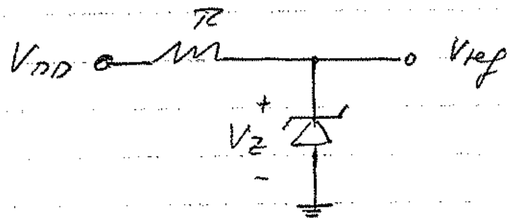
VI Voltage References

Solution 1 Making use of a Zener diode that breaks down at a specific (reverse) junction voltage

Basic Configuration

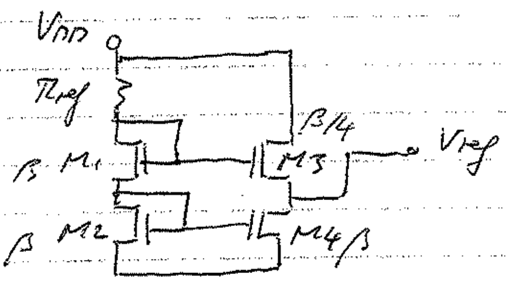


$V_{ref} < V_{DD}$

$$\| V_{ref} = V_Z \|$$

Solution 2 Making use of the Threshold voltage of an MOS device

Basic Configuration



$$V_{ref} = V_{t_1} + V_{eff_1} + V_{t_2} + V_{eff_2} - V_{t_3} - V_{eff_3}$$

If the width of M_3 is about 4 times smaller than the width of the other 3 devices

$$\| V_{ref} \cong V_{t_1} + V_{t_2} - V_{t_3} \cong V_{t_2} \|$$

Note: The above relationship holds independent of the supply voltage V_{DD}.

Problem: V_t does vary with temperature.

Temperature Dependence of n_i and Φ_F

$$n_i = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} e^{-\frac{E_c - E_{Fi}}{kT}}$$

m_n^* Effective mass of el

$$p_{io} = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} e^{-\frac{E_{Fi} - E_v}{kT}}$$

m_p^* effective mass of hole

Since $n_i = p_i$ (intrinsic semiconductor)

$$n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} \left(m_n^* m_p^*\right)^{3/4} e^{-\frac{E_c - E_v}{2kT}}$$

$$n_i(T) = n_0 \left(\frac{T}{T_0}\right)^{3/2} e^{-\frac{E_c - E_v}{2kT}}$$

$$\frac{\partial n_i}{\partial T} = n_0 \left(\frac{T}{T_0}\right)^{3/2} e^{-\frac{E_c - E_v}{2kT}} \left[\frac{3}{2}\frac{1}{T} + \frac{E_c - E_v}{2kT^2}\right]$$

$$\therefore \frac{\partial n_i}{\partial T} = n_i \left[\frac{3}{2}\frac{1}{T} + \frac{E_G}{2kT^2}\right] \qquad E_G = E_c - E_v$$

$$\Phi_F = \frac{kT}{q} \ln\left(\frac{N_{sub}}{n_i}\right)$$

$$\frac{\partial \Phi_F}{\partial T} = \frac{k}{q} \ln\left(\frac{N_{sub}}{n_i}\right) - \frac{kT}{q} \frac{\cancel{n_i}}{\cancel{N_{sub}}} \frac{\cancel{N_{sub}}}{n_i^{\cancel{2}}} \frac{\partial n_i}{\partial T}$$

$$\therefore \frac{\partial \Phi_F}{\partial T} = \frac{V_T}{T}\left[\ln\left(\frac{N_{sub}}{n_i}\right) - \frac{3}{2} - \frac{E_G}{2kT}\right] \qquad V_T = \frac{kT}{q}$$

@ $T = 300°K$ and $N_{sub} \approx 10^7 n_i$: $\quad \frac{\partial \Phi_F}{\partial T} \approx -0.5\, mV/°K$

Temperature Dependence of V_d and V_t

$$\boxed{V_d \cong V_T \ln\left(\frac{I_d}{I_s}\right)}$$

$$\boxed{I_S \cong I_{S0}\left(\frac{T}{T_0}\right)^{7/2} e^{-\frac{E_G}{kT}}}$$

$$\therefore \boxed{\frac{\partial I_S}{\partial T} = I_{S0}\left(\frac{T}{T_0}\right)^{7/2} e^{-\frac{E_G}{kT}}\left[\frac{7}{2}\frac{1}{T} + \frac{E_G}{kT^2}\right] = I_S\left[\frac{7}{2}\frac{1}{T} + \frac{E_G}{kT^2}\right]}$$

$$\frac{\partial V_d}{\partial T} = \frac{V_T}{T}\ln\left(\frac{I_d}{I_s}\right) + V_T\frac{I_s}{I_d}\left[\frac{\partial I_d}{I_s\partial T} - \frac{I_d}{I_s^2}\frac{\partial I_s}{\partial T}\right]$$

$$\therefore \frac{\partial V_d}{\partial T} = \frac{V_d}{T} + V_T\left[\frac{\partial I_d}{I_d\partial T} - \frac{\partial I_s}{I_s\partial T}\right]$$

$$\boxed{\frac{\partial V_d}{\partial T} = \frac{V_d}{T} + \frac{V_T}{T}\left[\frac{T}{I_d}\frac{\partial I_d}{\partial T} - \frac{7}{2} - \frac{E_G}{kT}\right]}$$

If $I_d = I_{d0}\cdot\frac{T}{T_0}$ and $T = 300°K$

$$\boxed{\frac{\partial V_d}{\partial T} = \frac{V_d}{T} - \frac{V_T}{T}\left[\frac{5}{2} + \frac{E_G}{kT}\right] \cong -1.8\,mV/°K}$$

$$\boxed{V_{t_n} = V_{FB} + 2\phi_{F_n} + \frac{1}{C_{ox}}\sqrt{2\phi_F\, 2\varepsilon_s\, q\, N_A}}$$

$$\therefore \boxed{\frac{\partial V_{tn}}{\partial T} \cong \frac{\partial \phi_{Fn}}{\partial T}\left[2 + \frac{\sqrt{2\varepsilon_s q N_A}}{C_{ox}\sqrt{2\phi_{F_n}}}\right]}$$

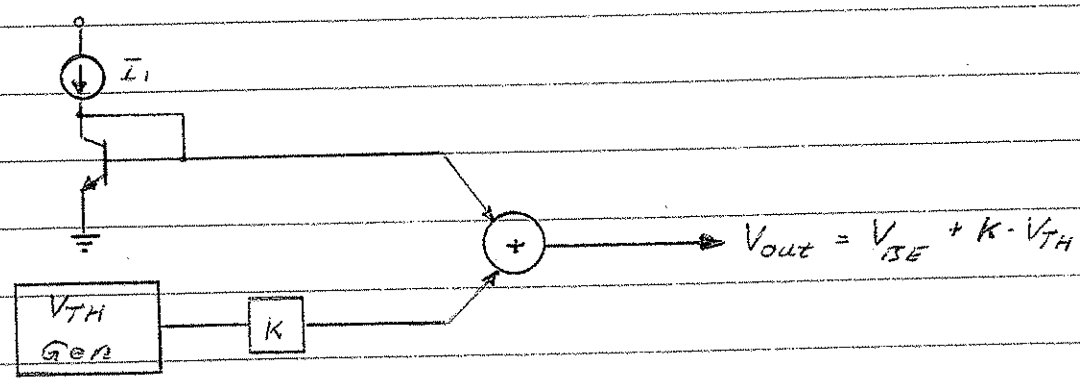
If $C_{ox} = 2\times 10^{-3}\frac{F}{m^2}$ and $N_A = 10^{23}\,m^{-3}$

$$\boxed{\frac{\partial V_{tn}}{\partial T} \cong -1.5\,mV/°K} \quad @\ T = 300°K$$

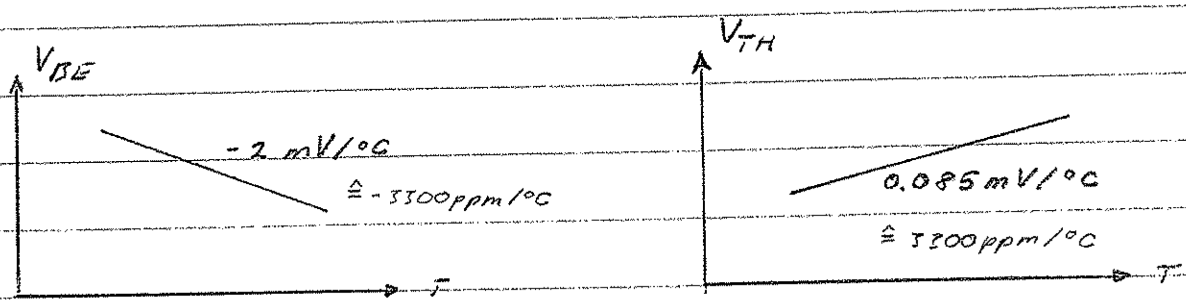
Note: $\frac{\partial V_{tp}}{\partial T} \cong -\frac{\partial V_{tn}}{\partial T}$

3. Temperature independent Biasing (Bandgap Reference)

Principle of Operation



Temp. Coefficients



T_c of $V_{BE(on)}$

$$I_1 \cong I_S\, e^{V_{BE}/V_{TH}} \Rightarrow \underline{V_{BE} \cong \overbrace{V_{TH}}^{\frac{kT}{q}} \ln\left(\frac{I_1}{I_S}\right)}$$

$$I_1 = \overset{\text{const}}{G} \cdot T^{\alpha}$$ typically $0 < \alpha < 1$

$$I_S = \underset{\text{const}}{B} \cdot T^{4-n}\, e^{-\frac{V_{G0}}{V_{TH}}}$$

V_{G0}: Bandgap voltage extrapolated to 0°K

n depends on doping level in Base e.g. $n = 3/2$

$$V_{BE} \cong V_{TH} \ln\left(G \cdot T^{\alpha} \cdot B^{-1} \cdot T^{n-4} e^{\frac{V_{G0}}{V_{TH}}}\right)$$

$$= V_{G0} + V_{TH} \ln\left(\frac{G}{B} T^{n-4+\alpha}\right)$$

$$\underline{V_{BE} = V_{G0} - V_{TH}\left([4-n-\alpha] \ln T - \ln \frac{G}{B}\right)}$$

output voltage after summer:

$$\boxed{V_{out} = V_{G0} - V_{TH}[4-n-\alpha] \ln T + V_{TH}\left(k + \ln \frac{G}{B}\right)}$$

$$\left.\frac{dV_{out}}{dT}\right|_{T=T_0} = -[4-n-\alpha][1+\ln T_0]\frac{V_{TH0}}{T_0} + \frac{V_{TH0}}{T_0}\left(k + \ln \frac{G}{B}\right)$$

$$= \frac{V_{TH0}}{T_0}\left(k + \ln \frac{G}{B} - [4-n-\alpha][1+\ln T_0]\right)$$

$$\underline{\left.\frac{dV_{out}}{dT}\right|_{T=T_0} = 0}$$

$$\Rightarrow \boxed{k + \ln \frac{G}{B} = [4-n-\alpha][1+\ln T_0]}$$

$$\Downarrow$$

$$\boxed{\begin{aligned} V_{out} &= V_{G0} - V_{TH}[4-n-\alpha] \ln T + V_{TH}[4-n-\alpha][1+\ln T_0] \\ &= V_{G0} + V_{TH}[4-n-\alpha]\left[1 + \ln\left\{\frac{T_0}{T}\right\}\right] \end{aligned}}$$

Note: - Temp. dependence of V_{out} is described by T_0
- T_0 is determined by k, B, G

Example: given: $n = 3/2$; $\alpha = 1$; $V_{G0}(Si) = 1.2\,V$

find: $V_{out}\Big|_{T_0 = 25°C}$ such that $T_C\Big|_{T_0=25°C} = 0$

solution: $T_C = 0$ if

$$V_{out} = V_{G0} + V_{TH}[4-n-\alpha][1+\ln\{\tfrac{T_0}{T}\}]$$

check: $$\frac{dV_{out}}{dT} = [4-n-\alpha]\Big[\underbrace{\frac{V_{TH}}{T}(1+\ln\{\tfrac{T_0}{T}\}) - \frac{V_{TH}}{T}\frac{T_0}{T}}_{=0 \text{ if } T=T_0}\Big]$$

$$V_{out} = 1.2\,V + 0.026\,V \cdot 1.5 = 1.239\,V$$

assume that due to component variations $V_{out} = 1.250\,V$

find Temp at which $T_C = 0$

and $T_C\Big|_{T=25°C}$

solution: $$V_{out} = V_{G0} + V_{TH}[4-n-\alpha][1+\ln\{\tfrac{T_0}{T}\}] + V_{TH}\,\Delta$$

$$\Delta = \frac{V_{outT_0} - V_{outT}}{V_{TH}}$$

$$\frac{dV_{out}}{dT} = [4-n-\alpha]\frac{V_{TH}}{T}\ln\{\tfrac{T_0}{T}\} + \frac{V_{TH}}{T}\Delta$$

$$\frac{dV_{out}}{dT} = 0 \Rightarrow [4-n-\alpha]\ln\{\tfrac{T_0}{T}\} + \Delta = 0$$

$$T = T_0\, e^{\frac{\Delta}{[4-n-\alpha]}} = 300°K\, e^{\frac{0.42}{1.5}} = 398°K$$

$$T_C\Big|_{T=25°C} = \frac{1}{V_{out}}\frac{dV_{out}}{dT}\Big|_{T=25°C} = \frac{1}{V_{out}}\frac{V_{TH}}{T_0}\Delta = 29\,ppm/°C$$

B. MOS

1. Circuit

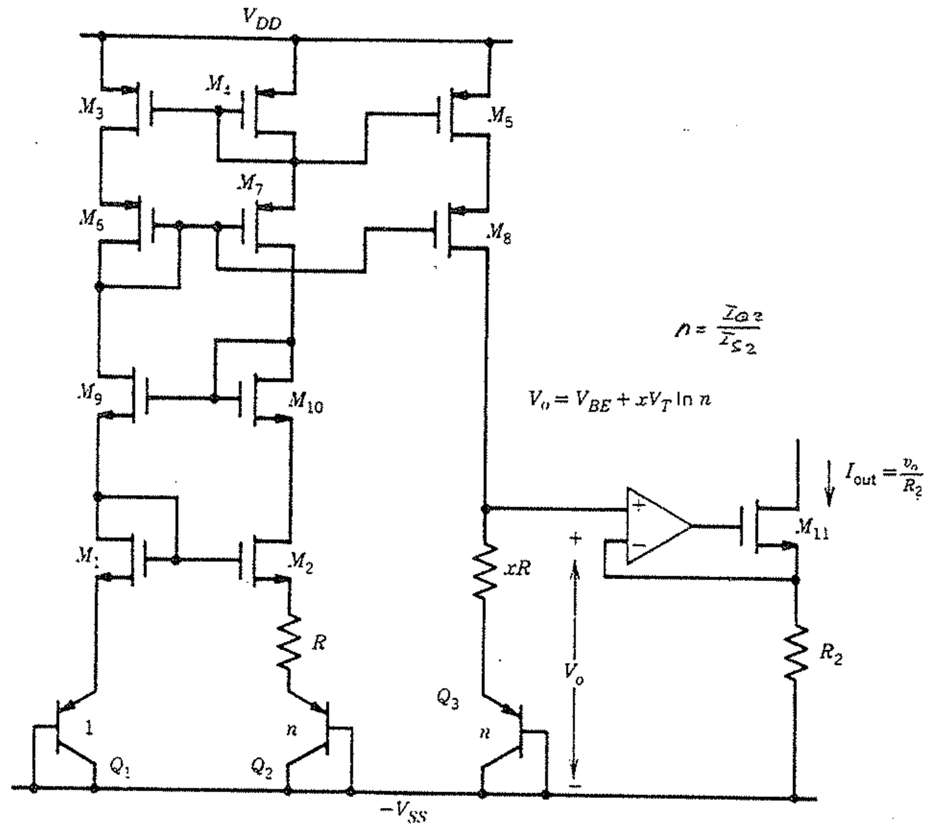


Figure 12.29 Example of a V_{BG}-referenced self-biased reference circuit.

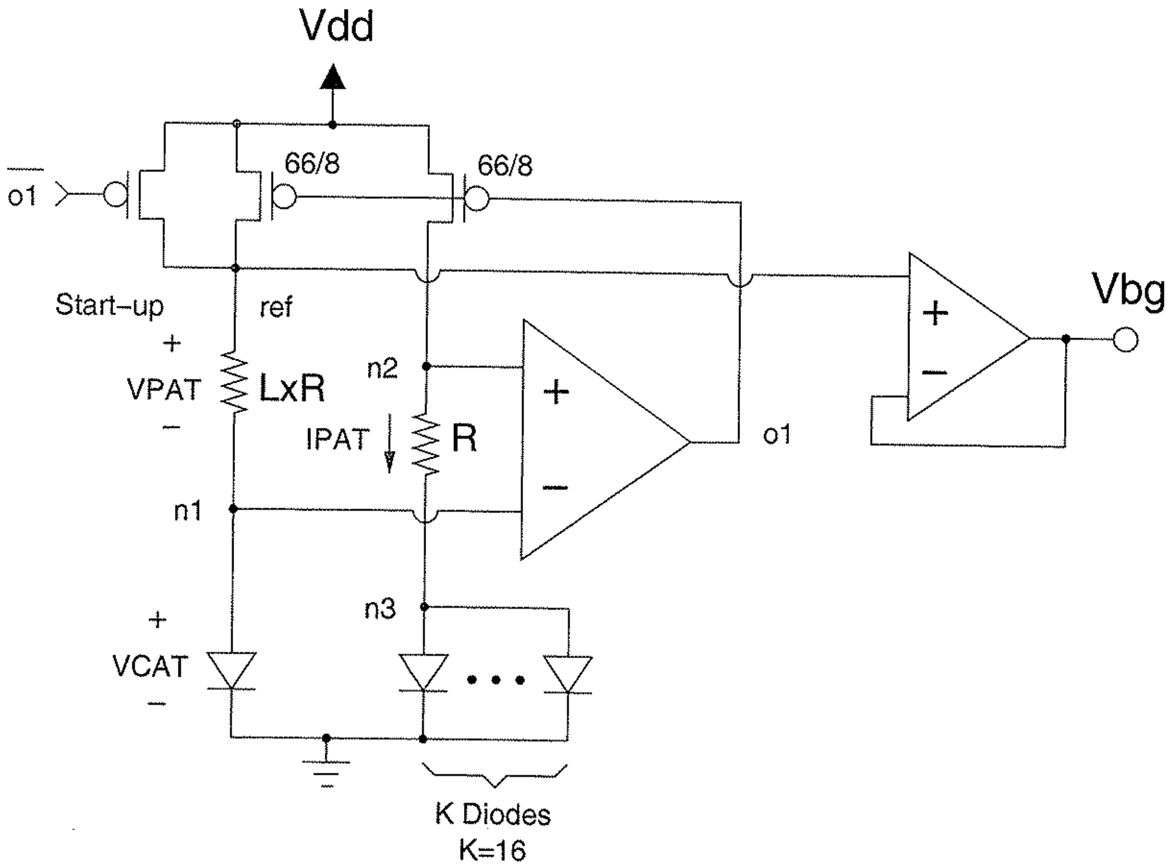
Note: $Q_1 - Q_3$ can only be implemented with an n-well process since their collectors must be connected to $-V_{SS}$

$I_{OUT} = V_0/R_2$

$V_{OUT} = I_{Q3}xR + V_{BE3}$

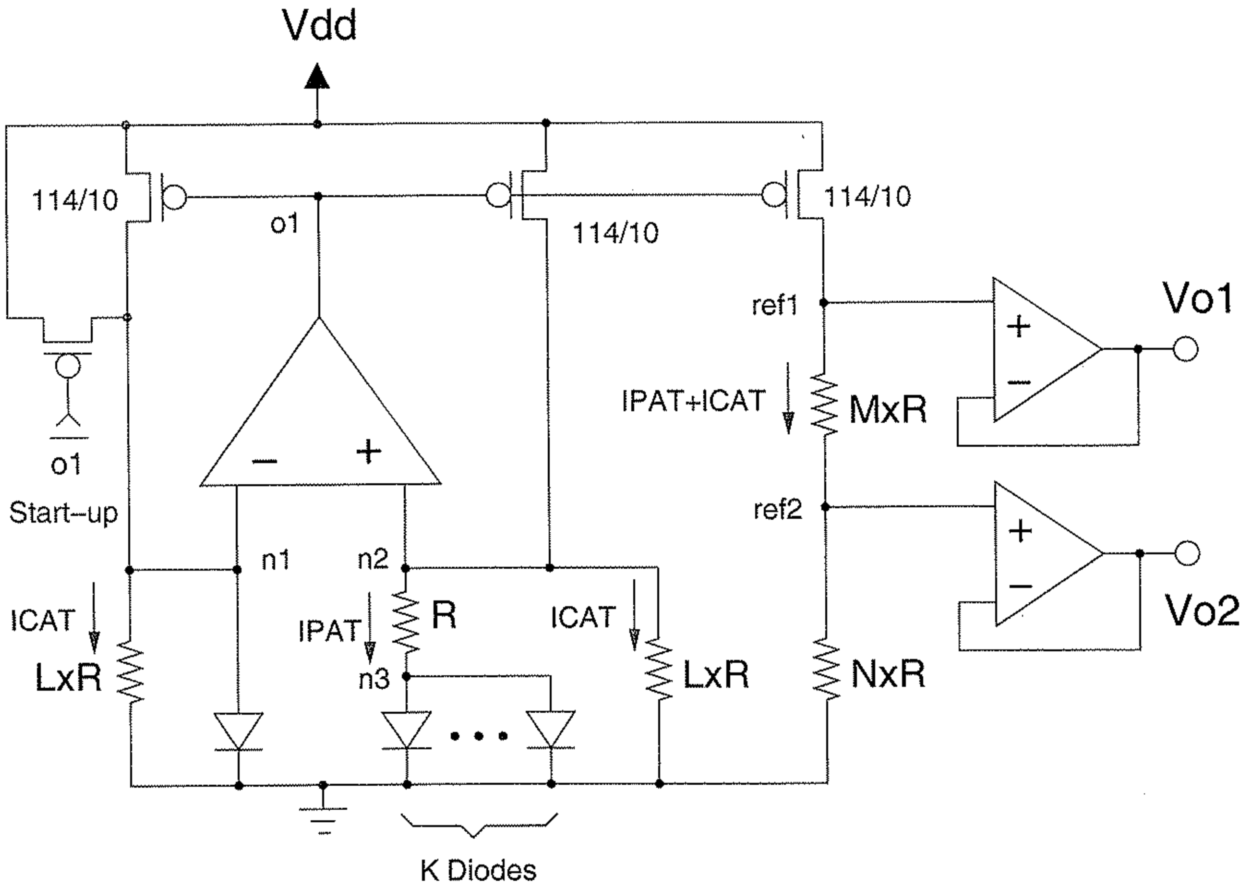
CMOS Bandgap Reference Circuit

Version1: Generating temperature compensated Voltage

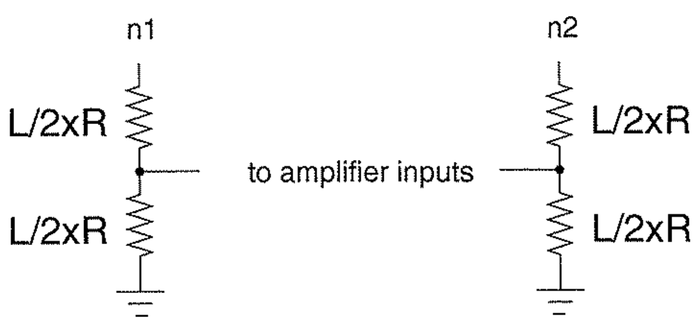


CMOS Bandgap Reference Circuit

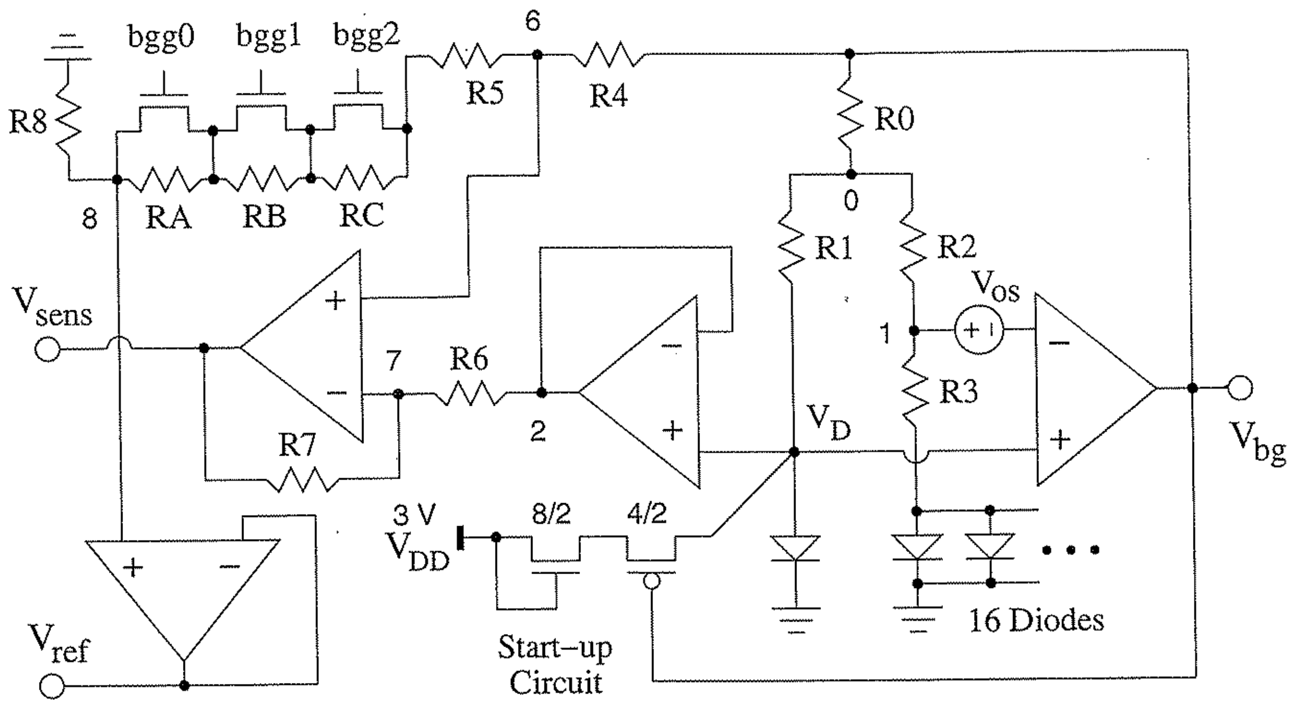
Version2: generating temperature compensated Current



To lower amplifier common mode input replace LxR branches by



Thermal Sensor & Bandgap Reference Circuit



Thermal Stability Condition

$$V_T \frac{R2}{R3}\left(1+\frac{R0}{R1}+\frac{R0}{R2}\right)\ln\left(16\,\frac{R2}{R1}\right) = V_G + 3V_T - V_D$$

Resulting Bandgap Voltage

$$V_{Bg} = V_G + 3V_T + V_{os}\left[1+\frac{R0}{R1}+\frac{R2}{R3}\left(1+\frac{R0}{R1}+\frac{R0}{R2}\right)\right]$$

Nominal Resistor Values

R0 = 160 k	R4 = 385 k	R6 = 50 k
R1 = 320 k	R5 = 325 k	R7 = 800 k
R2 = 320 k	RC = 16 k	R8 = 125 k
R3 = 88 k	RB = 32 k	
	RA = 64 k	