A	91-100
B	75-90
C	55-74

μ 87.2

σ 18.3

MED 95 !

Name SOLUTIONS

ECE Box # ____________

Problem	Average Score	Points
1	18.2	20
2	16.8	20
3	43.8	50
4	8.4	10

ECE4902 B2015

Analog IC Design

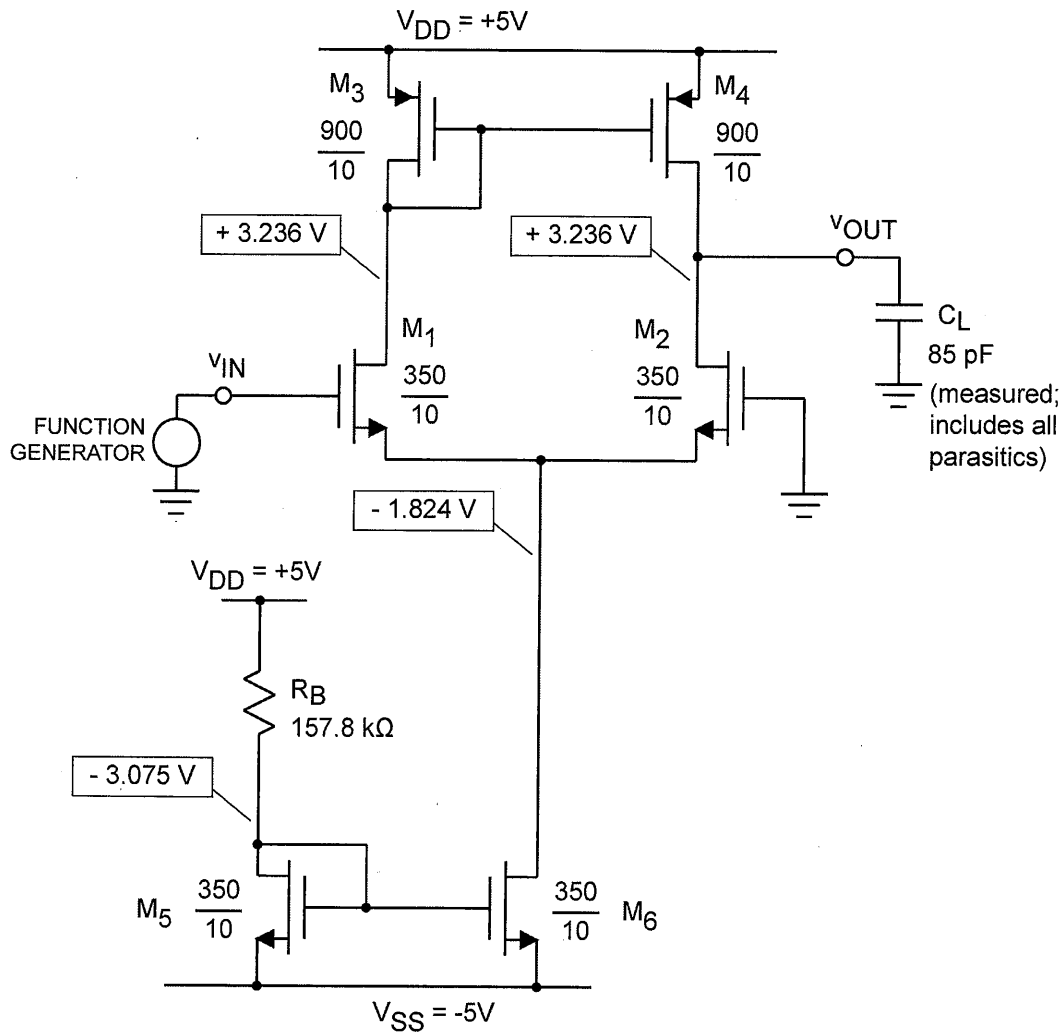
Quiz 4

December 4, 2015

- This is a **closed book, closed notes test**! Use of calculators is OK, but **no pre-stored data or formulas allowed**!
- The last page is a notes page which may be detached for convenience and need not be turned in with the exam
- Show **all** your work. Partial credit may be given. If you think you need something that you can't remember, write down what you need and what you'd do if you remembered it.
- **Look for the simple, straightforward way to solve the problem for the level of accuracy required. Don't get entangled in unnecessary algebra.**
- As in real life, some problems may give you more information than you need. Don't assume that all information must be used! It's your job to decide what's relevant to the solution.
- You have 60 minutes to complete this quiz. There are four problems on a total of 13 pages (including notes page).

It's the night before the end of the term and you've got to get the ECE4902 lab reports handed in. But your lab partner had heard the professor's "Confusing terminology = barrier to entry = high salary" line once too often and has dropped the course in frustration. Now all you have left is your sketchy lab notes for the differential pair amplifier with active load circuit shown below.

For the purposes of this question you may ignore channel length modulation. Also, since V_{SB}=0 for all MOSFETs, you may ignore the body effect as well.



The schematic above shows some of your measured data:

- the value of the resistor R_B setting the mirror bias current, and
- the DC voltages (in the boxes) at each node when v_{IN} = 0

You also recall that you have a scope photo showing the step response, with

- the measured 10%-to-90% rise time at the output, and
- the peak-to-peak amplitude (Pk-Pk) of the input and output waveforms.

And since your partner never believed the professor's "bandwidth-risetime relationship" story, you also have some photos for sinusoidal waveforms. In each case you have

- The scope photo of the input and output sinusoids, showing the measured frequency
- The rms amplitude (RMS) of the input and output waveforms.

Note that the scope photos (on the opposite page) were taken with AC coupling, for more accurate amplitude measurements. This means the scope waveforms don't have any DC information, but your partner said this was OK because you had the DC values above.

1. Determine the transfer function v_{out}/v_{in} assuming the form of a first order lowpass. You may use s or f or $j\omega$, but be sure to express the transfer function in a form that explicitly shows the DC gain and the 3-dB frequency (bandwidth). Accuracy ±10% for full credit. [20]

FROM STEP

$$\frac{V_{OUT}}{V_{IN}} = \frac{578\,mV}{10\,mV} = 57.8$$

$$\frac{v_{out}}{v_{in}} = \frac{57.8}{1 + j\left(\frac{f}{6.8\ KHz}\right)}$$

FROM LOW FREQUENCY

$$\frac{V_{out}}{V_{in}} = \frac{160\,mV}{2.77\,mV} = 57.8$$

Step Input

CH4

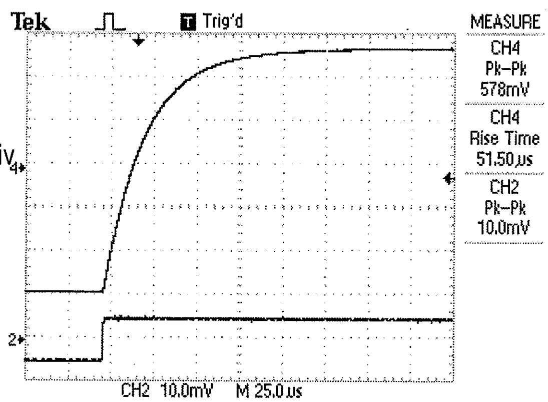
V_{OUT}

100mV/div

CH2

V_{IN}

10mV/div



BANDWIDTH FROM STEP RESPONSE

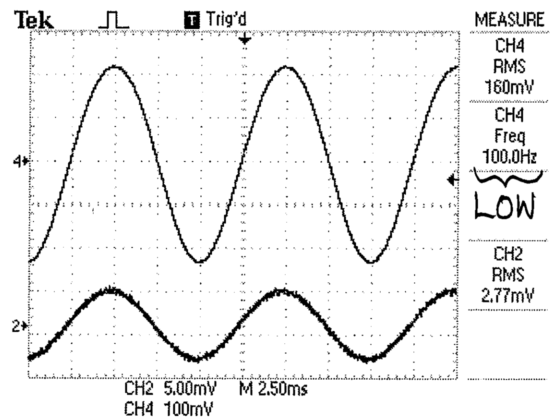
$$BW \times t_R = 0.35$$

t_R = 51.5µs

$$BW = \frac{0.35}{51.5\,\mu s} = 6.8\ KHz$$

BANDWIDTH FROM BODE PLOT: SEE P. 11

Sinusoid Input



CH4

V_{OUT}

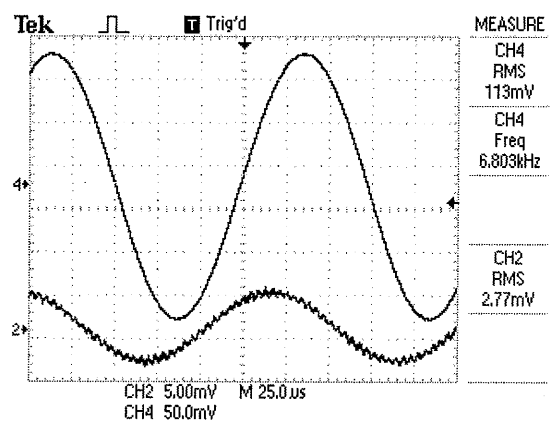
100mV/div

LOW FREQ

CH2

V_{IN}

5mV/div



CH4

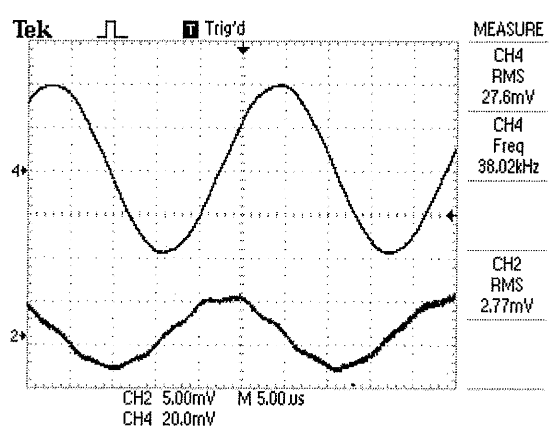
V_{OUT}

50mV/div

CH2

V_{IN}

5mV/div



CH4

V_{OUT}

20mV/div

CH2

V_{IN}

5mV/div

2. For the circuit and results of problem 1 (repeated for your convenience below and on the opposite page), determine the small signal transconductance g_m for devices M1 and M2. Accuracy ±10% for full credit.

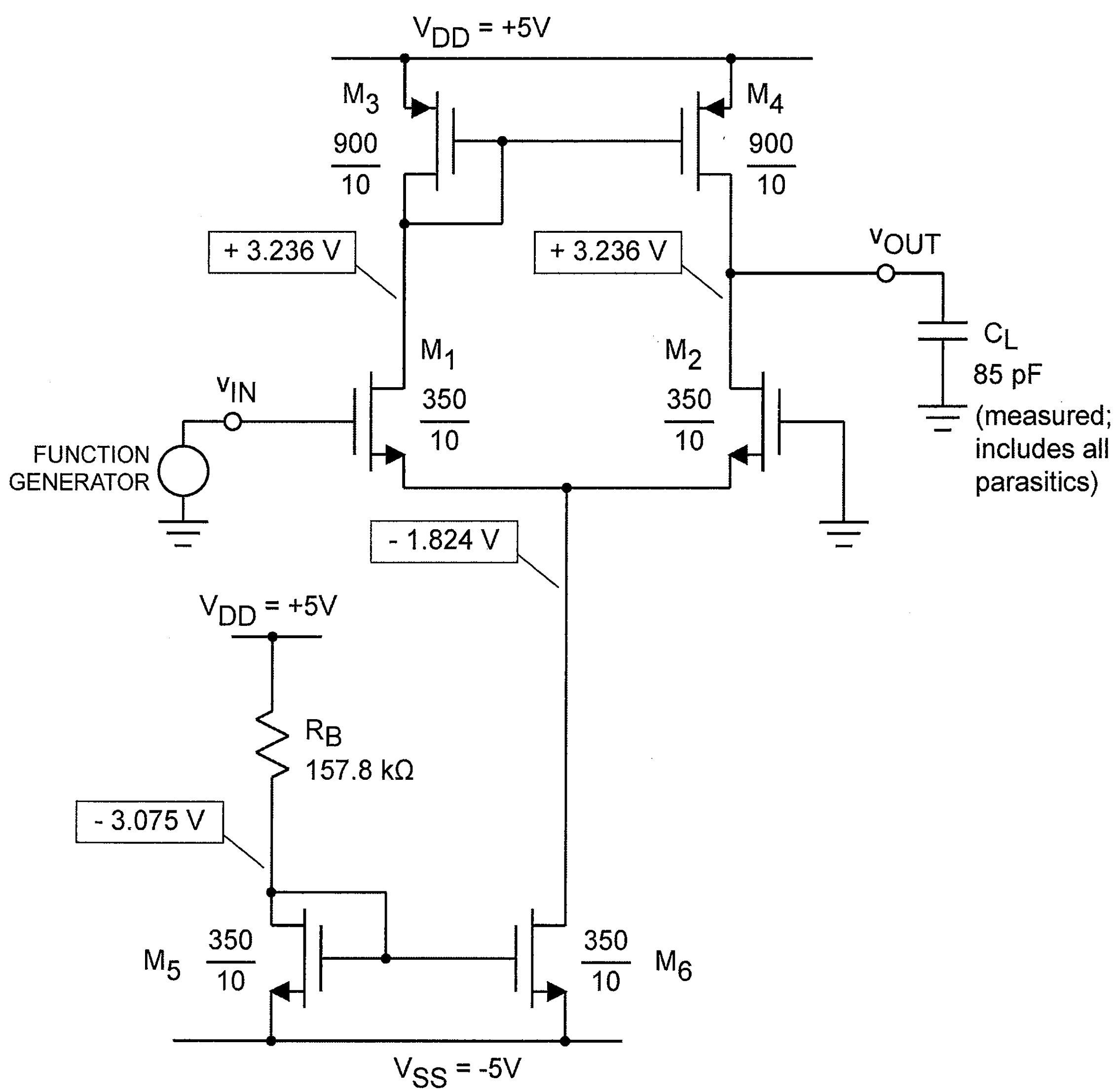
For the purposes of this question you may ignore channel length modulation. Also, since V_{SB}=0 for all MOSFETs, you may ignore the body effect as well.

[20]

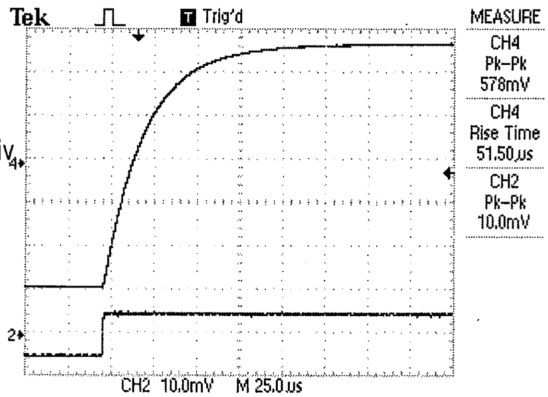
M1: g_{m1} = 206 μA/V

M2: g_{m2} = 206 μA/V

SAME FOR BOTH (SYMMETRY)



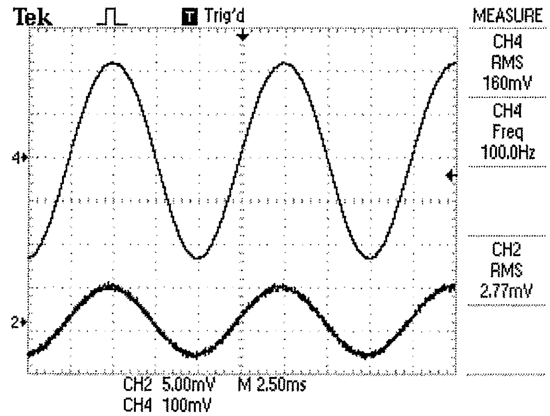
Step Input



CH4
V_{OUT}
100mV/div

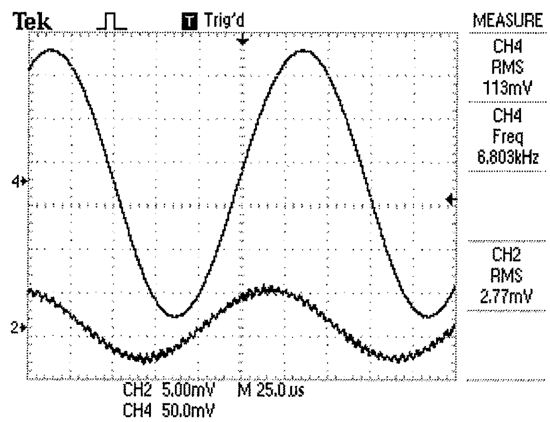
CH2
V_{IN}
10mV/div

Sinusoid Input



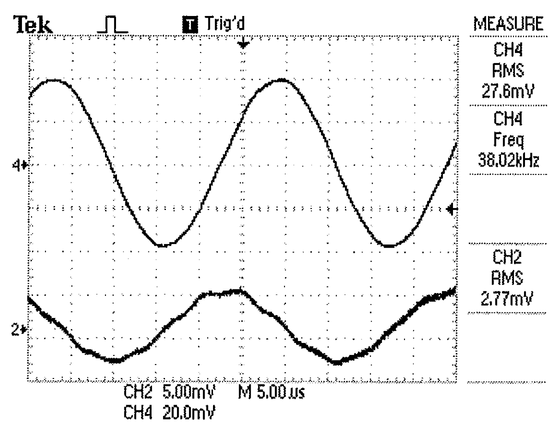
CH4
V_{OUT}
100mV/div

CH2
V_{IN}
5mV/div



CH4
V_{OUT}
50mV/div

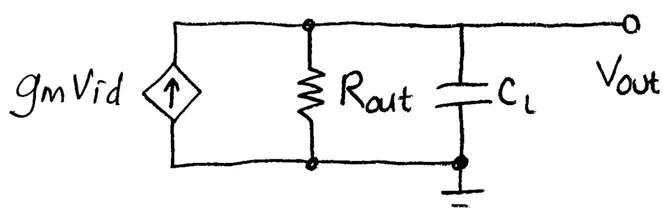
CH2
V_{IN}
5mV/div



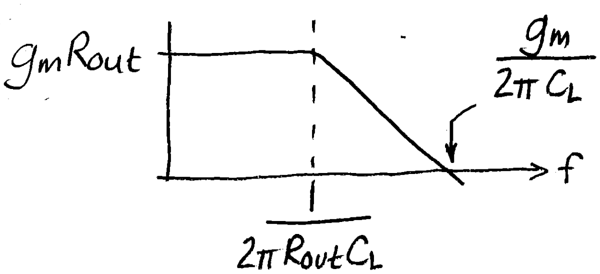
CH4
V_{OUT}
20mV/div

CH2
V_{IN}
5mV/div

SMALL SIGNAL MODEL



TRANSFER FUNCTION



CAN GET g_m DIRECTLY FROM f_T

$$380\text{ kHz} = \frac{g_m}{2\pi(85\text{ pF})} \Rightarrow g_m = 203\ \frac{\mu A}{V}$$

OR GET R_{out} FROM BW:

$$6.8\text{ kHz} = \frac{1}{2\pi R_{out}(85\text{ pF})} \Rightarrow R_{out} = 275\text{ k}\Omega$$

THEN g_m FROM DC GAIN

$$g_m(275\text{ k}\Omega) = 57.8 \Rightarrow g_m = 210\,\mu A/V$$

3. This problem concerns DC quantities for the MOSFETs in the circuit of problem 1 (schematic repeated on the following page for your convenience).

For the purposes of this question you may ignore channel length modulation. Also, since $V_{SB}=0$ for all MOSFETs, you may ignore the body effect as well.

[50]

Determine the DC bias conditions (DC drain current I_D and DC gate-source voltage V_{GS}) for all devices. Write your answers in the table below. Accuracy for full credit: ±10% for currents, ± 0.02V for voltages.

MOSFET	Drain current I_D [μA]	Gate-Source voltage V_{GS} [V]
M1	25.6	+ 1.824
M2	25.6	+ 1.824
M3	25.6	− 1.764
M4	25.6	− 1.764
M5	51.2	+ 1.925
M6	51.2	+ 1.925

KVL

OHM'S LAW

MIRROR

SYMMETRY SPLIT

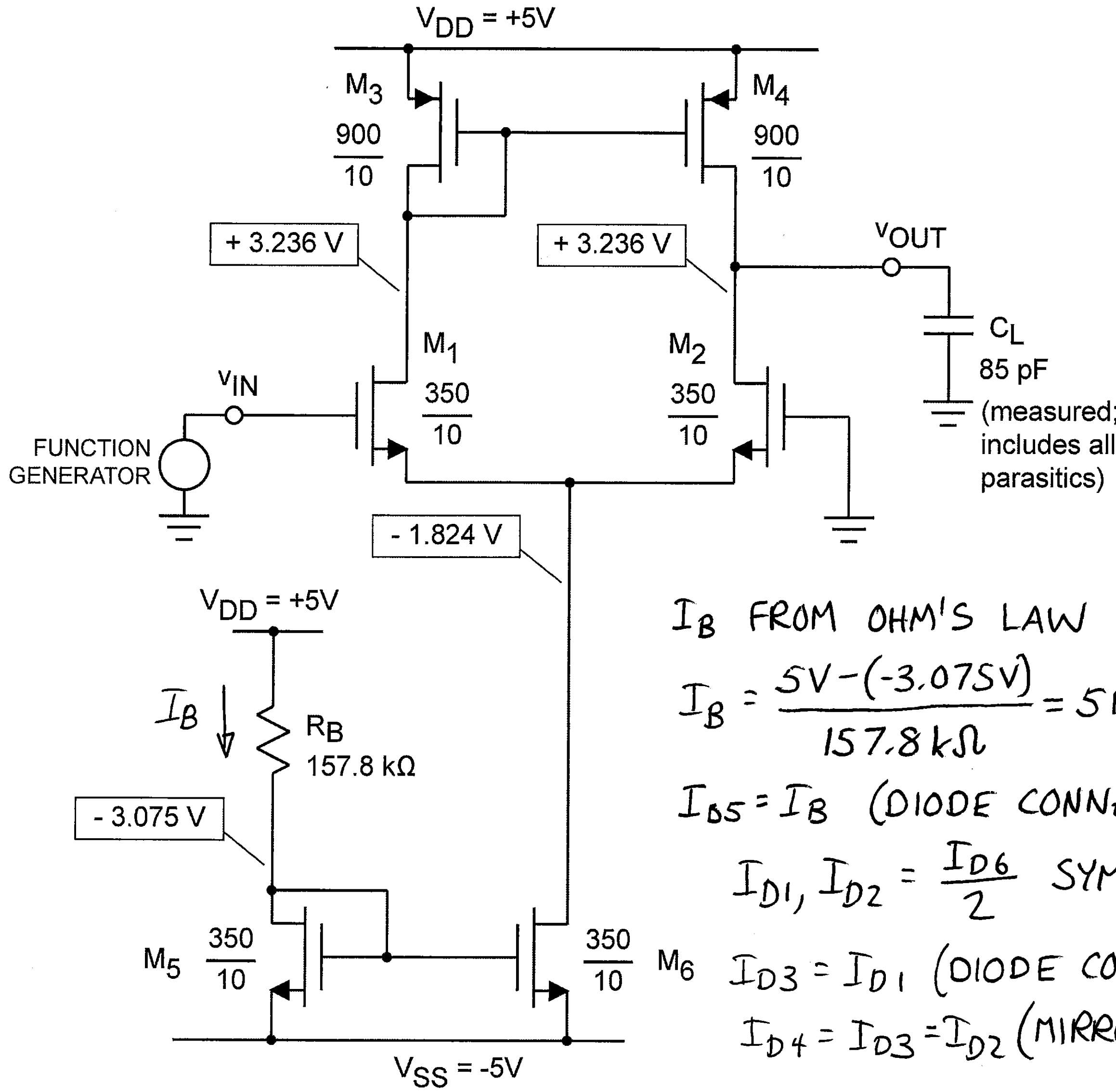
Determine μC_{OX} and V_{TH} for the NMOS devices. Write your answers in the table below. Accuracy for full credit: ±10% for μC_{OX}, ± 0.02V for V_{TH}.

Parameter	NMOS	Units
V_{TH}	+ 1.58V	V
μC_{ox}	2.49E-5	A/V^2

OR USE $\sqrt{I_D}$ VS. V_{GS} METHOD ON P. 12

CAN USE TO CHECK g_m FROM (2):

$$g_m = \frac{2I_D}{(V_{GS}-V_{TH})} = \frac{2(25.6\mu A)}{1.824-1.582} = 211\ \mu A/V \checkmark$$



I_B FROM OHM'S LAW

$$I_B = \frac{5V-(-3.075V)}{157.8\,k\Omega} = 51.2\,\mu A$$

$I_{D5} = I_B$ (DIODE CONNECTED)

$I_{D1}, I_{D2} = \frac{I_{D6}}{2}$ SYMMETRY

$I_{D3} = I_{D1}$ (DIODE CONNECTED)

$I_{D4} = I_{D3} = I_{D2}$ (MIRROR; KCL)

V_{GS} WITH SQUARE LAW FOR $\mu_N C_{ox}$, V_{THN}

$$M_1 :\ 25.6\,\mu A = \frac{\mu_N C_{ox}}{2}\,\frac{350}{10}\left(1.824 - V_{TH(N)}\right)^2$$

$$M_6 :\ 51.2\,\mu A = \frac{\mu_n C_{ox}}{2}\,\frac{350}{10}\left(1.925 - V_{TH(N)}\right)^2$$

DIVIDE

$$\frac{1}{\sqrt{2}} = \frac{1.824 - V_{TH(N)}}{1.925 - V_{TH(N)}} \Rightarrow 1.925 - V_{TH(N)} = 2.580 - 1.414\,V_{TH}$$

$$0.414\,V_{TH(N)} = 0.655\,V$$

$$V_{TH(N)} = +1.582\,V$$

IN M_6 SQUARE LAW FOR $\mu_N C_{ox}$

$$51.2\,\mu A = \frac{\mu_n C_{ox}}{2}\,\frac{350}{10}\left(1.925 - 1.582\right)^2 \Rightarrow \mu_n C_{ox} = 2.49E-5$$

4. You realize that results of problem 1 (repeated for your convenience below and on the opposite page) can't give you the individual channel length modulation parameters λ_n and λ_p for the NMOS and PMOS devices. But you can get the sum of the two. Determine the value of $\lambda_n + \lambda_p$ for the NMOS and PMOS devices. Write your answer in the space below. Accuracy for full credit: ±20%.

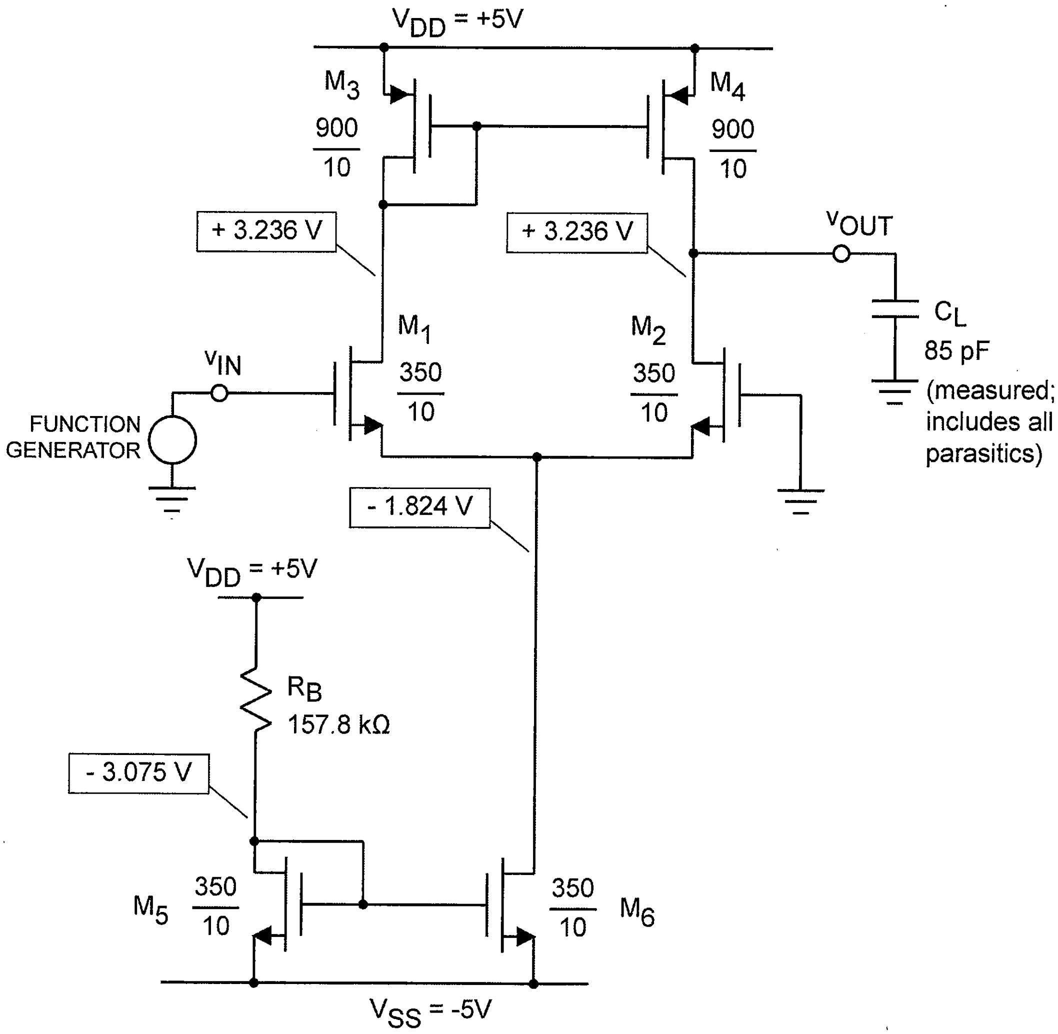
[10]

$\lambda_n + \lambda_p =$ 0.142 $[V^{-1}]$

$$R_{out} = \frac{1}{\frac{1}{r_{o2}} + \frac{1}{r_{o4}}} = \frac{1}{(\lambda_n + \lambda_p) I_D} \Rightarrow \lambda_n + \lambda_p = \frac{1}{(25.6\mu A)(275 k\Omega)} = 0.142$$

CHECK WITH DC GAIN

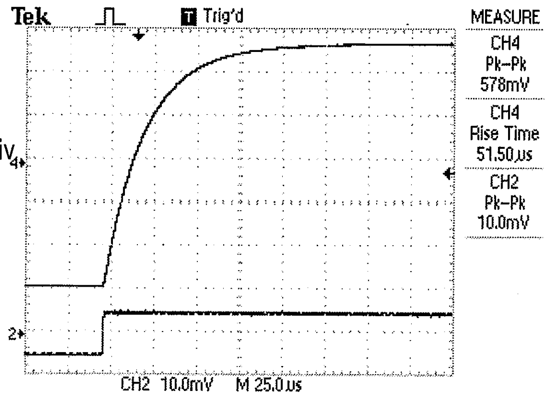
$$g_m R_{out} = \frac{2\cancel{I_D}}{(V_{GS} - V_{TH})(\lambda_n + \lambda_p)\cancel{I_D}} = \frac{2}{(1.824V - 1.582V)(0.142)} = 58.2 \checkmark$$



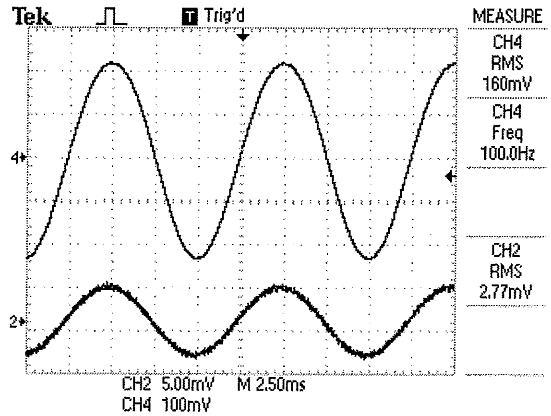
Step Input

CH4
V_{OUT}
100mV/div

CH2
V_{IN}
10mV/div

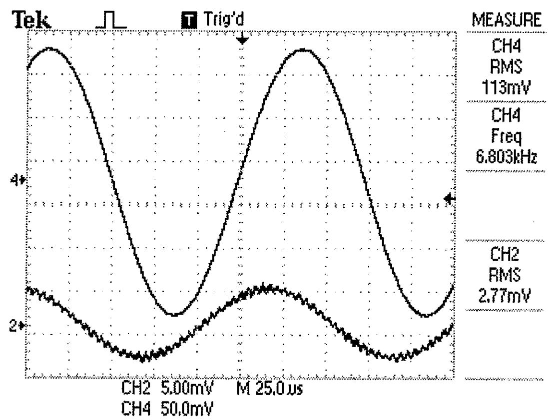


Sinusoid Input



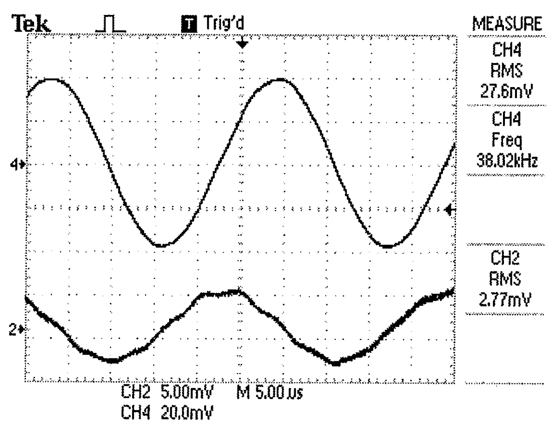
CH4
V_{OUT}
100mV/div

CH2
V_{IN}
5mV/div



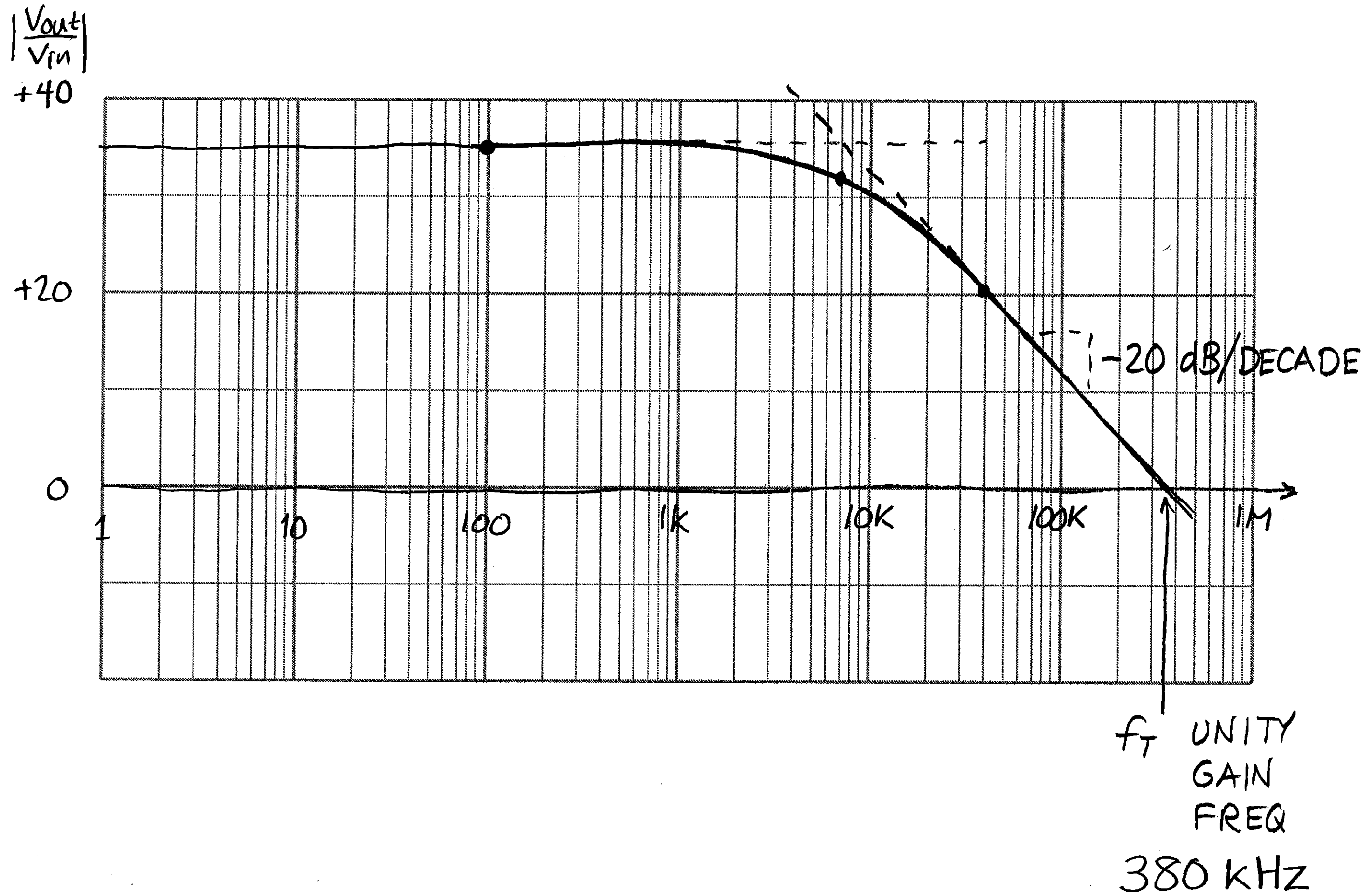
CH4
V_{OUT}
50mV/div

CH2
V_{IN}
5mV/div



CH4
V_{OUT}
20mV/div

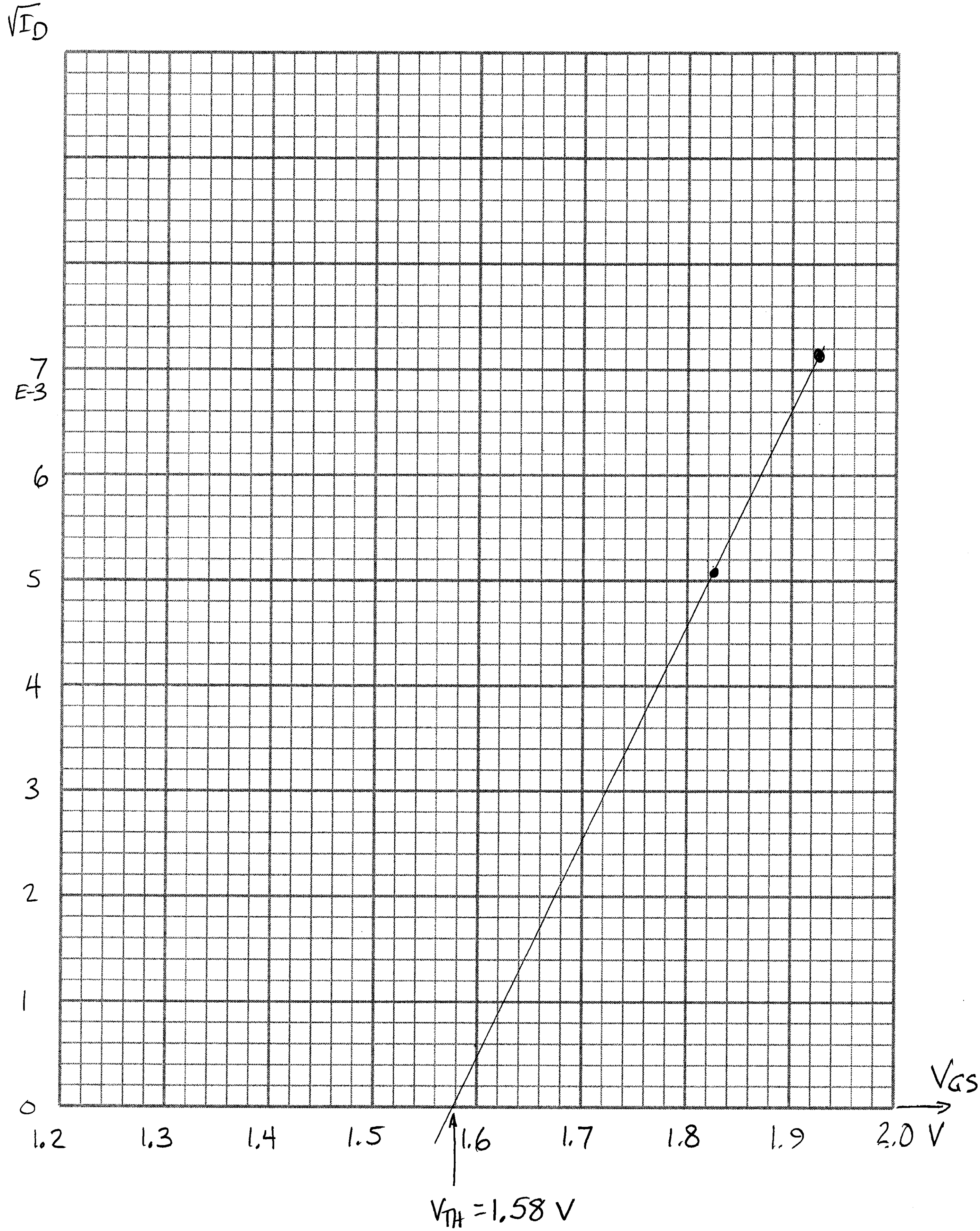
CH2
V_{IN}
5mV/div



DATA FROM SCOPE PHOTOS:

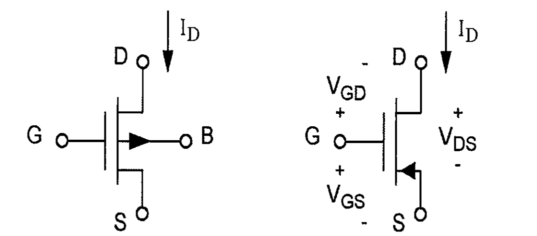
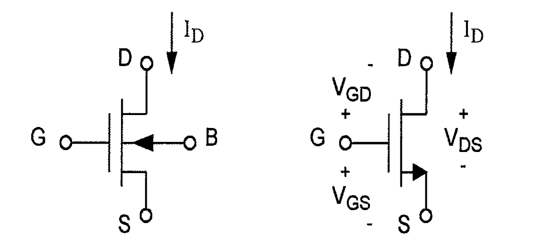
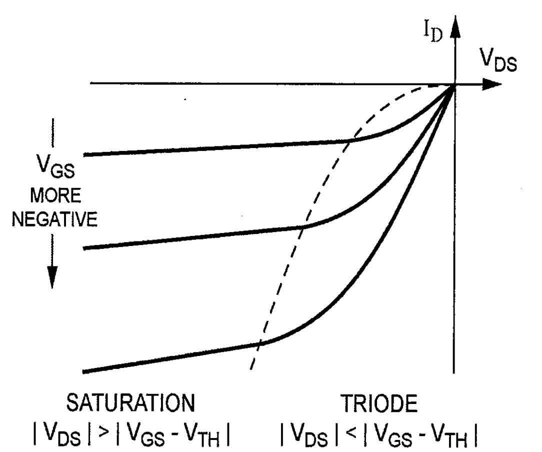
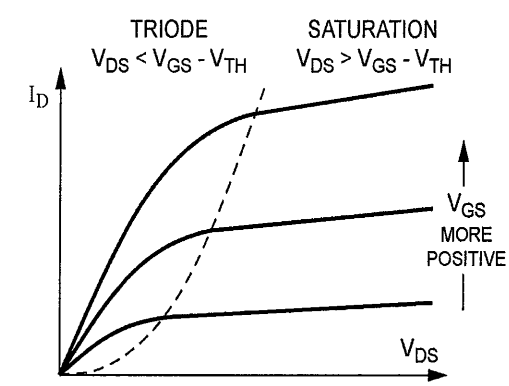
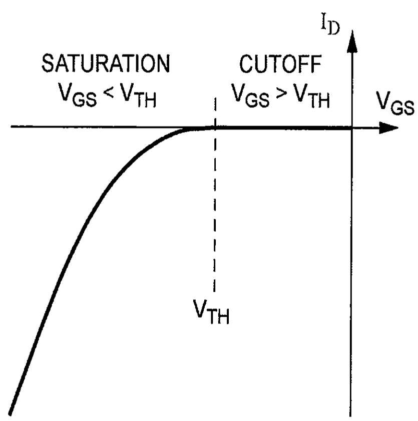
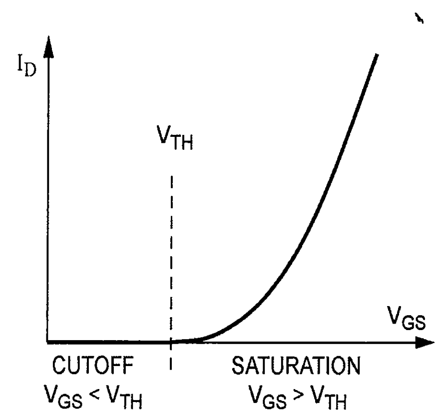
f	$\|V_{IN}\|_{RMS}$	$\|V_{OUT}\|_{RMS}$	GAIN $\frac{\|V_{out}\|}{\|V_{in}\|}$	dB
100 Hz	2.77 mV	160 mV	57.8	+35.2
BW → 6.8 kHz	|	113 mV	40.8	+32.2
38 kHz	|	27.6 mV	9.96	+20.0

−3dB



$\sqrt{I_D}$
7
E-3
6
5
4
3
2
1
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0 V
V_{GS}
$V_{TH} = 1.58$ V

MOSFET LARGE SIGNAL CHARACTERISTICS

	P CHANNEL	N CHANNEL
CIRCUIT SYMBOL		
SATURATION REGION	$I_D = -\frac{\mu_p C_{ox}}{2}\frac{W}{L}(V_{GS}-V_{TH})^2\left[1+\lambda\lvert V_{DS}\rvert\right]$	$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS}-V_{TH})^2\left[1+\lambda V_{DS}\right]$
I_D-V_{DS} CHARACTERISTIC		
I_D-V_{GS} CHARACTERISTIC (SATURATION REGION)		
TRIODE REGION	$I_D = -\mu_p C_{ox}\frac{W}{L}\left[(V_{GS}-V_{TH})V_{DS}-\frac{V_{DS}^{2}}{2}\right]$	$I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS}-V_{TH})V_{DS}-\frac{V_{DS}^{2}}{2}\right]$