Table 3.1

		Typical Parameter Value		
Parameter Symbol	Parameter Description	n-Channel	p-Channel	Units
V_{T0}	Threshold voltage(V_{BS}=0)	0.7	-0.8	V
K	Transconductance parameter(in saturation)	134	50	μA/V^2
γ	Bulk threshold parameter	0.45	0.4	V$^{1/2}$
λ	Channel length modulation parameter	0.1	0.2	V^{-1}
2|ϕ_F|	Surface potential at strong inversion	0.9	0.8	V

3-1 The circuit shown in Figure 3.1 illustrates a single-channel MOS resistor with a W/L of 2μm/2μm. Using Table 3.1 model parameters calculate the small-signal on resistance of the MOS transistor at various values for VS and fill in the table below. (Note that the transistor was in linear region)

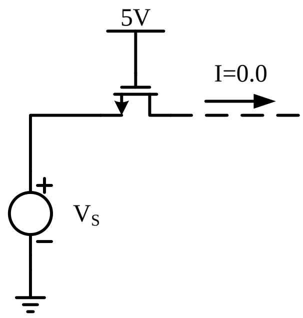

Figure 3.1

V_S(V)	R(Ω)
0.0	
1.0	
2.0	
3.0	
4.0	
5.0	

Solution:

The equation for threshold voltage is represented with absolute values so that it can be applied to n-channel or p-channel transistors without confusion.

$$|V_T| = |V_{T0}| + \gamma[\sqrt{2|\Phi_F| + |V_{SB}|} - \sqrt{2|\Phi_F|}]$$

$$r_{on} = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{L}{K'W(|V_{GS}| - |V_T| - |V_{DS}|)}$$

For n-channel device

$V_{T0} = 0.7$ $\gamma = 0.45$ $2|\Phi_F| = 0.9$ $K^{'} = 134$

(1) When $V_S = 0, V_{GS} = 5$and $V_{SB} = 0$

$$|V_T| = |V_{T0}| + \gamma[\sqrt{2|\Phi_F| + |V_{SB}|} - \sqrt{2|\Phi_F|}] = 0.7$$

$$r_{on} = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{L}{K'W(|V_{GS}| - |V_T| - |V_{DS}|)} = 1.736K\Omega$$

(2) When $V_S = 1, V_{GS} = 4$and $V_{SB} = 1$

$$|V_T| = |V_{T0}| + \gamma[\sqrt{2|\Phi_F| + |V_{SB}|} - \sqrt{2|\Phi_F|}] = 0.893$$

$$r_{on} = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{L}{K'W(|V_{GS}| - |V_T| - |V_{DS}|)} = 2.402K\Omega$$

(3) When $V_S = 2, V_{GS} = 3$and $V_{SB} = 2$

$$|V_T| = |V_{T0}| + \gamma[\sqrt{2|\Phi_F| + |V_{SB}|} - \sqrt{2|\Phi_F|}] = 1.039$$

$$r_{on} = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{L}{K'W(|V_{GS}| - |V_T| - |V_{DS}|)} = 3.806K\Omega$$

(4) When $V_S = 3, V_{GS} = 2$and $V_{SB} = 3$

$$|V_T| = |V_{T0}| + \gamma[\sqrt{2|\Phi_F| + |V_{SB}|} - \sqrt{2|\Phi_F|}] = 1.162$$

$$r_{on} = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{L}{K'W(|V_{GS}| - |V_T| - |V_{DS}|)} = 8.905K\Omega$$

(5) When $V_S = 4, V_{GS} = 1$and $V_{SB} = 4$

$$|V_T| = |V_{T0}| + \gamma[\sqrt{2|\Phi_F| + |V_{SB}|} - \sqrt{2|\Phi_F|}] = 1.269$$

$V_{GS} < V_T$ The device is cutoff, so $r_{on} = \text{infinity}$

(6) When $V_S = 5, V_{GS} = 0$and $V_{SB} = 5$

The device is cutoff, so $r_{on} = \text{infinity}$

V_S(V)	R(Ω)
0.0	1.736K
1.0	2.402K
2.0	3.806K
3.0	8.905K
4.0	infinity
5.0	infinity

3-2 Suppose the common-source stage of Fig 3.2 is to provide an output swing from 1V to 2.5V. Assume that $(W/L)_1 = 50/0.5$, $R_D = 2k\Omega$, $V_{DD} = 3V$ and $\lambda = 0$. Use model parameters in Table 3.1.

a) Calculate the input voltages that yield $V_{out} = 1V$ and $V_{out} = 2.5V$.

b) Calculate the drain current and the transconductance of M_1 for both cases.

c) How much does the small-signal gain, g_mR_D, vary as the output goes from 1V to 2.5V?

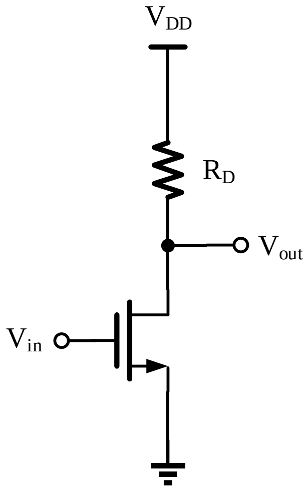

Figure 3.2

解：

a), b):

Vout=1V 时：

$$I_{D1} = \frac{V_{DD} - V_{out}}{R_D} = 1mA$$

$$V_{in} = V_{TH1} + \sqrt{\frac{2I_{D1}}{\mu_n C_{ox}\left(\frac{W}{L}\right)_1}} = 1.086V$$

$$g_{m1} = \sqrt{2\mu C_{ox}\left(\frac{W}{L}\right)_1 I_D} = 5.18 \times 10^{-3}$$

Vout=2.5V 时：

$$I_{D1} = \frac{V_{DD} - V_{out}}{R_D} = 0.25mA$$

$$V_{in} = V_{TH1} + \sqrt{\frac{2I_{D1}}{\mu_n C_{ox}\left(\frac{W}{L}\right)_1}} = 0.893V$$

$$g_{m1} = \sqrt{2\mu C_{ox}\left(\frac{W}{L}\right)_1 I_D} = 2.588 \times 10^{-3}$$

c):

$$\Delta g_m R_D = 5.18$$

3-3 Consider the circuit of Fig 3.3 with $(W/L)_1 = 50/0.5$ and $(W/L)_2 = 10/0.5$. Assume that $\lambda = \gamma = 0$, $V_{DD} = 3V$.

a) At what input voltage is M_1 at the edge of the triode region? What is the small-signal gain under this condition?

b) When V_{out} is 0.66V, What is the small-signal gain under this condition?

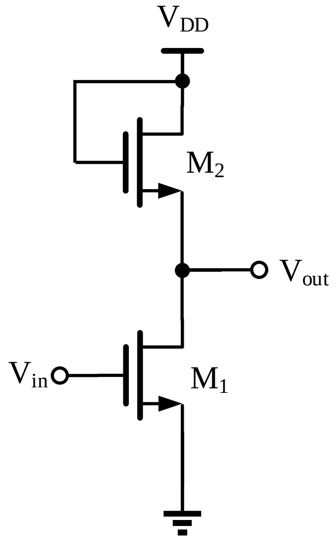

Figure 3.3

解：

a)

M_1 在临界点：

$$V_{out} = V_{in} - V_{TH1}$$

$$I_{D1} = I_{D2} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{in} - V_{TH1})^2 = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{DD} - V_{out} - V_{TH2})^2$$

解得$V_{in} = 1.41V$，此时$V_{out} = 0.71V$

$$A_V = -\sqrt{\frac{2\mu_n C_{ox}\left(\frac{W}{L}\right)_1 I_{D1}}{2\mu_n C_{ox}\left(\frac{W}{L}\right)_2 I_{D2}}} = -2.236$$

b)

由于 Vout=0.66V＜0.71V，所以 M_1 工作在三极管区

$$\frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{DD} - V_{out} - V_{TH2})^2 = \mu_n C_{ox}\left(\frac{W}{L}\right)_1 \left[(V_{in} - V_{TH1})V_{out} - \frac{V_{out}^2}{2}\right]$$

解得$V_{in} = 1.84V$

$$I_D = \mu_n C_{ox}\left(\frac{W}{L}\right)_1 \left[(V_{in} - V_{TH1})V_{out} - \frac{V_{out}^2}{2}\right]$$

$$\frac{\partial I_D}{\partial V_{in}} = \mu_n C_{ox}\left(\frac{W}{L}\right)_1 V_{out}$$

$$A_V = -\frac{g_{m1}}{g_{m2}} = -\frac{\mu_n C_{ox}\left(\frac{W}{L}\right)_1 V_{out}}{\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{DD} - V_{out} - V_{TH2})} = -2.015$$

3-4 In the circuit of Fig 3.4, $(W/L)_1 = 20/0.5$, $I_1 = 1mA$, and $I_S = 0.75mA$. Assuming $\lambda = 0$, $V_{DD} = 3V$, calculate $(W/L)_2$ such that M_1 is at the edge of triode region. What is the small-signal voltage gain under this condition? Use model parameters in Table 3.1.

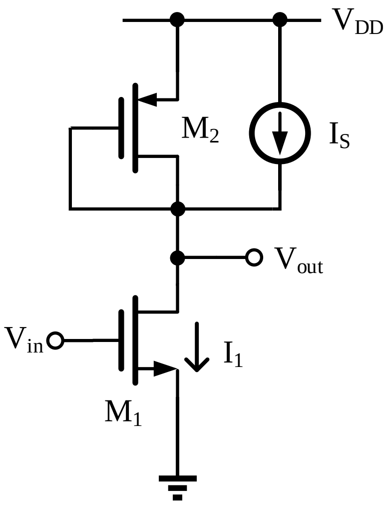

Figure 3.4

$$V_{out} = V_{in} - V_{TH1}$$

且：

$$\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_2 (V_{DD} - V_{out} - |V_{TH2}|)^2 + I_S = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{in} - V_{TH1})^2 = 10^{-3}$$

解得：$V_{in} = 1.311$，$\left(\frac{W}{L}\right)_2 = 3.961$

所以：$A_V = -\frac{g_{m1}}{g_{m2}} = -\sqrt{\frac{\mu_n C_{ox}\left(\frac{W}{L}\right)_1 I_1}{\mu_p C_{ox}\left(\frac{W}{L}\right)_2 I_2}} = -10.4$

3-5 Consider the circuit of Fig 3.5 with $(W/L)_1 = 50/0.5$, $R_D = 2k\Omega$, and $R_S = 200\Omega$, $V_{DD} = 3V$. Use model parameters in Table 3.1.

(a) Calculate the small-signal voltage gain if $I_D = 0.5mA$.

(b) Assuming that $\lambda = \gamma = 0$, calculate the input voltage that places M1 at the edge of the triode region. What is the gain under this condition?

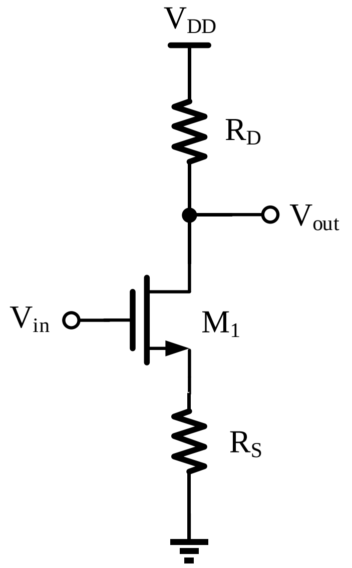

Figure 3.5

解：

a)：

$$V_S = R_S I_D = 0.1V$$

$$V_{TH1} = V_{TH1,0} + \gamma\left(\sqrt{2|\varphi_F| + V_{SB}} - \sqrt{2|\varphi_F|}\right) = 0.7 + 0.45\left(\sqrt{0.9+0.1} - \sqrt{0.9}\right) = 0.723$$

$$V_{out} = V_{DD} - R_D I_D = 2V$$
$$V_{DS} = 2 - 0.1 = 1.9V$$

$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (1+\lambda V_{DS}) I_D} = 3.993 \times 10^{-3}$$

$$A_V = -\frac{g_m R_D}{1 + g_m R_S} = -4.44$$

b):

M_1在临界点，所以

$$V_{out} = V_{in} - V_{TH1}$$
$$V_{in} = V_{GS1} + R_S I_D$$
$$V_{DD} - R_D I_D = V_{out}$$

所以$V_{DD} - (R_S + R_D) I_D = V_{GS1} - V_{TH1}$

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS1} - V_{TH1})^2 = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 [V_{DD} - (R_S + R_D) I_D]^2$$

解得$I_{D1} = 1.58mA$（此时 $V_{GS}<V_{TH}$，舍去），$I_{D2} = 1.17mA$

$$V_{in} = V_{DD} - R_D I_D + V_{TH1} = 1.36V$$

$$g_{m1} = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_1 I_D} = 5.60 \times 10^{-3}$$

$$G_m = \frac{g_{m1}}{1 + g_{m1}R_S} = 2.642 \times 10^{-3}$$

$$A_V = -G_m R_D = -5.283$$