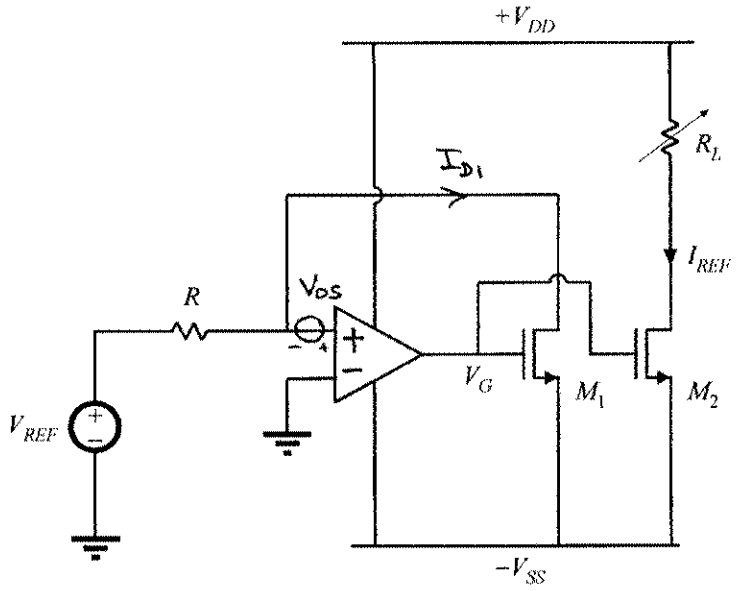

Note that M_1 is an inverting gain stage from gate to drain. Hence, feedback is returned to the + input to have a negative feedback circuit

Figure 1: Reference current source circuit; $+V_{DD} = 5$ V, $-V_{SS} = -5$ V, $V_{REF} = 1$ V; M_1 and M_2 are two identical NMOS transistors; in the active/saturation region the drain current is given by: $I_D = K(V_{GS} - V_t)^2$, where $V_t = 1$ V, $K = 100$ μA/V^2.

(a) **[1]** In Fig.1, label + and – inputs of the op-amp so that the circuit operates as a reference current source.

(b) **[2]** Assuming that all components are ideal and that M_1 and M_2 operate in the active/saturation region, find an expression for I_{REF}. Find R so that $I_{REF} = 100$ μA.

$I_{REF} = \frac{V_{REF}}{R}$, $R = 10$ kΩ

$I_{D1} = V_{REF}/R$. Since M_1, M_2 are in act/sat. the current mirror M_1–M_2 gives $I_{REF} = I_{D1}$

(c) **[2]** Suppose that all components are ideal, except that the op-amp input offset voltage is $V_{OS} = \pm 5$ mV. Find the relative tolerance $\Delta I_{REF}/I_{REF}$

$I_{REF} = \frac{V_{REF} + V_{os}}{R}$ $\quad \frac{\Delta I_{REF}}{I_{REF}} = \frac{R}{V_{REF}} \frac{\partial I_{REF}}{\partial V_{OS}} V_{os} = \frac{V_{os}}{V_{REF}} = \frac{\pm 5\text{mV}}{1\text{V}} = \pm 0.5\%$

(d) **[2]** Suppose that temperature drifts in all components except R can be neglected. Assuming $TC_F(R) = +2000$ ppm/°C, find $T_{CF}(I_{REF})$.

$TC_F(I_{REF}) = \frac{\Delta I_{REF}}{I_{REF}} \cdot \frac{1}{\Delta T} = \frac{R}{V_{REF}} \frac{\partial I_{REF}}{\partial R} \cdot \frac{\Delta R}{\Delta T} = -\frac{\cancel{R}}{\cancel{V_{REF}}} \frac{\cancel{V_{REF}}}{R^{\cancel{2}}} \frac{\Delta R}{\Delta T} = -TC_F(R) = -2000$ ppm/°C

(e) **[1]** Is it necessary for the op-amp in Fig. 1 to have a rail-to-rail output voltage swing? (Just answer YES or NO, there is no need to justify the answer)

NO. ($V_{GS} = V_t + \sqrt{I_{REF}/K} = 2$V, so V_G is well above $-V_{SS}$ and well below $+V_{DD}$

(f) **[1]** Is it necessary for the op-amp in Fig. 1 to have a rail-to-rail input common mode voltage range? (Just answer YES or NO, there is no need to justify the answer)

NO. $V(+) = V(-) = \varnothing$ well above $-V_{SS}$ and well below $+V_{DD}$

(g) **[1]** Find the maximum value of R_L such that $I_{REF} = 100$ μA.

Triode boundary: $V_{GD2} = V_t$, $V_G = -V_{SS} + V_{GS} = -V_{SS} + V_t + \sqrt{\frac{I_{REF}}{K}} = -3$V

$V_{D2min} = V_G - V_t = -4$V

$R_{Lmax} = \frac{V_{DD} - V_{D2min}}{I_{REF}} = \frac{9\text{V}}{100\mu\text{A}} = 90$ kΩ