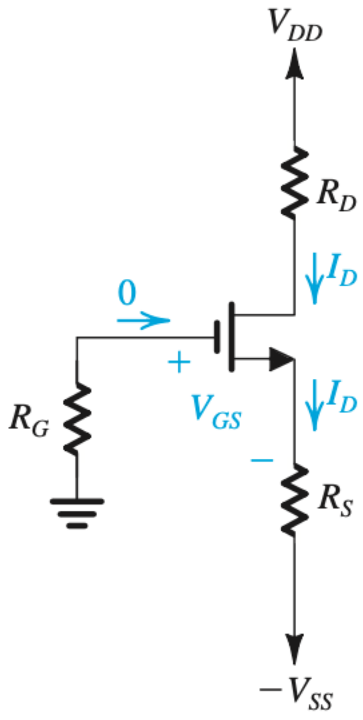
$$V_G - V_S = V_{OV} + V_t$$

$$\boxed{V_S = -2\ V}$$

$$I_D = \frac{V_S - V_{SS}}{R_S} \qquad R_S = 6\ k\Omega$$

$$I_D = \frac{V_{DD} - V_D}{R_D} \qquad R_D = 6\ k\Omega$$

Because of the standard resistor, there only exists $R = 6.2\ k\Omega$



From the textbook of 6ed

Example problem 2 continued

If we choose $R_S = R_D = 6.2k\Omega$

$$V_{GS} = V_G - V_S = -V_S = V_{SS} - I_D R_s$$

$$I_D = \frac{1}{2}(k_n' W/L)(V_{GS} - V_t)^2 = \frac{1}{2}(V_{SS} - I_D R_s - V_t)^2$$

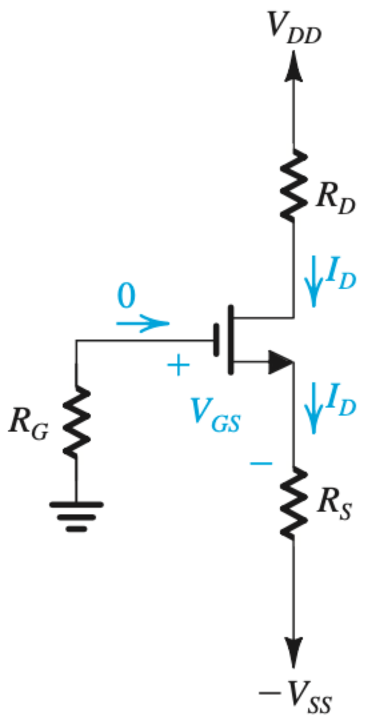
$$R_S^2 I_D^2 - \big(2 + R_S(V_{SS} - V_t)\big)I_D + (V_{SS} - V_t)^2 = 0$$

$\boxed{I_D = 0.49\ mA \text{ or } \cancel{0.86\ mA}}$

$V_s > 0$

$\boxed{V_s = -1.96\ V}$

$\boxed{V_D = 1.96\ V}$



Example problem 3

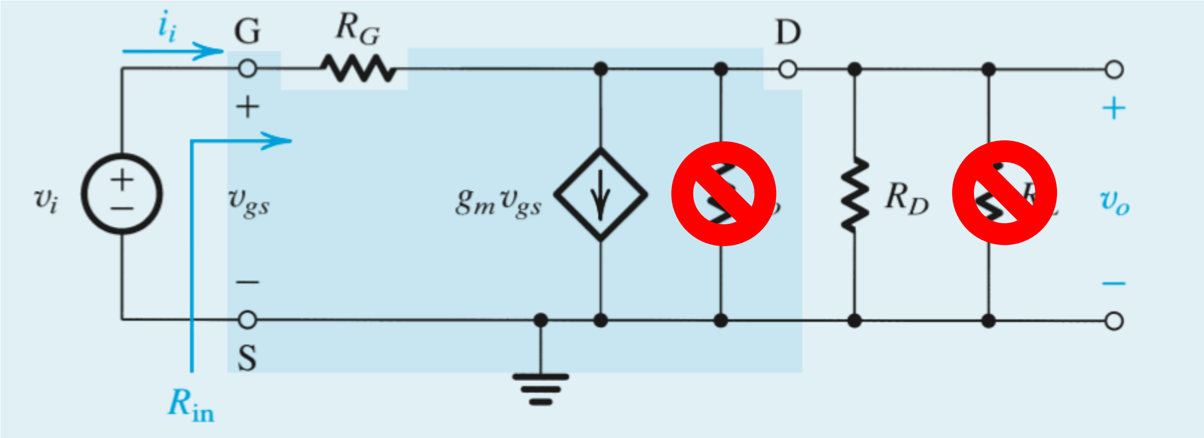
D7.4 Consider the amplifier circuit of Fig. 7.15(a) without the load resistance R_L and with channel-length modulation neglected. Let $V_{DD} = 5$ V, $V_t = 0.7$ V, and $k_n' = 1$ mA/V^2. Find V_{OV}, I_D, R_D, and R_G to obtain a voltage gain of -25 V/V and an input resistance of 0.5 M Ω. What is the maximum allowable input signal, $\hat{v}_i$?

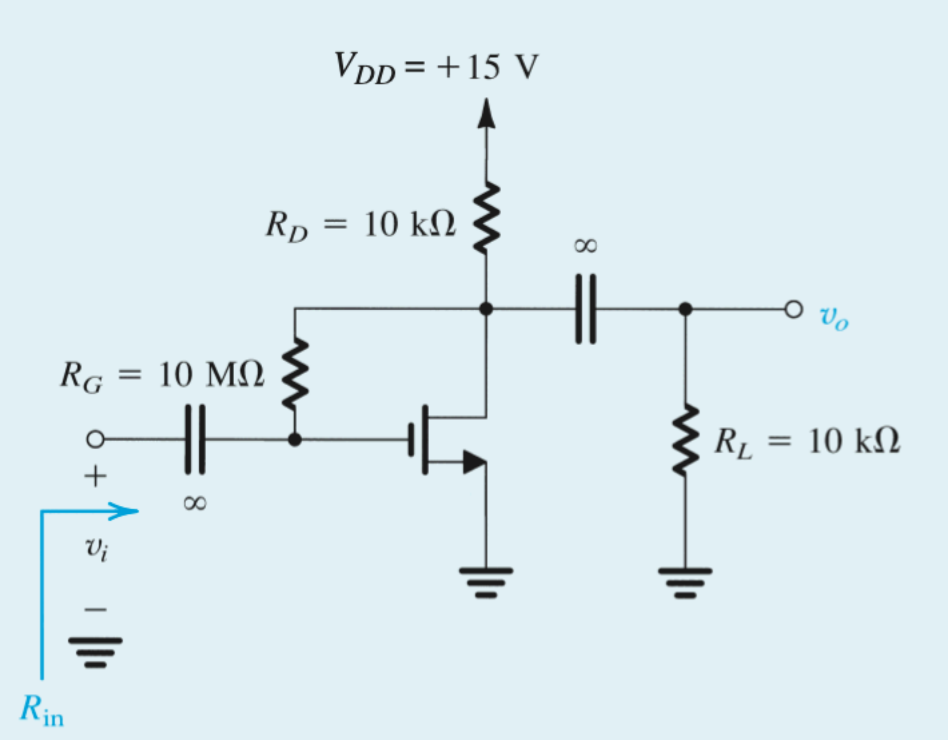
We want $A_v = -25\ V/V$ and $R_{in} = 0.5\ M\Omega$

By KVL

$$R_{in} = \frac{v_i}{i_i} = \frac{v_i}{v_i - v_o} R_G = \frac{R_G}{26}$$

$$\boxed{R_G = 26 R_{in} = 13\ M\Omega}$$





Example problem 3 continued

$A_v = -g_m R_D$, we have $g_m R_D = 25 = k_n V_{OV} R_D$

$$I_D R_D = \frac{1}{2} k_n V_{OV}^2 R_D = \frac{1}{2} g_m V_{OV} R_D = 12.5 V_{OV}$$

$$V_{OV} = V_{DD} - I_D R_D - V_t = 5 - 12.5 V_{OV} - 0.7$$

$$\boxed{V_{OV} = 0.319\ V}$$

$$\boxed{g_m = k_n V_{OV} = 319\ \mu A/V}$$

$$\boxed{R_D = 78.5\ k\Omega}$$

To obtain max allowable input signal, we need to keep the MOSFET in saturation. In other words,

$$v_{DS} \geq v_{GS} - V_t$$

For the equality condition, $v_{DS} = v_{GS} - V_t \quad V_{DS} - |A_v|\hat{v}_i = V_{GS} + \hat{v}_i - V_t$

$$\boxed{\hat{v}_i = \frac{V_t}{|A_v| + 1} = \frac{0.7V}{26} = 26.9\ mV}$$

Table J.1 Standard Resistance Values

5% Resistor Values (kΩ)	1% Resistor Values (kΩ) 100–174	178–309	316–549	562–976
10	100	178	316	562
11	102	182	324	576
12	105	187	332	590
13	107	191	340	604
15	110	196	348	619
16	113	200	357	634
18	115	205	365	649
20	118	210	374	665
22	121	215	383	681
24	124	221	392	698
27	127	226	402	715
30	130	232	412	732
33	133	237	422	750
36	137	243	432	768
39	140	249	442	787
43	143	255	453	806
47	147	261	464	825
51	150	267	475	845
56	154	274	487	866
62	158	280	499	887
68	162	287	511	909
75	165	294	523	931
82	169	301	536	953
91	174	309	549	976