4. References

Voltage or Current References

Circuit that yields a precise DC voltage or current independent of external influences is called a voltage reference or a current reference.

The primary external influences are:

- Power supply variations
- Temperature variations

Sensitivity and Fractional Temp. Coefficient

Used to characterize the dependence of a reference on power supply and temperature.

A. The Sensitivity of V_{ref} to changes in power supply V_{DD} is given by,

$$S^{V_{ref}}_{V_{DD}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial V_{DD}} \quad \text{——— (1)}$$

$$\text{Or,} \quad \frac{\partial V_{ref}}{V_{ref}} = S^{V_{ref}}_{V_{DD}} \cdot \frac{\partial V_{DD}}{V_{DD}} \quad \text{——— (2)}$$

Sensitivity

Sensitivity may vary from 0.0 to 1.0.

Sensitivities less than 0.01 are practical values for a monolithic voltage reference.

The above formulation is valid for current references by simply replacing V_{ref} by I_{ref}.

Fractional Temp. Coefficient

B. The Sensitivity of V_{ref} to changes in temperature T is given by, $S_T^{V_{ref}}$.

$$S^{V_{ref}}_{T} = \frac{T}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial T}$$

Got just by replacing V_{DD} by T in eqn (1)

$$\text{Or,} \quad \frac{\partial V_{ref}}{V_{ref}} = S^{V_{ref}}_{T} \cdot \frac{\partial T}{T}$$

Fractional Temp. Coefficient

<u>Fractional Temp. Coefficient</u>, $TC_F(V_{ref})$:

This is another popular concept used to measure the degree of temperature dependence of reference.

$$TC_F(V_{ref}) = 1/V_{ref}\,(\partial V_{ref}/\partial T) = 1/T\,(S_T^{V_{ref}})$$

Units of TC_F - parts per million/°C or ppm/°C.

Example:

Sensitivity, $S_T^{V_{ref}} = 0.01$ at room temperature,

$\Rightarrow TC_F(V_{ref}) = 1/T\,(S_T^{V_{ref}})$

$= (1/300) \times 0.01 \times 1{,}000{,}000$

$= \underline{33.3\ \text{ppm}/°C}$

References with TC_F of less than 50ppm/°C are considered to be stable w.r.t. temperature.

Simple Voltage References

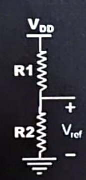
In CMOS IC design, we can derive reference voltages from the power supplies using resistors and MOSFETs.

1. Resistor – Only Voltage Reference
2. Resistor – MOSFET Voltage Reference
3. MOSFET – Only Voltage Reference

1. Resistor – Only Voltage Reference

This voltage divider, formed with 2 resistors, provide a DC voltage between V_{DD} and ground depending on values of R_1 and R_2.

Here, $V_{ref} = \dfrac{R_2}{(R_1+R_2)} V_{DD}$



Advantages:

- Simple
- Temperature Insensitive
- Process Insensitive – changes in the sheet resistance have no effect on the voltage division.

Disadvantages:

- To reduce the power dissipation, the resistors must be made large. But large resistors require a large die area.
- The sensitivity of V_{ref} w.r.t. V_{DD} is found to be,

$$S_{V_{DD}}^{V_{ref}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial V_{DD}} = 1$$

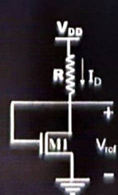
2. Resistor – MOSFET Voltage Reference

Since gate and drain terminals are shorted, M_1 always remains in saturation.

Here, $V_{DS} = V_{GS} = V_{ref}$

$I_D = (V_{DD} - V_{ref})/R = ½\beta_1 (V_{GS} - V_{tn})^2$

Or, $V_{ref} = V_{tn} + \sqrt{\dfrac{2I_D}{\beta_1}} = V_{tn} + \sqrt{\dfrac{2(V_{DD}-V_{ref})}{R\beta_1}}$



$$S_{V_{DD}}^{V_{ref}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial V_{DD}} = \frac{1}{V_{tn} \cdot \sqrt{\dfrac{2R\beta_1}{V_{DD}}} + 2}$$

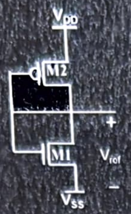
$$TC_F(V_{ref}) = \frac{1}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial T}$$

$$TC_F(V_{ref}) = \frac{1}{V_{ref}} \left[\underbrace{\frac{\partial V_{tn}}{\partial T}}_{V_{tn} \cdot TCV_{tn}} - ½\sqrt{\frac{2V_{DD}}{R\beta_1}} \left(\frac{1}{R}\frac{\partial R}{\partial T} - \frac{1.5}{T} \right) \right]$$

3. MOSFET – Only Voltage Reference

This generates a reference voltage equal to the voltage on the gates of the MOSFETs w.r.t. ground.

$$\tfrac{1}{2}\beta_1(V_{ref}-V_{SS}-V_{tn})^2 = \tfrac{1}{2}\beta_2(V_{DD}-V_{ref}-V_{tp})^2$$



Or the reference voltage is given by,

$$V_{ref} = \frac{V_{DD} - V_{tp} + \sqrt{\frac{\beta_1}{\beta_2}}\,(V_{SS} + V_{tn})}{\sqrt{\frac{\beta_1}{\beta_2}} + 1}$$

$$\frac{\beta_1}{\beta_2} = \left[\frac{(V_{DD}-V_{ref}-V_{tp})}{(V_{ref}-V_{SS}-V_{tn})}\right]^2$$

Sensitivity of V_{ref} w.r.t. V_{DD} is given by,

$$S_{V_{DD}}^{V_{ref}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial V_{DD}} = \frac{V_{DD}}{V_{DD} - V_{tp} + \sqrt{\frac{\beta_1}{\beta_2}}\,(V_{SS}+V_{tn})}$$

Assuming the temperature dependence of the ratio of the transconductance parameters, β_1/β_2, is negligible, the $TC_F(V_{ref})$ is given by,

$$TC_F(V_{ref}) = \frac{1}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial T}$$

$$TC_F(V_{ref}) = \frac{1}{V_{ref}} \frac{1}{\sqrt{\frac{\beta_1}{\beta_2}} + 1}\left[\frac{\partial(-V_{tp})}{\partial T} + \sqrt{\frac{\beta_1}{\beta_2}}\,\frac{\partial V_{tn}}{\partial T}\right]$$

To achieve $TC_F(V_{ref}) = 0$ requires,

$$TC_F(V_{ref}) = \frac{1}{V_{ref}} \frac{1}{\sqrt{\frac{\beta_1}{\beta_2}} + 1}\left[\frac{\partial(-V_{tp})}{\partial T} + \sqrt{\frac{\beta_1}{\beta_2}}\,\frac{\partial V_{tn}}{\partial T}\right] = 0$$

i.e., $\frac{\partial(-V_{tp})}{\partial T} = -\sqrt{\frac{\beta_1}{\beta_2}}\,\frac{\partial V_{tn}}{\partial T} \Rightarrow 2.7\text{mV}/°\text{C} = \sqrt{\frac{\beta_1}{\beta_2}}\,(2.4\text{mV}/°\text{C})$

i.e., $\beta_1/\beta_2 = 1.125$

Zero temperature coefficient, to a first order can be met by satisfying this equation. However, this ratio is most often set by the desired V_{ref}. So for a particular single value of V_{ref}, the reference becomes temperature insensitive.

Design Example:

Design a 3V MOSFET-Only voltage reference. Determine the temperature coeff. of the reference. Data given: V_{DD}=+5V, V_{SS}=0V, V_{tn}=0.8V, V_{tp}=0.9V, L_1=L_2=5μm, K_n=50μA/V², K_p=17μA/V².

$$\frac{\beta_1}{\beta_2} = \left[\frac{(5-3-0.9)}{(3-0-0.8)}\right]^2 = 0.25$$

Setting $L_1 = L_2 = W_1 = 5\mu m$,

$$\frac{\beta_1}{\beta_2} = \frac{K_n W_1 L_2}{K_p W_2 L_1} = \frac{50\mu A/V^2\ 5\mu m\ 5\mu m}{17\mu A/V^2\ W_2\ 5\mu m} = 0.25$$

Solving gives, $W_2 = 60\mu m$.

The temp. coeff. is given by,

$$TC_F(V_{ref}) = \frac{1}{V_{ref}} \frac{1}{\sqrt{\frac{\beta_1}{\beta_2}} + 1}\left[\frac{\partial(-V_{tp})}{\partial T} + \sqrt{\frac{\beta_1}{\beta_1}}\,\frac{\partial V_{tn}}{\partial T}\right]$$

But, $\frac{\partial V_{tn}}{\partial T} = V_{tn} \cdot TCV_{tn} = (0.8\text{V})(-0.003/°\text{C}) = -2.4\text{mV}/°\text{C}$

$-\frac{\partial V_{tp}}{\partial T} = -V_{tp} \cdot TCV_{tp} = -(0.9\text{V})(-0.003/°\text{C}) = 2.7\text{mV}/°\text{C}$

$$TC_F(V_{ref}) = \frac{1}{3} \frac{1}{\sqrt{\frac{50\times5}{17\times60}} + 1}\left[0.0027 + \sqrt{\frac{50\times5}{17\times60}}\,(-0.0024)\right]$$

$$= 337\text{ppm}/°\text{C}$$

Current Source Self-Biasing Circuits

The drawback of the 3 references discussed so far are that, they are very sensitive to power supply and temperature.

Here, we discuss 3 methods of biasing which reduce the effects of power supply variations and possibly temp.

1. Threshold Voltage Referenced Self-Biasing
2. Diode Referenced Self-Biasing
3. Thermal Voltage Referenced Self-Biasing

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1. Threshold Voltage Referenced Self-Biasing

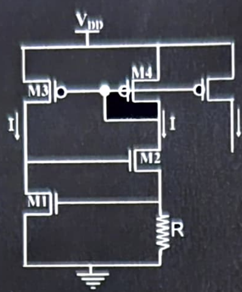
MOSFETs M3 & M4 force the same current to flow through M1 & M2.

$IR = V_{GS1} = V_{TN} + \sqrt{\frac{2I}{\beta_1}}$

If β_1 is very large, then, I is given by,

$\boxed{I \approx V_{TN}/R}$

i.e., current is independent of the power supply voltage (neglecting channel length modulation and body effect).



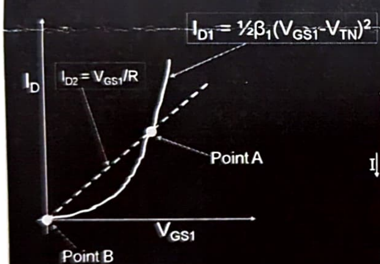
$I = ½\beta_1(V_{GS1}-V_{TN})^2$

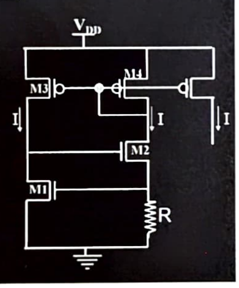
Or, $V_{GS1} = V_{TN} + \sqrt{\frac{2I}{\beta_1}}$

Note:

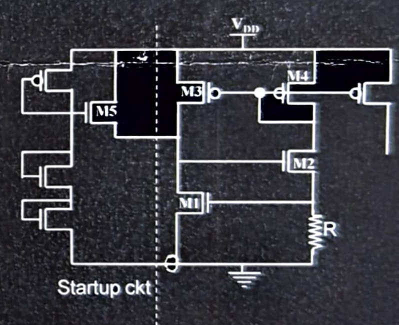
- Here we assumed the output resistance of the MOSFET were infinite. But by cascoding M3 and M4 helps to make the bias circuit behave more ideal.
- The accuracy of I is limited by the threshold voltage accuracy, which may vary by 20%, and the n+ resistivity, which may vary by 20% as well.
- $TC_F(I)$ depends on $TC_F(V_{TN})$ and $TC_F(R)$.
  But $TC_F(V_{TN})$ = -3000 ppm/°C and $TC_F(R)$ = +2000ppm/°C.
  So, the reference current, I has a large negative temperature coefficient.

Startup Circuit



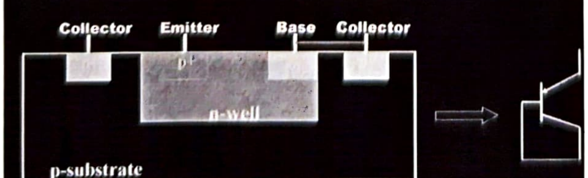


Startup Circuit



2. Diode Referenced Self-Biasing

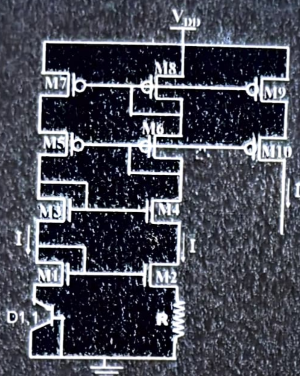
The parasitic PNP transistor, available in the n-well process, in conjunction with the CMOS transistors, is used to generate the reference current or voltage.



A Base-Collector connected transistor is equivalent to a Diode.

The no. '1' indicates the minimum sized emitter.
The current through a forward-biased Diode is given by,

$I_d = I_s\, e^{V_d/nV_T}$, Where V_T is the thermal voltage = kT/q
I_s is the saturation current



Diode Referenced Self-Biasing Circuit

Here the cascode mirrors made with M1 through M8 force the same current, I, to flow through D1 and R

$$\boxed{I = V_d/R = I_s \cdot e^{V_d/\eta V_T}}$$

Or, $V_d = \eta V_T \ln(I/I_s)$

Solving for the resistor gives,

$$R = \frac{\eta V_T}{I} \ln(I/I_s)$$

The main benefit of this circuit over the threshold referenced self-biasing circuit is the better matching, from wafer to wafer and on the same die, of the diode voltage over the threshold voltage.

Sensitivity and $TC_F(I_{ref})$:

$$I_{ref} = V_d/R$$

This shows that the reference is insensitive to power supply variations.

$$TC_F(I_{ref}) = \frac{1}{I_{ref}}\frac{\partial I_{ref}}{\partial T} = \frac{1}{I_{ref}}\frac{\partial}{\partial T}\left(\frac{V_d}{R}\right)$$

$$= \frac{1}{I_{ref}}\frac{\left[R\frac{\partial V_d}{\partial T} - V_d\frac{\partial R}{\partial T}\right]}{R^2}$$

$$TC_F(I_{ref}) = \frac{1}{V_d}\frac{\partial V_d}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T} = TC_F(V_d) - TC_F(R)$$

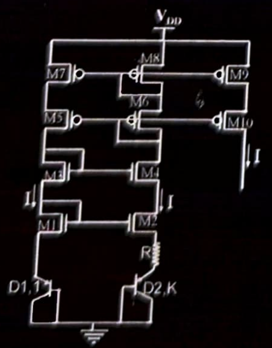
$$TC_F(I_{ref}) = TC_F(V_d) - TC_F(R)$$

Drawback: Temperature dependence.

The temp. coeff. of the diode ≈ - 3,300ppm/°C and R has +2000ppm/°C. This causes the biasing circuit to have a large negative temperature coefficient.

Therefore, this reference is also called as CTAT (Complimentary To Absolute Temperature).

3. Thermal Voltage Referenced Self-Biasing



M1 through M8 forces the same current through D1 and D2.

$$V_{d1} = IR + V_{d2} \longrightarrow (1)$$

$$I_{d1} = I_s \cdot e^{V_{d1}/\eta V_T} \longrightarrow V_{d1} = \eta V_T \ln\frac{I}{I_s}$$

$$I_{d2} = K\, I_s \cdot e^{V_{d2}/\eta V_T} \longrightarrow V_{d2} = \eta V_T \ln\frac{I}{K\, I_s}$$

From eqn. (1), solving for the resistor, R, gives,

$$R = (V_{d1} - V_{d2})/I = \frac{\eta V_T}{I}\ln(K)$$

Or, $\boxed{I = \frac{\eta V_T \ln(K)}{R}} = \frac{\eta k}{qR}\ln(K).T$ | $V_T = kT/q$

Or, $I = \frac{\eta V_T \ln(K)}{R} = \frac{\eta k \ln(K).T}{qR}$

Here, the current is proportional to the absolute temperature (PTAT).

$$TC_F(I_{ref}) = \frac{1}{I_{ref}} \frac{\partial I_{ref}}{\partial T} = \frac{1}{I_{ref}} \frac{\partial}{\partial T}\left(\frac{\eta V_T \ln(K)}{R}\right)$$

$$TC_F(I_{ref}) = \frac{1}{V_T}\frac{\partial V_T}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T} = TC_F(V_T) - TC_F(R)$$

$$TC_F(I_{ref}) = TC_F(V_T) - TC_F(R)$$

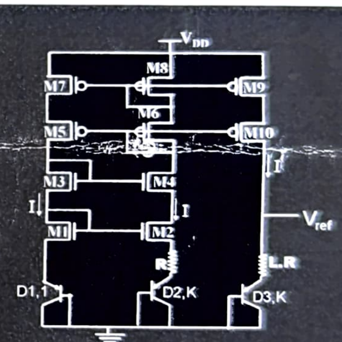
Advantages:
Since both V_T and R exhibit positive temperature coeff., it gives better temperature characteristics than the diode or threshold voltage references.

$TC_F(V_T) \approx +3{,}300$ ppm/°C, and $TC_F(R) = +2000$ ppm/°C
Hence, $TC_F(I_{ref}) \approx 1{,}300$ ppm/°C

Drawbacks:
Mismatches in the gate-source voltages of M1 and M2 can result in large variations in I_{ref}.

Bandgap Voltage References

Bandgap voltage references combine the ***positive TC*** of the thermal voltage with the ***negative TC*** of the diode forward voltage in a circuit to achieve a voltage reference with a ***zero TC***.



Bandgap Voltage Reference

Diode D3 is the same size as D2, while the resistor in series with D3 is L times larger than the resistor in series with D2.

The current I in the figure is given by,

$$I = \frac{\eta V_T \ln(K)}{R}$$

The reference output voltage w.r.t. ground is given by,

$$V_{ref} = I.\ L.R + V_{d3}$$

Or, $V_{ref} = (L.\eta \ln K)\ V_T + V_{d3} = (L.\eta \ln K)\ V_T + \eta V_T \ln \frac{I}{K I_s}$

The TC of the bandgap reference is zero when,

$$\frac{\partial V_{ref}}{\partial T} = L.\eta \ln K \frac{\partial V_T}{\partial T} + \frac{\partial V_{d3}}{\partial T} = 0$$

$$\frac{\partial V_{ref}}{\partial T} = L.\eta \ln K \underbrace{\frac{\partial V_T}{\partial T}}_{0.085\,mV/°C} + \underbrace{\frac{\partial V_{d3}}{\partial T}}_{-2\,mV/°C} = 0$$

This is true when,

$L.\eta \ln K = 2/0.085 = 23.5$

For η=1 and K=8 the factor L = 11.3 ≈ 12 for a zero TC.

The value of V_{ref} [for η=1, K=8, L=12, V_T=26mV, I=10µA, I_s=10^{-15}A, T=300°K] will be,

$$V_{ref} = (L.\eta \ln K)\ V_T + \eta V_T \ln \frac{I}{K I_s} = 1.25V$$

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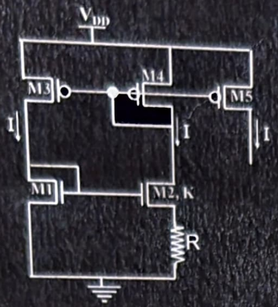
Beta Multiplier Referenced Self-Biasing



Width of M2 is made 'K' times larger than width of M1, so that,

$\beta_2 = K\,\beta_1$ assuming $L_1 = L_2$ and $W_2 = K\,W_1$

and therefore,

$$V_{GS1} = V_{GS2} + IR \qquad (1)$$

But,

$$V_{GS1} = V_{TN} + \sqrt{\frac{2I}{\beta_1}}$$

Neglecting body effect,

$$V_{GS2} = V_{TN} + \sqrt{\frac{2I}{K\,\beta_1}}$$

$$I = \tfrac{1}{2}\beta(V_{GS}-V_{TN})^2$$

$$\text{Or, } V_{GS} = V_{TN} + \sqrt{\frac{2I}{\beta}}$$

Solving for I,

$$\boxed{I = \frac{2}{R^2\beta_1}\left[1-\sqrt{\frac{1}{K}}\right]^2} \longrightarrow (2)$$

This is the basic design equation for this reference. K is always greater than 1.

Temperature coeff. of the current reference is,

$$TC_F(I_{ref}) = \frac{1}{I}\frac{\partial I}{\partial T} = -2\frac{1}{R}\frac{\partial R}{\partial T} - \frac{1}{\beta_1}\frac{\partial \beta_1}{\partial T}$$

$$= -4000\text{ppm/°C} + \frac{1.5}{T}$$

Biasing β multiplier reference