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Temperature sensor using cascoded diode-connected MOSFETs operating in sub-threshold region

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Abstract

This paper analyses the feasibility of using cascoded diode-connected metal–oxide–semiconductor field-effect transistors (MOSFETs) operating in sub-threshold region as high-sensitivity and high-linearity temperature sensors. The cascoded structure is biased by a mirrored current coming from a current reference. The output voltages are drain voltages of the MOSFETs in the cascoded configuration. Temperature dependence of the drain voltages of the higher cascoded diode-connected MOSFETs can exhibit higher sensitivity and better linearity. The influence of bias current, device size, and body effect in MOSFET on linearity and sensitivity is studied. The measured temperature dependence of the drain voltage of the top diode-connected MOSFET exhibits the sensitivity of -4.36 mV/°C with linearity of 99.9977% over a temperature range from 0 to 100 °C.

1. Introduction

Traditional bipolar junction transistor (BJT) based temperature sensors have the issue of curvature correction of emitter-base voltage V_{EB} [1]. Diode-connected metal–oxide–semiconductor field-effect transistors (MOSFETs) operating in sub-threshold region have similar current-voltage characteristics to those of BJTs. Recently, the temperature sensors based on diode-connected MOSFETs have been presented [2, 3]. The gate-source voltage V_{GS} of the diode-connected MOSFET operating in sub-threshold region with constant current bias exhibits linear temperature dependence. But the sensitivity is limited because the transistor is operated in the sub-threshold region and there still exists non-negligible nonlinearity over a large temperature range. In this paper, a cascoded configuration of three diode-connected MOSFETs is used to implement temperature sensors which have large sensitivity and high linearity owing to the body effect in MOSFET. The temperature sensor has been implemented by TSMC 0.18um processes. The supply voltage is 1.8V.

2. Sensor Design

Figs. 1(a) and 1(b) show the circuit schematics of a diode-connected MOSFET with constant current bias and the designed temperature sensor using a cascoded configuration of three diode-connected MOSFETs, respectively. The designed temperature sensor is biased by a current reference.

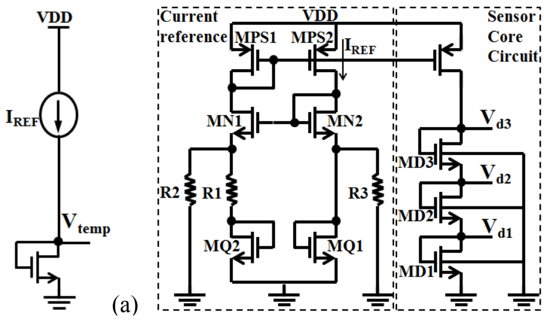

Fig. 1 Circuit schematics of (a) a diode-connected MOSFET with constant current bias and (b) the designed temperature sensor using a cascoded configuration of three diode-connected MOSFETs.

The sub-threshold drain current I_D of a MOSFET is an exponential function of the gate-source voltage V_{GS} and the drain-source voltage V_{DS}, and can be expressed by [2]

$$I_D = \frac{W}{L}\mu C_{ox}(\eta-1)V_T^2 \exp(\frac{V_{GS}-V_{TH}}{\eta V_T})[1-\exp(-\frac{V_{DS}}{V_T})] \quad (1)$$

where μ is the mobility of carriers, C_{ox} is the gate-oxide capacitance, V_T (= k_BT/q) is the thermal voltage, k_B is the Boltzmann constant, T is temperature, q is the electronic charge, V_{TH} is the threshold voltage of a MOSFET, and η is the sub-threshold slope factor. For $V_{DS} \geq 5V_T$, the term in the square brackets has a value larger than 0.99 and can be neglected. Hence, the current I_D is almost independent of V_{DS} and V_{GS} can be expressed by [3]

$$V_{GS} = V_{TH} + \eta V_T \ln(\frac{I_D}{\mu C_{ox}\frac{W}{L}(\eta-1)V_T^2}) \quad (2)$$

μ and V_{TH} depend on temperature and can be expressed by

$$\mu(T) = \mu_0(\frac{T}{T_0})^{\alpha} \quad (3)$$

$$V_{TH}(T) = V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F} = V_{TH0} + \beta(T-T_0) \quad (4)$$

$$\gamma = \frac{\sqrt{2\varepsilon_S q N_A}}{C_{ox}} \quad (5)$$

where μ_0 is the carrier mobility at T_0, α is a constant generally between −1.5 and −2, V_{TH0} is the threshold voltage at T_0, and β is a negative value. In eq. (4), the body effect resulting from non-zero V_{SB} is not considered. The threshold voltage inclusive of the body effect can be expressed by

$$V_{TH,body} = V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F}\sqrt{1+\frac{V_{SB}}{2\phi_F}}$$

$$\approx V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F}\,[1 + f(\frac{V_{SB}}{2\phi_F})] \quad (6)$$

The square root term related to V_{SB} is expressed as the sum of 1 and a function of $V_{SB}/2\phi_F$. Replacing now (4) in (6) yields the temperature dependence of $V_{TH,body}$.

$$V_{TH,body}(T) = V_{TH0} + \beta(T - T_0) + \gamma\sqrt{2\phi_F}\, f(\frac{V_{SB}}{2\phi_F}) \quad (7)$$

Substituting eqs. (3) and (7) in (2) yields

$$V_{GS} = V_{TH0} + \beta(T - T_0) + \gamma\sqrt{2\phi_F}\, f(\frac{V_{SB}}{2\phi_F})$$

$$+\eta\frac{kT}{q}\ln(\frac{I_D}{\mu_0 C_{ox}\frac{W}{L}(\eta-1)V_{T0}^2}) + (\alpha+2)\eta V_T \ln(\frac{T_0}{T}) \quad (8)$$

For $T_0/T \approx 1$, $\ln(T_0/T) \approx T_0/T - 1$ [3]. Consequently, eq. (8) can be simplified and be expressed as

$$V_{GS} = V_{TH0} - \beta T_0 + \gamma\sqrt{2\phi_F}\, f(\frac{V_{SB}}{2\phi_F}) + (\alpha+2)\eta\frac{kT_0}{q}$$

$$+[(\beta+\chi)T - (\alpha+2)\eta\frac{k}{q}]T \quad (9)$$

where χ is defined as

$$\chi = \eta\frac{k}{q}\ln(\frac{I_D}{\mu_0 C_{ox}\frac{W}{L}(\eta-1)V_{T0}^2})$$

The last term in eq. (9) has a linear temperature dependency. The temperature coefficient is negative. By choosing smaller I_D and larger (W/L) to make χ smaller, the sensitivity of V_{GS} related to temperature can be more negative and hence the sensitivity is enhanced. In reality, the terms related to $V_{SB}/2\phi_F$ and $\ln(T_0/T)$ in eq. (8) introduce nonlinear temperature dependence. Fortunately, the relationship of two terms related to temperature probably exhibits complementary nonlinear curvatures [1]. Hence, the body effect probably improves the nonlinearity which is brought about by temperature dependence of mobility. The term related to $V_{SB}/2\phi_F$ also enhances the sensitivity if the source voltage decreases with the increase of temperature. The cascoded diode-connected MOSFETs, which is biased by a mirrored current of 602 nA coming from a current reference with temperature coefficient of 10 PPM/°C or so, is used to implement a high-linearity temperature sensor as shown in Fig 1(b). The drain voltages of the cascoded MOSFETs are linearly dependent on temperature. These outputs are interconnected through unit-gain buffers, which amplifier has a gain of at least 86 dB, to bonding pads.

Fig. 2 shows simulated and measured temperature characteristics of output drain voltages, its linear regression line and nonlinear temperature error. The measured sensitivities are -4.36, -2.61, and -1.17 mV/°C with linearity of 99.9977%, 99.9971%, and 99.9947%, respectively for V_{d3}, V_{d2}, and V_{d1}. The temperature errors related to linear regression lines are within the range from -0.31 to 0.16 °C, from -0.33 to 0.20 °C, and from -0.20 to 0.46 °C, respectively. In Fig. 1(b), there exists no body effect in MD1 but the body effect exists in MD2 and MD3. V_{d3} and V_{d2} exhibit more linear temperature dependence as compared with V_{d1}. The measured and simulated results are approximate. Fig. 3 shows simulated temperature characteristics of the V_{d3} and V_{d1} under the bias currents of 300, 600, and 1200 nA, respectively. In Fig. 3, the sensitivity increases with the decrease of the bias current and the linearity still remains high. Hence, the temperature sensor with larger sensitivity and high linearity can be realized under lower power consumption. The linearity of temperature characteristics of V_{d1} is smaller owing to the temperature dependence of mobility.

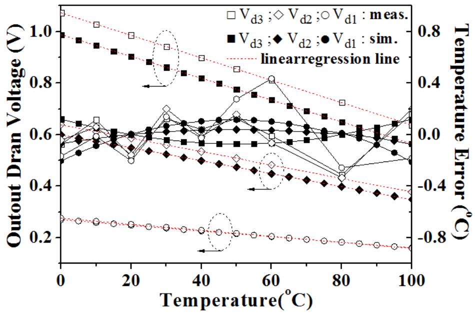

Fig. 2 Simulated and measured output drain voltages against temperature, its linear regression line and nonlinear temperature error.

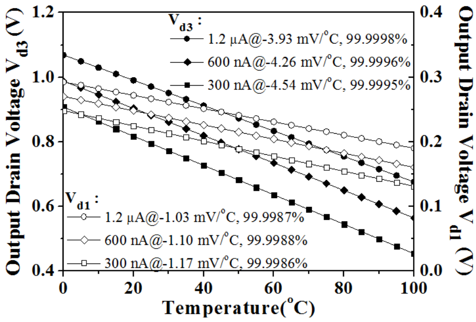

Fig. 3 Simulated temperature dependence of the V_{d3} and V_{d1} under the bias currents of 300, 600, and 1200 nA, respectively.

3. Conclusions

A high-linearity temperature sensor has successfully been implemented by cascoding three diode-connected MOSFETs operating in sub-threshold region. It is shown that the existence of body effect in MOSFET probably enhances sensitivity and linearity of temperature characteristics of the drain voltages of the cascoded MOSFETs. The larger sensitivity can be obtained by using a smaller bias current. With a bias current of 602 nA, the drain voltages of the top and bottom MOSFETs exhibit the measured linearity of 99.9977% and 99.9947%, respectively. The simulated linearity is 99.9996% and 99.9988%, respectively. The temperature sensor occupies a chip area of $610\times90\ \mu m^2$.

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