Name: . . . .

Only solve **three** of the four problems stated!

1) **Device Physics**

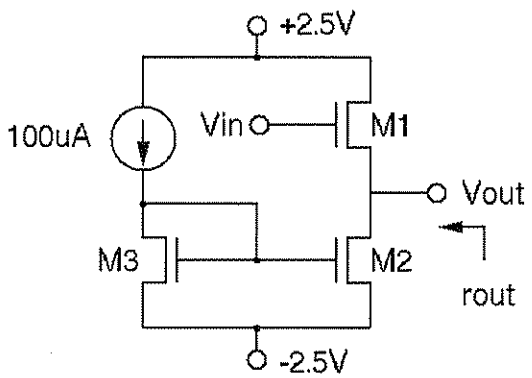
An n-well CMOS process features a p-substrate doping concentrations of $N_A=1.0x10^{23}m^{-3}$. Furthermore, we know that $\varepsilon_{ox}=3.6x10^{-11}$As/Vm and $n_i=2.0x10^{16}m^{-3}$ at T=300K

a) Determine the n-channel Fermi potential ϕ_{Fn} at room temperature.

b) The n-channel flat-band voltage is approximately $V_{FBn}=-0.7$ V. Calculate the gate oxide thickness $\mathbf{t_{ox}}$ such that $V_{tn}=0.8$ V.

c) **How much** does the threshold voltage $\mathbf{V_{tn}}$ of an n-channel device change if its source is 2V above the substrate potential? To find your answer, use the t_{ox} value listed in the BSIM parameters on page 3.

2) **Common Drain Amplifier**



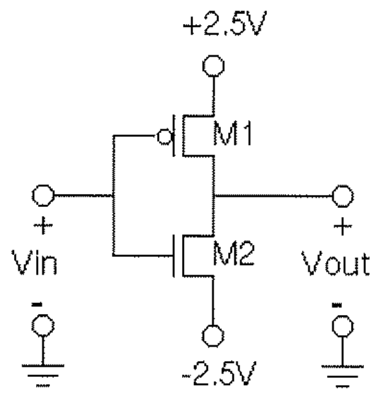
All transistors have the same W/L ratio of **100/4** and their physical parameters are: $\mu=4x10^{-2}\ m^2/Vs$, $Cox=2.5x10^{-3}\ F/m^2$, $\phi_F=0.4$ V, $V_{t0}=0.7$ V, $\gamma=0.6\ V^{1/2}$ and $\lambda=0.02\ V^{-1}$. Assume that $\mathbf{V_{in}}$ is generated by an **ideal ac** voltage source.

a) Find the **dc component** of the output voltage $\mathbf{V_{out}}$ if all transistor substrates are connected to -2.5V.

b) Find an expression and a numerical value for the output resistance $\mathbf{r_{out}}$.

c) Derive an expression for the voltage transfer function $\mathbf{A_v=V_{out}/V_{in}}$ and find the numerical value for the given transistor parameters.

CMOS Inverter

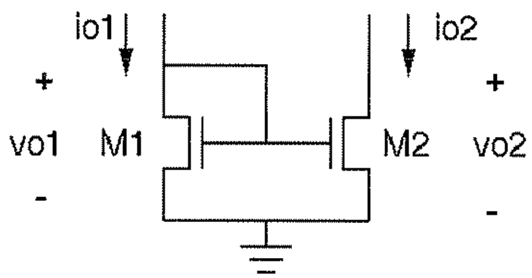


a) Sketch the **small signal linear equivalent circuit** for this amplifier under the assumption that both devices are operated in saturation.

b) Derive an expression for the **dc voltage gain $A_V=V_{out}/V_{in}$** (assume $V_{inQ}=V_{outQ}=0$). Your final gain expression should contain only **physical device parameters** and pertinent bias voltages. No numerical value is required.

c) Determine the 3 dB corner frequency (in Hz) if the circuit drives a capacitive load of C_L=500fF. Use $(W/L)_1=6$, $(W/L)_2=2$ and $\lambda_1=\lambda_2=0.02V^{-1}$.

3) **Differential Load**



a) Sketch the **ac equivalent** circuit for the differential load stage depicted above.

b) Assume that the two branches are operated under **common-mode** conditions, where **io1=io2**. Find the two equivalent output resistors $r_{o1cm}=v_{o1}/i_{o1}$ and $r_{o2cm}=v_{o2}/i_{o2}$, respectively. Only provide **symbolic** expressions, no numerical values!

c) Find the two equivalent output resistors under **differential-mode** conditions, where **io1=-io2**. Again, no numerical values are required.

SPICE BSIM3 VERSION 3.1 PARAMETERS

```
.MODEL nfet NMOS (                                       LEVEL   = 49
+VERSION = 3.1          TNOM    = 27                     TOX     = 1.39E-8
+XJ      = 1.5E-7       NCH     = 1.7E17                 VTH0    = 0.6398186
+K1      = 0.8857752    K2      = -0.0935679             K3      = 22.1010569
+K3B     = -7.6711263   W0      = 1E-8                   NLX     = 1E-9
+DVT0W   = 0            DVT1W   = 0                      DVT2W   = 0
+DVT0    = 2.7950058    DVT1    = 0.4085592              DVT2    = -0.1237812
+U0      = 453.2010286  UA      = 2.494433E-13           UB      = 1.488658E-18
+UC      = 2.022743E-11 VSAT    = 1.730467E5             A0      = 0.5543744
+AGS     = 0.1151449    B0      = 2.792031E-6            B1      = 5E-6
+KETA    = -1.371458E-3 A1      = 0                      A2      = 0.3560219
+RDSW    = 1.319508E3   PRWG    = 0.0381943              PRWB    = 0.0141195
+WR      = 1            WINT    = 2.507126E-7            LINT    = 2.304464E-8
+XL      = 0            XW      = 0                      DWG     =-1.755808E-8
+DWB     = 4.946821E-8  VOFF    = 0                      NFACTOR = 0.7910748
+CIT     = 0            CDSC    = 2.4E-4                 CDSCD   = 0
+CDSCB   = 0            ETA0    = 0.0051332              ETAB    = -1.252309E-3
+DSUB    = 0.1945608    PCLM    = 2.253484               PDIBLC1 = -1
+PDIBLC2 = 2.440187E-3  PDIBLCB = -0.1294159             DROUT   = 0.6751288
+PSCBE1  = 5.348212E8   PSCBE2  = 3.233314E-5            PVAG    = 0
+DELTA   = 0.01         RSH     = 80.3                   MOBMOD  = 1
+PRT     = 0            UTE     = -1.5                   KT1     = -0.11
+KT1L    = 0            KT2     = 0.022                  UA1     = 4.31E-9
+UB1     = -7.61E-18    UC1     = -5.6E-11               AT      = 3.3E4
+WL      = 0            WLN     = 1                      WW      = 0
+WWN     = 1            WWL     = 0                      LL      = 0
+LLN     = 1            LW      = 0                      LWN     = 1
+LWL     = 0            CAPMOD  = 2                      XPART   = 0.5
+CGDO    = 2.12E-10     CGSO    = 2.12E-10               CGBO    = 1E-9
+CJ      = 4.279445E-4  PB      = 0.9616445              MJ      = 0.4374524
+CJSW    = 3.492439E-10 PBSW    = 0.1                    MJSW    = 0.1245165
+CJSWG   = 1.64E-10     PBSWG   = 0.1                    MJSWG   = 0.1245165
+CF      = 0            PVTH0   = 0.0431719              PRDSW   = -30.376525
+PK2     = -0.0350028   WKETA   = -0.0230093             LKETA   = 2.090253E-3)
*
.MODEL pfet PMOS (                                       LEVEL   = 49
+VERSION = 3.1          TNOM    = 27                     TOX     = 1.39E-8
+XJ      = 1.5E-7       NCH     = 1.7E17                 VTH0    = -0.9488171
+K1      = 0.5429357    K2      = 9.433657E-3            K3      = 3.2656684
+K3B     = -0.8567156   W0      = 1E-8                   NLX     = 1.48542E-8
+DVT0W   = 0            DVT1W   = 0                      DVT2W   = 0
+DVT0    = 2.530444     DVT1    = 0.5291909              DVT2    = -0.1040273
+U0      = 220.9301068  UA      = 3.049951E-9            UB      = 1E-21
+UC      = -5.63429E-11 VSAT    = 2E5                    A0      = 0.9085767
+AGS     = 0.1506017    B0      = 9.121548E-7            B1      = 5E-6
+KETA    = -2.819843E-3 A1      = 0                      A2      = 0.3
+RDSW    = 3E3          PRWG    = -0.0464229             PRWB    = -0.0398483
+WR      = 1            WINT    = 2.90101E-7             LINT    = 4.254314E-8
+XL      = 0            XW      = 0                      DWG     = -2.169468E-8
+DWB     = 1.788287E-8  VOFF    = -0.0659109             NFACTOR = 0.8188201
+CIT     = 0            CDSC    = 2.4E-4                 CDSCD   = 0
+CDSCB   = 0            ETA0    = 1.380153E-3            ETAB    = -0.0429727
+DSUB    = 0.7658995    PCLM    = 2.0797597              PDIBLC1 = 0.1113965
+PDIBLC2 = 4.521707E-3  PDIBLCB = -0.0437905             DROUT   = 0.3065171
+PSCBE1  = 1.25116E10   PSCBE2  = 1.227353E-9            PVAG    = 8.477076E-6
+DELTA   = 0.01         RSH     = 104.9                  MOBMOD  = 1
+PRT     = 0            UTE     = -1.5                   KT1     = -0.11
+KT1L    = 0            KT2     = 0.022                  UA1     = 4.31E-9
+UB1     = -7.61E-18    UC1     = -5.6E-11               AT      = 3.3E4
+WL      = 0            WLN     = 1                      WW      = 0
+WWN     = 1            WWL     = 0                      LL      = 0
+LLN     = 1            LW      = 0                      LWN     = 1
+LWL     = 0            CAPMOD  = 2                      XPART   = 0.5
+CGDO    = 2.25E-10     CGSO    = 2.25E-10               CGBO    = 1E-9
+CJ      = 7.308538E-4  PB      = 0.9416073              MJ      = 0.4948413
+CJSW    = 2.852637E-10 PBSW    = 0.99                   MJSW    = 0.3001719
+CJSWG   = 6.4E-11      PBSWG   = 0.99                   MJSWG   = 0.3001719
+CF      = 0            PVTH0   = 5.98016E-3             PRDSW   = 14.8598424
+PK2     = 3.73981E-3   WKETA   = 4.127712E-3            LKETA   = -2.567864E-3)
```

1)

a) $\| \phi_p = \frac{kT}{q} \ln\left(\frac{N_{sub}}{n_i}\right) \cong 400 mV \|$ 3

b) $V_t = V_{FB} + 2\phi_{Fp} + \frac{t_{ox}}{\varepsilon_{ox}} \sqrt{2 \varepsilon_s 2\phi_{Fn} q N_{sub}}$

$\therefore \| t_{ox} = \frac{\varepsilon_{ox}}{\sqrt{2\varepsilon_s 2\phi_{Fn} q N_{sub}}} \left(V_t - V_{FB} - 2\phi_{Fn} \right) \cong 18 nm \|$ 4

c) $V_t(V_{SB}) = V_{t0} + \gamma \left[\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right]$

where $| \gamma = \frac{t_{ox}}{\varepsilon_{ox}} \sqrt{2 \varepsilon_s q N_{sub}} \cong 0.69 \sqrt{V} |$

$\therefore \| V_t (V_{SB} = 2V) = 1.34 V \|$ 3

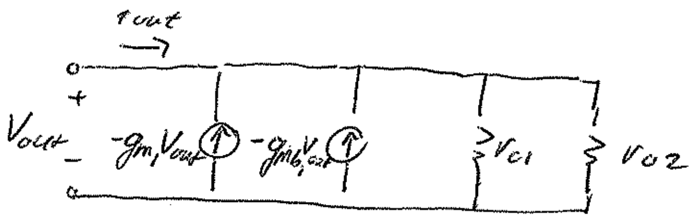
10

2) a) $V_{out_{dc}} = -V_t - \sqrt{\frac{2 I_{DQ}}{\mu C_{ox} W/L}}$ $I_{DQ} = 100\mu A$

where $V_t = V_{t0} + \gamma \left[\sqrt{2\varphi_F + V_{SB}} - \sqrt{2\varphi_F}\right] \cong 1.0V$ 1

$\therefore \left\| V_{out_{dc}} = -1.0V - \sqrt{\frac{2 I_{DQ}}{\mu C_{ox} W/L}} \cong -1.3V \right\|$ 3

b) linear eq. circuit to determine r_{out}

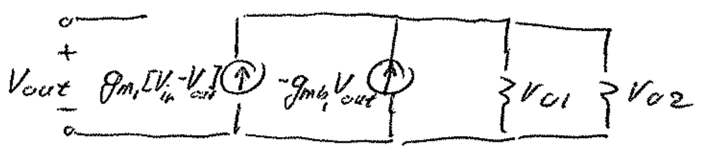


$r_{o1} = r_{o2} = 500k\Omega$
$g_{m1} = 0.71 mS$
$g_{mb1} = g_{m1} \cdot 0.21$

$\therefore \left| V_{out} = \left[i_{out} - (g_{m1} + g_{mb1}) V_{out} \right] \tilde{r}_o \right|$ $\tilde{r}_o = r_{o1} \| r_{o2}$

$\left\| r_{out} = \frac{V_{out}}{i_{out}} = \frac{\tilde{r}_o}{1 + (g_{m1} + g_{mb1})\tilde{r}_o} \approx \frac{1}{g_{m1} + g_{mb1}} \cong 1.2k\Omega \right\|$ 3

c) linear eq. circuit to determine voltage transfer function

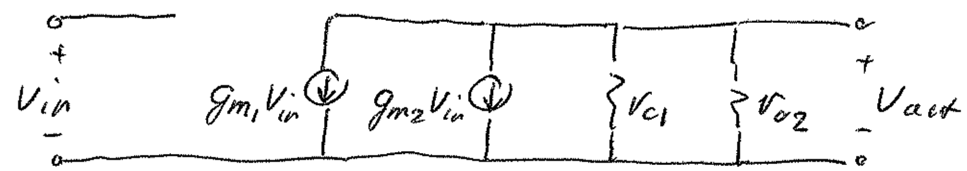


$\therefore V_{out} = g_{m1} \tilde{r}_o \left[V_{in} - V_{out} \right] - g_{mb1} \tilde{r}_o V_{out}$

$\left\| A_v = \frac{V_{out}}{V_{in}} = \frac{g_{m1} \tilde{r}_o}{1 + g_{m1}\tilde{r}_o + g_{mb1}\tilde{r}_o} \cong \frac{g_{m1}}{g_{m1} + g_{mb1}} \cong 0.83 \right\|$ 3

10

3) a)



3

b) $A_v = \frac{V_{out}}{V_{in}} = -(g_{m1} + g_{m2})\, r_{o1} \parallel r_{o2}$ 2

$g_m = \mu C_{ox} \frac{W}{L}[V_{DD} - V_t]$ $r_o = \frac{2}{\lambda \mu C_{ox} \frac{W}{L}[V_{DD} - V_t]^2}$

$\therefore A_v \cong -\frac{2[(\mu C_{ox} \frac{W}{L})_1 + (\mu C_{ox} \frac{W}{L})_2]}{[V_{DD} - V_t][(\lambda \mu C_{ox} \frac{W}{L})_1 + (\lambda \mu C_{ox} \frac{W}{L})_2]}$ $|V_{t1}| \approx V_{t2}$

If $\lambda_1 \approx \lambda_2$ and $(\mu C_{ox} \frac{W}{L})_1 \approx (\mu C_{ox} \frac{W}{L})_2$

$A_v \approx -\frac{2}{[V_{DD} - V_t]\lambda}$ 2

c) Corner frequency due to C_L

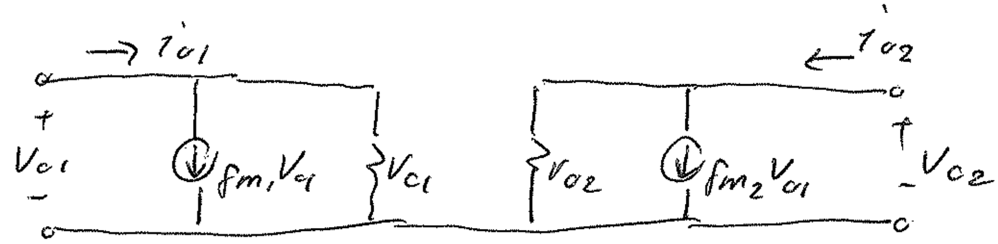
$\omega_p = \frac{1}{\tilde{r}_o C_L}$

$\tilde{r}_o = \frac{2}{[(\lambda \mu C_{ox} \frac{W}{L})_1 + (\lambda \mu C_{ox} \frac{W}{L})_2][V_{DD} - V_t]^2} \approx 56\,k\Omega$

$\therefore f = \frac{1}{2\pi} \frac{1}{\tilde{r}_o C_L} \cong 5.7\,MHz$ 3

10

4) a)



3

b) common mode $\therefore\ i_{o1} = i_{o2}$

$$\left| \begin{aligned} V_{o1} &= (i_{o1} - g_{m1}V_{o1})\, r_{o1} \\ V_{o2} &= (i_{o2} - g_{m2}V_{o1})\, r_{o2} \end{aligned} \right| \quad \therefore\ V_{o1} = i_{o1}\frac{r_{o1}}{1+g_{m1}r_{o1}}$$

$$\therefore\ V_{o2} = \left(i_{o2} - i_{o2}\frac{g_{m2}r_{o1}}{1+g_{m1}r_{o1}}\right) r_{o2}$$

$$r_{o1cm} = \frac{r_{o1}}{1+g_{m1}r_{o1}} \cong \frac{1}{g_{m1}}$$ 2

$$r_{o2cm} = \frac{r_{o2}}{1+g_{m1}r_{o1}} \cong \frac{1}{g_{m1}}$$ 2

c) differential mode $i_{o1} = -i_{o2}$

$$\therefore\ V_{o2} = \left(i_{o2} + i_{o2}\frac{g_{m2}r_{o1}}{1+g_{m1}r_{o1}}\right) r_{o2}$$

$$r_{o1dm} = r_{o1cm} \cong \frac{1}{g_{m1}}$$

$$r_{o2dm} = \frac{1+(g_{m1}+g_{m2})r_{o1}}{1+g_{m1}r_{o1}} \cong 2\, r_{o1}$$ 3

10