Note Title 05-09-2023

5/9/2023

EE5320W Analog IC Design – Lec 1

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HW/Projects : 20%
Quiz 1 : 20%
Quiz 2 : 20%
Final Exam : 40%

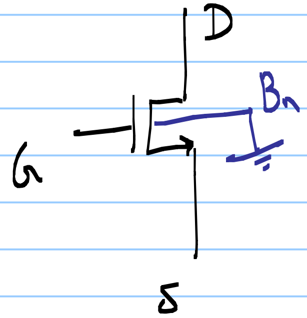
) 100%

Ref. Textbook

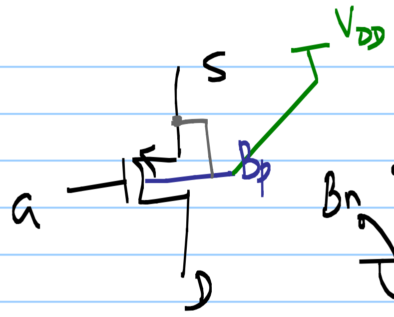
Behzad Razavi : "Design of Analog CMOS Integrated Circuits"

Classes : Every Tue & Thu @ 4-5:15 pm
Alternate Fri @ ?

1) MOSFETs

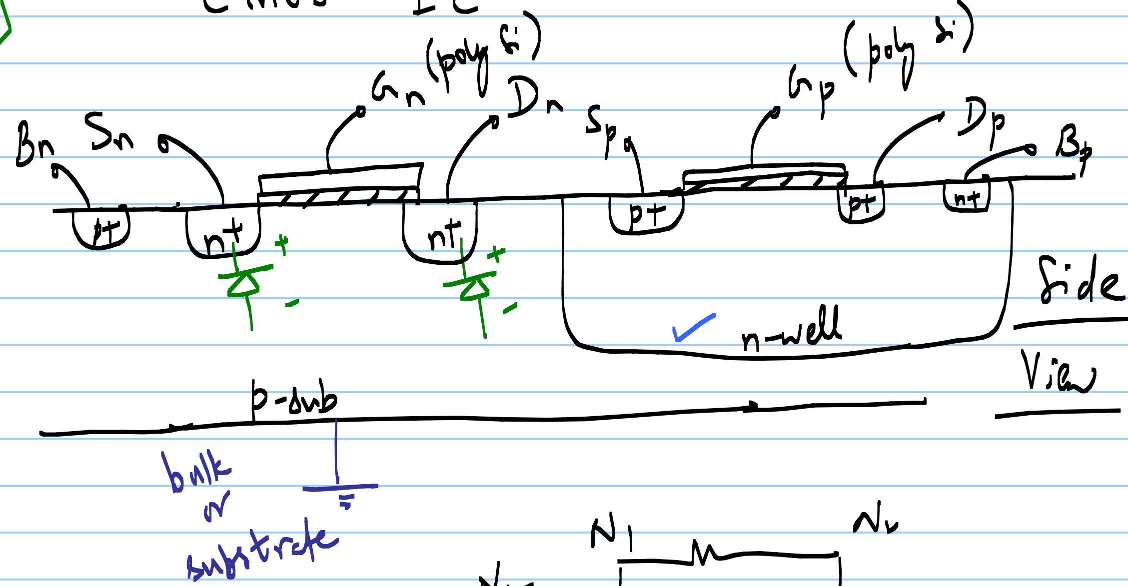


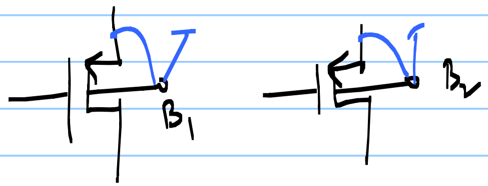
NMOS ✓

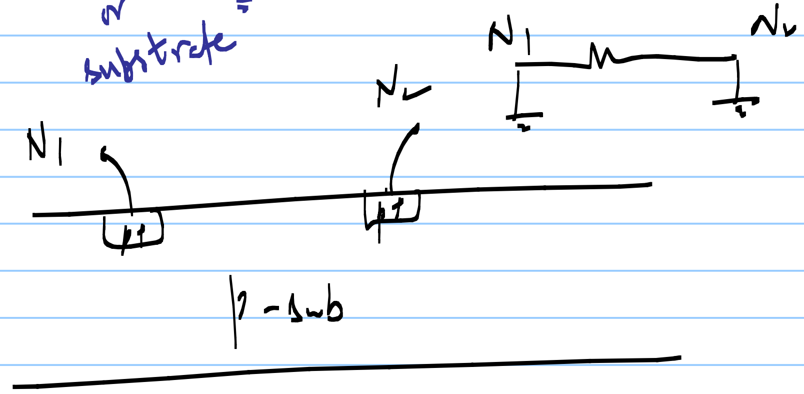


PMOS ✓

CMOS IC





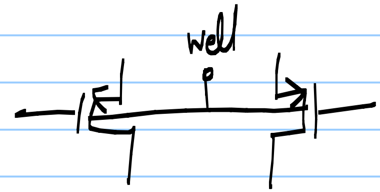


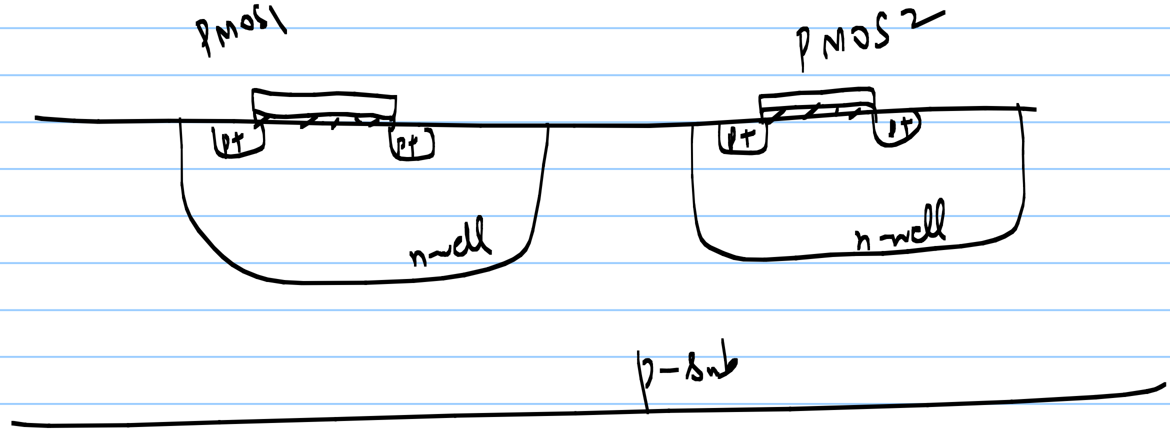
2) Resistors

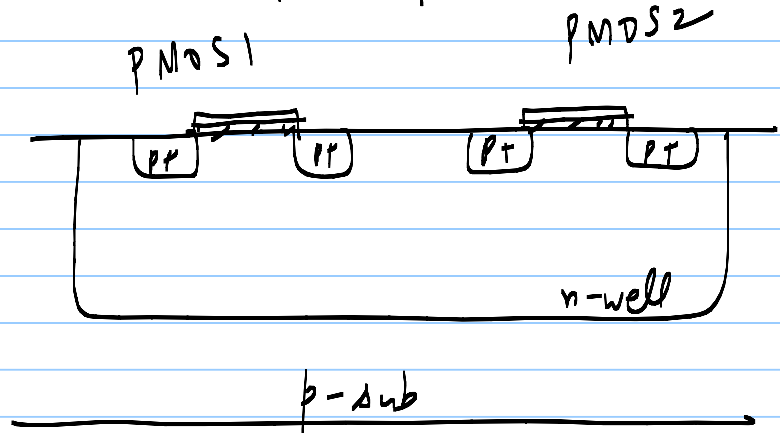
* poly R — 10's of Ω
* Metal R — mΩ – Ω "silicide"
  "salicide"
* n-well R — 10's of kΩ
* diffusion R — kΩ

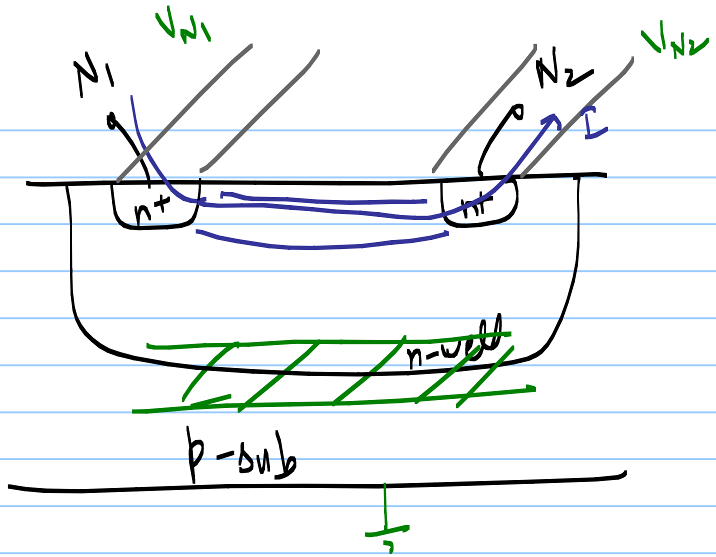
OFF MOSFET (leakage)

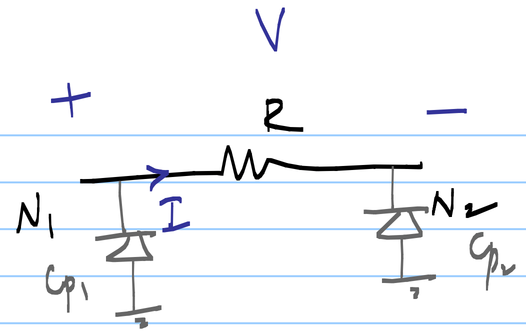
triode MOS (non-linear)







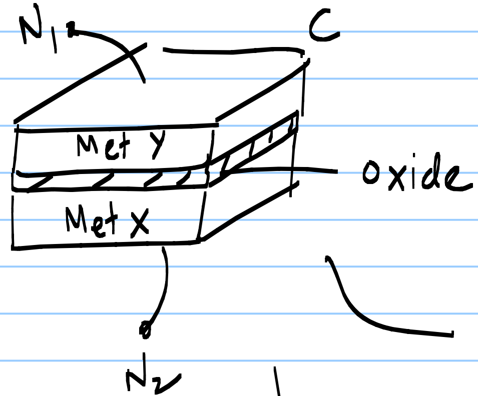




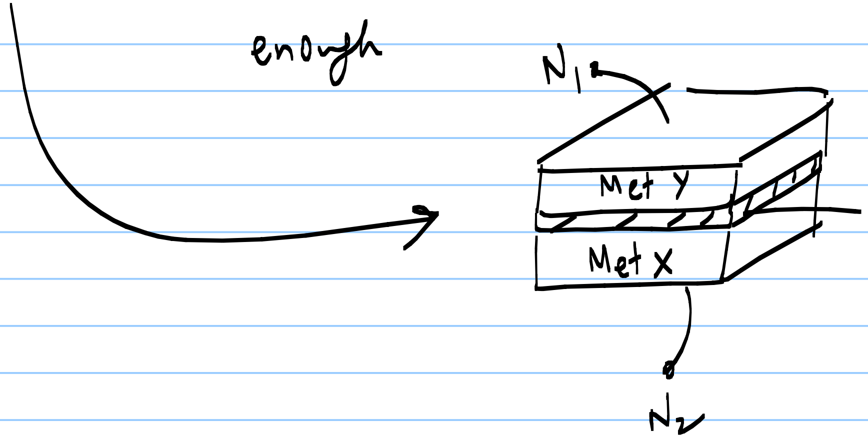
$$I = \frac{1}{R}(V) + \frac{1}{(\ )}\cdot(V)^2 + \frac{1}{(\ )}(V)^3 + \dots$$

non-linear R

3) Capacitors C

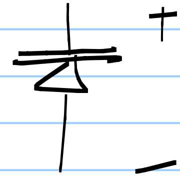


Not dense enough



High k dielectric

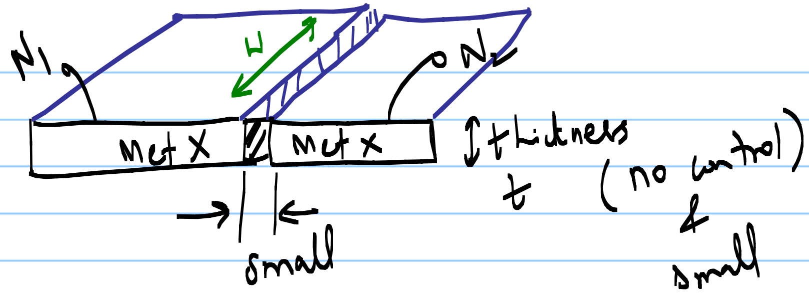
larger C



Non linear cap.

Varactor

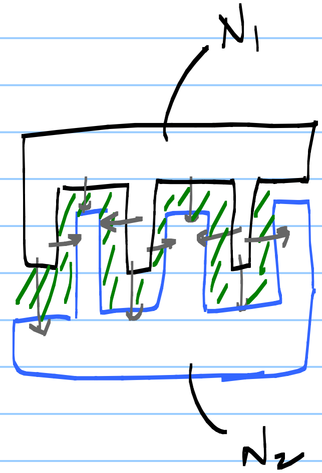
$C = f(V)$



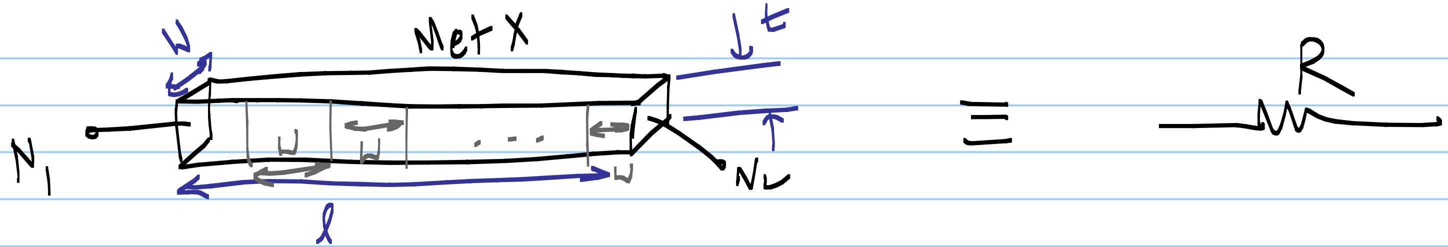
Area of plate = W.t

low density cap

top view



larger cap



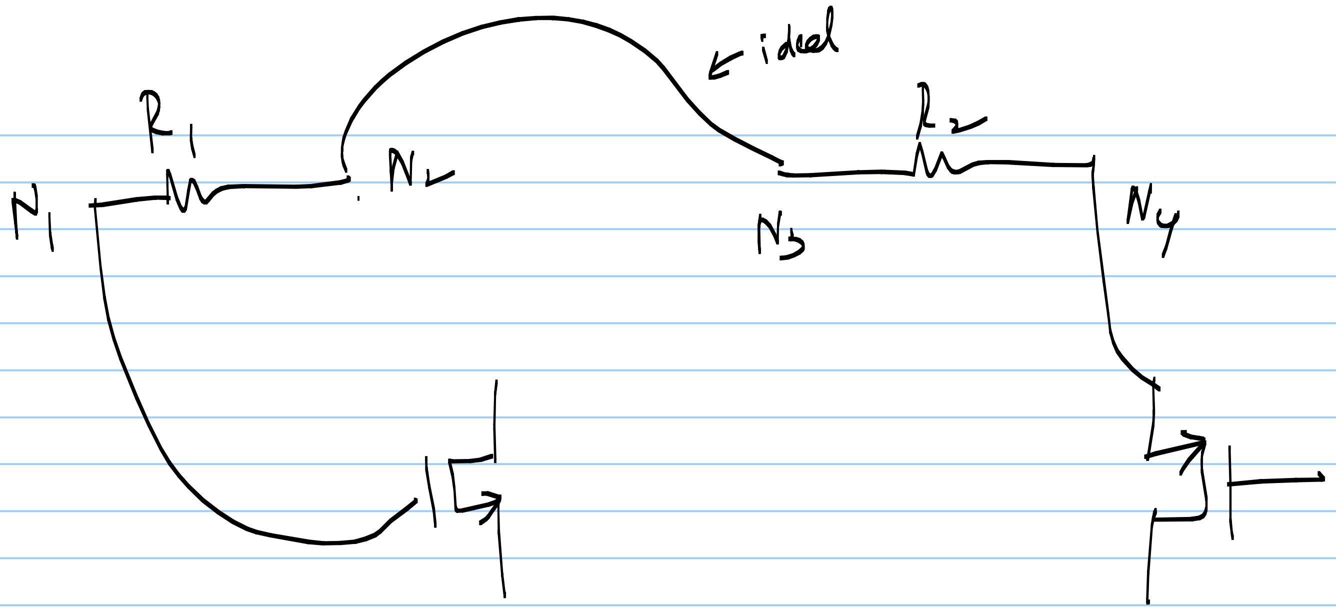
$$R = \frac{\rho \cdot l}{A} = \frac{\rho \cdot l}{w \cdot t} = \left(\frac{\rho}{t}\right) \cdot \left(\frac{l}{w}\right)$$

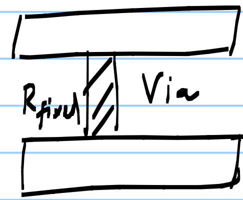
$\left(\frac{\rho}{t}\right)$: fixed for a given metal layer

$\left(\frac{l}{w}\right)$: number of squares

"sheet" resistance

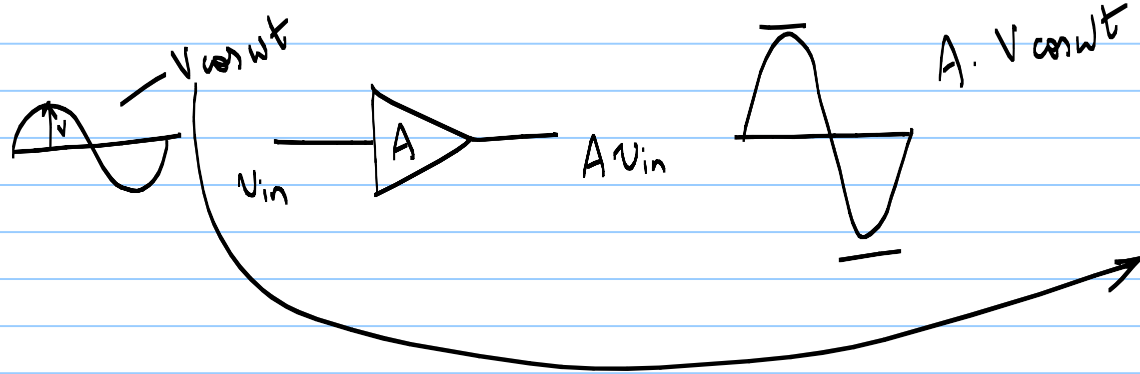
in $\Omega/\square$


ideal
R1
R2
N1
N2
N3
N4


Via

14/9/2023

Lec 2



$V \uparrow$

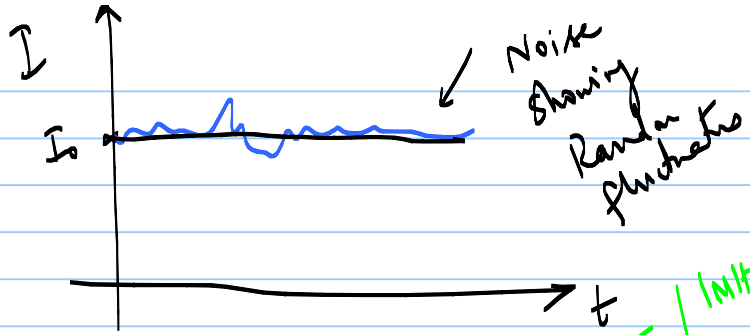
swing limits — Triode limit

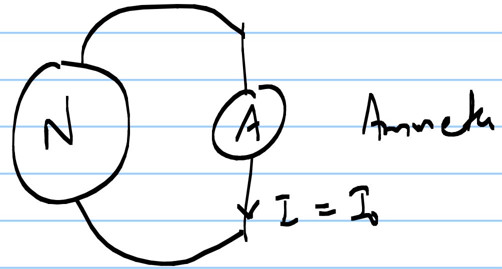
— Cut off limit

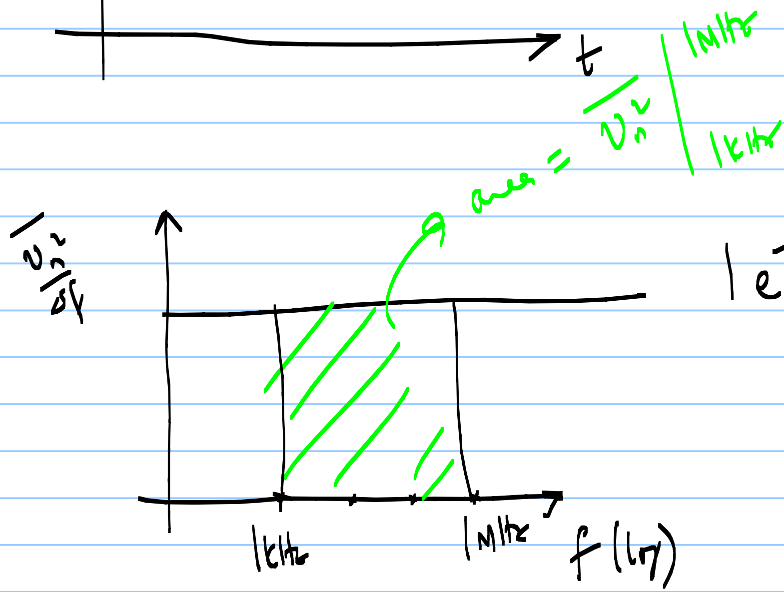
$V_{max} = \min.\{V_{max_1}, V_{max_2}, \dots\}$

$V \downarrow$ → Noise limits the dynamic range on the lower end

→ Random processes → lead to uncertainties in V_x & I_x inside device







$1e^{-18}\ V^2/Hz$

Power Spectral Density

$\dfrac{\overline{v_n^2}}{\Delta f}$ or $\dfrac{\overline{i_n^2}}{\Delta f}$

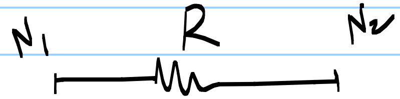
Δf → observation BW

$$\frac{\overline{v_n}}{\sqrt{\Delta f}} = 1nV/\sqrt{Hz}$$

$$\overline{v_n^2}\Big|_{1kHz}^{1MHz}$$

Noise in Devices

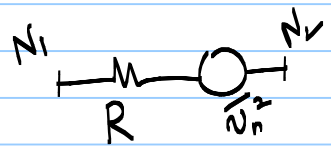
1) Resistor R

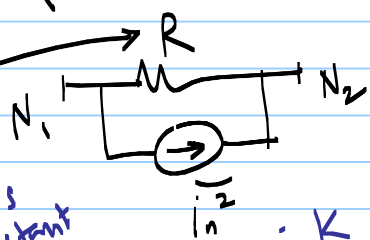


"thermal" noise

(noise depends on abs. temp. T

"white" noise – flat PSD





ideal resistor (noiseless)

Boltzmann's constant

abs. temp in K

$$\overline{v_n^2} = 4kTR\,\Delta f$$

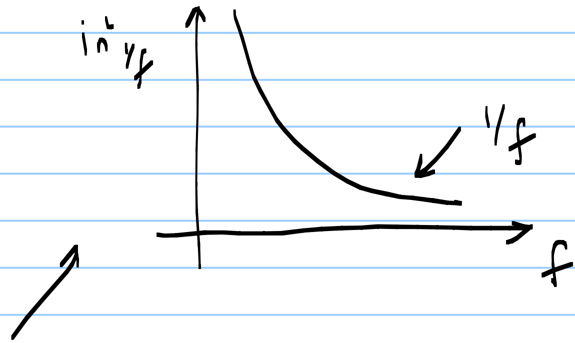
$$\frac{\overline{v_n^2}}{\Delta f} = 4kTR$$

$$\overline{i_n^2} = \frac{\overline{v_n^2}}{R^2} = \frac{4kT}{R}\Delta f$$

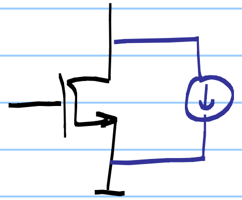
$$\frac{\overline{i_n^2}}{\Delta f} = \frac{4kT}{R} = 4kTG$$

2) L, C, M – Noiseless

3) MOSFETs

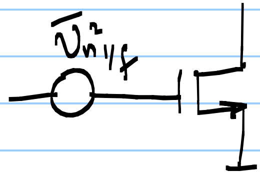


a) Flicker noise
or
1/f noise



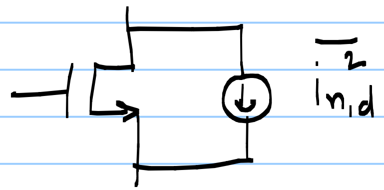
$$\overline{i^2_{n,1/f}} = \frac{K_f \cdot g_m^2}{W \cdot L \cdot C_{ox}} \cdot \frac{1}{f} \cdot \Delta f$$

Significant @ low freq.



$$\overline{v^2_{n\,1/f}} = \frac{K_f}{WL\,C_{ox}} \cdot \frac{1}{f} \cdot \Delta f$$

b) **Drain Thermal Noise**



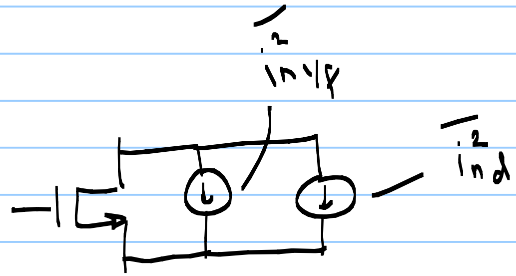
linear regime

$$\overline{i_{nd}^2} = 4kT\, g_{ds}\, \Delta f \qquad g_{ds} = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{op.pt.}$$

saturation regime

$$\overline{i_{nd}^2} = \frac{8kT}{3}\, g_m\, \Delta f \qquad g_m = \frac{\partial I_D}{\partial V_{GS}}$$

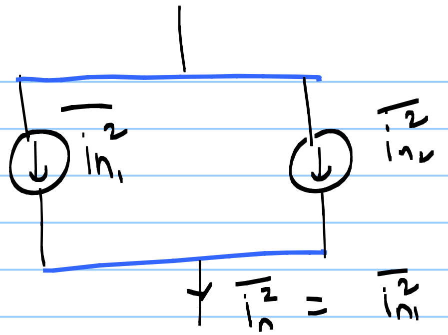
flat PSD = "white" noise



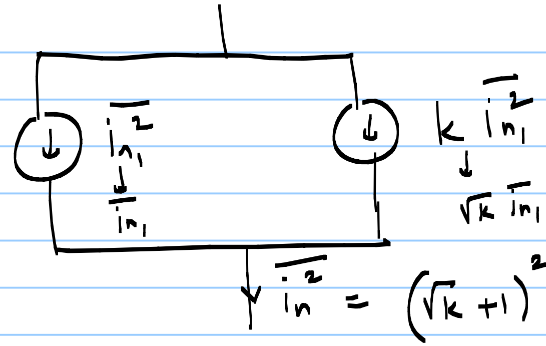
Correlated vs Uncorrelated Noise

Correlated → add amplitudes

Uncorrelated → add mean squared values

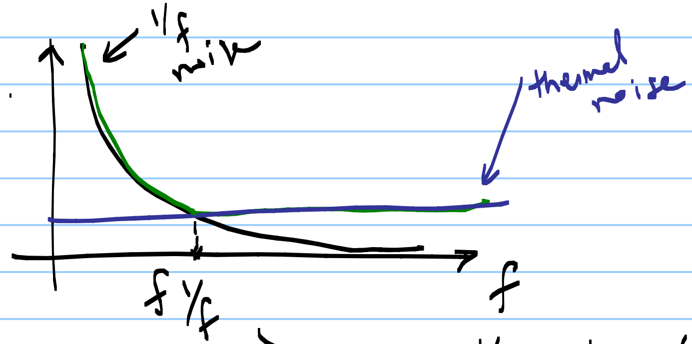


$\overline{i_n^2} = \overline{i_{n_1}^2} + \overline{i_{n_2}^2}$



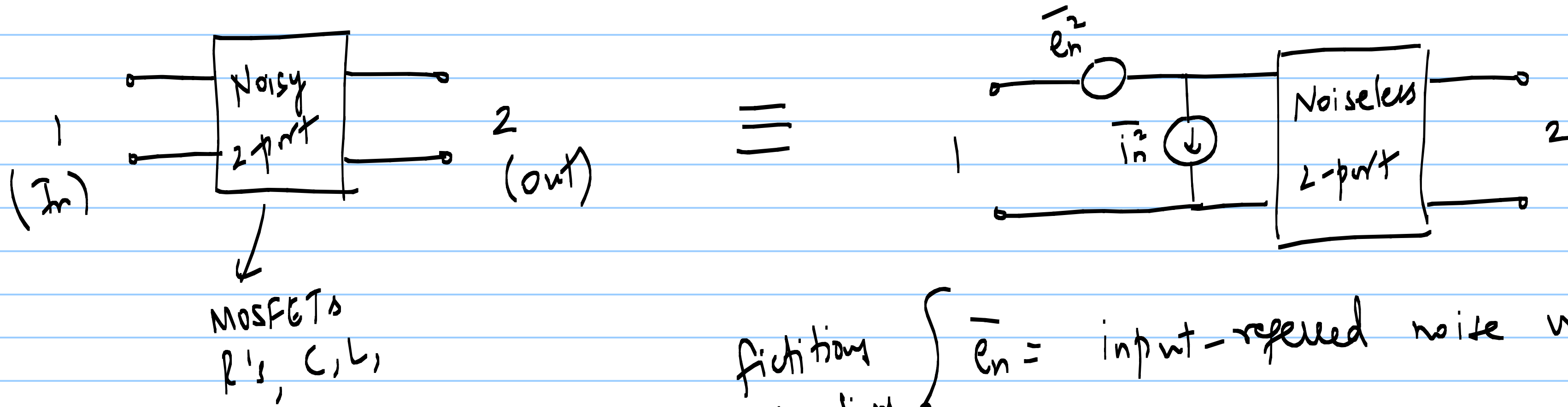
$\overline{i_n^2} = (\sqrt{k}+1)^2\,\overline{i_{n_1}^2}$

partial correlation — correlated part / uncorrelated part

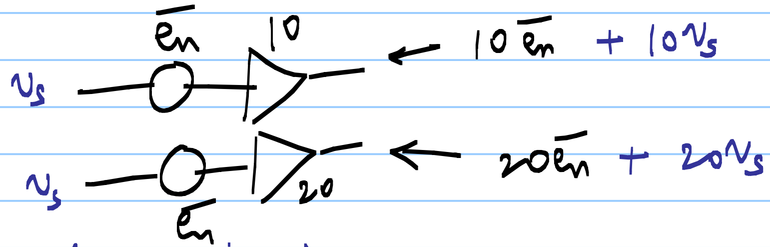


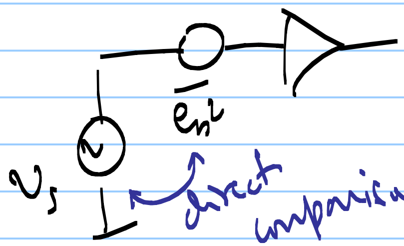
$\overline{i_{n,tot}^2} = \overline{i_{n_{1/f}}^2} + \overline{i_{n,d}^2}$

$f_{1/f}$ — 1/f noise corner of device

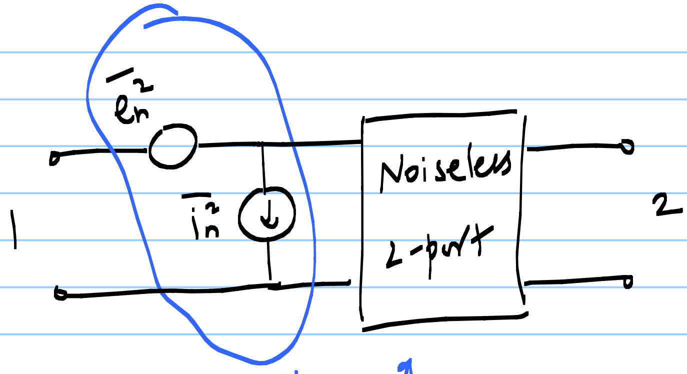


fictitious = abstraction
- $\overline{e_n}$ = input-referred noise voltage
- $\overline{i_n}$ = input-referred noise current



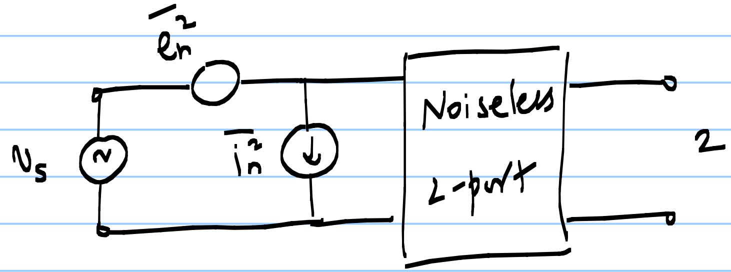


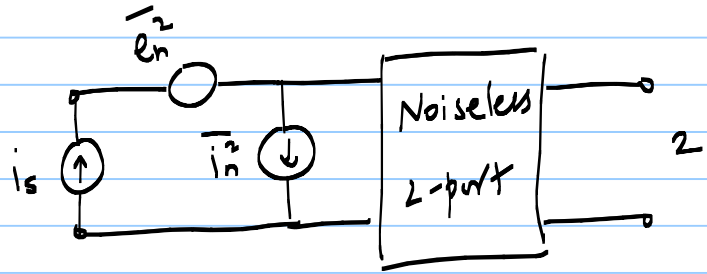
direct comparison → SNR degradation is known

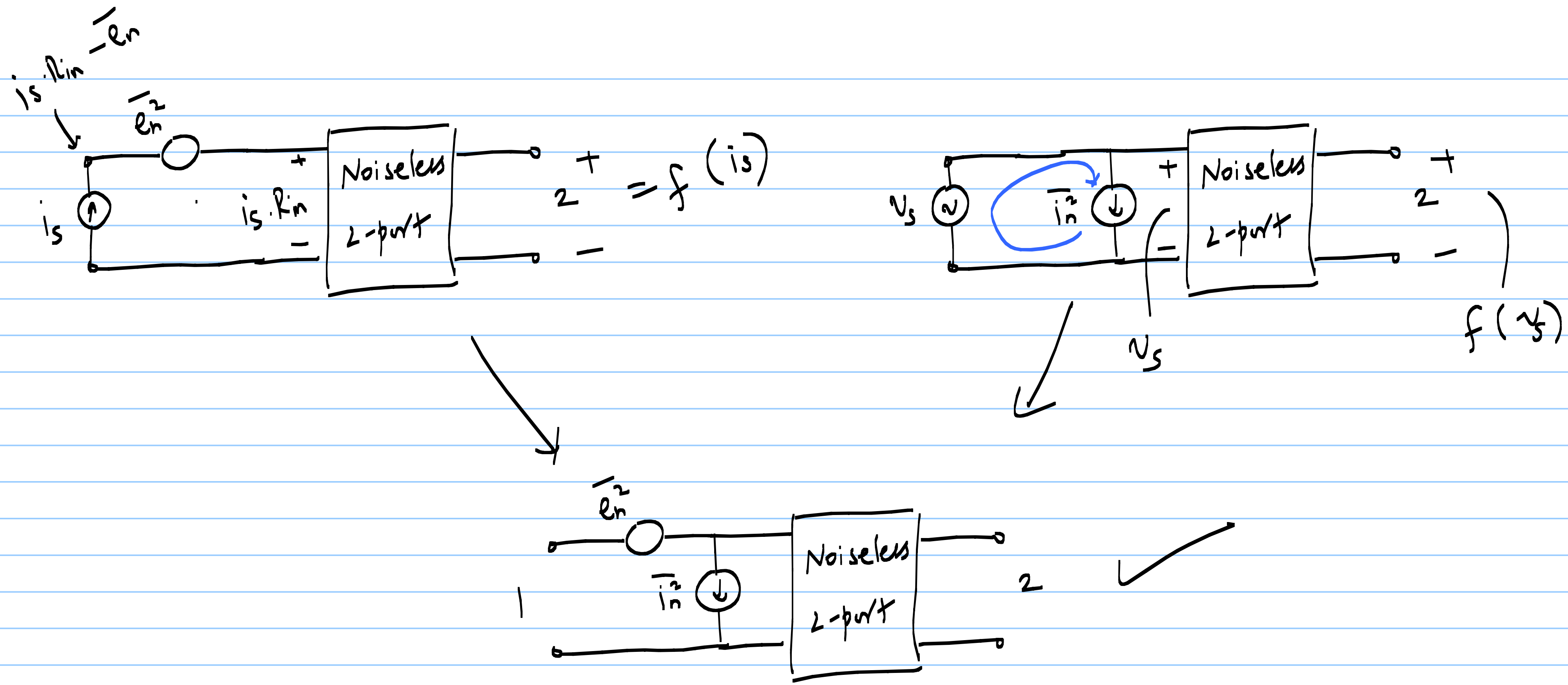


characteristic of a particular 2-port

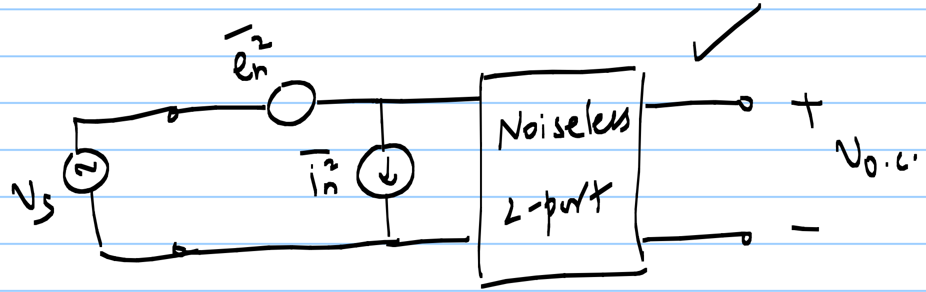
should not depend on R_s, R_L



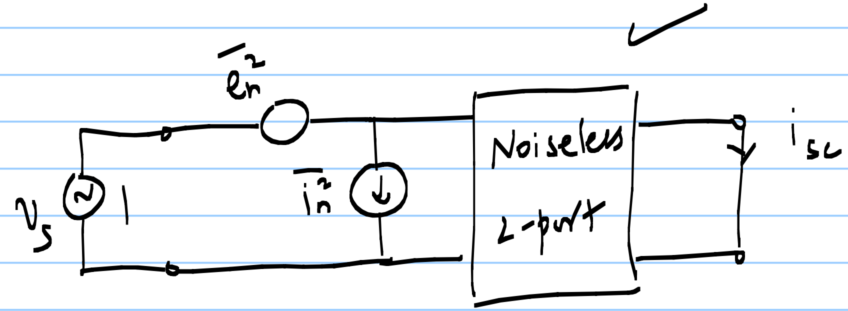




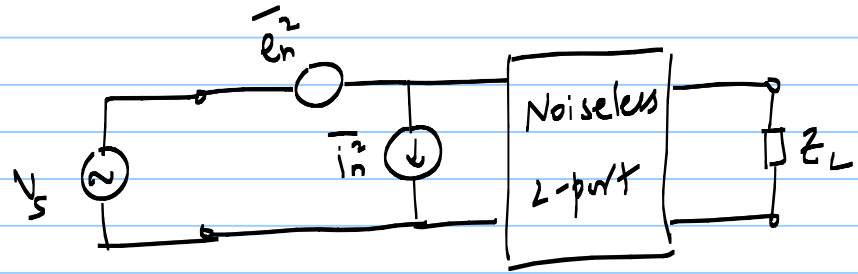
$i_s \cdot R_{in} - \overline{e_n}$
$\overline{e_n^2}$
i_s
$i_s \cdot R_{in}$
+
−
Noiseless
2-port
2
+
−
$= f(i_s)$
v_s
$\overline{i_n^2}$
Noiseless
2-port
2
v_s
$f(v_s)$
$\overline{e_n^2}$
$\overline{i_n^2}$
1
Noiseless
2-port
2



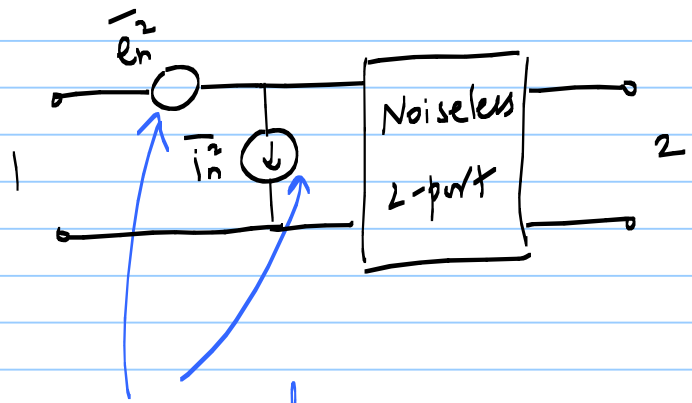
$\overline{e_n^2}$
$\overline{i_n^2}$
v_s
Noiseless
2-port
+
$v_{o.c.}$
−



$\overline{e_n^2}$
$\overline{i_n^2}$
v_s
Noiseless
2-port
i_{sc}



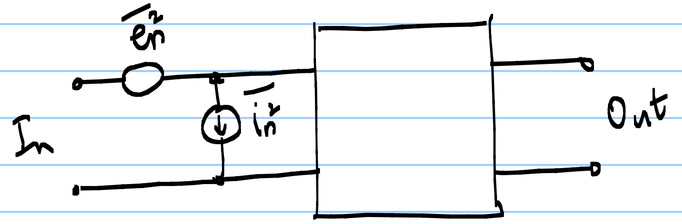
$\overline{e_n^2}$
$\overline{i_n^2}$
v_s
Noiseless
2-port
Z_L



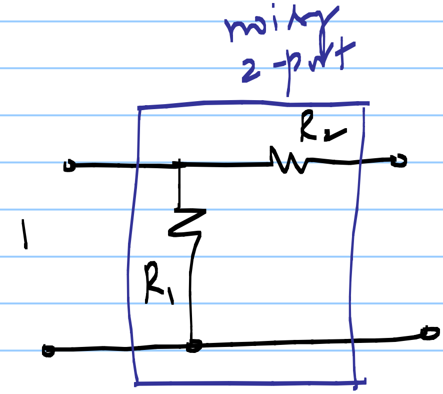
in general,
$\overline{i_n}$ & $\overline{e_n}$ are
partially correlated

19/9/23

Lec 3

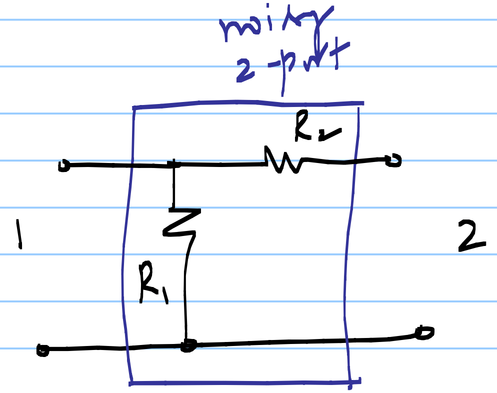


Example #1

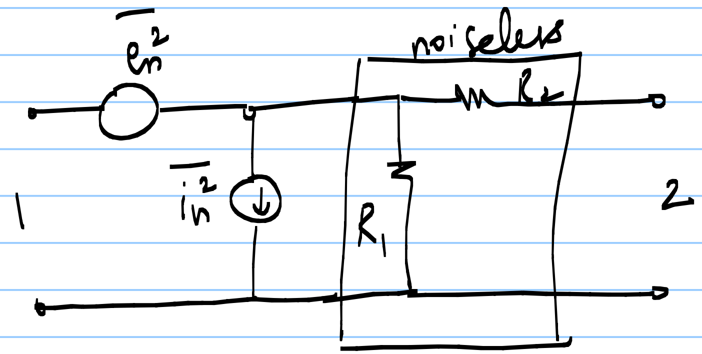


$\overline{e_n^2} = ?$

$\overline{i_n^2} = ?$

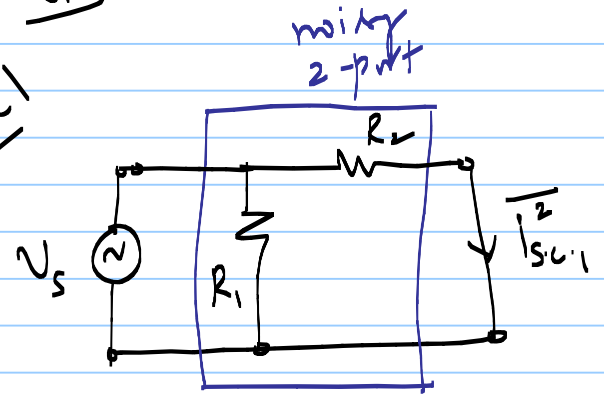


$\equiv$

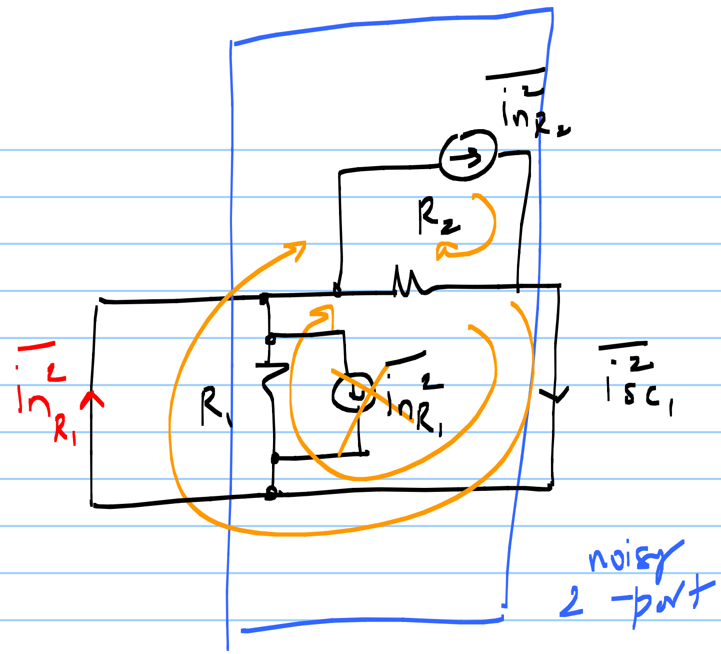


$\overline{e_n^2}$

Case 1



$\rightarrow$

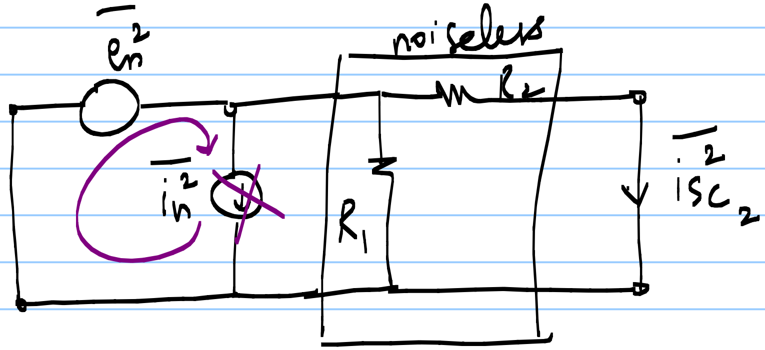


$$\overline{i_{nR_1}^2} \rightarrow \overline{i_{sc_1(R_1)}^2} = 0$$

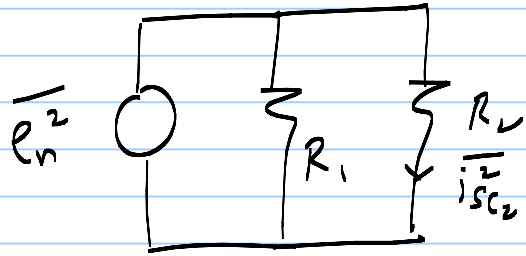
$$\overline{i_{nR_2}^2} \rightarrow \overline{i_{sc_1(R_2)}^2} = \overline{i_{nR_2}^2} = \frac{4kT}{R_2}\Delta f$$

$$\overline{i_{sc_1}^2} = \frac{4kT}{R_2}\Delta f$$

Case 2



$$\overline{i_{sc_2}^2} = \frac{\overline{e_n^2}}{R_2^2}$$

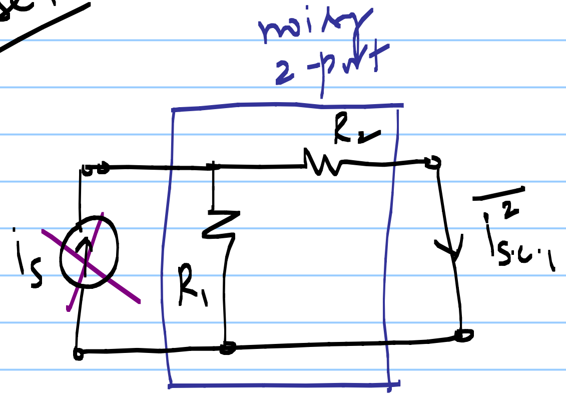


$$\overline{i_{sc_1}^2} = \overline{i_{sc_2}^2}$$

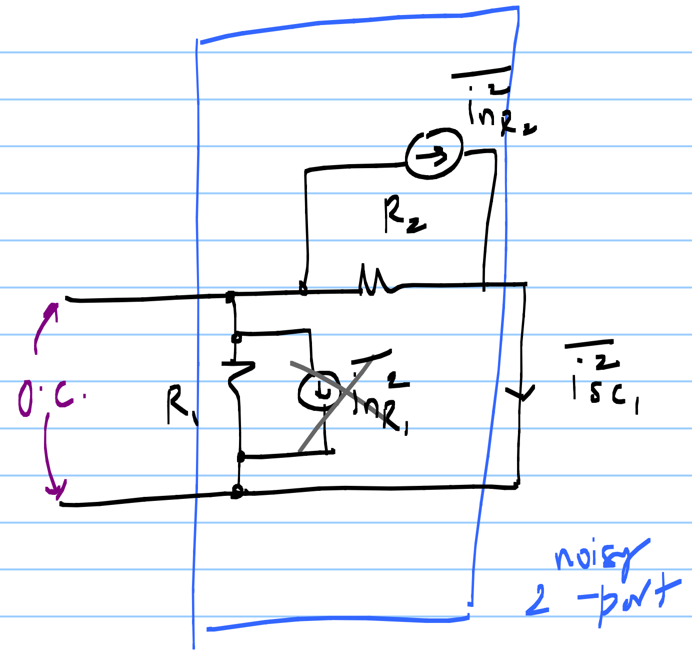
$$\frac{4kT}{R_2} \cdot \Delta f = \frac{\overline{e_n^2}}{R_2^2} \Rightarrow \frac{\overline{e_n^2}}{\Delta f} = 4kTR_2 \left(\frac{V^2}{Hz}\right)$$

$\overline{i_n^2}$

case 1

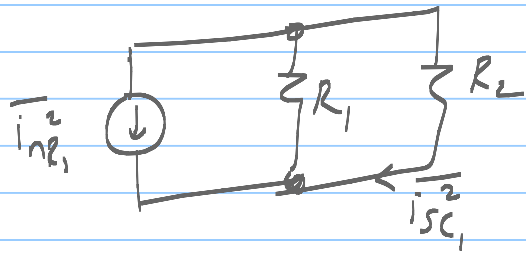


$\longrightarrow$



$$\overline{i_{nR_1}^2} : \quad \overline{i_{sc_1}^2}_{(R_1)} = \overline{i_{nR_1}^2} \cdot \left(\frac{R_1}{R_1+R_2}\right)^2$$

$$\overline{i_{nR_2}^2} : \quad \overline{i_{sc_1}^2}_{(R_2)} = \overline{i_{nR_2}^2} \left(\frac{R_2}{R_1+R_2}\right)^2$$

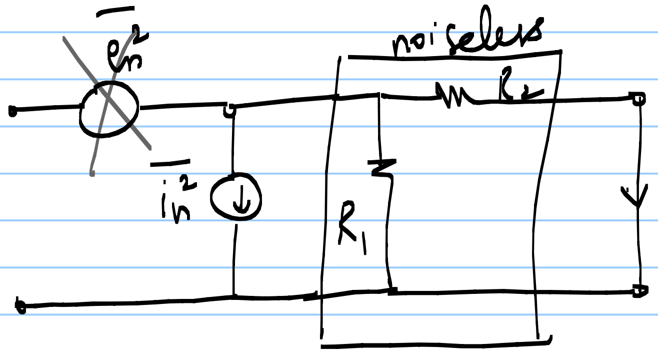


$$\frac{\overline{i_{sc_1}^2}}{\Delta f} = \frac{4kT}{R_1} \times \frac{R_1^2}{(R_1+R_2)^2} + \frac{4kT}{R_2} \times \frac{R_2^2}{(R_1+R_2)^2}$$

$$= \frac{4kT}{(R_1+R_2)^2} \cdot \left\{ R_1 + R_2 \right\} = \frac{4kT}{R_1+R_2}$$

$$\overline{i_{sc_1}^2} = \frac{4kT}{R_1+R_2} \cdot \Delta f$$

Case 2



$$\overline{i_{sc_2}^2} = \overline{i_n^2} \cdot \left(\frac{R_1}{R_1 + R_2} \right)^2$$

$$\overline{i_{sc_1}^2} = \overline{i_{sc_2}^2} \Rightarrow \overline{i_n^2} \left(\frac{R_1}{R_1 + R_2} \right)^2 = \frac{4kT}{R_1 + R_2} \cdot \Delta f$$

$$\frac{\overline{i_n^2}}{\Delta f} = \frac{4kT}{R_1} \left(1 + \frac{R_2}{R_1} \right) = \frac{4kT}{R_1} + 4kT \cdot \frac{R_2}{R_1^2} \quad \left(\frac{A^2}{Hz} \right)$$

✓

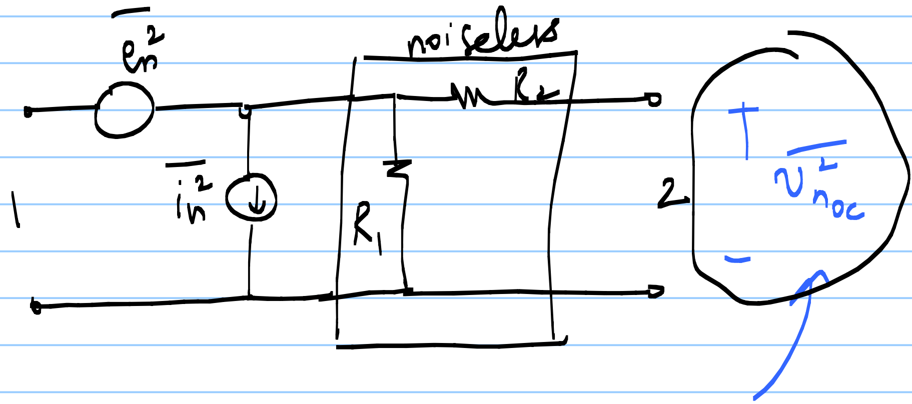
$$\frac{\overline{e_n^2}}{\Delta f} = 4kTR_2 \left(\frac{V^2}{Hz}\right)$$

noise of R_2 only

partially correlated

$$\frac{\overline{i_n^2}}{\Delta f} = \frac{4kT}{R_1} + 4kT \cdot \frac{R_2}{R_1^2} \left(\frac{A^2}{Hz}\right)$$

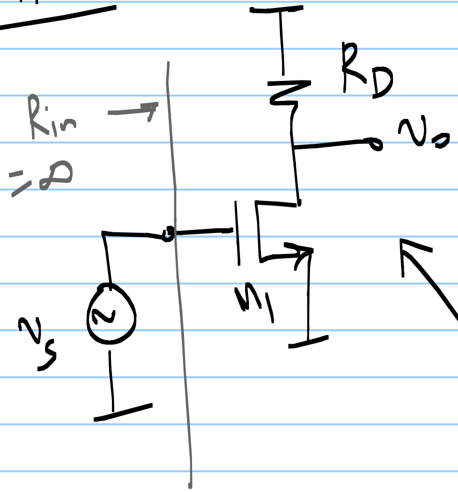
noise of R_1 & R_2

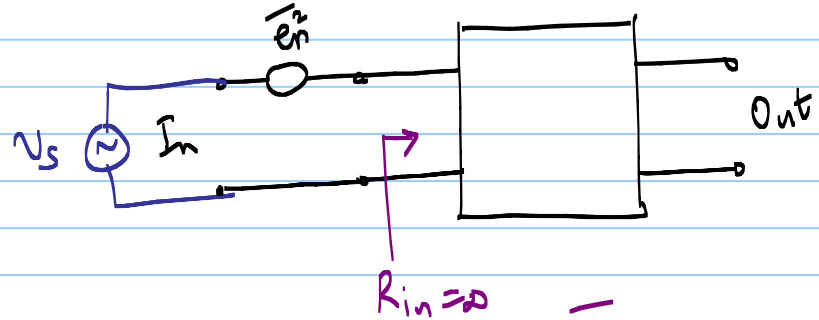


HW Repeat with open circuit @ Port 2

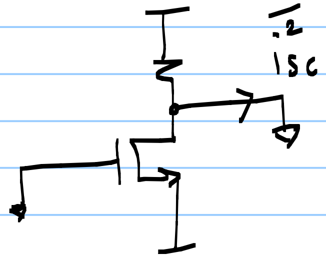
Should get same answer

Example #2



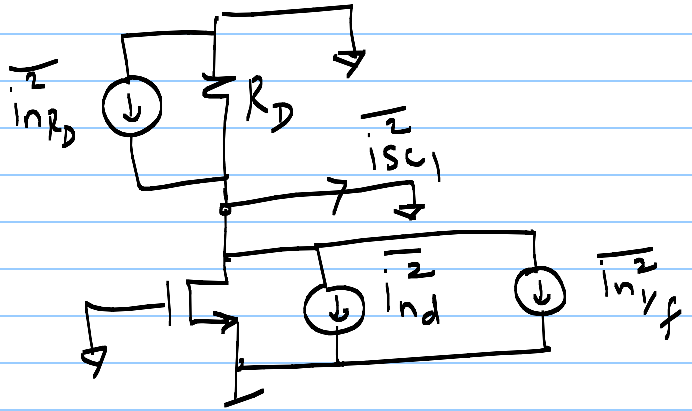


→ no $\overline{i_n^2}$ input referred noise current



Low - frequency $\overline{e_n}$ = ?

Case 1 :

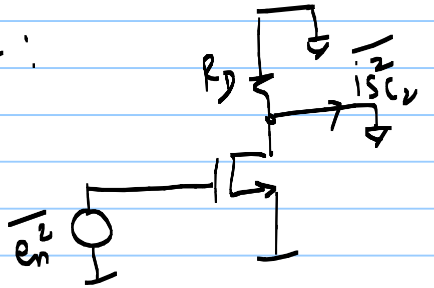


$$\overline{i_{sc_1}^2} = \overline{i_n^2}_{R_D} + \overline{i_{nd}^2} + \overline{i_{n1/f}^2}$$

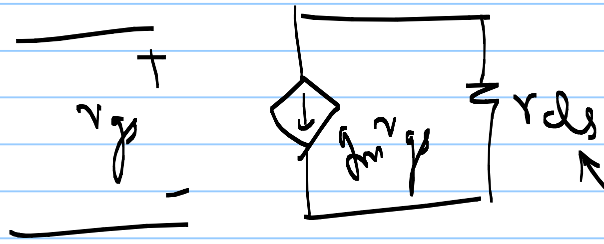
$$\overline{e_n^2} = \frac{\overline{i_n^2}_{R_D} + \overline{i_{nd}^2} + \overline{i_{n1/f}^2}}{g_m^2}$$

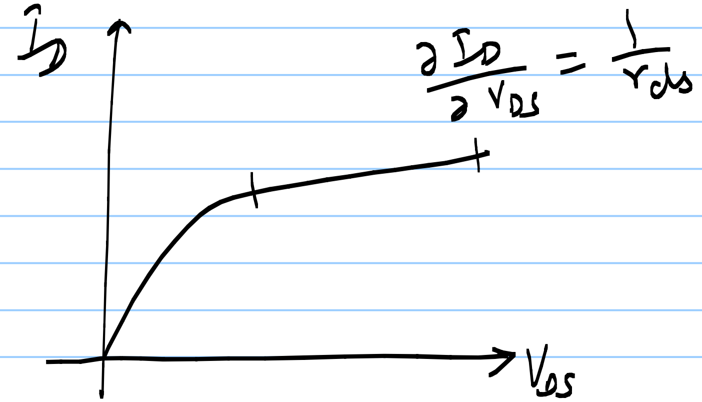
$$\frac{\overline{e_n^2}}{\Delta f} = \frac{4kT}{g_m^2 R_D} + \frac{8kT}{3g_m} + \frac{k_f}{W \cdot L \cdot C_{ox}^2} \cdot \frac{1}{f}$$

Case 2 :



$$\overline{i_{sc_2}^2} = g_m^2 \cdot \overline{e_n^2}$$



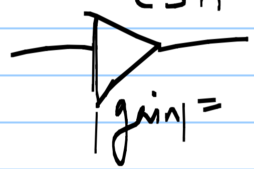


$\overline{e_n^2}$ & $\overline{i_n^2}$ → measure SNR degradation due to the 2-port

CSA

$$\frac{\overline{e_n^2}}{\Delta f} = \frac{4kT}{g_m^2 R_D} + \frac{8kT}{3 g_m} + \frac{k_f}{W \cdot L \cdot C_{ox}} \cdot \frac{1}{f}$$

* Want to reduce $\overline{e_n^2}$



gain = $g_m R_D$

keep $g_m R_D$ constant

$$\frac{\overline{e_n^2}}{\Delta f} = \frac{4kT}{g_m(g_m R_D)} + \frac{8kT}{3 g_m} + \frac{k_f}{W \cdot L \cdot C_{ox}} \cdot \frac{1}{f}$$

constant

reduce by ↑ g_m

reduce by ↑ g_m

reduce by ↑ W & L keeping $\frac{W}{L}$ constant

↑ g_m by ↑ I_{bias} or ↑ $\left(\frac{W}{L}\right)$ or both

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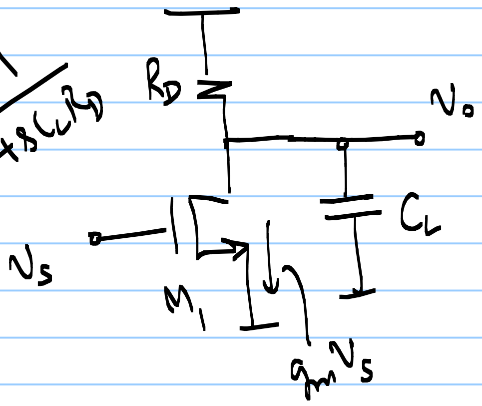
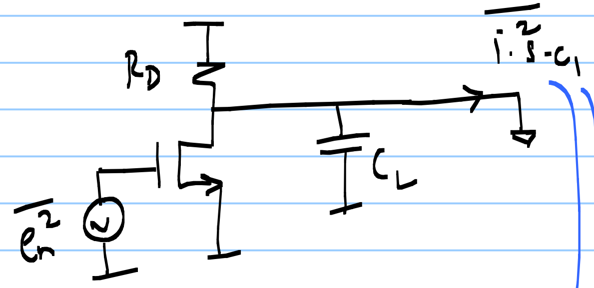
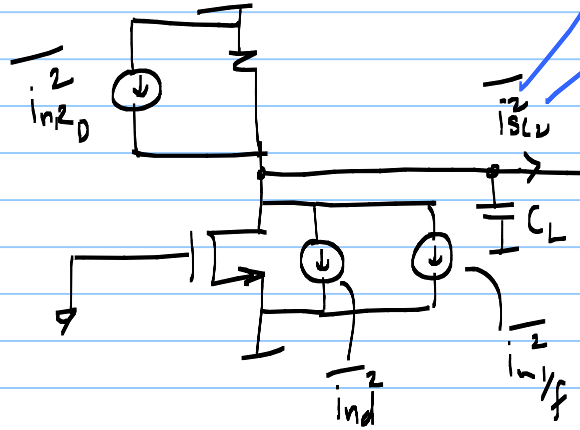
$$\frac{v_o}{v_s} = -g_m R_D \cdot \frac{1}{1+sC_L R_D}$$



$\overline{e_n^2} = ?$

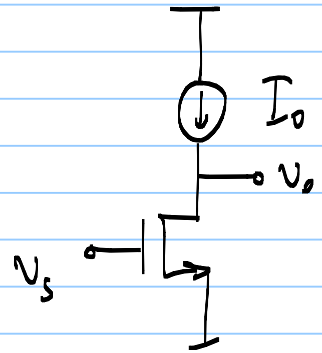


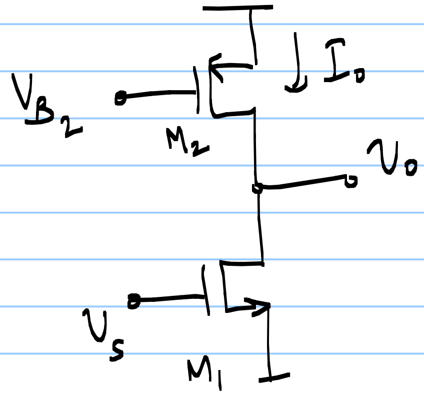


$\overline{e_n^2} =$

$\overline{e_n^2}$ = same as before (without C_L)

Example #3 CSA with active load (only thermal noise)



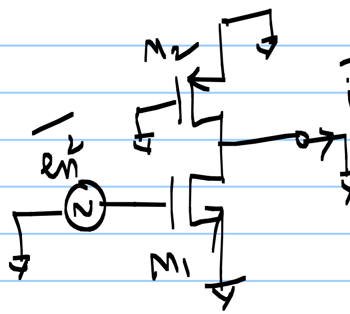


$$\frac{v_o}{v_s} = -\frac{g_{m_1}}{g_{ds_1} + g_{ds_2}}$$

$$= -g_{m_1}(r_{ds_1} \| r_{ds_2})$$

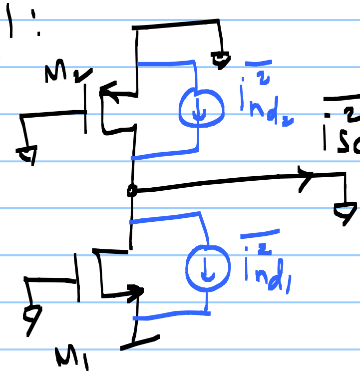
$\overline{i_n^2}$ doesn't exist because $R_{in} = \infty$

case 2:



$$\overline{i_{sc_2}^2} = g_{m_1}^2 \overline{e_n^2}$$

case 1:



$$\overline{i_{sc_1}^2} = \overline{i_{nd_1}^2} + \overline{i_{nd_2}^2}$$

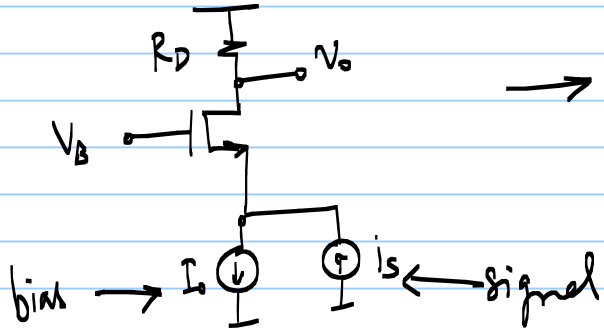
$$= \frac{8kT}{3}(g_{m_1} + g_{m_2})\Delta f$$

$$g_{m_1}^2\,\overline{e_n^2} = \frac{8kT}{3}\left(g_{m_1}+g_{m_2}\right)\Delta f$$

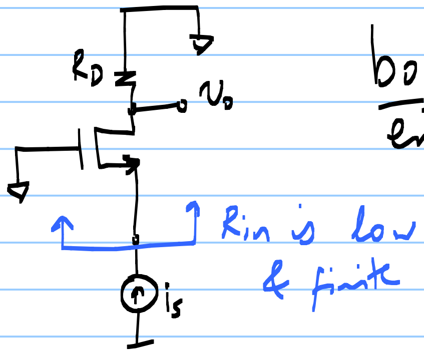
$$\frac{\overline{e_n^2}}{\Delta f} = \underbrace{\frac{8kT}{3g_{m_1}}}_{M_1} + \underbrace{\frac{8kT\,g_{m_2}}{g_{m_1}^2}}_{M_2}$$

Low Noise : $\uparrow g_{m_1}$ and $\downarrow g_{m_2}$

Example #4 CGA



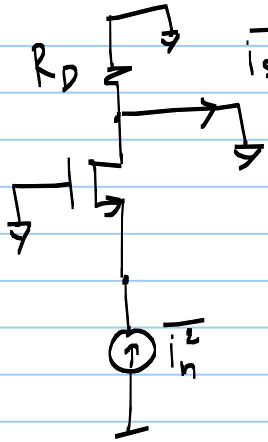
$\longrightarrow$



both $\overline{e_n^2}$ & $\overline{i_n^2}$

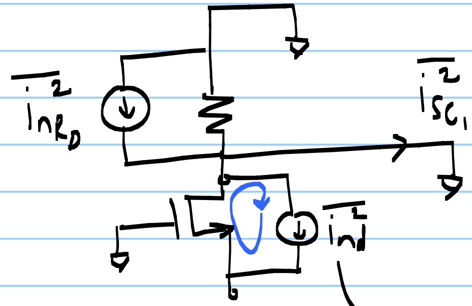
$\overline{i_n^2}$

Case 2 :

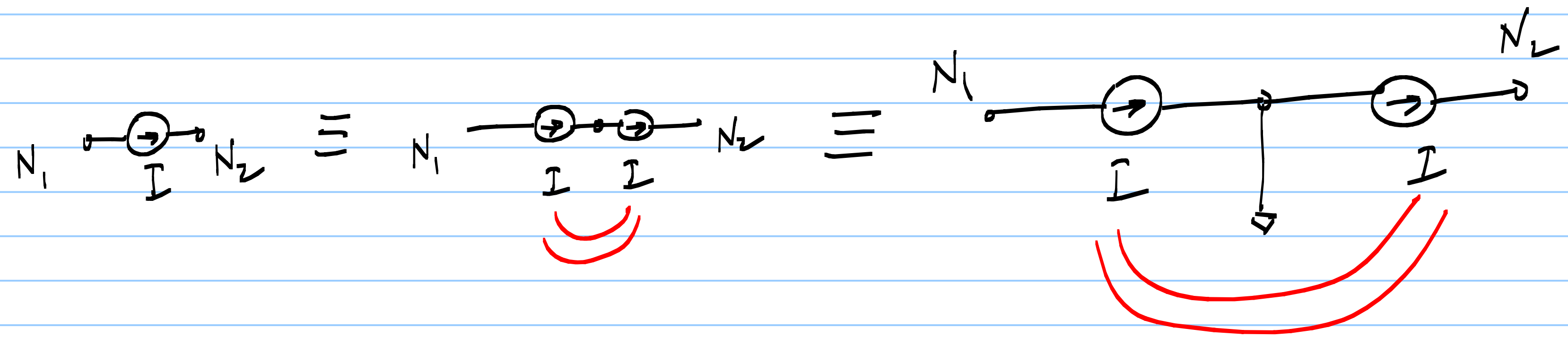


$\overline{i_{sc_2}^2} = \overline{i_n^2}$

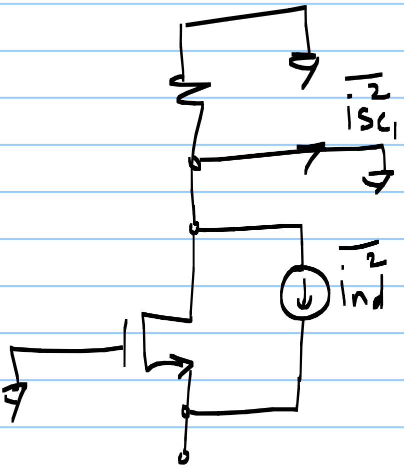
Case 1 :



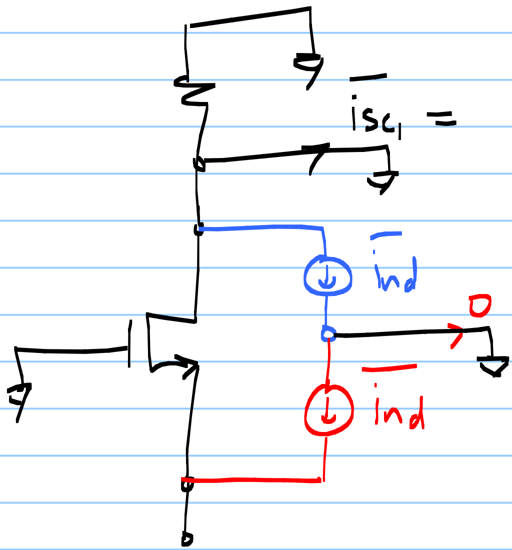
$$\overline{i_{sc_1}^2} = \frac{4kT}{R_D}\cdot\Delta f + (0)$$



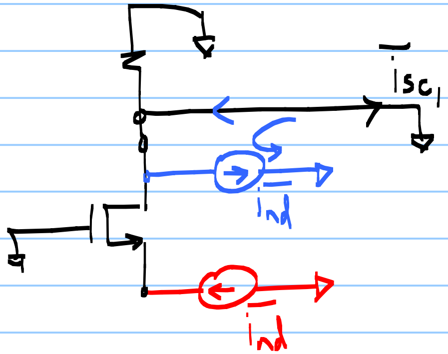
case 1 : $\overline{i_{nd}^2}$



$\equiv$



$\overline{i_{sc_1}} = (\quad) + (\quad)$



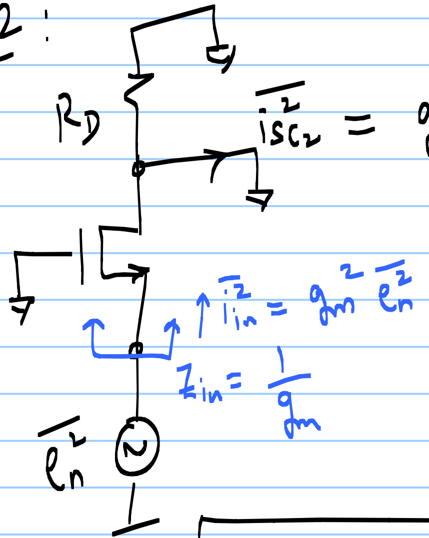
$\overline{i_{sc_1}} = -\overline{i_{nd}} + \overline{i_{nd}} = 0$

$\overline{i_{sc_1}^2} = \overline{i_{sc_2}^2}$

$$\frac{\overline{i_n^2}}{\Delta f} = \frac{4kT}{R_D}$$

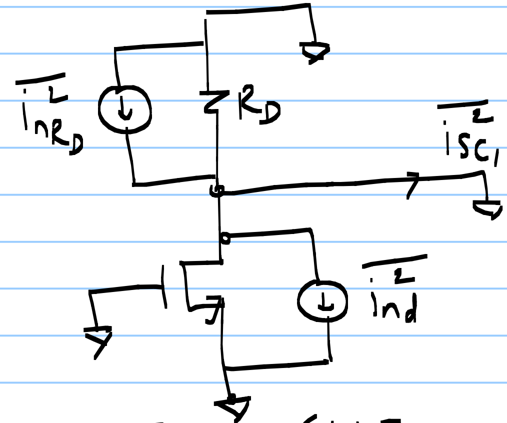
$\overline{e_n^2}$

Case 2 :



$$\overline{i_{sc_2}^2} = g_m^2 \overline{e_n^2}$$

Case 1 :



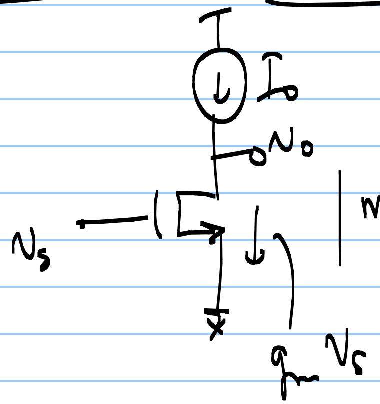
$$\overline{i_{sc_1}^2} = \overline{i_{nR_D}^2} + \overline{i_{nd}^2} = \left(\frac{4kT}{R_D} + \frac{8kT g_m}{3} \right) \Delta f$$

$$\overline{i_{sc_1}^2} = \overline{i_{sc_2}^2} \Rightarrow \boxed{\frac{\overline{e_n^2}}{\Delta f} = \frac{8kT}{3 g_m} + \frac{4kT}{g_m^2 R_D}}$$

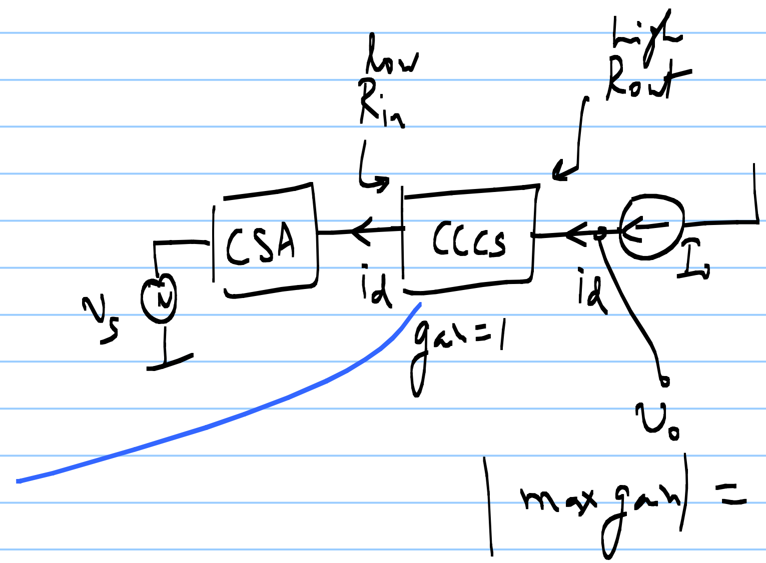
$$\frac{\overline{i_n^2}}{\Delta f} = \frac{4kT}{R_D}$$

partially correlated

Example #5 Cascoded CSA

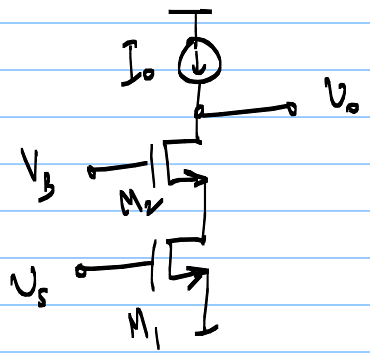


$|\text{max gain}| = g_m r_{ds}$



$|\text{max gain}| = g_m R_{out}$

$R_{out} \gg r_{ds}$



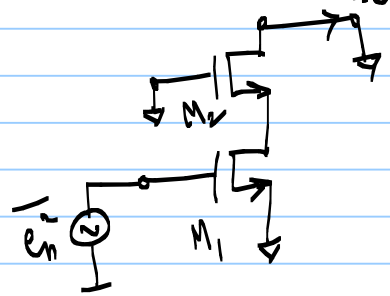
$$\frac{v_o}{v_s} = - g_{m_1} \cdot g_{m_2} \; r_{ds_1} r_{ds_2}$$

Cascoded CS amplifier

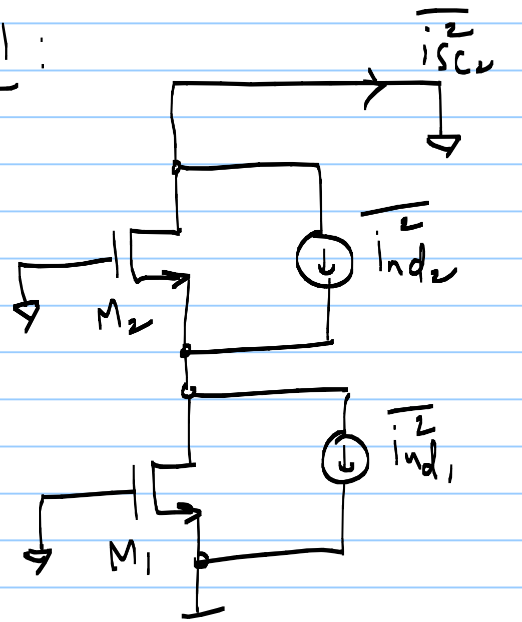
$\overline{e_n^2} = ?$

~~case 2~~

$$\overline{i_{sc_2}^2} = g_{m_1}^2 \, \overline{e_n^2}$$

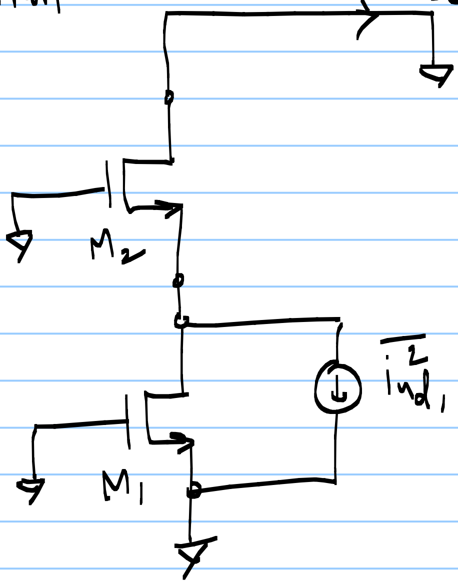


case 1 :

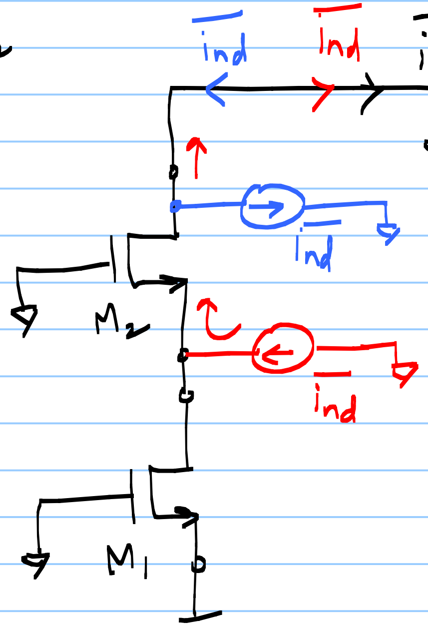


(a) $\overline{i_{nd_1}^2}$

$\overline{i_{sc_2}^{2\,\prime}} = \overline{i_{nd_1}^2}$



(b) $\overline{i_{nd_2}^2}$



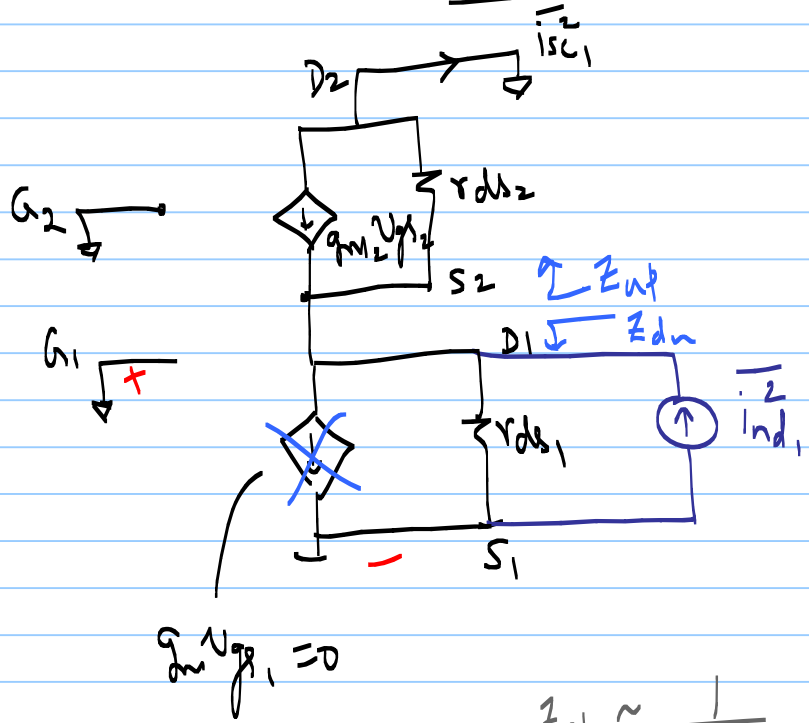
$\overline{i_{sc_2}''} = -\overline{i_{nd}} + \overline{i_{nd}}$

≈ 0

HW: calculate $\overline{i_{sc_2}''}$ with g_{m_1}, g_{m_2} r_{ds_1}, r_{ds_2}

22/9/2023

Lec 5



$$\overline{i^2_{sc_1}} = \left[\frac{r_{ds_1}}{\frac{1}{g_{m_2}} \| r_{ds_2} + r_{ds_1}}\right]^2 \cdot \overline{i^2_{nd_1}}$$

$$Z_{dn} = r_{ds_1}$$

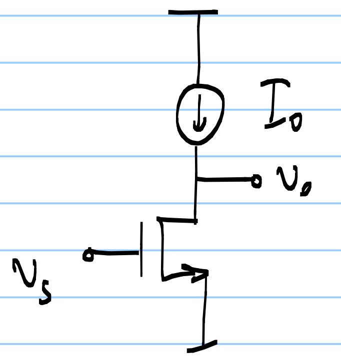
$$Z_{up} = \frac{1}{g_{m_2} + g_{ds_2}} = \frac{r_{ds_2}}{1 + g_{m_2} r_{ds_2}}$$

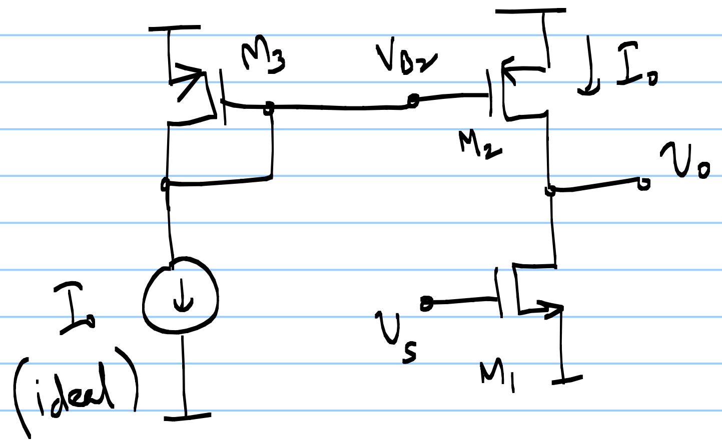
$$\overline{i^2_{up}} = \overline{i^2_{sc_1}} = \left[\frac{Z_{dn}}{Z_{dn} + Z_{up}}\right]^2 \cdot \overline{i^2_{nd_1}}$$

$$Z_{up} \approx \frac{1}{g_{m_2}} \quad \text{if } g_{m_2} r_{ds_2} >> 1$$

$$\overline{i^2_{sc_1}} \approx \overline{i^2_{nd_1}} \quad \text{if } g_{m_2} >> \frac{1}{r_{ds_1}}$$

Example #6 CSA with active load (only thermal noise)

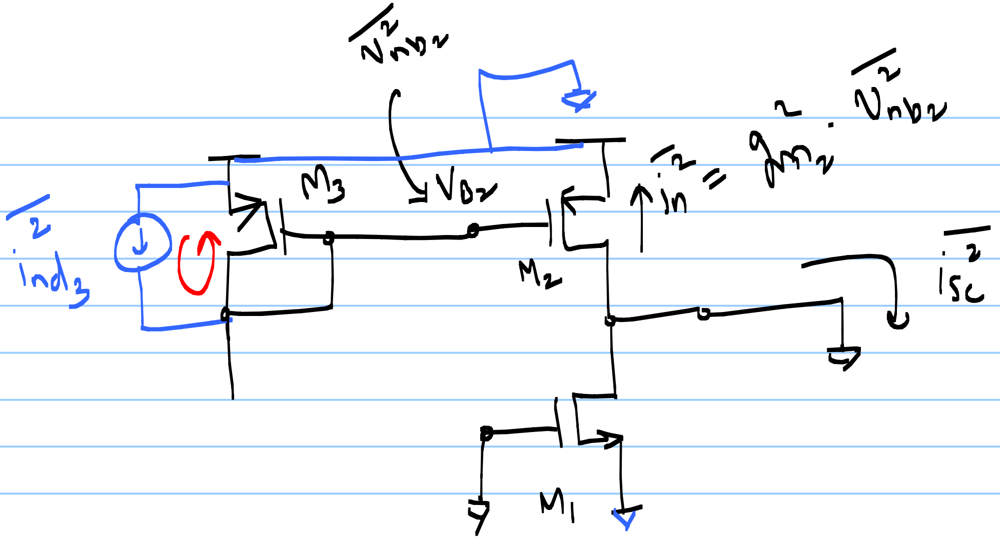




$\overline{e_n^2} = ?$

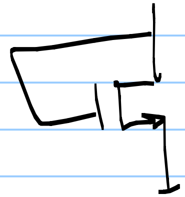
Without M_3 } :

$$\frac{\overline{e_n^2}}{\Delta f} = \frac{8kT}{3g_{m_1}} + \frac{8kT g_{m_2}}{g_{m_1}^2}$$



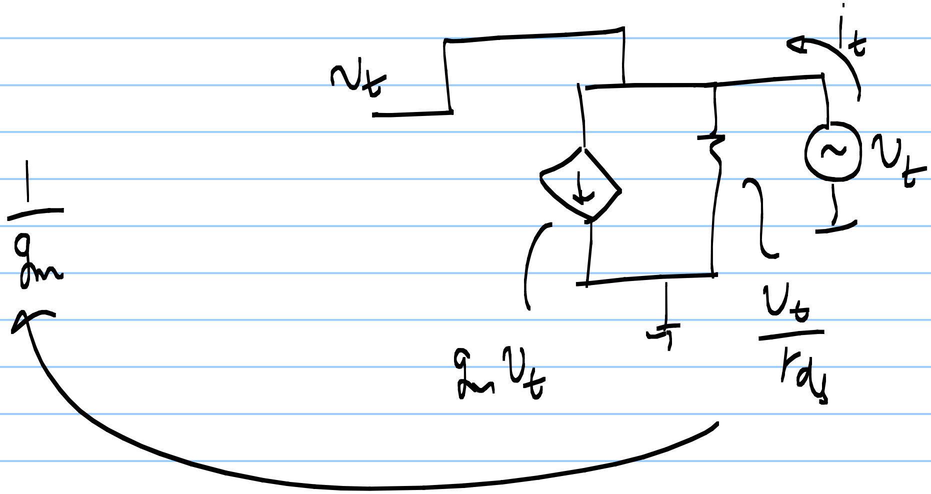
1) ~~No effect?~~ $\overline{i_{nd_3}^2}$ circulates inside M_3 ✓

2) $\overline{v_{nb_2}^2} = \dfrac{\overline{i_{nd_3}^2}}{g_{m_3}^2}$ → applied to M_2



$\equiv$

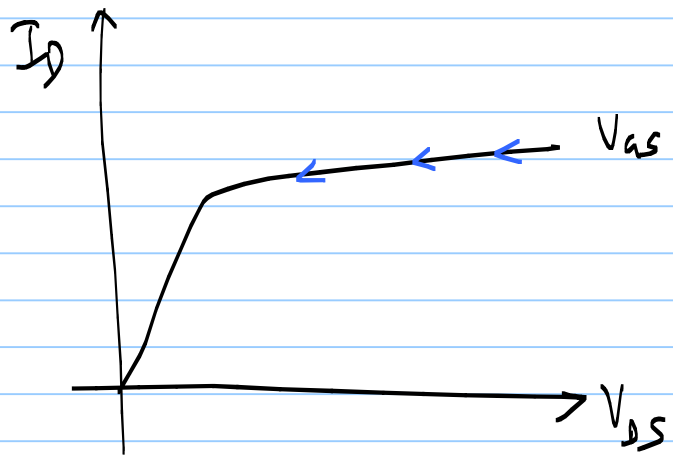
$\dfrac{1}{g_m + g_{ds}} \approx \dfrac{1}{g_m}$



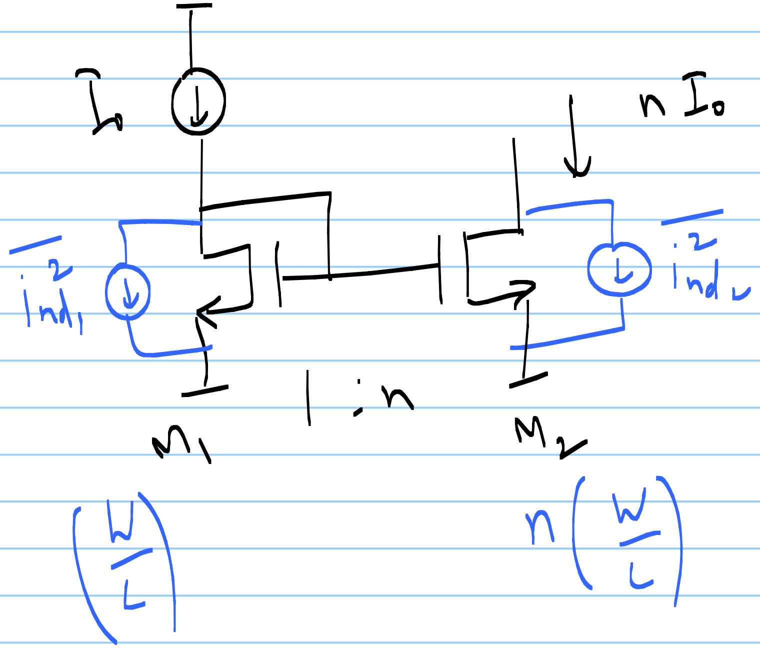
$$\overline{i_{sc_1}^2} = \frac{g_{m_2}^2}{g_{m_3}^2} \cdot \overline{i_{nd_3}^2}$$

here 1:1 C. Mirror

$$\overline{i_{sc_1}^2} = \overline{i_{nd_3}^2}$$



$$\frac{\overline{e_n^2}}{\Delta f} = \underbrace{\frac{8kT}{3g_{m_1}}}_{M_1} + \underbrace{\frac{8kT g_{m_2}}{g_{m_1}^2}}_{M_2} + \underbrace{\frac{8kT g_{m_3}}{g_{m_1}^2}}_{M_3}$$



$$\downarrow \quad \overline{i_{nd_2}^2} + n^2 \overline{i_{nd_1}^2} = \frac{8kT}{3} g_{m_2} + n^2 \cdot \frac{8kT}{3n} \cdot g_{m_2}$$

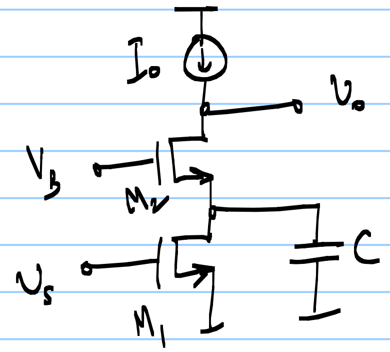
$$= \frac{8kT}{3} g_{m_2} (1+n)$$

$$g_{m_2} = n\, g_{m_1}$$

$$\overline{i_{nd_2}^2} = \frac{8kT}{3} \cdot g_{m_2}$$

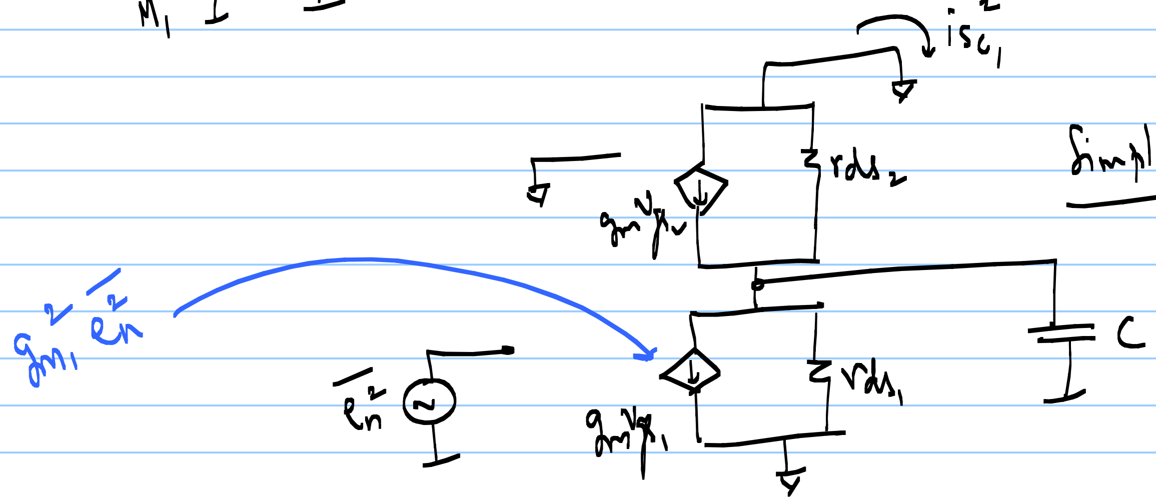
$$\overline{i_{nd_1}^2} = \frac{8kT}{3} \cdot g_{m_1} = \frac{8kT}{3n} \cdot g_{m_2}$$

Example #7 Cascoded CSA with a cap

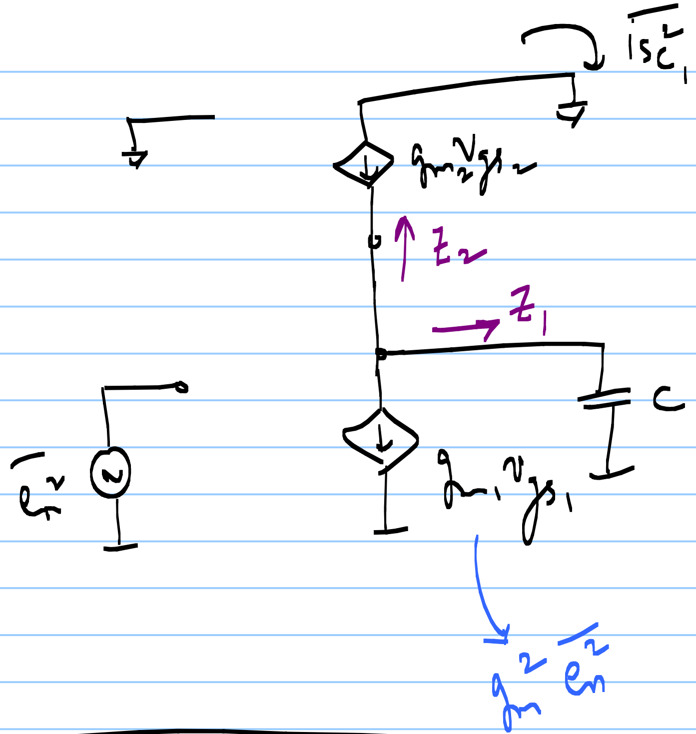


$\overline{e_n^2} = ?$

1)



Simplify: $r_{ds_1} = r_{ds_2} = \infty$



$$\overline{i_{sc_1}^2} = \overline{i_{Z_2}^2}$$

$$\overline{i_{Z_2}^2} = g_{m_1}^2 \overline{e_n^2} \left| \frac{Z_1}{Z_1 + Z_2} \right|^2$$

$$\overline{i_{sc_1}^2} = g_{m_1}^2 \overline{e_n^2} \cdot \underbrace{\left| \frac{1/j\omega C}{1/j\omega C + 1/g_{m_2}} \right|^2}_{\frac{g_{m_2}^2}{g_{m_2}^2 + \omega^2 C^2}}$$

$$\boxed{\overline{i_{sc_1}^2} = \frac{g_{m_1}^2 \cdot g_{m_2}^2}{g_{m_2}^2 + \omega^2 C^2} \cdot \overline{e_n^2}}$$