Current Reference & Voltage Reference

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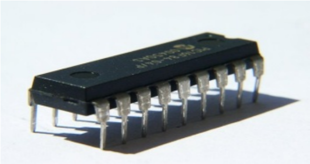
Current and Voltage Reference



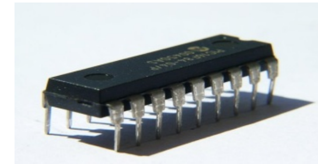
- Reference Vs Source

  - Reference is more *precise* and *stable* than source.
  - Source must be capable of driving Load.
  - Reference is more complex

- Properties

  - Independent of PVT (*Process-Voltage-Temperature*) variation
  - Independent of output Voltage or Current
  - Independent of Noise and other Interference
  - Easy to design / tune

Power Supply Dependency



- How to characterize ?

Sensitivity :

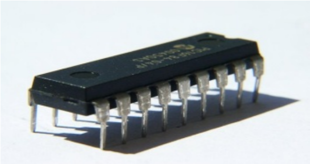
$$S_{V_{DD}}^{I_{REF}} = \frac{\partial I_{REF} / I_{REF}}{\partial V_{DD} / V_{DD}} = \frac{V_{DD}}{I_{REF}}\left(\frac{\partial I_{REF}}{\partial V_{DD}}\right)$$

Power supply Dependence :

$$\frac{\partial I_{REF}}{I_{REF}} = \left(S_{V_{DD}}^{I_{REF}}\right)\frac{\partial V_{DD}}{V_{DD}}$$

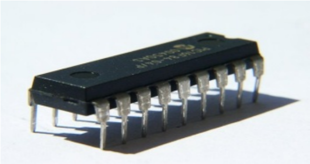
- So the fractional change in the reference current is equal to the sensitivity times fractional change in the supply voltage
- *Ideally this sensitivity to be zero for Power Supply Independence*

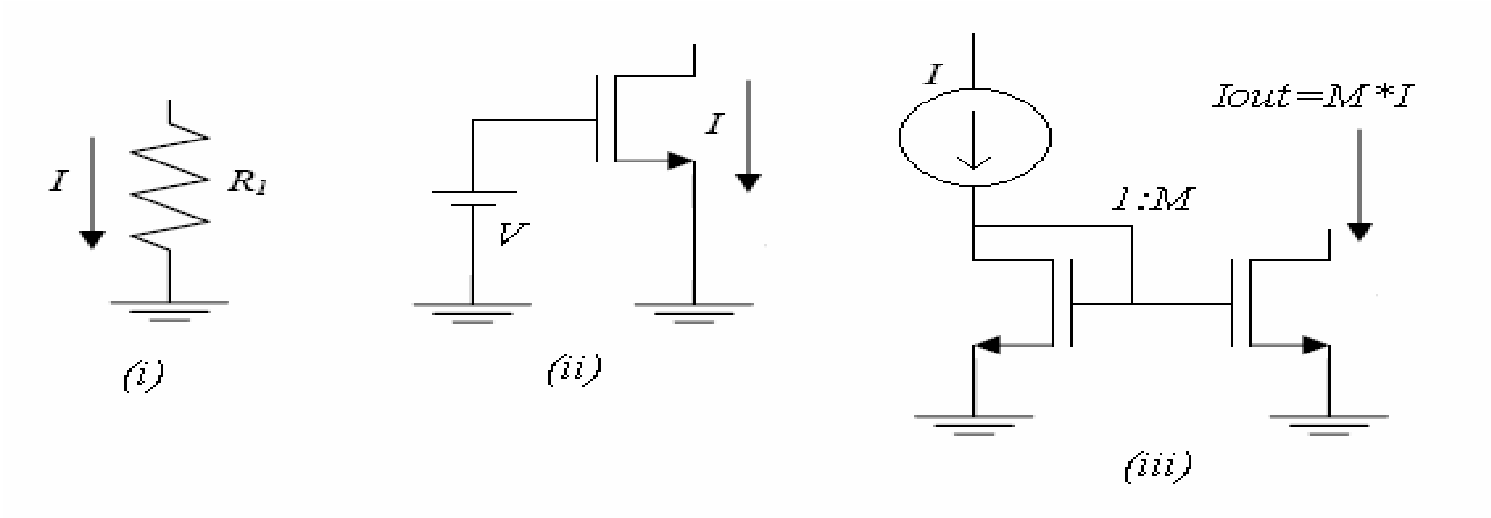
Need of Current Reference



- Required in different places in IC, e.g.- Op-amp, Comparator, Oscillator etc.
- Generate one current reference and used in multiple places by current mirror principle.
- Saves area and power.

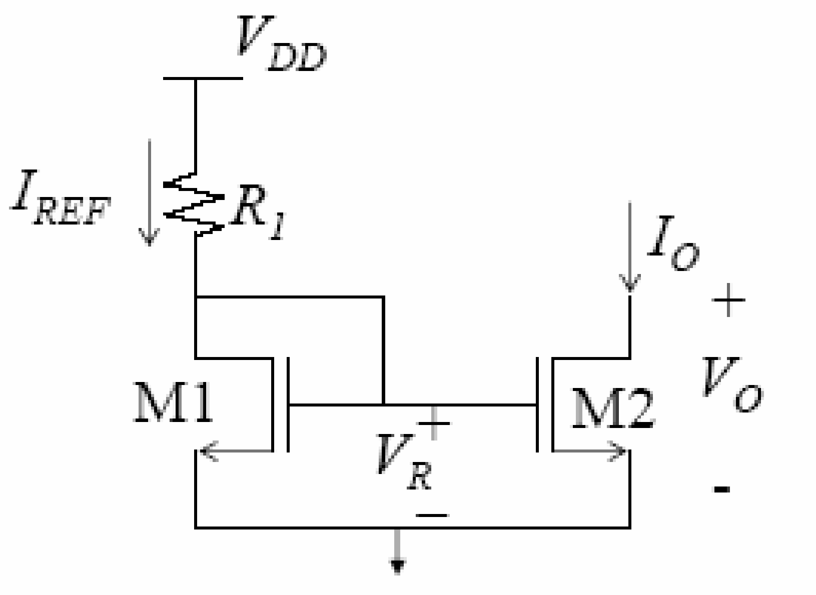
Some Crude Current References





- **Problems-**
  - (i) Not independent of VDD, Resistor should be accurate.
  - (ii) Need reference voltage V, difficult to control current – strong function of Vgs, more sensitive to Process variation.
  - (iii) Need Stable I. Easy to adjust current, less sensitive to Process variation

Resistance Biasing



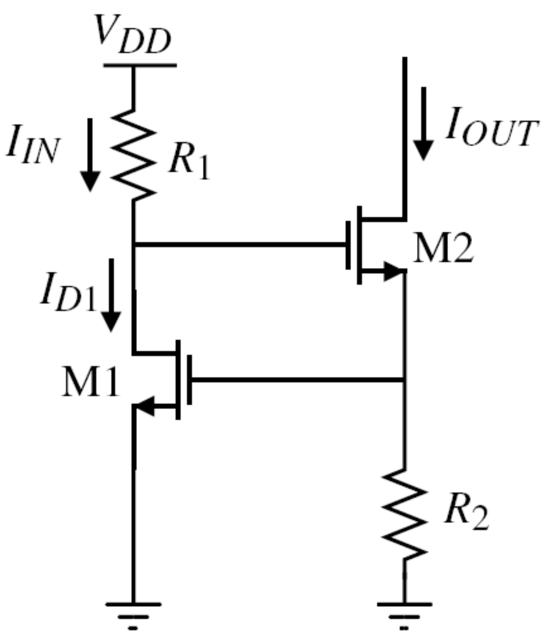
$$I_o = \frac{V_{DD}}{R_1 + 1/g_{m1}} \frac{W_2}{W_1}$$

$$\Delta I_o = \frac{\Delta V_{DD}}{R_1 + 1/g_{m1}} \frac{W_2}{W_1}$$

$$S_{V_{DD}}^{I_{REF}} = 1$$

- I_0 – much sensitive to V_{DD}
- How to make it less sensitive to V_{DD} ?

Threshold Referenced Current Reference



$$I_{OUT} = \frac{V_{GS1}}{R_2} = \frac{V_T + \sqrt{\frac{2I_{IN}}{K'(W_1/L_1)}}}{R_2}$$

$$\approx \frac{V_T}{R_2} \text{ if } V_T > V_{ON1}$$

The sensitivity of I_{OUT} with respect to V_{DD} is

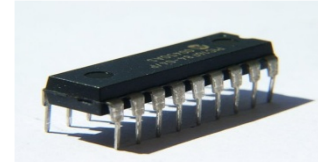
$$S_{V_{DD}}^{I_{OUT}} = \left(\frac{V_{ON1}}{I_{OUT}R_2}\right) S_{V_{DD}}^{I_{IN}} = \left(\frac{V_{ON1}}{2V_{GS1}}\right) S_{V_{DD}}^{I_{IN}}$$

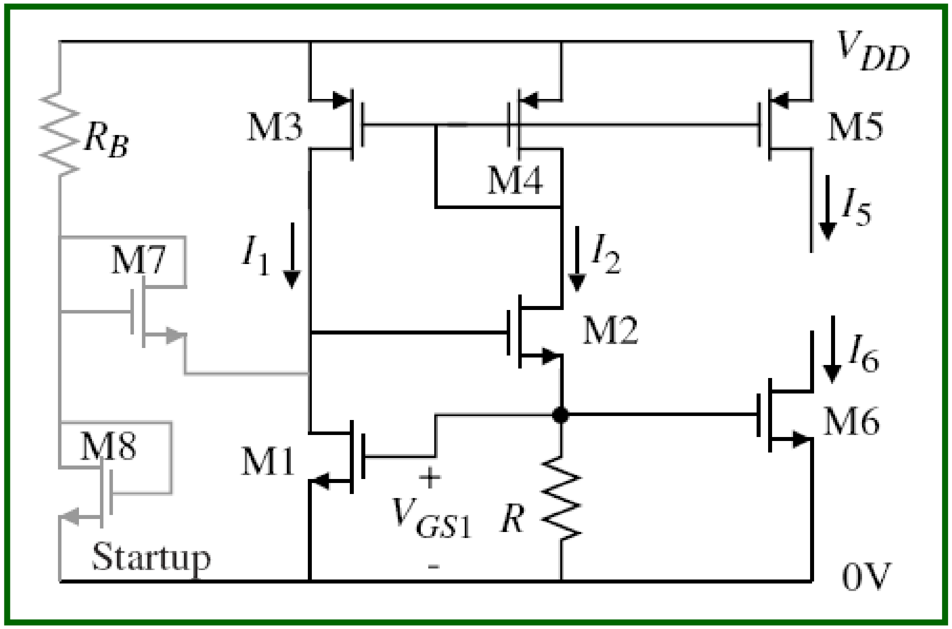
For example, if $V_T = 1\text{V}$, $V_{ON1} = 0.1\text{V}$ and $S_{V_{DD}}^{I_{IN}} \approx 1$, then

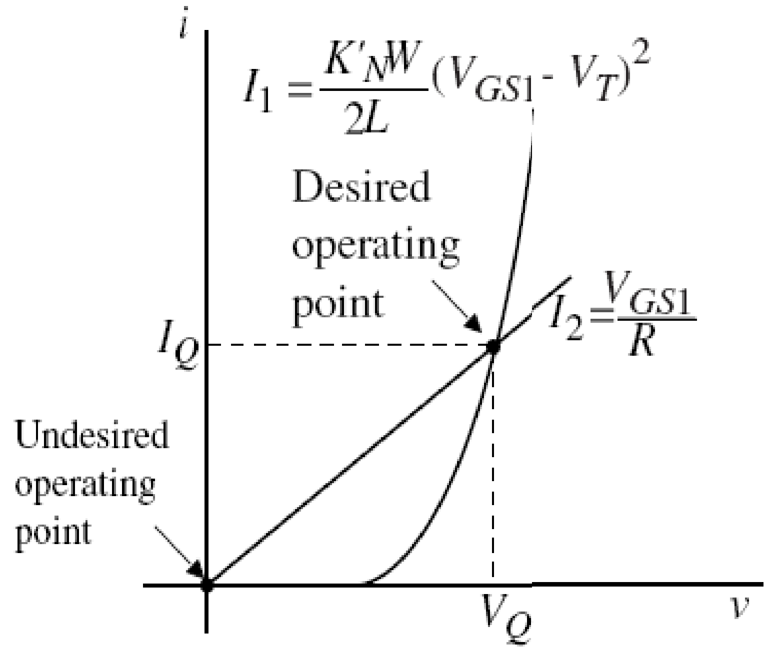
$$S_{V_{DD}}^{I_{OUT}} = \left(\frac{0.1}{2 \cdot 1.1}\right) = 0.045$$

- Supply dependency much less

Self Biasing Threshold Current Reference I







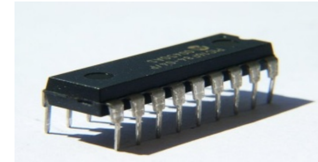
If M3 = M4, then $I_1 \approx I_2$. However, the M1-R loop gives $V_{GS1} = V_{T1} + \sqrt{\dfrac{2I_1}{K_N'(W_1/L_1)}}$

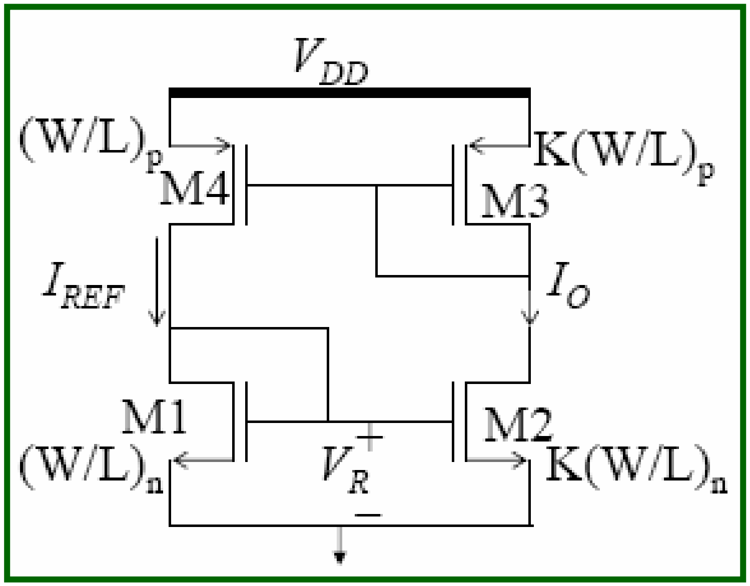
Solving these two equations gives $I_2 = \dfrac{V_{GS1}}{R} = \dfrac{V_{T1}}{R} + \left(\dfrac{1}{R}\right)\sqrt{\dfrac{2I_1}{K_N'(W_1/L_1)}}$

The output current, $I_{out} = I_1 = I_2$ can be solved as $I_{out} = \dfrac{V_{T1}}{R} + \dfrac{1}{\beta_1 R^2} + \dfrac{1}{R}\sqrt{\dfrac{2V_{T1}}{\beta_1 R} + \dfrac{1}{(\beta_1 R)^2}}$

- **Two current level supported, need a start-up circuit**

Self Biasing Current Reference II

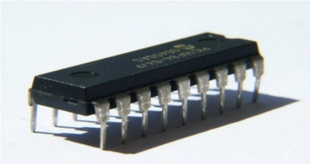


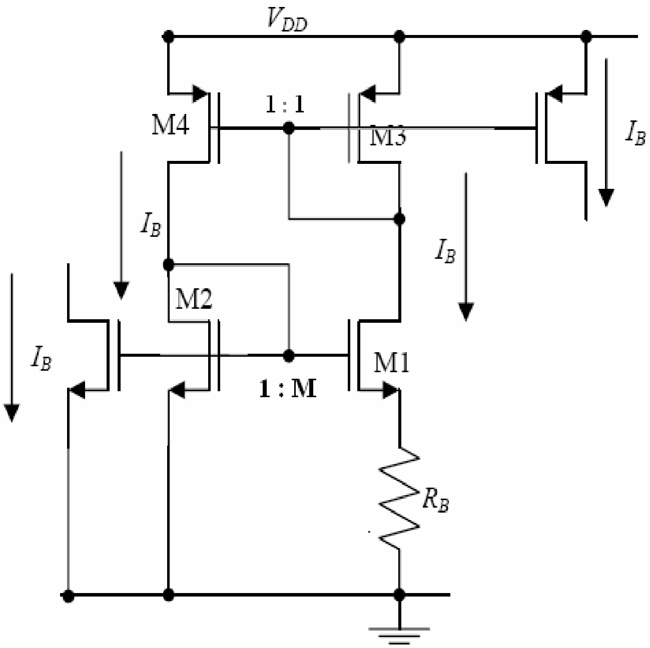


- I_{REF} is bootstrapped to I_0
- $I_0 = K\, I_{REF}$
- Supply dependent

- If all the transistors are in saturation the circuit can support any current ! ! !
- Then how to fix the current ?

Self Biasing Current Reference II





From the circuit,

$$\Rightarrow \quad I_B R_B + V_{GS1} = V_{GS2}$$

$$\Rightarrow \quad I_B R_B + V_{THN1} + \sqrt{\frac{2I_B}{\mu_N C_{ox}\left(\frac{W}{L}\right)_1}} = V_{THN2} + \sqrt{\frac{2I_B}{\mu_N C_{ox}\left(\frac{W}{L}\right)_2}}$$

By neglecting the body effect, $V_{TH1} = V_{TH2}$ and the above equation is rewritten as

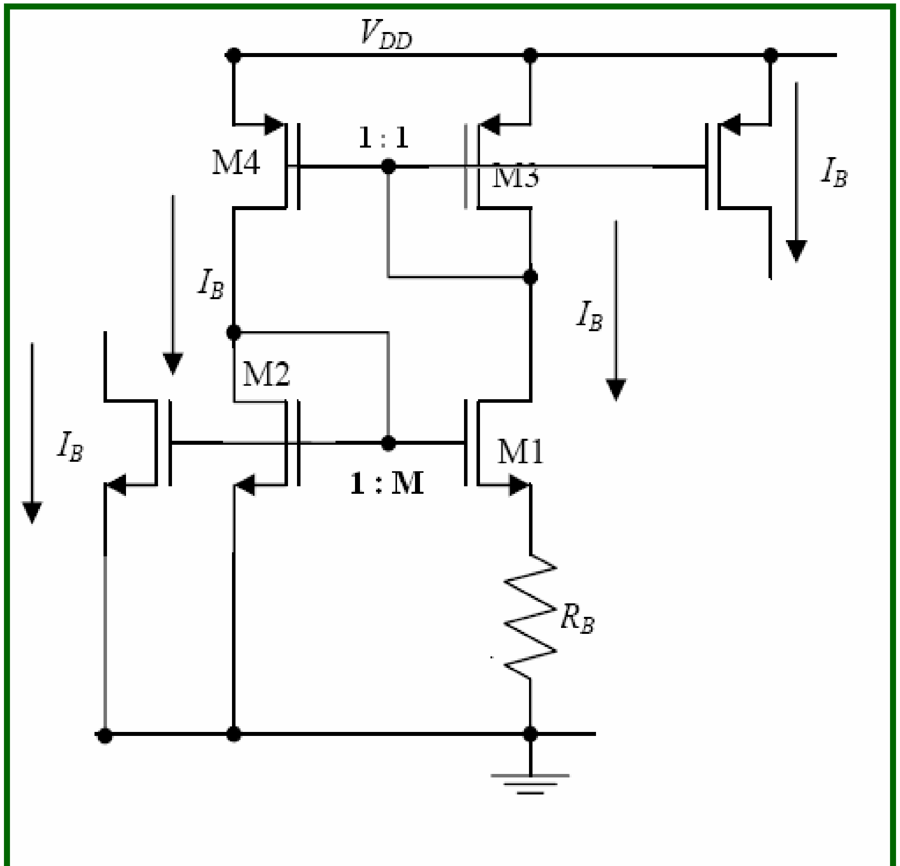
$$\Rightarrow \quad I_B R_B = \sqrt{\frac{2I_B}{\mu_N C_{ox}\left(\frac{W}{L}\right)_2}} - \sqrt{\frac{2I_B}{\mu_N C_{ox}\left(\frac{W}{L}\right)_1}} \quad \left(\text{Assuming} \quad I_B \neq 0\right)$$

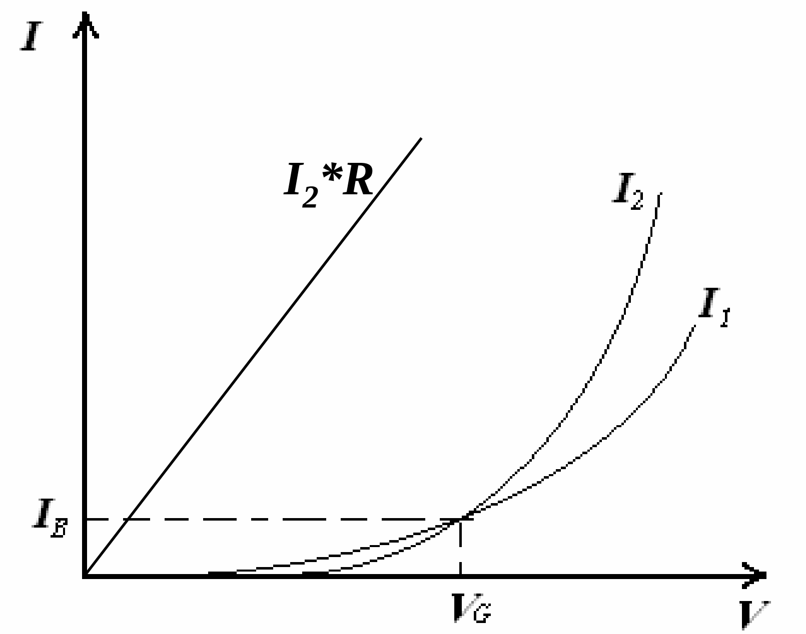
$$\Rightarrow \quad I_B = \frac{2}{R_B^{\,2} \cdot \mu_N C_{ox}\left(\frac{W}{L}\right)_2} \cdot \left(1 - \sqrt{\frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}}\right)^2 = \frac{2}{R_B^{\,2} \cdot \mu_N C_{ox}\left(\frac{W}{L}\right)_2} \cdot \left(1 - \frac{1}{\sqrt{M}}\right)^2$$

which is independent of V_{DD}.

- ❑ **Current uniquely defined**
- ❑ **Supply Independent**
- ❑ **Temperature Dependent**

Self Biasing Current Reference II





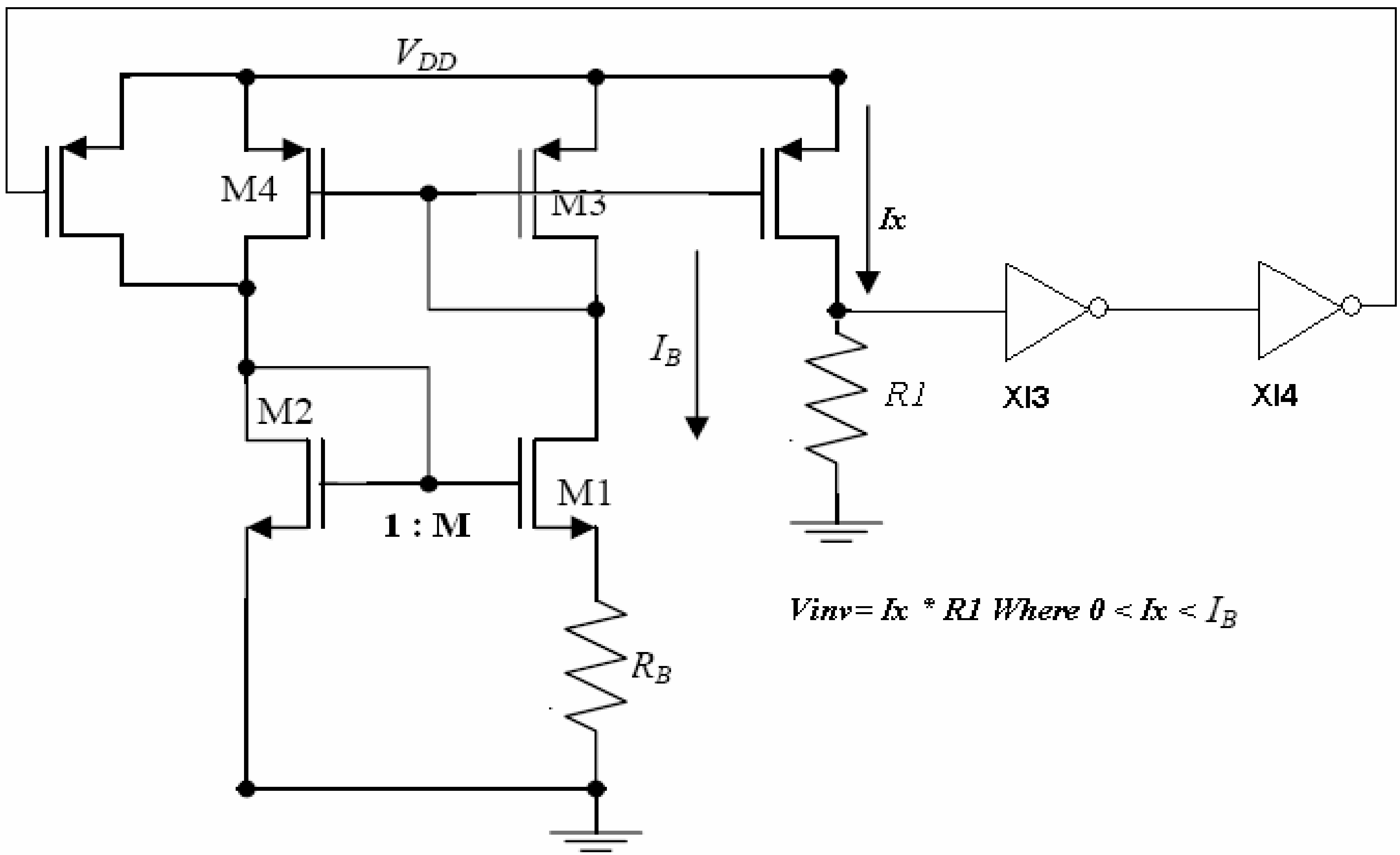
Two stable reference current point- zero current & finite IB current

- Two meeting points – two stable reference current – zero and finite I_B

  How to fix ?

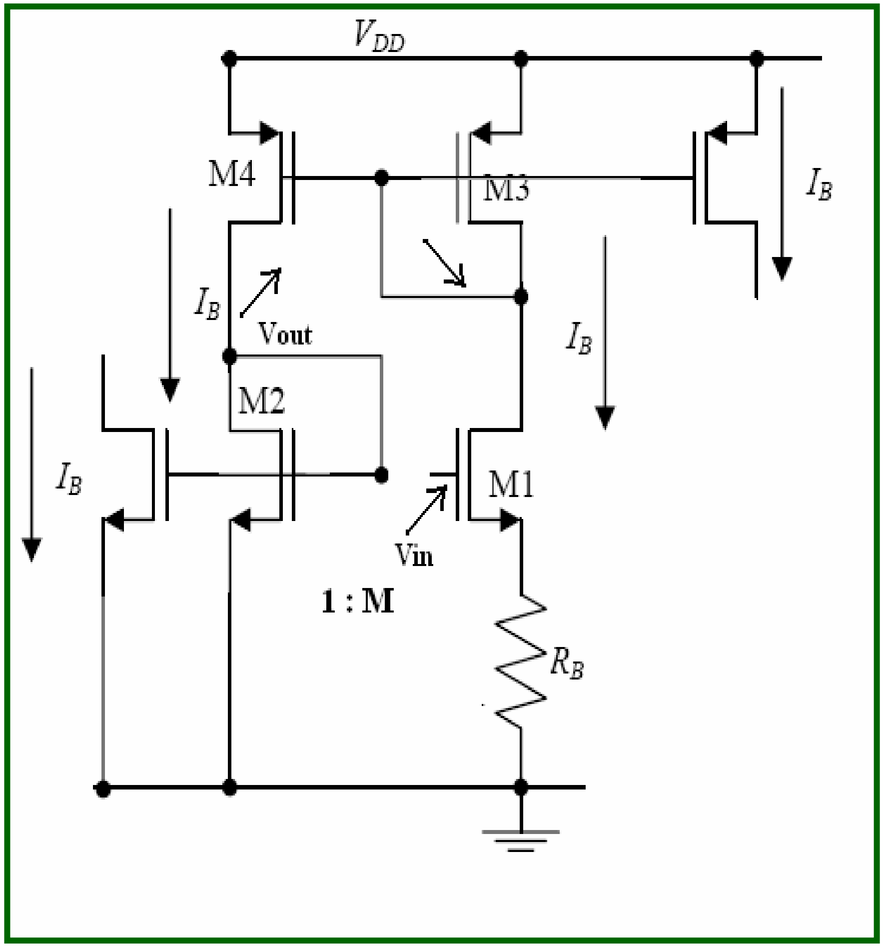
- Slope more – more stable

Self Biasing Current Reference II - Startup



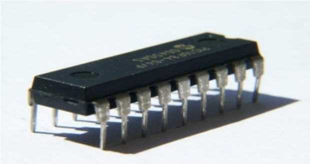
Vinv= Ix * R1 Where 0 < Ix < I_B

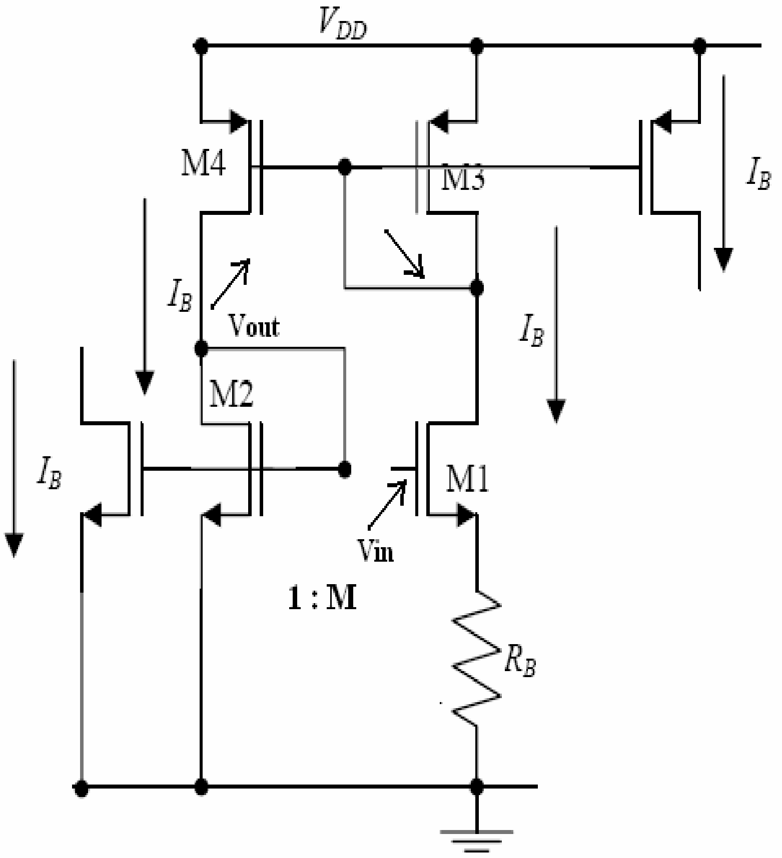
Stability and Feedback



- Break the loop and find loop gain and polarity
- What type of feedback it is ?

Loop Gain of the positive feedback





$$A_v = \frac{g_{m1}}{1 + g_{m1} * R_B} * \frac{1}{g_{m3}} * g_{m4} * \frac{1}{g_{m2}}$$

$$g_m = \sqrt{2 I_D * \mu * C_{ox}\left(\frac{W}{L}\right)}$$

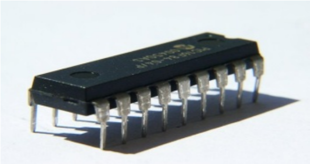
$$g_{m3} = g_{m4} \qquad g_{m1} = g_{m2}\sqrt{M}$$

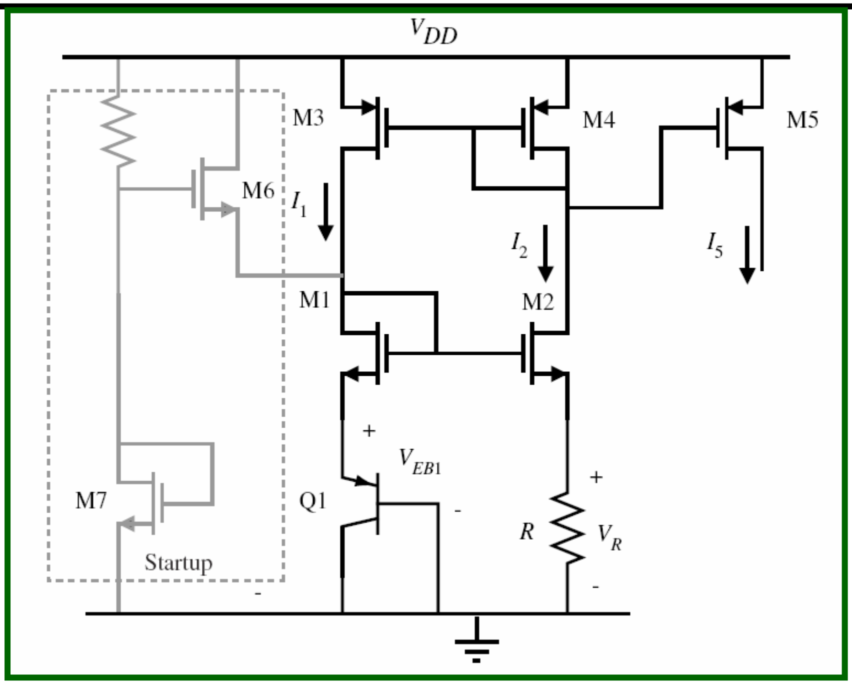
$$A_v = \frac{g_{m2}\sqrt{M}}{1 + g_{m2} * R_B\sqrt{M}} * \frac{1}{g_{m2}} = \frac{\sqrt{M}}{1 + g_{m2} * R_B\sqrt{M}}$$

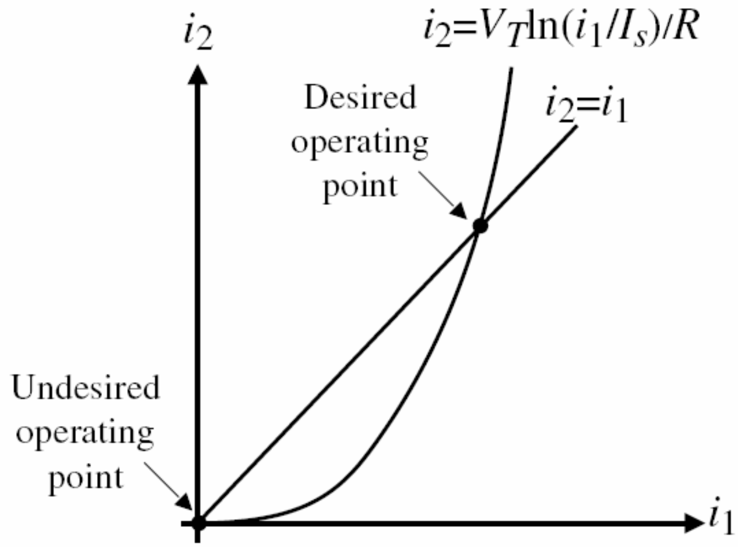
$$= \frac{\sqrt{M}}{2\sqrt{M} - 1} = \frac{1}{2 - \frac{1}{\sqrt{M}}}$$

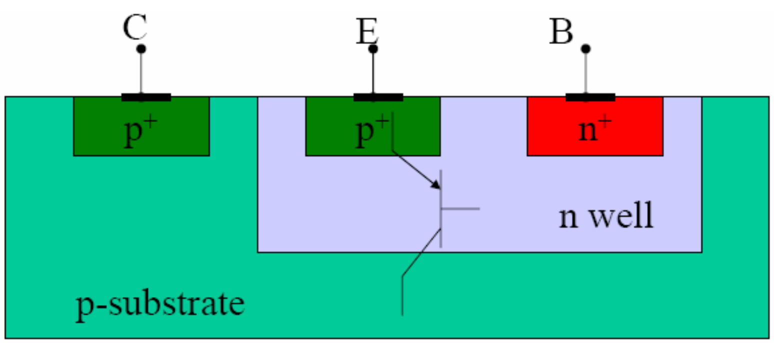
$$M > 1 \quad A_v < 1$$

V_{BE} Referenced Current Reference III





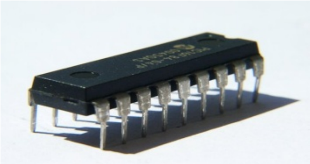




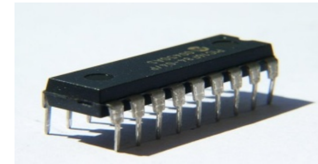
- **Parasitic bipolar devices in CMOS process**
- ***pnp* for p-substrate, *npn* for n-substrate**

The p-substrate, connected to most negative potential (Gnd) acts as a collector whereas n-well and p^+ region act as base & emitter

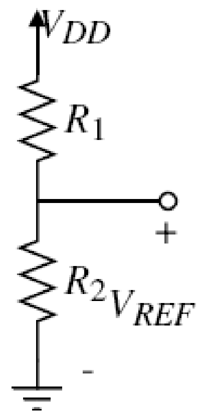
Voltage Reference: Applications & Properties



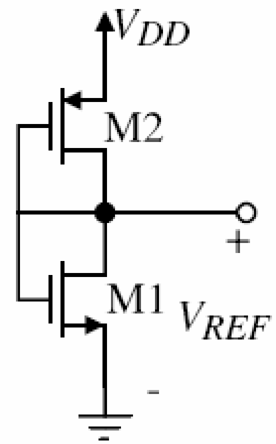
- **Applications:**
  - Error amplifier, comparator, A/D and D/A converters.
- **Properties :**
  - Independent of PVT.
  - Low area.
  - Easy to design / tune.



Some Crude Voltage References



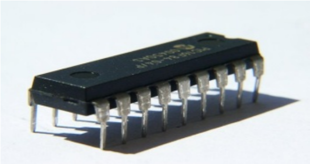
Resistor voltage divider.



Active device voltage divider.

MOSFET – Resistance Voltage reference

Temperature Independent Reference



- **Concept :** ***Generate the reference by combining two voltages of Which one has negative temperature coefficient and the other one has a positive temperature coefficient***

$$V_{REF} = \alpha_1 V_1 + \alpha_2 V_2$$

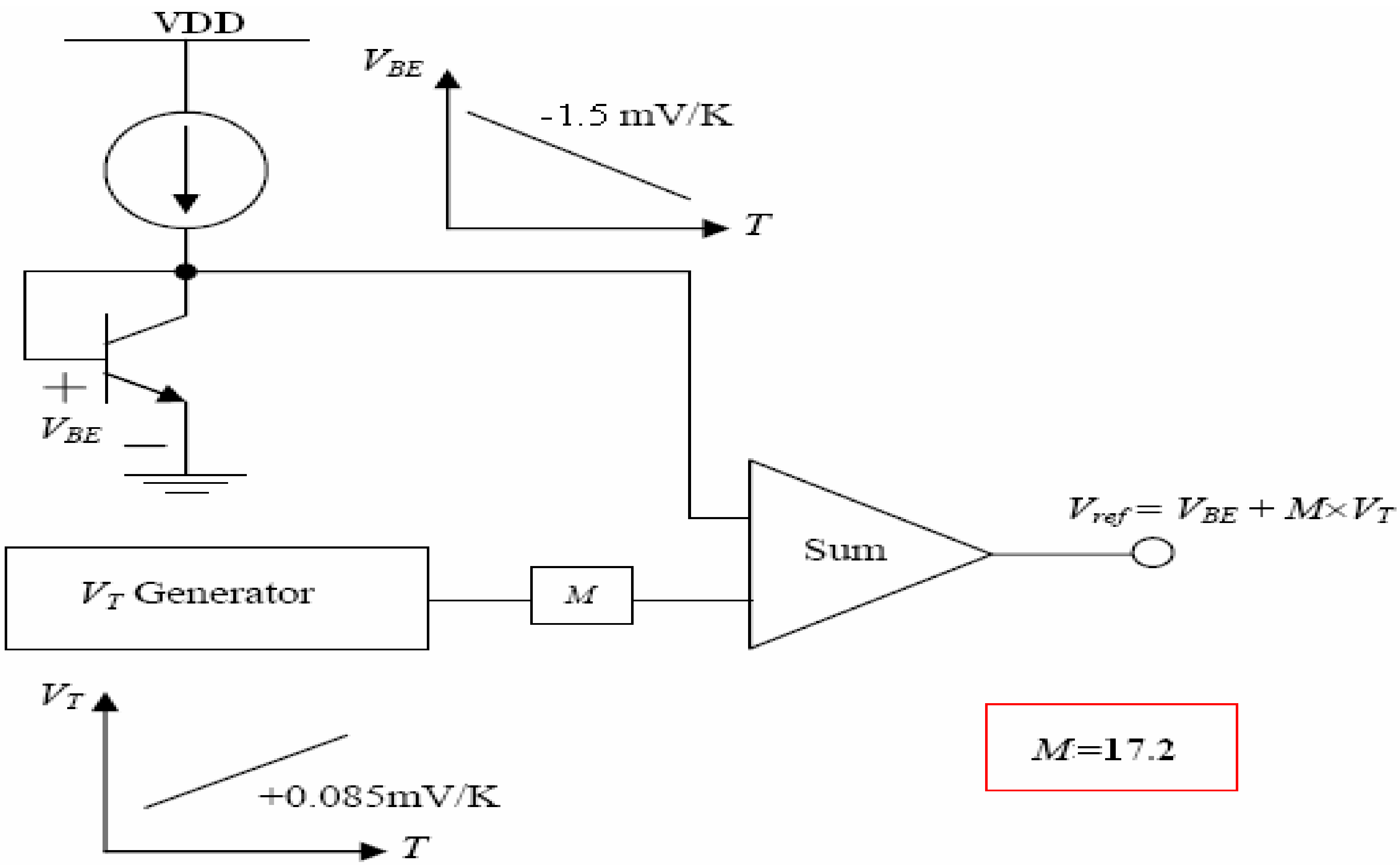
If $\frac{\partial V_1}{\partial T} = -ve$ **and** $\frac{\partial V_2}{\partial T} = +ve$

So that $\alpha_1 \frac{\partial V_1}{\partial T} + \alpha_2 \frac{\partial V_2}{\partial T} = 0$

Candidate :

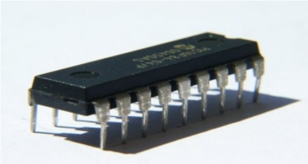
- ***V_{BE} of BJT / Diode or V_{TH} of MOSFET for - ve temp. coefficient***
- ***ΔV_{BE} between two different V_{BE}s or resistors for + ve temp. coefficient***

Band-gap Reference

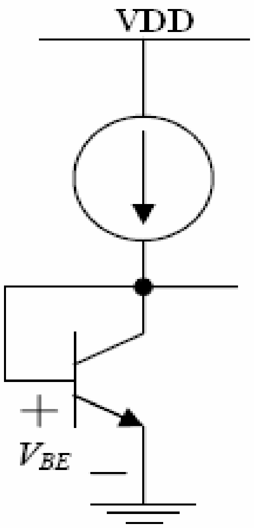


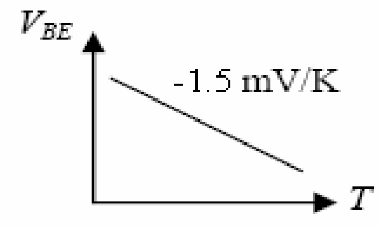
- ❑ **Why it is called Band gap reference ?**

Negative TC Voltage



- $I_C = I_s \exp\left(\frac{V_{BE}}{V_T}\right)$ and $I_S \propto \ T^{(4+M)} \exp\left(\frac{-E_g}{kT}\right)$

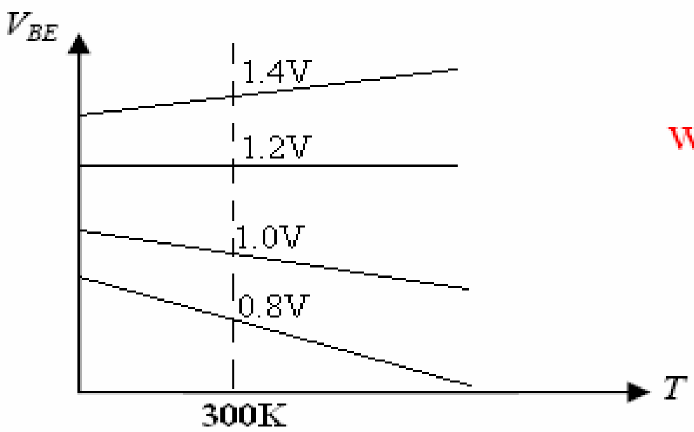




- $V_{BE} = V_T \ln\left(\frac{I_C}{I_s}\right)$
- $\left.\frac{\partial V_{BE}}{\partial T}\right|_{\text{constant } I_C} = \frac{V_{BE} - (4+M)V_T - V_G}{T}, V_G = \frac{E_g}{q}$

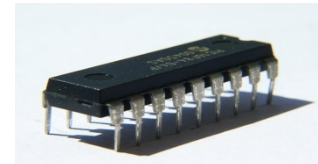
with $V_{BE} \approx 800mV, \frac{\partial V_{BE}}{\partial T} \cong -1.5mV/^{o}K @ T = 300K$

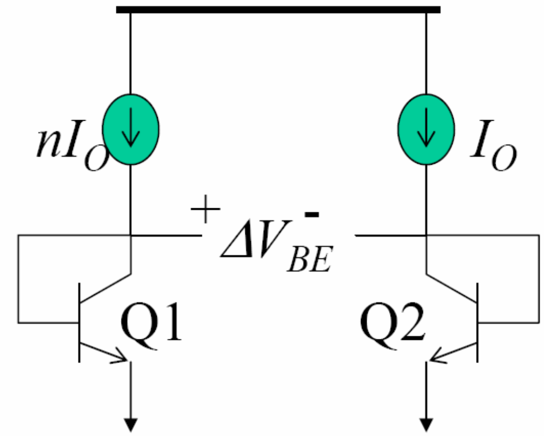
- $\frac{\partial V_{BE}}{\partial T}$ is dependent on V_{BE} . For different V_{BE} Temperature dependancy will be-



When VBE is 1.2V then, TC=0. But, What is the problem?

Positive TC Voltage





$$\Delta V_{BE} = V_{BE1} - V_{BE2}$$

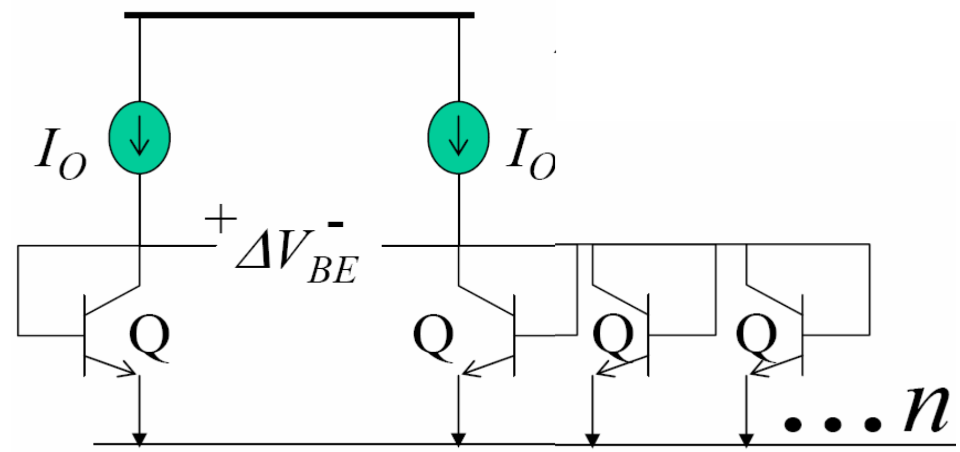
$$= V_T \ln \frac{nI_O}{I_S} - V_T \ln \frac{I_O}{I_S}$$

$$= V_T \ln n = \frac{kT}{q} \ln n$$

$$\frac{\partial \Delta V_{BE}}{\partial T} = \frac{k}{q} \ln n$$

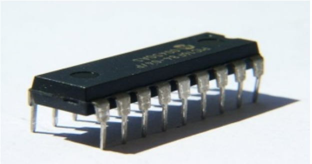
$$= +0.087 \ln n \quad \text{mV/}^{\circ}\text{K}$$

- **So ΔV_{BE} is a PTAT (*Proportional To Absolute Temperature*) source**



- ***Practical implementation by realizing 1 unit transistor for Q1 and n unit transistors in parallel for Q2 and forcing equal current I_0***

Band gap Ref-Implementation



$$V_{REF} = \alpha_1 V_1 + \alpha_2 V_2$$

Choose $V_1 = V_{BE}$ and $V_2 = \Delta V_{BE}$, $\alpha_1 = 1$ *and* $\alpha_2 = 1$

$$V_{REF} = V_{BE} + V_T \ln(n)$$

Since dV_{BE}/dT = -1.5mV/°K , Choose n *such that*

$$0.087 \ln(n) = 1.5 \Rightarrow \ln(n) = 17.2 \Rightarrow n = 30749347$$

$$V_{REF} = V_{BE} + 17.2 V_T$$

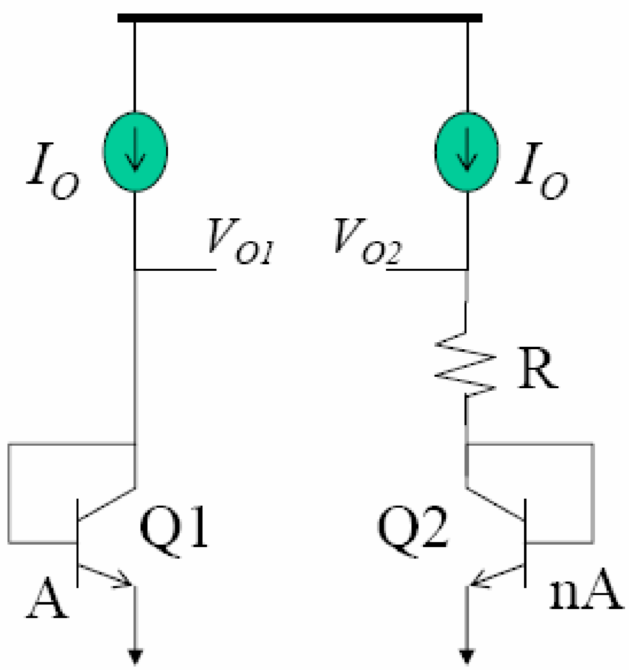
For $V_{BE} = 0.75V$ *and* $T = 300$°K, $V_{REF} = 1.19V$

Note: V_{REF} can also be expressed as

$$V_{REF} \approx \frac{E_g}{q} + (4+m)V_T$$

- **If T $\rightarrow$ 0, $V_{REF} \rightarrow E_g/q$, Therefore BGR**

Band gap Ref-Implementation I



Q1 is unit transistor with area A
Q2 has n unit transistors in parallel
The current in one unit of Q2 is I_O/n

Suppose that V_{O1} and V_{O2} are made equal by some external means

Then,

$$V_{BE1}=RI_O+V_{BE2}$$

$$RI_O = V_{BE1} - V_{BE2} = V_T\ln n$$

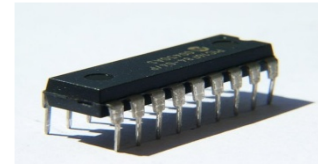
$$V_{O2}=V_{BE2} + V_T\ln n$$

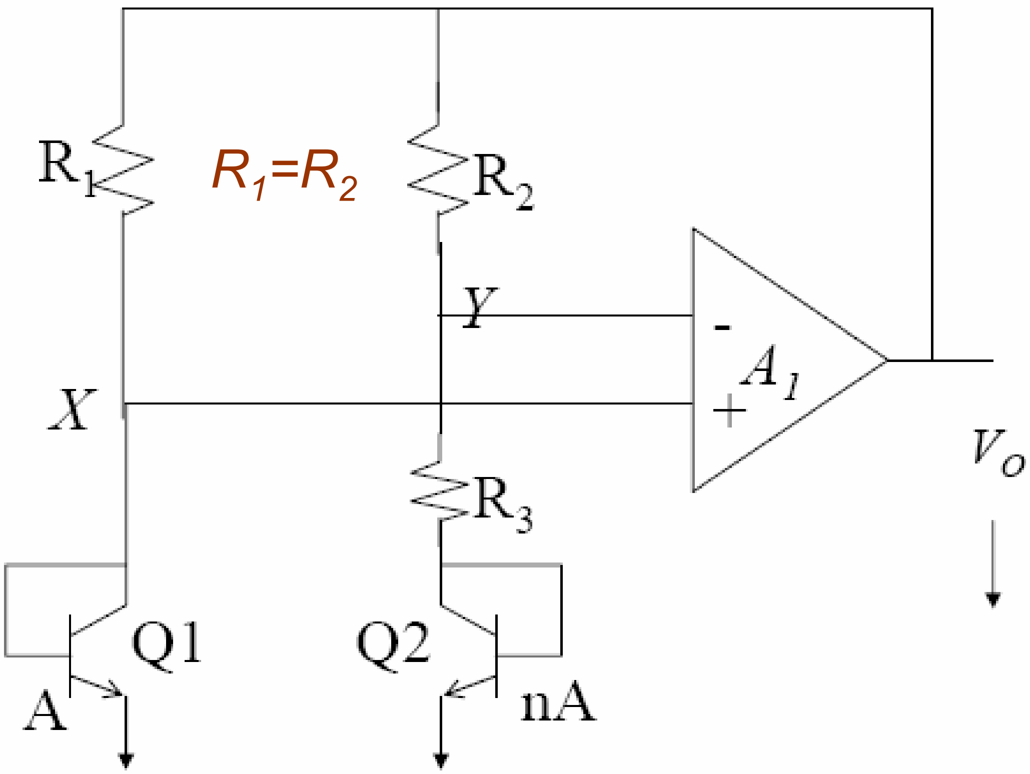
which is the required reference

Need a mechanism for $V_{O1} = V_{O2}$

$\ln n$ =17.2 results in impractical n and hence should some how scaled properly

Band gap Ref-Implementation I





The OPAMP forces $V_X = V_Y$

$$V_{BE1} - V_{BE2} = V_T \ln n$$

This results in a current through the right branch

$$I_{R3} = V_T \ln n / R_3$$

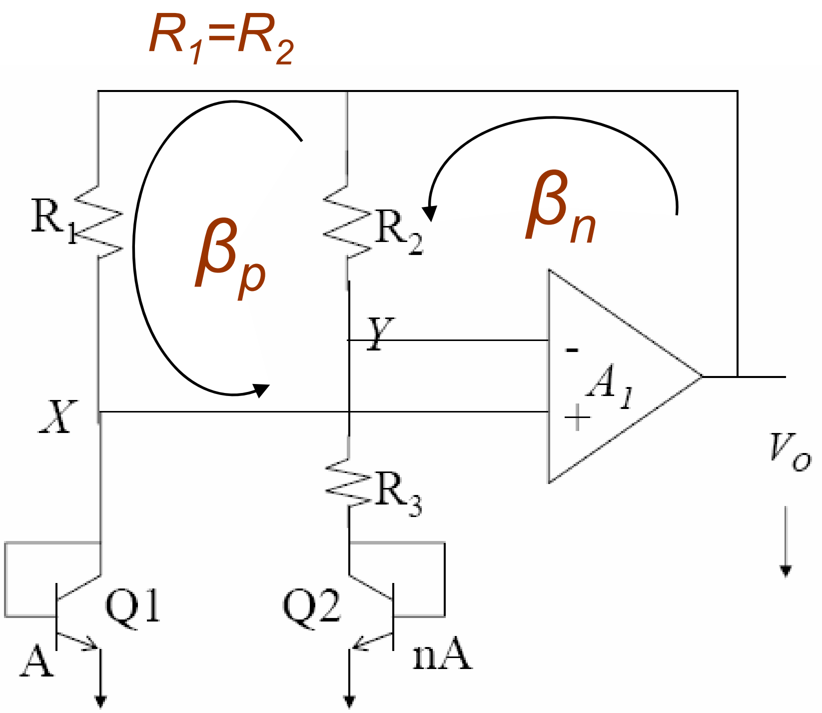
$$Vo = V_{BE2} + \frac{V_T \ln n}{R_3}(R_2 + R_3)$$

$$Vo = V_{REF} = V_{BE2} + V_T \ln n\left(1 + \frac{R_2}{R_3}\right)$$

If R2/R3 = 10, then n=5

- **The Op-amp output V_0 is the desired reference voltage**

Different feed backs



$$\beta_n = \frac{R_3 + 1/g_{m2}}{R_2 + R_3 + 1/g_{m2}} \qquad \beta_p = \frac{1/g_{m1}}{R_1 + 1/g_{m1}}$$

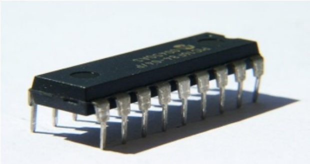
$$g_{m1} = g_{m2} = \frac{I_C}{V_T} = \frac{\ln(N)}{R}$$

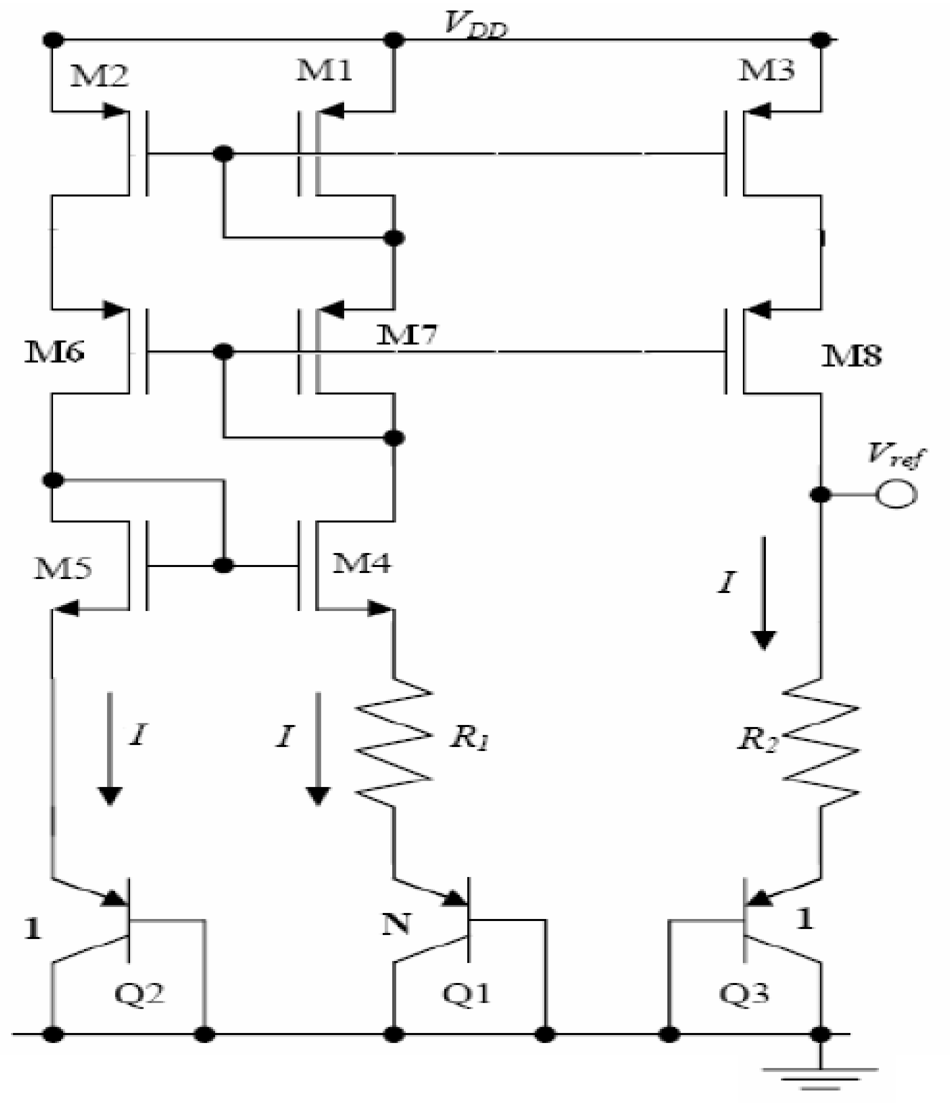
$$\beta_n = \frac{1 + R_3 * g_{m2}}{(R_1 + R_3)g_{m2} + 1} = \frac{1 + \ln(N)}{18.2}$$

$$\beta_p = \frac{1}{1 + R_1 * g_{m1}} = \frac{1}{18.2 - \ln(N)}$$

- **For stable operation β_n must be greater than β_p ; negative feedback should dominate positive feedback**

Band gap ref: Implementation II





$$I = \frac{V_T \ln(N)}{R_1}$$ **PTAT Current**

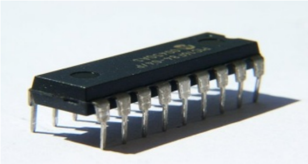
$$V_{REF} = V_{BE3} + V_T \ln(N) * \frac{R_2}{R_1}$$

- **For temp. independence**

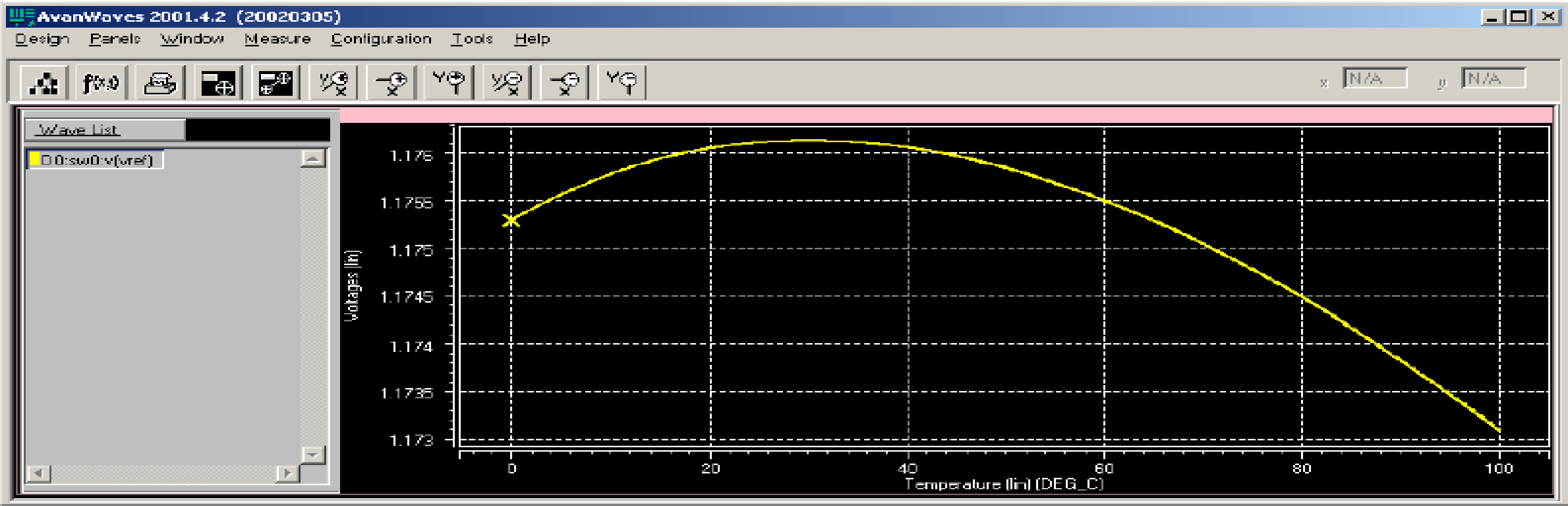
$$\frac{R_2}{R_1} * \ln(N) = 17.2$$

- **Design Steps:**
  - Choose N=8.
  - Fix R1 based on current budget.
  - Calculate R2.
  - Size all transistors.
  - Simulate and tune R1 and R2 ratio slightly to get temp compensated Vref.

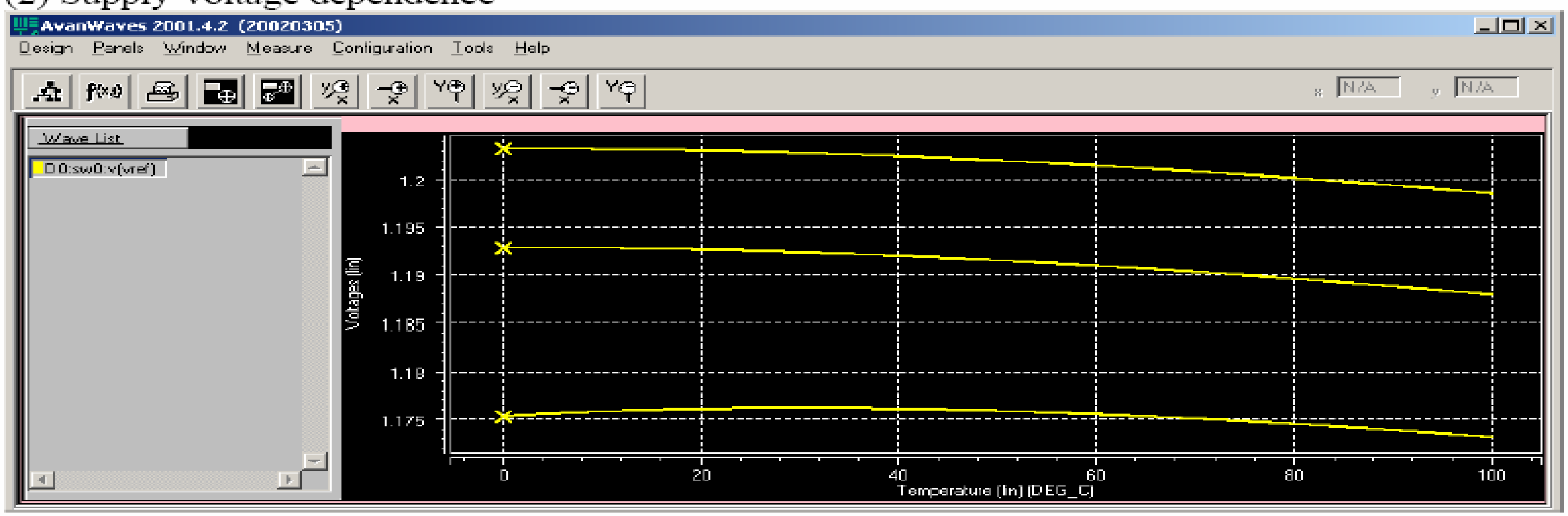
Band gap reference: Results



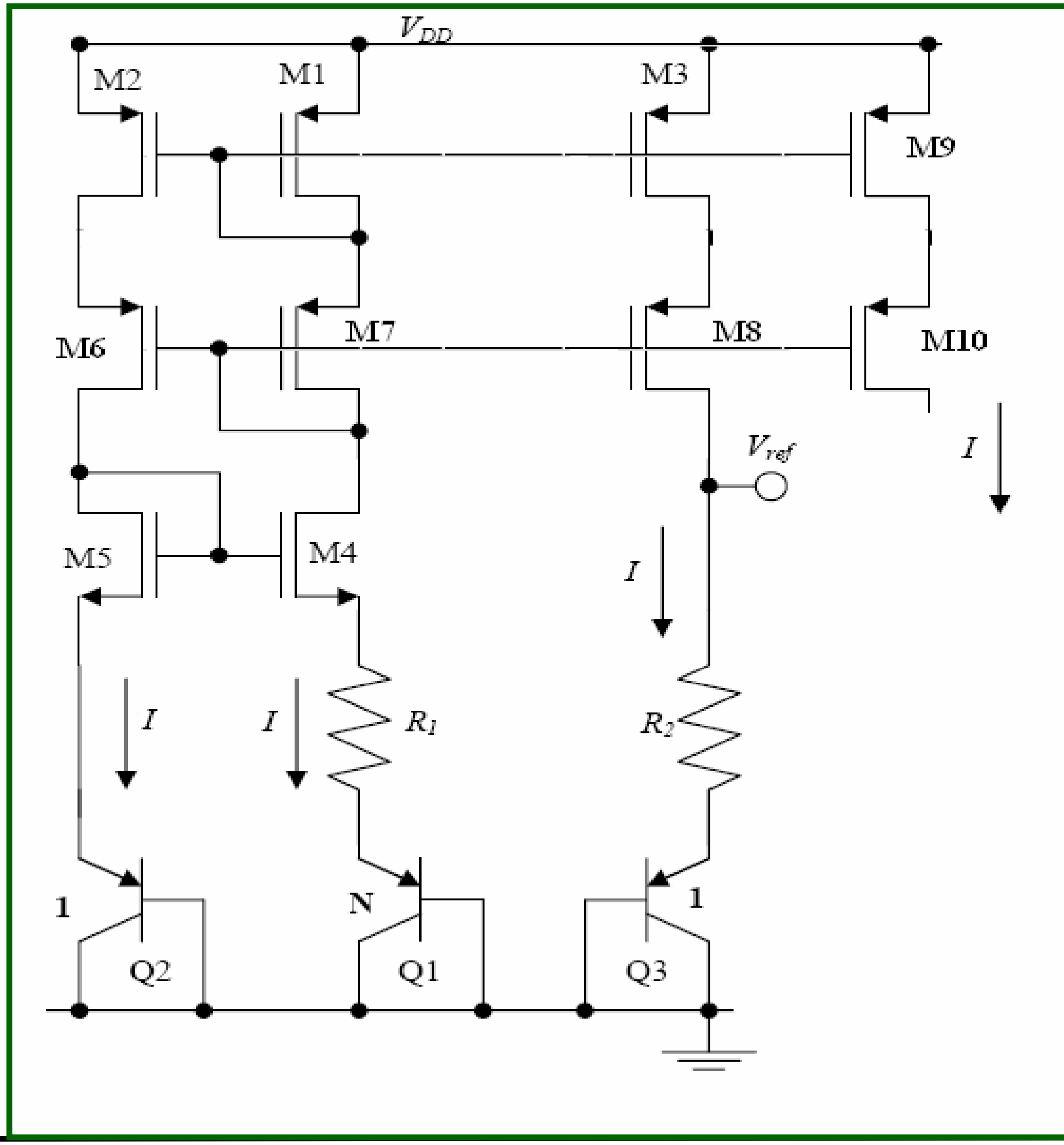
(1) Tempco at $V_{DD} = 3.3\text{V}$



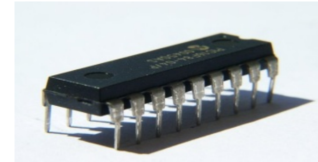
(2) Supply-voltage dependence

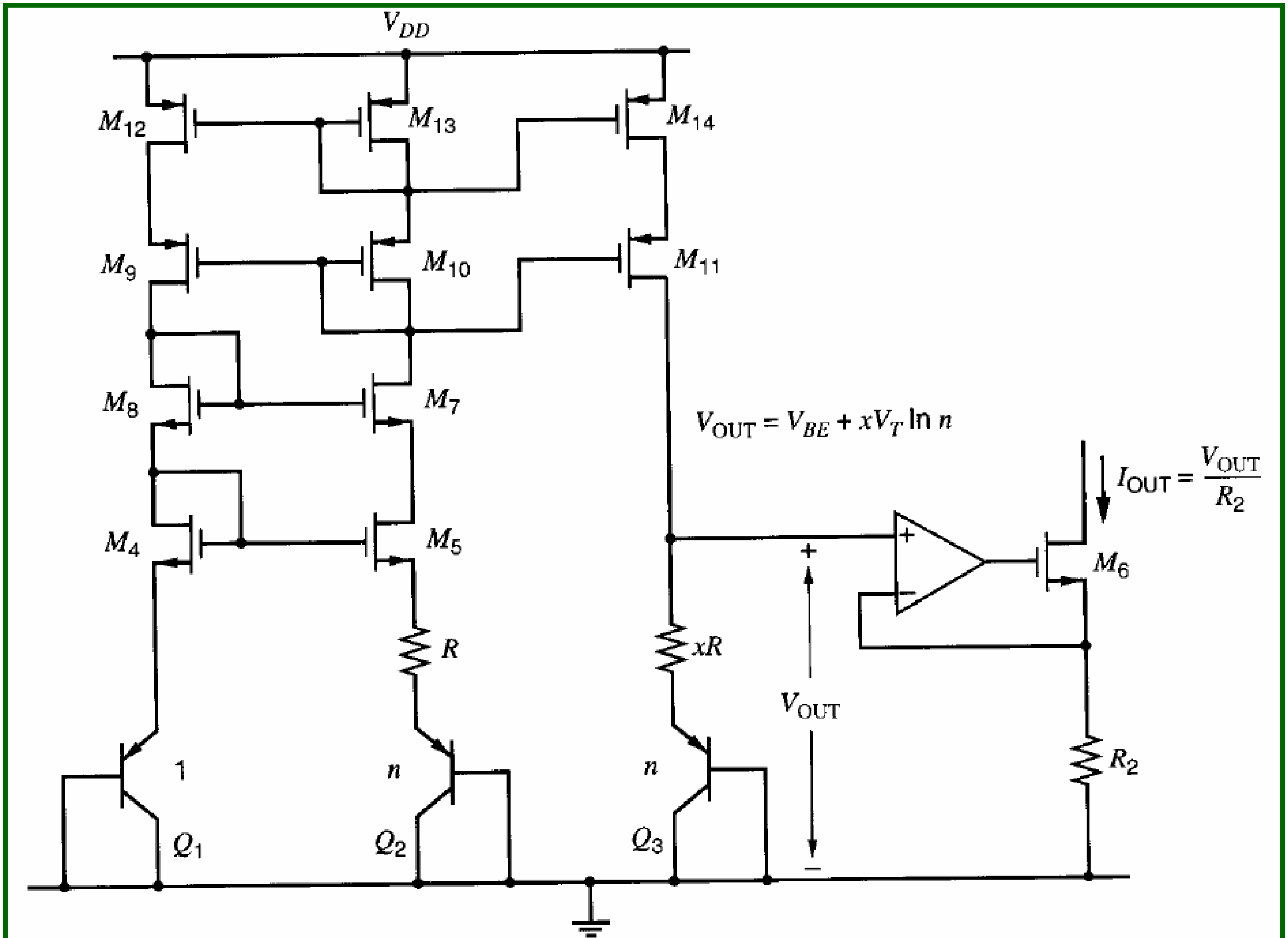


PTAT Current Reference from Band gap voltage reference

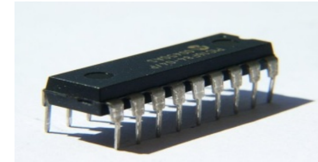


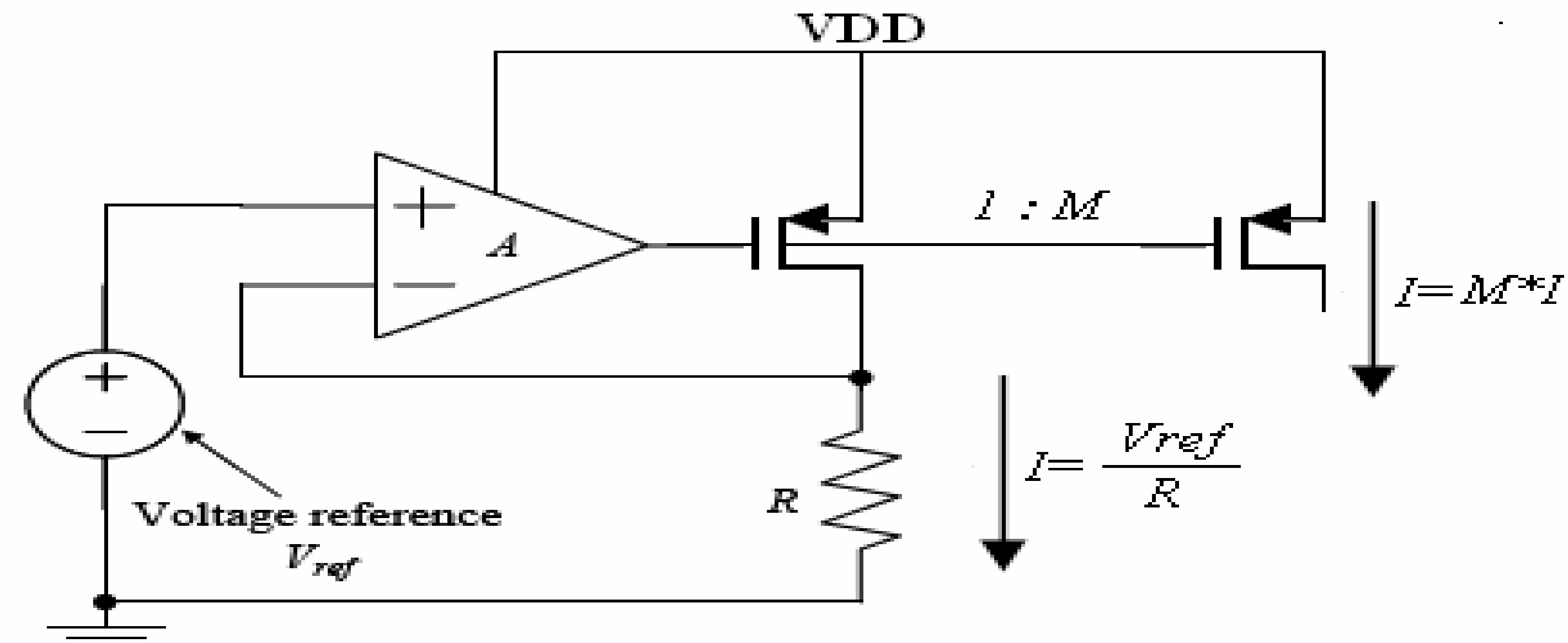
Temperature Independent Current Reference





Current reference generated from voltage reference





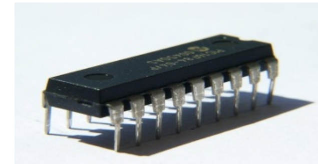
Resistor can be modeled

$$R(T) = R(T_r)\cdot\left[1 + k_1(T - T_r) + k_2(T - T_r)^2\right] \approx R(T_r)\cdot\left[1 + k_1(T - T_r)\right]$$

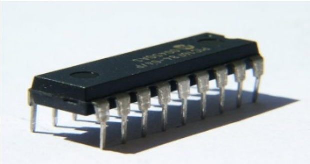
Material	n-well	poly	p-diffusion	n-diffusion	high-R poly
k_1	$6.60 \times 10^{-3}K^{-1}$	$0.75 \times 10^{-3}K^{-1}$	$1.80 \times 10^{-3}K^{-1}$	$1.65 \times 10^{-3}K^{-1}$	$-1.05 \times 10^{-3}K^{-1}$

Lesser Temp co.

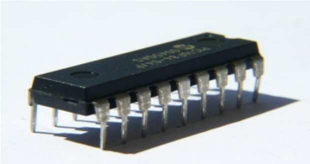
LAB Assignments



- Design a 100uA current reference (Current Reference II).
- Design a band-gap reference which consumes 100uA current. Get a temperature compensated voltage at $27^{o}C$ (Band gap Implementation- II).



Q & A



Thank U!