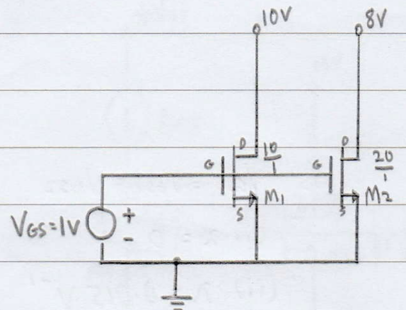
No.: .... Date: ....

Esmund Lim

A.E Tutorial 9

1)



(i) $\lambda = 0$

(ii) $\lambda = 0.015\,V^{-1}$

$$I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)(V_{GS}-V_{TN})^2(1+\lambda V_{DS})$$

i) When $\lambda = 0$

$$I_{D1} = \frac{k_n'}{2}\left(\frac{W}{L}\right)_1 (V_{GS1}-V_{TN})^2$$

$$I_{D2} = \frac{k_n'}{2}\left(\frac{W}{L}\right)_2 (V_{GS2}-V_{TN})^2$$

For the ideal case, when $\lambda = 0$, the drain current of a NMOS, I_D depends only on V_{GS}, V_{TN}, k_n' and $\left(\frac{W}{L}\right)$ ratio. of these, only V_{GS} and $\left(\frac{W}{L}\right)$ can be modified for different transistors while the other two are constant

Since $V_{GS1} = V_{GS2}$:

$$\frac{I_{D2}}{I_{D1}} = \frac{\frac{k_n'}{\cancel{2}}\left(\frac{W}{L}\right)_2 (\cancel{V_{GS}-V_{TN}})^2}{\frac{k_n'}{2}\left(\frac{W}{L}\right)_1 (\cancel{V_{GS}-V_{TN}})^2}$$

$$= \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}$$

$$= \frac{20}{10}$$

$$= 2$$

ii) When $\lambda \neq 0$

$$I_{D1} = \frac{k_n'}{2}\left(\frac{W}{L}\right)_1 (V_{GS1}-V_{TN})^2(1+\lambda V_{DS1})$$

$$I_{D2} = \frac{k_n'}{2}\left(\frac{W}{L}\right)_2 (V_{GS2}-V_{TN})^2(1+\lambda V_{DS2})$$

For the non-ideal case, when $\lambda \neq 0$, I_D also depends on V_{DS} and λ. of these, only V_{DS} can be modified for different transistor but λ is a constant

$$\frac{I_{D2}}{I_{D1}} = \frac{\frac{k_n'}{\cancel{2}}\left(\frac{W}{L}\right)_2 (\cancel{V_{GS2}-V_{TN}})^2(1+\lambda V_{DS2})}{\frac{k_n'}{\cancel{2}}\left(\frac{W}{L}\right)_1 (\cancel{V_{GS1}-V_{TN}})^2(1+\lambda V_{DS1})}$$

$$= \frac{\left(\frac{W}{L}\right)_2 (1+\lambda V_{DS2})}{\left(\frac{W}{L}\right)_1 (1+\lambda V_{DS1})}$$

$$= \frac{20(1+0.015(8))}{10(1+0.015(10))}$$

$$= 1.947826087$$

$$\approx 1.948$$

The ratio $\frac{I_{D2}}{I_{D1}}$ is independent of V_{GS} but the value of I_{D1} or I_{D2} itself is dependent on V_{GS}

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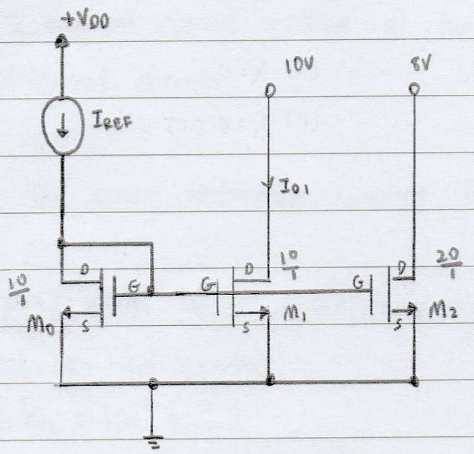
b)



$V_{GS0} = V_{GS1} = V_{GS2}$

(i) $\lambda = 0$

(ii) $\lambda = 0.015\ V^{-1}$

Since there is no gate current in MOSFET, $I_{D1} = I_{REF}$ (same size)

Also, all the transistors have the same V_{GS}

i) When $\lambda = 0$

$$\frac{I_{O1}}{I_{DO}} = \frac{\cancel{\frac{k_n'}{2}}\left(\frac{W}{L}\right)_1 (\cancel{V_{GS1} - V_{TN}})^2}{\cancel{\frac{k_n'}{2}}\left(\frac{W}{L}\right)_0 (\cancel{V_{GS0} - V_{TN}})^2}$$

$$= \frac{10}{10}$$

$$= 1$$

ii) When $\lambda \neq 0$

$$\frac{I_{O1}}{I_{DO}} = \frac{\cancel{\frac{k_n'}{2}}\left(\frac{W}{L}\right)_1 (\cancel{V_{GS1} - V_{TN}})^2 (1 + \lambda V_{DS1})}{\cancel{\frac{k_n'}{2}}\left(\frac{W}{L}\right)_0 (\cancel{V_{GS0} - V_{TN}})^2 (1 + \lambda V_{DS0})}$$

$$= \frac{\left(\frac{W}{L}\right)_1 (1 + \lambda V_{DS1})}{\left(\frac{W}{L}\right)_0 (1 + \lambda V_{DS0})}$$

$$= \frac{10(1 + 0.015(10))}{10(1 + 0.015(V_{GS}))}$$

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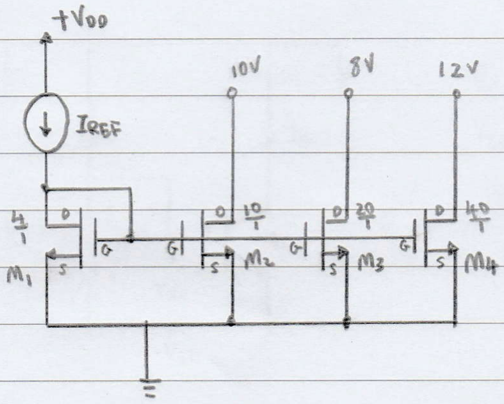
2)



$I_{REF} = 30\mu A$

$K_n' = 25\mu A/V^2$

$V_{TN} = 0.75V$

$\lambda = 0.015V^{-1}$

Since there is no gate current in MOSFET, $I_{D1} = I_{REF} = 30\mu A$

All NMOS transistors have the same V_{GS}

For the diode connected transistors M_1, $V_{DS1} = V_{GS}$

$I_D = \frac{K_n'}{2}\left(\frac{W}{L}\right)(V_{GS} - V_{TN})^2$ * Ignore $(1+\lambda V_{DS})$ if not have to solve quadratic equation

$I_D \times \frac{2}{K_n'} \times \frac{L}{W} = (V_{GS} - V_{TN})^2$

$\sqrt{I_D\left(\frac{2}{K_n'}\right)\left(\frac{L}{W}\right)} = V_{GS} - V_{TN}$

$V_{GS} = \sqrt{I_D\left(\frac{2}{K_n'}\right)\left(\frac{L}{W}\right)} + V_{TN}$

$= \sqrt{30\times10^{-6}\left(\frac{2}{25\times10^{-6}}\right)\left(\frac{1}{4}\right)} + 0.75$

$= 1.524596669V$

$\approx 1.52V$

$\frac{I_{D2}}{I_{D1}} = \frac{\cancel{\frac{K_n'}{2}}\left(\frac{W}{L}\right)_2(V_{GS2} - V_{TN})^2(1+\lambda V_{DS2})}{\cancel{\frac{K_n'}{2}}\left(\frac{W}{L}\right)_1(V_{GS1} - V_{TN})^2(1+\lambda V_{DS1})}$

$= \frac{10(1+0.015(10))}{4(1+0.015(1.52))}$

$= 2.810911224$

$I_{D2} = 2.810911224(30\mu A)$

$= 84.32733672\mu A$

ideal $75\mu A$ $\approx 84.33\mu A$

$r_{o2} = \frac{\left(\frac{1}{\lambda} + V_{DS2}\right)}{I_{D2}}$

$= \frac{\frac{1}{0.015} + 10}{84.33\mu A}$

$= 909.126843 k\Omega$

$\approx 909 k\Omega$

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$$\frac{I_{D3}}{I_{D1}} = \frac{\left(\frac{W}{L}\right)_3 \left(1+\lambda V_{DS3}\right)}{\left(\frac{W}{L}\right)_1 \left(1+\lambda V_{DS1}\right)}$$

$$= \frac{20\,(1+0.015(8))}{4\,(1+0.015(1.52))}$$

$$= 5.47516621$$

$$I_{D3} = 5.47516621\,(30\mu A)$$

$$= 164.2549863\,\mu A$$

$$\approx 164\,\mu A$$

$$r_{o3} = \frac{\frac{1}{\lambda} + V_{DS}}{I_{D3}}$$

$$= \frac{\frac{1}{0.015} + 8}{164\,\mu A}$$

$$= 454.5777778\,k\Omega$$

$$\approx 455\,k\Omega$$

$$\frac{I_{D4}}{I_{D1}} = \frac{40\,(1+0.015(12))}{4\,(1+0.015(1.52))}$$

$$= 11.53645737$$

$$I_{D4} = 11.53645737 \times 30\,\mu A$$

$$= 346.1087212\,\mu A$$

$$\approx 346\,\mu A$$

$$r_{o4} = \frac{\frac{1}{0.015} + 12}{346\,\mu A}$$

$$= 227.2888889\,k\Omega$$

$$\approx 227\,k\Omega$$

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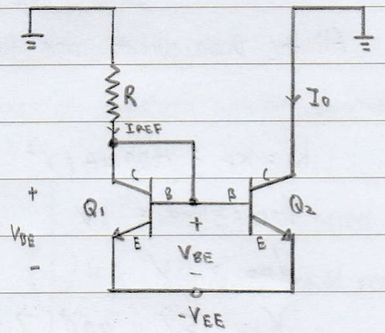
3a)



$R = 43k\Omega$

$V_{EE} = 5V$ and $7.5V$

$V_{BE} = 0.7V$

* If it is a good constant current source
  → change in voltage source should not have a big change in the current

Assume base current negligible and both transistors are identical

$I_o = I_{REF}$

For $-V_{EE} = -5V$

$$I_o = \frac{0-(-V_{EE}+V_{BE})}{R}$$

$$= \frac{5-0.7}{43k\Omega}$$

$$= 100\,\mu A$$

For $-V_{EE} = -7.5V$

$$I_o = \frac{0-(-V_{EE}+V_{BE})}{R}$$

$$= \frac{7.5-0.7}{43k\Omega}$$

$$= 158.1395349 \times 10^{-6}$$

$$\approx 158\,\mu A$$

The change in the current is linearly related to the change in power supply

$0 + V_{CE} - V_{EE} + \cancel{I_oR_{EE}}$

$I_oR = \frac{V_{EE} - V_{BE}}{R}$

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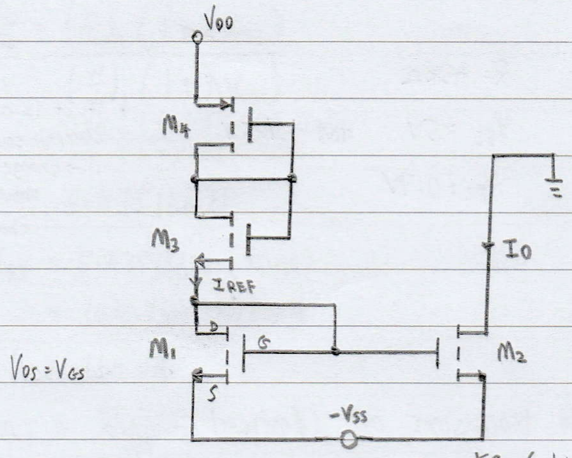
b)



All the Drain current are the same

$k_n = k_p = 400\,\mu A / V^2$

$V_{TN} = -V_{TP} = 1V$

$V_{DD} = 0V$

$V_{SS} = 5V$ and $7.5V$

$$I_D = \frac{k_n}{2}(|V_{GS}| - |V_T|)^2$$

Assume all NMOS transistors are identical

$I_{D1} = I_{D3} = I_{D4} = I_{REF}$

$\therefore V_{GS1} = V_{GS3} = V_{GS4} = |V_{GS}|$

$V_{GS1} + V_{GS3} + V_{GS4} = V_{DD} - (-V_{SS})$

$$3|V_{GS}| = V_{DD} + V_{SS}$$

$$|V_{GS}| = \frac{V_{DD} + V_{SS}}{3} = \frac{0+5}{3} = 1.667V$$

Hence

$$I_{D2} = I_{D1} = \frac{400\,\mu A}{2}(1.667-1)^2 = 88.9778 \times 10^{-6} A \approx 89\,\mu A$$

For $V_{DD} = 0V$ and $V_{SS} = -7.5V$

$$|V_{GS}| = \frac{0+7.5}{3} = 2.5V$$

$$I_{D2} = I_{D1} = \frac{400\mu}{2}(2.5-1)^2 = 450\,\mu A$$

not a good implementation

Note that the variation of current in this case is related to the square of change in supply voltage due to the square law relationship of I_D and V_{GS} of MOSFET

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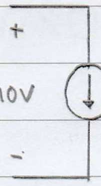
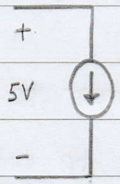
Concept for this tutorial

current mirror
deal with ratio

→ How to build a constant current source ?

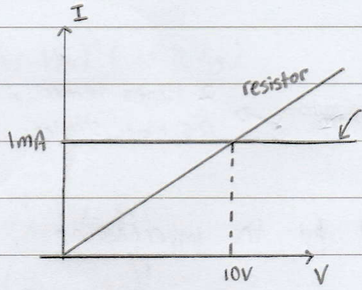


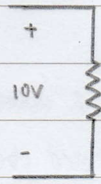
When I put it across another voltage source it should remain as 1mA



→ How to implement this using component I already know

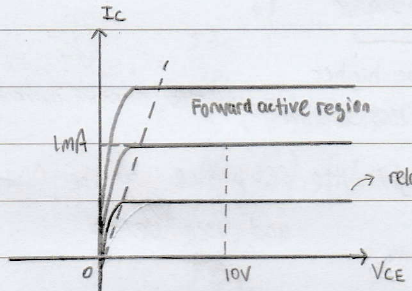
by resistor ?





- not a good design
→ when the voltage fluctuate, current also fluctuate

BJT

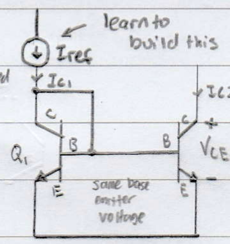


→ relatively flat, doesn't change with respect to voltage that much

∴ change in voltage, current change very little

→ better implementation of a constant current source as compare to a resistor

learn to build this



by making it diode connected it is unconditionally in forward active region

Only want it in the forward active region → BEJ forward bias, → BCJ reversed bias

→ make it diode connected

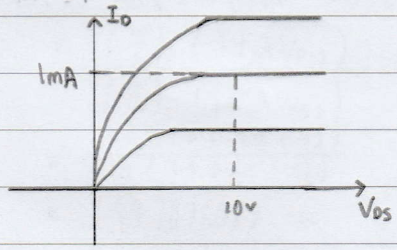
Iref → part of it will go base → base current very small

and part of it will go collector

$$\boxed{I_C = I_S e^{\left(\frac{V_{BE}}{V_T}\right)}\left(1+\frac{V_{CE}}{V_A}\right)}$$

↳ ideal case $V_A = \infty$

MOSFET



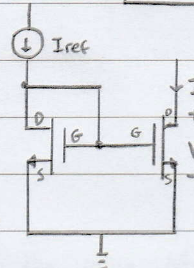
Current mirror?

→ If everything equal, $I_S, V_{BE}, V_T, V_{CE}, V_A$

but this will be slightly different

will study the imperfection

$$I_{C1} = I_{C2}$$



Use this to control current across another terminal

$$\boxed{I_D = \frac{k_n}{2}(V_{GS}-V_{TN})^2(1+\lambda V_{DS})}$$

↳ ideal case $\lambda = 0$

$k_n = k_n'\left(\frac{W}{L}\right)$

Saturation : $V_{DS} \geq V_{GS} - V_{TN}$

* V_A (BJT), λ (MOSFET) } cause the graph to have slope → V_{CE} depend on V_{DS}

If you need 2 constant current source at two different branch with different terminal voltage and different current

Can I use the same reference current to control it? Yes

How? → Don't want to be exact copy but larger / smaller

↘ use K_n to control

$$K_n = K_n' \left(\frac{W}{L}\right)$$

size of transistor → 2 times larger, current also 2 time larger
0.5 times smaller, current also 0.5 time smaller

slope mentioned before that was caused by the imperfection, λ, V_A

Slope is the $\underbrace{\text{ac resistance}}_{\text{must be higher to be less sensitive}}$ r_o

must be higher to be less sensitive → better constant current source

the higher the resistance = the flatter the slope is and vice versa