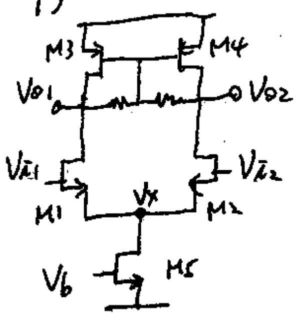
EE140 HW4 Solutions Mike Chen ①

1)



a) $V_{ic} = 0.9V$. determine V_b, s.t. tail current = 10μ

∵ M5 in Saturation region.

$$\frac{1}{2}K'\left(\frac{W}{L}\right)_5 (V_b - V_t)^2 (1 + \lambda \cancel{V_{ds5}}^{\to 0}) = 10\ \mu A.$$

$\Rightarrow V_b \sim 0.5V$. in Spice, this gives a tail current of 10.8 μA, because we ignored V_{ds5}! To improve the accuracy, we should consider effect of λV_{ds5}.

$$V_{ds5} = V_{ic} - V_{gs1} = 0.9 - \left(V_{t0} + \sqrt{\frac{2 I_{d1}}{K'_n\left(\frac{W}{L}\right)_1}}\right) = 0.4$$

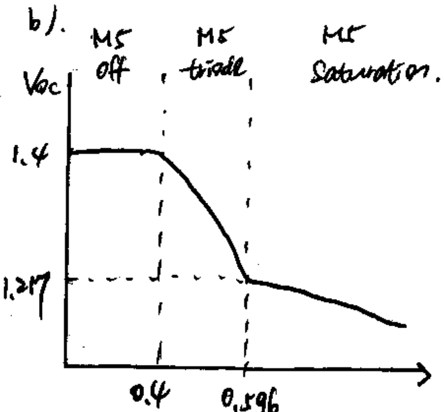
∴ $V_b = 0.4962$ (V) $\Rightarrow$ this gives tail current of 10 μA in spice. ※

$V_x = V_{ic} - V_{gs1} = 0.4$ (V) ※ Spice: 0.407V

$$V_{o1} = V_{o2} = V_{dd} - |V_{gs3}| = 1.8 - \left(|-0.4| + \sqrt{\frac{2 \cdot I_{d1}}{K'_p\left(\frac{W}{L}\right)_3}}\right)$$

$= 1.217$ (V) ※ Spice: 1.2248 V

b).



I: when $V_x \le 0$, M5 is off.

∴ $V_{ic} \le 0.4V$, no current flows!

$V_{oc} = V_{dd} - |V_{t3}| = 1.8 - 0.4 = 1.4$ (V) ※

II: $0 \le V_x \le V_{d,sat5}$, M5 in triode

∴ $0.4 \le V_{ic} \le V_{ds,sat5} + |V_{gs1}| = 0.5 + 0.0962 = 0.5962$

$V_{oc}\big|_{V_{ic}=0.596} = V_{dd} - |V_{gs3}| = 1.217$ (V) ※

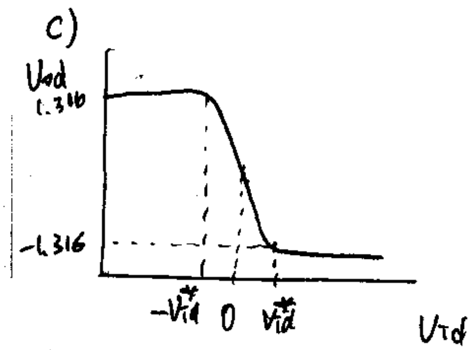
M3, M4 always in saturation! ($\because V_{Gd}=0$) ※ ②

M1, M2, stays in saturation if $V_{ds1} \geq V_{dsat1}$.

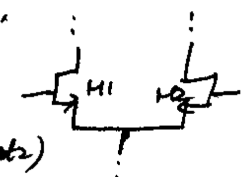
$$V_{ic} - V_{oc} \leq V_t, \quad V_{ic} \leq 1.217 + 0.4 = 1.617\ (V).$$

$\therefore$ Once $V_{ic} > 1.617$, M1, M2 enters triode mode. ※

c)



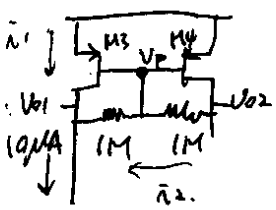
Vod saturates whenever tail current steers to either side.



$$\therefore V_{id}^* = (V_t + V_{dsat1}) - (V_t + \cancel{V_{dsat2}}) \quad (V_{dsat2} \to 0)$$

$$= \sqrt{\frac{2 \cdot 10\mu}{K_n'(\frac{W}{L})_1}} = 0.141\ (V) \quad ※$$

What about Vod?



Consider $V_{id} > 0$ case. ($V_{id} < 0$ is symmetric to the solution derived here)

$\max(V_{o2} - V_{o1}) = 1.8V$.

$\therefore i_{2,max} = 0.9\ \mu A$.

$\therefore$ can ignore i_2, and assumes all $10\mu A$ flows into M3.

$$\therefore V_P = V_{dd} - |V_{gs3}| = 1.8 - \left(0.4 + \sqrt{\frac{2 \cdot 5\mu}{K_p' \frac{W}{L}}}\right)$$

$$= 1.142\ (V).$$

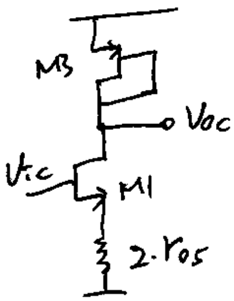
$V_{o2} \sim 1.8V$.

$$\therefore V_{o1} = V_P - (V_{o2} - V_P) \cong 0.484\ (V).$$

One can do iteration to improve the accuracy of V_{o1} & V_{o2}.

To 1st order analysis, $V_{od} = (V_{o1} - V_{o2}) = -1.316\ (V)$ ※

d) common mode half circuit:



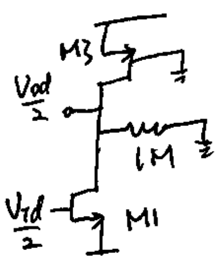
$$R_{oc} \simeq \frac{1}{g_{M3}} = \frac{1}{\sqrt{2 \cdot K_p' \left(\frac{W}{L}\right)_3 \cdot I_{d1}}} \sim 16.95\ k\Omega \ ※$$

Spice: 17.3 kΩ

$$A_{cm} = \frac{-g_{m1}}{1 + g_{m1} \cdot 2 \cdot \frac{1}{\lambda_n \cdot 10\mu}} \cdot R_{oc} \cong -16.95\,(m)$$

Spice: −15.75 m

e) differential mode half circuit



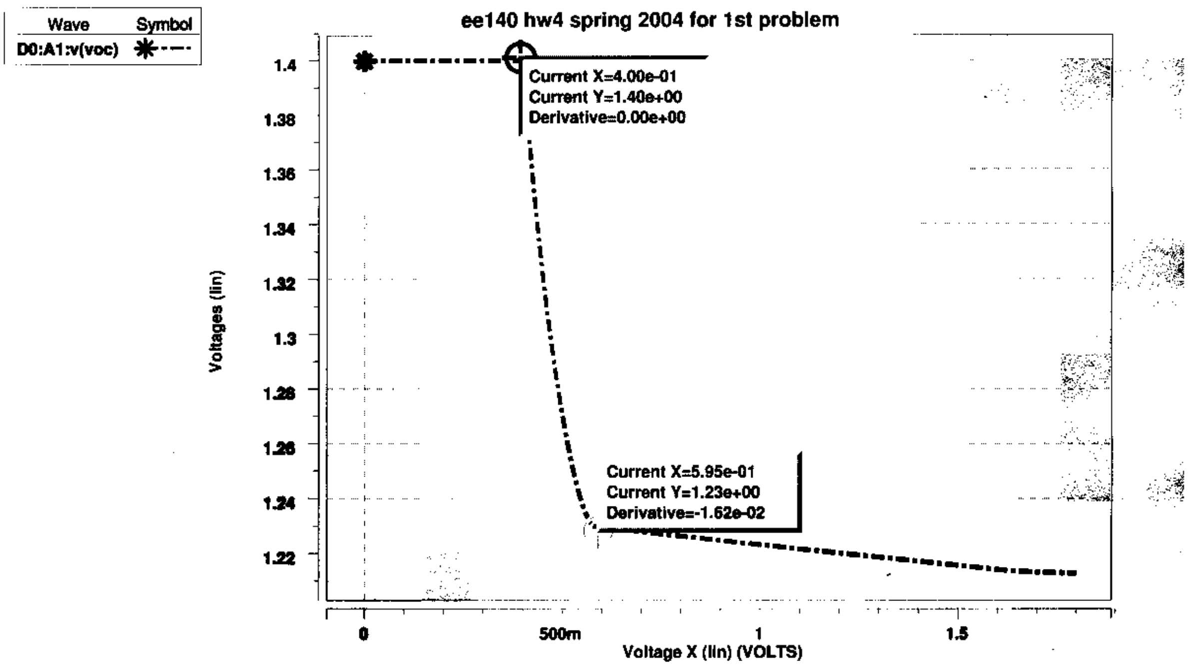
$$\frac{R_{od}}{2} \cong (1M \parallel r_{o3} \parallel r_{o1})$$

$$= \left(1M \parallel \frac{1}{0.15 \cdot 5\mu} \parallel \frac{1}{0.2 \cdot 5\mu}\right) \cong 363.39\ k\Omega$$

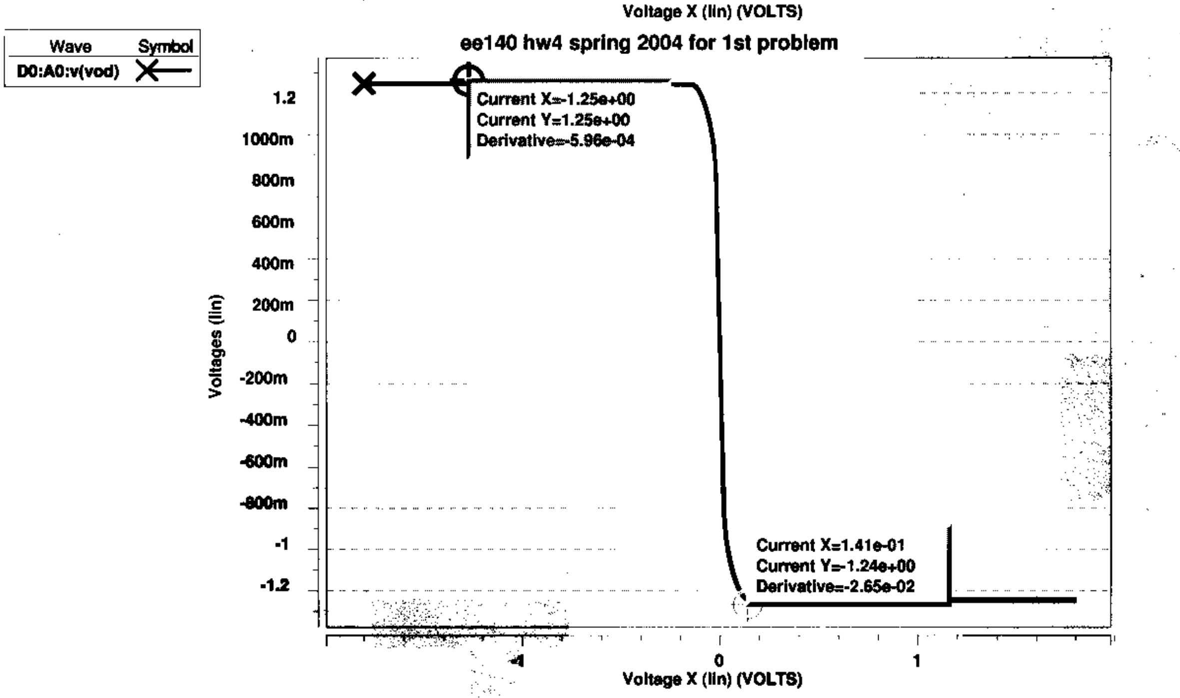
$\therefore R_{od} \sim 726.78\,k\Omega$. spice: 783.95 kΩ

$$A_{dm} = -g_{m1} \cdot \frac{R_{od}}{2} = -\sqrt{2K' \frac{W}{L} I_D} \cdot \frac{R_{od}}{2} \simeq -36.3$$

Spice: −42.3



Wave Symbol
D0:A1:v(voc)
ee140 hw4 spring 2004 for 1st problem
Current X=4.00e-01
Current Y=1.40e+00
Derivative=0.00e+00
Current X=5.95e-01
Current Y=1.23e+00
Derivative=-1.62e-02
Voltages (lin)
1.4
1.38
1.36
1.34
1.32
1.3
1.28
1.26
1.24
1.22
0
500m
1
1.5
Voltage X (lin) (VOLTS)



Wave Symbol
D0:A0:v(vod)
ee140 hw4 spring 2004 for 1st problem
Current X=-1.25e+00
Current Y=1.25e+00
Derivative=-5.96e-04
Current X=1.41e-01
Current Y=-1.24e+00
Derivative=-2.65e-02
Voltages (lin)
1.2
1000m
800m
600m
400m
200m
0
-200m
-400m
-600m
-800m
-1
-1.2
-1
0
1
Voltage X (lin) (VOLTS)

EE140 HW4 Spring 2004 for 1st problem

```
.model nch nmos LEVEL=1 TOX=25 VTO=0.4 KP=100.0e-6 LAMBDA=0.2
+GAMMA=0.01 PHI=0.6 CAPOP=0 CGSO=5.0e-10 CGDO=5.0e-10
+CGBO=4.0e-10 CJ=6.0e-4 CJSW=2.0e-10

.model pch pmos LEVEL=1 TOX=25 VTO=-0.4 KP=60.0e-6 LAMBDA=0.15
+GAMMA=0.01 PHI=0.6 CAPOP=0 CGSO=5.0e-10 CGDO=5.0e-10
+CGBO=4.0e-10 CJ=6.0e-4 CJSW=2.0e-10

*------------------------------------------
vdd vdd 0 1.8

vic vic 0 0.9
vid vid 0 0
e1 vi1 vic vid 0 0.5
e2 vi2 vic vid 0 -0.5

e3 voc1 voc2 vo1 0 0.5
e4 voc voc1 vo2 0 0.5
voc voc2 0 0
fco1 vo1 0 voc -1
fco2 vo2 0 voc -1

m1 vo1 vi1 s s nch w=10u l=1u
m2 vo2 vi2 s s nch w=10u l=1u
m3 vo1 g vdd vdd pch w=5u l=1u
m4 vo2 g vdd vdd pch w=5u l=1u
rl1 vo1 g 1000k
rl2 vo2 g 1000k
vb vb 0 0.4962
m5 s vb 0 0 nch w=20u l=1u

*------------------------------------------
.dc vid -1.8 1.8 0.01
.dc vic 0 1.8 0.01
.option nomod post
.op
.probe dc vod=v(vo1,vo2) voc=v(voc)
.tf v(vo1,vo2) vid
.alter
.tf v(voc) vic
.end

**** mosfets
```

subckt

element	0:m1	0:m2	0:m3	0:m4	0:m5
model	0:nch	0:nch	0:pch	0:pch	0:nch
region	Saturati	Saturati	Saturati	Saturati	Saturati
id	**5.0041u**	**5.0041u**	**-5.0041u**	**-5.0041u**	**10.0082u**
ibs	0.	0.	0.	0.	0.
ibd	-8.1750f	-8.1750f	5.7524f	5.7524f	-4.0725f
vgs	492.7460m	492.7460m	-575.2450m	-575.2450m	496.2000m
vds	817.5010m	817.5010m	-575.2450m	-575.2450m	407.2540m
vbs	0.	0.	0.	0.	0.
vth	400.0000m	400.0000m	-400.0000m	-400.0000m	400.0000m
vdsat	92.7460m	92.7460m	-175.2450m	-175.2450m	96.2000m
beta	1.1635m	1.1635m	325.8860u	325.8860u	2.1629m
gam eff	10.0000m	10.0000m	10.0000m	10.0000m	10.0000m
gm	107.9100u	107.9100u	57.1099u	57.1099u	208.0711u
gds	860.1820n	860.1820n	690.9930n	690.9930n	1.8509u
gmb	696.5560n	696.5560n	368.6427n	368.6427n	1.3431u
cdtot	5.0000f	5.0000f	2.5000f	2.5000f	10.0000f
cgtot	102.4843f	102.4843f	51.4421f	51.4421f	204.5686f
cstot	97.0843f	97.0843f	48.5421f	48.5421f	194.1686f
cbtot	4.000e-16	4.000e-16	4.000e-16	4.000e-16	4.000e-16
cgs	97.0843f	97.0843f	48.5421f	48.5421f	194.1686f
cgd	5.0000f	5.0000f	2.5000f	2.5000f	10.0000f

Differential Mode

**** small-signal transfer characteristics

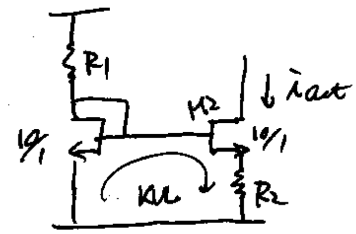
v(vo1,vo2)/vid = -42.2981
input resistance at vid = 1.000e+20
output resistance at v(vo1,vo2) = 783.9513k

Common Mode

**** small-signal transfer characteristics

v(voc)/vic = -15.7483m
input resistance at vic = 1.000e+20
output resistance at v(voc) = 17.2986k

2.



a) design for $I_{out} = 100\,\mu A$. $I_{in} = 400\,\mu A$.

write KVL equation: (ignore λ effect).

$$I_{out} \cdot R_2 + V_{to} + \sqrt{\frac{2 \cdot I_{out}}{K' \frac{W}{L}}} = V_{to} + \sqrt{\frac{2 \cdot I_{in}}{K'(\frac{W}{L})}}$$

$$= V_{dd} - I_{in} \cdot R_1.$$

$$\therefore R_2 = \frac{1}{100\mu}\left(\sqrt{\frac{2 \cdot 400\mu}{K' \cdot 10/1}} - \sqrt{\frac{2 \cdot 100\mu}{K' \cdot 10/1}}\right) = 4.472\,(k\Omega)$$

$$\Rightarrow R_1 = \frac{1}{I_{in}}\left(V_{dd} - V_{to} - \sqrt{\frac{2 \cdot I_{in}}{K'(\frac{W}{L})}}\right) = 1.264\,(k\Omega)$$

b) $R_{out} = R_S + r_o(1 + g_m R_S)$, where $R_S = R_2$.

(CS with source degeneration)

$$= 4.472k + \frac{1}{0.1 \cdot 100\mu A}\left(1 + \sqrt{2K'\frac{W}{L} \cdot 100\mu} \cdot 4.472k\right)$$

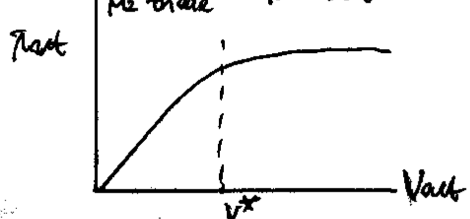
$$\simeq 300\,k\Omega$$ ※

spice: $334\,k\Omega$

mismatch, because $i_{out} \neq 100\,\mu A$. ($\because$ ignore λ when designing)

To improve accuracy, one should include λ effect, and iterate the equations to get a more accurate value of R_1 & R_2.

c)



$$V^* = I_{out} \cdot R_2 + V_{dsat2}$$

$$= 0.4472 + \sqrt{\frac{2 \cdot 100\mu}{K' \cdot 10/1}} \simeq 0.8944\ (V)$$ ※

spice: $0.808\,(V)$

EE140 HW4 Spring 2004 for 2nd problem

```
.model nch nmos LEVEL=1 TOX=25 VTO=0.4 KP=100.0e-6 LAMBDA=0.1
+GAMMA=0.01 PHI=0.6

*-----------------------------------------
vdd vdd 0 1.8
vout out 0 1
m1 g g 0 0 nch w=10u l=1u
m2 out g s 0 nch w=10u l=1u

r1 vdd g 1.264k
r2 s 0 4.472k
*-----------------------------------------

.dc vout 0 1.8 0.01
.option nomod post
.op

.tf i(m2) vout
.end

subckt
 element  0:m1      0:m2
 model    0:nch     0:nch
 region   Saturati  Saturati
 id       422.4604u  97.1935u
 ibs      0.        -4.3465f
 ibd      -12.6601f -10.0000f
 vgs      1.2660    831.3609m
 vds      1.2660    565.3508m
 vbs      0.        -434.6492m
 vth      400.0000m 402.4258m
 vdsat    866.0101m 428.9351m
 beta     1.1266m   1.0565m
 gam eff  10.0000m  10.0000m
 gm       975.6478u 453.1850u
 gds      37.4987u  9.1993u
 gmb      6.2978u   2.2277u
 cdtot    2.332e-16 1.041e-16
 cgtot    92.3375f  92.2185f
 cstot    92.0843f  92.0843f
 cbtot    2.000e-17 3.010e-17
 cgs      92.0843f  92.0843f
 cgd      2.332e-16 1.041e-16
```

9

**** small-signal transfer characteristics

i(m2)/vout = 2.9890u
input resistance at vout = 334.5640k
output resistance at i(m2) = 334.5640k