AEC lecture: Constant Current Sources

Topics Covered: Need of constant current sources, MOSFET current sources Basic two transistor MOSFET current mirror, three transistor MOSFET current mirror

Module or sub-module covered: 5.2

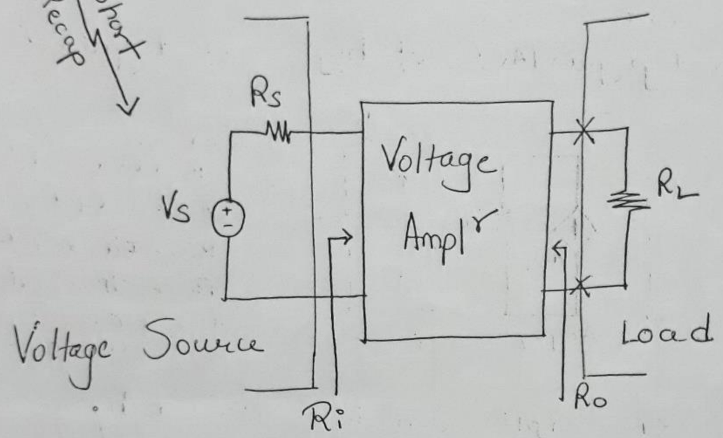
01

Constant Current Sources

Intro: To understand current sources, let's first understand current amplifier's & its requirements.

So, far we have discussed in majority on only voltage sources and voltage amplifiers.

Short Recap



where, $R_s \rightarrow$ internal source resistance

We know following w.r.t voltage ampl^r that,

1) It's I/P impedance should be high (R_i)
2) It's O/P impedance should be low (R_o)

Requirements for voltage source, is

1) It's source resistance (internal) should be v. low

ie $\boxed{R_s << R_i}$ $\rightarrow$ so that entire source voltage (V_s) reach amplifier I/P and to prevent loading effect

Load requirements:-

1) O/P impedance (R_o) of amplifier should be Low

ie $\boxed{R_o << R_L}$ $\rightarrow$ so that entire O/P reaches Load (R_L).

Concept:

- Current Amplifiers:-

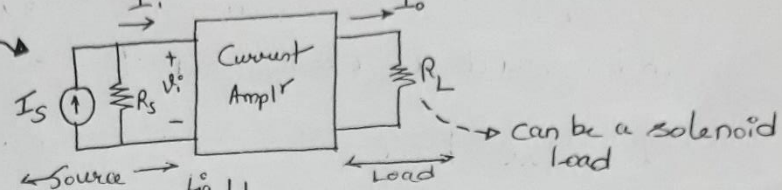


fig 1.1

→ It's o/p current (I_o) is proportional to its I/P current (I_i)
→ It's I/P is a "Current Source".
→ Provides modest voltage gain (A_v) but high current gain (A_i)

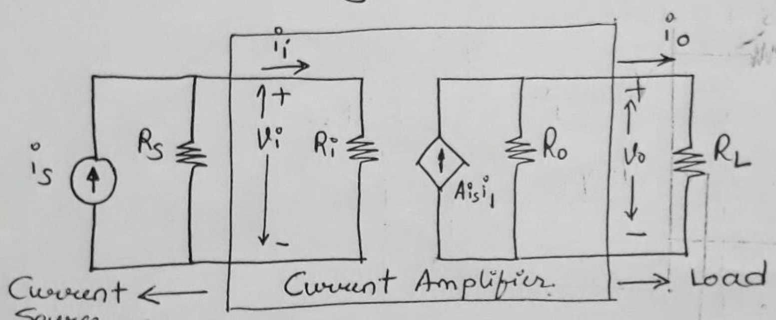


fig 1.2

where,
R_L → Load resistance
A_{is} → current gain
R_i → I/P resistance
R_o → o/p resistance
$A_{is} i_1$ → Current-controlled current source

- o/p current (i_o) of the ampl^r can be obtained by using current-divider rule (CDR),

$$i_o = A_{is} i_i \left(\frac{R_o}{R_o + R_L} \right) \quad — (1)$$

From (1), we see that $R_o >> R_L$ → so that max current (i_o) flows thr the Load

Also, i/p current i_i of the ampl^r is related to s/g source current i_s by CDR,

$$i_i = \left(\frac{R_s}{R_s + R_i} \right) i_s \quad — (2)$$

From (2), if $R_i << R_s$, then $\boxed{i_i = i_s}$, ie entire source current reaches I/P of ampl^r.

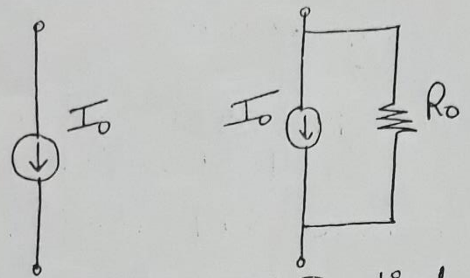
From (1) & (2), the requirements of current Amplifier are

1) $R_i << R_s$
2) $R_o >> R_L$

→ If these condition's are met, there will be no Loading effect.

- In summary, an ideal current amplifier should have $R_o \to \infty$ & $R_i \to 0$, so that there is no reduction in the current gain.

- From fig 1.2, it is evident that a current source should very $\boxed{\text{high o/p resistance}}$



where,
R_o – internal current source resistance (or o/p resistance of current source).

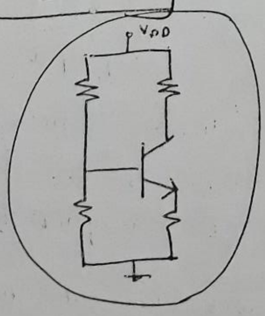
fig 1.3 a) Ideal current source ($R_o \to \infty$) b) Practical current source. ($R_o \to$ v. high)

→ An ideal current source should have <u>constant current</u> and a <u>v. large o/p resistance</u> ($R_o \to \infty$).

⊢ Why use Current Source's ?

1) Current-source biasing technique eliminates the need for <u>resistor-intensive biasing</u> used up to this point.

Remember this !



2) Current-source are used for biasing transistor's in Integrated circuits.

· Let's justify points (1) and (2),

· Biasing techniques for FET and BJT amplifiers employing voltage divider resistor networks can be used for discrete circuits, it is $\boxed{\text{NOT}}$ suitable for integrated circuits.

Because of the following reasons: -

1) Resistor's occupy large areas on an integrated circuit (IC) compared to transistor.
∴ A resistor - intensive ckt would necessitate a large chip area.

2) Transistor's can easily be fabricated in IC's with matched or identical parameters (which may not be possible in discrete circuits).

Let's consider another justification for using current source's.

· Why we do DC biasing in BJTs (let's say): Imagine a voltage-divider DC biasing ckt.

a) to turn the device on
b) to place Q-point in region of characteristics where device operates most linearly so that any changes in the I/P source causes a proportional change in the o/p signal.
c) ckt elements are selected so as to bias C-B & E-B J^n of BJT in appropriate magnitude & polarity.
d) Since B-E J^n behaves like a diode, transistor needs a B-E voltage V_{BE} of 0.7V to conduct.
e) If we apply more than 0.7V, then transistor will be damaged due to excessive current.
f) Hence, resistor (R_C, R_B, R_E) are used to limit the transistor currents (I_B, I_C, I_E).

- Recollect that voltage gain (A_v) of a CE ampl^r was

$\boxed{A_v = -g_m R_C}$ → small-signal mid-band voltage gain (with C_E, w/o R_L)

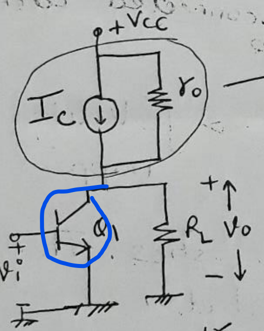
- In order to ↑se value of A_v, <u>we need to ↑se R_C.</u>

But ↑se in R_C will lead to more power dissipation or loss

So replace R_C by a current source

A current source has a high o/p resistance → Thereby, producing a high A_v.

- <u>Example:</u>

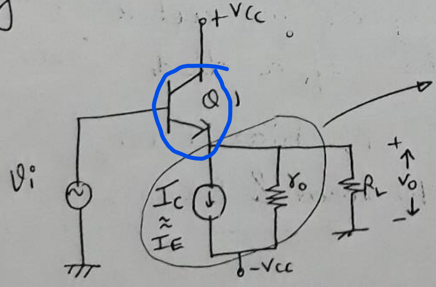


current source → I_C flows $\boxed{\text{out}}$ of current source into Q_1.

This type of current source is referred to as "Sourcing Current source."

Q1 is a MOSFET

fig 1.3 a) CE ampl^r



current source → Source current flows from Q_1 $\boxed{\text{into}}$ the current source.

This type of current source is referred to as "Sinking Current Source."

b) Emitter follower

fig: 1.3 Amplifier with a biasing current source.

Need of Constant current sources:

- For increasing CMRR in case of diffamp's, either emitter or source resistance (R_E or R_S) has to increase which has the following problems.

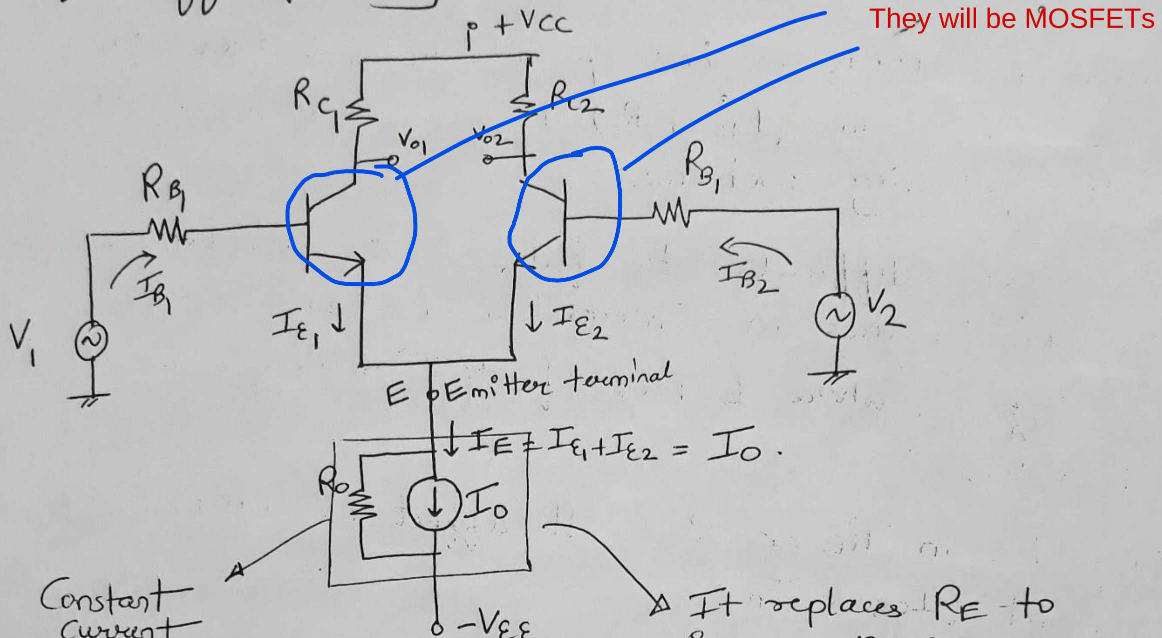
1) It is very difficult to fabricated very large resistance values in Integrated ckts (ICs) since $R = \rho\left(\frac{L}{A}\right)$, where L ↑ses if R is required of high value.
2) Any ↑se in R_E or R_S will affect or change Q point (I_{CQ} or I_{DQ}).
3) In order to keep Q point constant for large value of R_E or R_S, very large negative power supplies ($-V_{EE}$ or $-V_{SS}$) are required.
4) Such a large value of R_E or R_S leads to very high power dissipation ⇒ means loss of dc power.

Hence for all practical diffamp's applications, the source or emitter resistance (R_E or R_S) are replaced by a (CCS) constant current source, which only ↑se value of R_E or R_S electrically, not physically at the same time providing constant bias current (I_{CQ} or I_{DQ}).

- This is possible becoz, o/p resistance (R_o) of current source is very high.

→ This explain's the need of CCS in diffamp.

→ Diffamp using Constant current source



Constant current source → It's o/p resistance (R_0) → is extremely large compared to R_E.

It replaces R_E to improve CMRR.

→ Now, this constant current source ckt's we are going to study and analyze in details.

ie We will consider types of ckts that can be designed to establish the bias current I_0.

• **Advantages of using Constant Current Sources :-**

1. Transistor current sources are widely used in analog Integrated ckts both as biasing elements and as Loads for amplifying stages.

2. Active current sources helps in ↑sing the voltage gain of an amplifier.

3. Constant current sources have a very high o/p resistance (R_o) and its O/P current is not sensitive to the transistor parameter β.

4. Current sources are less sensitive to variation's in DC power supply and temperature.

5. Especially, For a small value of bias current, the current sources are more economical than resistor's in terms of die area required for resistors.

→ A current source can be designed by using either MOSFET's or BJT's.

We have analyzed various BJT current sources'.

→ Let's analyze MOSFET current source's next.

• MOSFET current sources are analogous to BJT current sources

MOSFET Current Sources

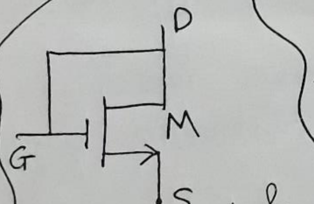
→ The choice of a BJT current source or a MOSFET current source generally depends on the type of integrated ckt involved (eg bipolar or MOS).

→ BJT current sources have some advantages over MOSFET current sources, such as a wider compliance range and a higher O/P resistance.

→ However, a higher o/p resistance can be obtained by cascode-Like connections of MOSFETs.

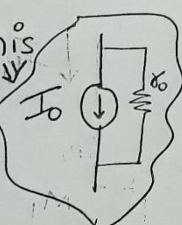
• How MOSFET can be used as a Current Source?

We need to achieve this



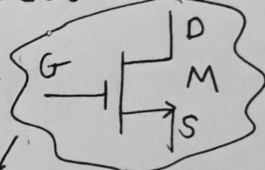
nMOS with gate & drain terminals shorted

behaves Like



Consider a nMOS (E-type)

Start here



Current Io flowing in Tr M will be constant, if M is biased in saturation region

For MOSFET to be in saturatn condn is

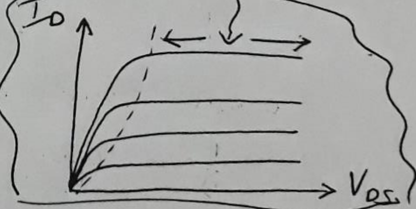
$V_{GS} \geq V_{TN}$

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

Remember this

For this case, $V_{DS} \approx V_{GS}$ always so these condns will be satisfied

Thus, M will be always be biased in saturatn region



NB: Voltage compliance range :- It is the voltage range over which the ckt can maintain a constant current.

V_{TN} → Threshold voltage of NMOS-E type.

Types of MOSFET constant current sources which we will be studying are

a) Basic two-transistor current source

b) ~~Three~~-transistor current source.

c) Cascoded current source

d) Wilson current source.

A] Basic two-transistor MOSFET Current Source.

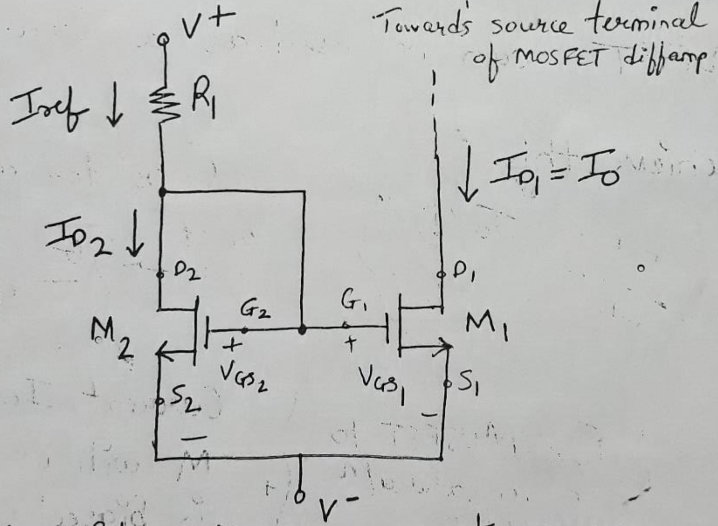


fig 7.1 Two-transistor NMOS current source.

- The direction of current flow in fig 7.1 is into the current source; this type of constant-current source is often referred to as a current sink.

- let us assume that the two transistors M_1 and M_2 are identical (ie $V_{GS_1} = V_{GS_2}$, ie $I_{D_1} = I_{D_2}$)

- ∴ Thus, the o/p current $I_o (= I_{D1})$ will be the mirror of I_{D2}.
- Also, since $V_{DS2} = V_{GS2}$, M_2 is always biased in the saturation region.
- Let V_{TN1} and V_{TN2} be the threshold voltages of M_1 & M_2.
- For M_1 to be in saturation, V_{DS1} which is greater than or equal to $(V_{GS2} - V_{TN2})$, must be greater than $(V_{GS1} - V_{TN1})$.
- This condition reduces the voltage compliance range of the MOSFET current source and prevents it from operating from a low power supply.

Current Relationship:

- Drain current eq^n of an E-type NMOS biased in saturation region is,

$$I_{Dsat} = K_n (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \quad \text{— (a)}$$

where, $\boxed{K_n = \mu_n C_{ox} \left(\frac{W}{L}\right) \times \frac{1}{2}}$, λ - channel length modulation parameter

- The o/p current 'I_o', which is equal to drain current of M_1 is given by,

$$I_{D1} = I_o = K_{n1} (V_{GS1} - V_{TN1})^2 (1 + \lambda V_{DS1}) \quad \text{— (1)}$$

- Drain current I_{D2} which is equal to the reference current I_{ref} is

$$I_{D2} = I_{ref} = K_{n2} (V_{GS2} - V_{TN2})^2 (1 + \lambda V_{DS2}) \quad \text{— (2)}$$

- Since, all the components of the current source are processed on the same IC, all the physical parameters such as (V_{TN}, μ_n, C_{ox} & λ) are identical for both devices (M_1 and M_2)

$\therefore$ Ratio of I_o to I_{ref} is given by (using ① & ②),

$$\frac{I_o}{I_{ref}} = \frac{K_{n1}(V_{GS_1}-V_{TN_1})^2(1+\lambda V_{DS1})}{K_{n2}(V_{GS_2}-V_{TN_2})^2(1+\lambda V_{DS2})} \quad — ③$$

$$= \frac{\cancel{\mu_n C_{ox}}\left(\frac{W}{L}\right)_1 \times \cancel{\frac{1}{2}}(V_{GS_1}-V_{TN_1})^2(1+\lambda V_{DS1})}{\cancel{\mu_n C_{ox}}\left(\frac{W}{L}\right)_2 \times \cancel{\frac{1}{2}}(V_{GS_2}-V_{TN_2})^2(1+\lambda V_{DS2})}$$

$$\boxed{\frac{I_o}{I_{ref}} = \frac{(W/L)_1}{(W/L)_2} \times \frac{(1+\lambda V_{DS1})}{(1+\lambda V_{DS2})}} \quad — ④$$

In practice, $\lambda V_{DS} << 1$, then eq^n ④ can be approximatied by,

$$\boxed{\frac{I_o}{I_{ref}} = \frac{(W/L)_1}{(W/L)_2}} \quad — ⑤$$

ie $\boxed{I_o = \frac{(W/L)_1}{(W/L)_2} \cdot I_{ref}}$ ⟶ By controlling the ratio (W/L), we can change the o/p current.

By choosing identical transistors with $W_1 = W_2$ and $L_1 = L_2$, a designer can ensure that the o/p current I_o is <u>almost equal</u> to the reference current <u>I_{ref}</u>.

From fig 7.1,

• Since $V_{GS_2} = V_{DD} - I_{ref} R_1$ and $V_{DS_2} = V_{GS_2}$ (From eqn ②)

$$\therefore \boxed{I_{Ref} = I_{O_2} = K_{n_2}(V_{DD} - I_{ref} R_1 - V_{TN_2})^2} \quad -⑥$$

I_{ref} can be solved for known values of V_{TN_2}, K_{n_2}, V_{DD} and R_1.

• O/P resistance:

The stability of the Load current as a function of V_{DS} voltage is an important consideration in many applicatns.

• The small-s/g o/p resistance of the current source can be estimated as follows, (fig 7.2)

$\boxed{R_O = r_{O_1}}$; $r_{O_1} = \frac{V_x}{I_x}$, {since $g_{m_2} V_{gs_2} \approx 0$, V_{gs_1} so $g_{m_1} V_{gs_1}$ becomes redundant}

where, r_{O_1} is o/p resistance looking into transistor M_1

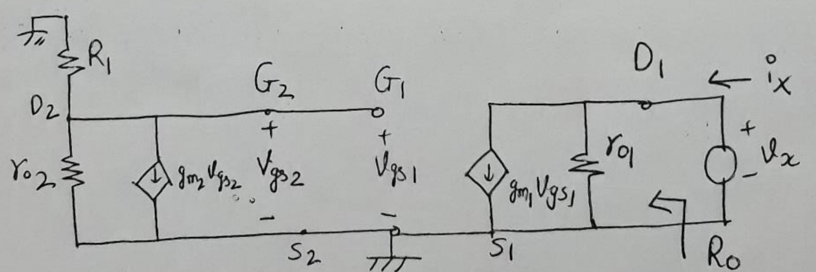


fig 7.2 : Small-s/g equivalent ckt. of fig 7.1

• The stability of the load current ($I_O = I_{D_1}$) can be described in terms of o/p resistance,

From fig 7.1, $V_{DS_2} = V_{GS_2}$ = constant for a given reference current

Normally, $\lambda V_{DS_2} = \lambda V_{GS_2} << 1$, & if $(W/L)_1 = (W/L)_2$] (a)

Then the change in bias current w.r.t to a change in V_{DS_1} is

$$\frac{1}{R_0} = \frac{\partial I_0}{\partial V_{DS_1}} = \frac{1}{r_{o_1}} = \frac{\partial I_{D_1}}{\partial V_{DS_1}} \quad --- \ (b)$$

from (a) & eq^n (1) and (4),

$$\frac{\partial I_{D1}}{\partial V_{DS_1}} \approx \frac{K_{n_1} \left(V_{GS_1} - V_{TN_1}\right)^2 \left(1 + \lambda V_{DS1}\right)}{\lambda}$$

$$\approx I_{D_1} \lambda$$

ie $\frac{1}{r_{o_1}} \approx I_0 \lambda$

$\therefore \boxed{r_{o_1} \approx \frac{1}{\lambda I_0}}$ where, r_{o_1} is the o/p resistor of the transistor M_1.

$\therefore \boxed{R_0 = r_{o_1} = \frac{1}{\lambda I_0}}$ which is relatively small.

- This small o/p resistance is a disadvantage of having only one MOSFET M_1 at the o/p side of a current source.

—x—

8) Modified three-transistor MOSFET Current Source:

- Reference current in BJT current sources is generally established by bias voltage and a resistor. Since MOSFETs can be configured to act like a resistor, the reference current in MOSFET current sources is usually established by using additional transistor.
- The reference resistance R_1 in fig 7.1 can be replaced by another MOSFET M_3 as shown in fig 8.1.

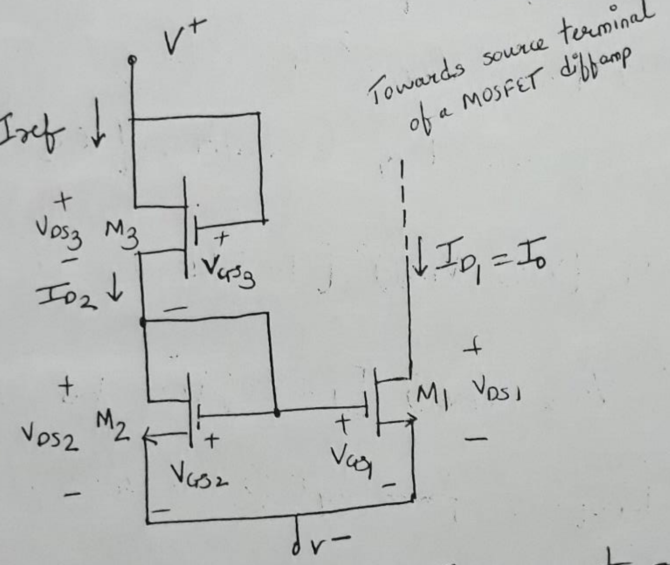


fig 7.1 → Three-transistor MOSFET current source.

- Transistor M_2 and M_3 are used as voltage divider's to control the gate-source voltage of M_1.
- If M_1 and M_2 are identical, the o/p current (I_o) exactly mirrors the drain current through M_2 and M_3

$$\underline{I_o \approx I_{D_1}} \quad (\text{From fig 7.1})$$

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Current Relationship:

Since $V_{GS_1} = V_{GS_2}$, from fig (7.1)

The drain current $I_{D_1} (= I_o)$ is equal to the drain current I_{D_2} and is given by

$$I_{D_1} = I_{D_2} = I_{ref} = K_{n_1}(V_{GS_1} - V_{TN_1})^2 (1 + \lambda V_{GS_1}) \quad — ①$$

Since $V_{DS_2} = V_{GS_2}$ → I_{DS} is equal to reference current I_R,

$$I_{D_2} = I_{ref} = K_{n_2}(V_{GS_2} - V_{TN_2})^2 (1 + \lambda V_{GS_2}) \quad — ②$$

Since $V_{GS_3} = V^+ - V_{GS_2}$, the drain current of M_3 is

$$I_{D_3} = I_{ref} = K_{n_3}(V_{GS_3} - V_{TN_3})^2 [1 + \lambda V_{DS_3}] \quad — ③$$

$$I_{D_3} = K_{n_3}(V^+ - V_{GS_2} - V_{TN_3})^2 [1 + \lambda (V^+ - V_{GS_2})] \quad — ④$$

Since $I_{D_2} = I_{D_3} = I_{ref}$, from eq^n ② & ④, we get

$$\frac{K_{n_2}(V_{GS_2} - V_{TN_2})^2 (1 + \lambda V_{GS_2})}{K_{n_3}(V^+ - V_{GS_2} - V_{TN_3})^2 [1 + \lambda (V^+ - V_{GS_2})]} = 1 \quad — ⑤$$

Thus, by controlling the constants K_{n_2} & K_{n_3}, we can obtained the desired value of $V_{GS_2} = V_{GS_1}$, which will give the desired o/p current (I_o) (from eq^n ①).

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Finally the Load current, for $\lambda = 0$, is given by

$$\boxed{I_0 = \frac{k_n'}{2}\left(\frac{W}{L}\right)_1 (V_{GS_1} - V_{TN_1})^2} \quad — (6)$$

where $k_n' = \mu_n C_{ox}$

- Since the designer has control over the (W/L) ratios of transistors, there is considerable flexibility in the design of MOSFET current sources.

- O/P resistance (Ro):

→ The o/p resistance of three-transistor MOSFET constant current source can be determined by looking into O/P transistor M_1.

→ It is similar to two-transistor's o/p resistance

$$\therefore \boxed{R_o = r_{o1} = \frac{1}{\lambda I_{D_1}}}$$ which is relatively small.

- This small o/p resistance is a disadvantage of having only one MOSFET M_1 at the o/p side of a current source.

→ The o/p resistance of a MOSFET basic current source & modified MOSFET current source can increased by connecting MOSFETs in a cascode-like connection.

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