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Low power, area efficient, and temperature-variation tolerant bidirectional current source for sensor applications

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ABSTRACT

This paper presents a novel temperature invariant, low power, and area efficient bidirectional current source. The current source can be used as an analog front end R–V converter for different types of resistive sensor applications. The current source is based on weighted sum of thermal voltages and difference of threshold voltages. High V_{TH} transistors operating in sub-threshold region along with regular V_{TH} transistors in strong inversion region form a temperature invariant current source. A current switching technique is presented in this paper for producing a periodic bidirectional current source, fabricated in 180 nm CMOS technology for low cost sensor applications. The maximum total current variation simulated is 13 nA ($\pm 0.5\%$) for typical value of ± 715 nA reference current over the temperature range of 25–125 °C. The fabricated test circuit lies in SNFP corner and shows $\pm 1\%$ variation in positive and $\pm 1.67\%$ variation over the temperature range of 25–125 °C. Total area consumed by the circuit is 100 μm × 35 μm. The behavior of the bidirectional current source has been tested using a piezoresistive cantilever based explosive detector sensor, with 20 ppb TNT vapor concentration and 10 parts per billion resolutions with sensitivity of 10 μV/ppb.

1. Introduction

Signal conditioning plays an important role in the overall resolution and sensitivity of the sensing systems, where the change in a physical quantity is converted to a change in an electrical signal. An on chip, low power, novel temperature invariant current source for resistive sensors is proposed in this paper. It uses current excitation method, which enables measuring up-to 1.5 ppm resistance change. Even though there are many designs explaining low power, small area, clock-free temperature invariant voltage reference designs [1–4], very few architectures focus on current reference designs. Authors in [5] have used a bidirectional current source to develop a low voltage and highly sensitive circuit for resistive sensor measurements. A bidirectional current source was used to drive a sensor load. As a result, the amplitude of the AC output voltage is proportional to the change in the base resistance of the resistive sensor. This makes the measurements immune to the voltage offset due to stray noise and temperature changes at Wheatstone's bridge output. Furthermore, the current excitation method uses a lower voltage compared to the traditional methods with the same sensitivity of detection. However the authors in [5] use a diode bridge made of off-chip diodes with commercial chips. On-chip integration of the diode bridge configuration consumes area and imposes constraint on the supply voltage because of its high voltage dropout. Another technique, proposed in [6], uses several switches to change the polarity of the constant current source. This again leads to current spikes because of different turn on delays of the switches. Furthermore, integrated analog instrumentation demands low power and area efficient current sources, which are robust against temperature drift and process variations. As a straightforward approach, a bandgap voltage reference might be used to design a temperature insensitive current source [7]. The main drawback of this method is large area of on-chip resistors. In mainstream CMOS technologies of $\pm 15\%$ on-chip resistance variation is very common. The modified fixed g_m bias circuit proposed in [8], produces a constant current reference but the temperature coefficient (TC) is as high as 1088 ppm/°C.

2. Operating principle of proposed current source

The proposed bidirectional current source in this paper is meant for sensor applications, where current excitation method is used to measure change in the resistance of a resistive sensor [5,9]. As shown in Fig. 1, the sensor is stimulated using bidirectional periodic current and measures peak-to-peak amplitude of the output voltage. Hence the measurement is immune to base line variations due to thermoelectric voltage and stray noise effects. The required periodic, temperature independent bidirectional current source is realized from a novel temperature independent single-ended current source. The theory behind proposed temperature independent current source is explained as follows. Threshold voltage and mobility are the

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important parameters that determine the temperature behavior of the gate to source voltage of the MOSFET [10].

First order approximation, which is frequently adequate, relates the V_{TH} to temperature as specified in Eq. (1).

$$V_{TH}(T) = V_{TH0} + \alpha(T - T_0) \tag{1}$$

where V_{TH0} is the threshold voltage at T_0 and α is the TC of the threshold voltage, which is negative. Mobility variation as a function of temperature is given by Eq. (2) [11].

$$\mu(T) = \mu(T_0) \times \left(\frac{T}{T_0}\right)^{\beta} \tag{2}$$

where $\mu(T_0)$ is the mobility at T_0 and exponent β lies in the range of -2 to -1.5 for CMOS transistors in standard 180 nm mixed mode CMOS technology. As temperature varies MOSFET drain current varies less due to mobility variation as compared to the variation due to V_{TH} with transistors biased in subthreshold region in the target CMOS process. We use a novel technique to show how compensation of threshold voltage variation with temperature significantly reduces the total variation of the reference voltage. The TC of high threshold voltage MOSFET (H-V_{TH} MOSFET) is larger than that of regular threshold voltage MOSFET (R-V_{TH} MOSFET) due to different channel doping concentrations. Hence a temperature insensitive current source can be designed if the output current I_{ref} satisfies relation (3).

$$I_{ref} \propto N_1\left(V_{TH_{high}} - N_3 V_{TH_{reg}}\right) + N_2 V_T \tag{3}$$

where $V_{TH_{high}}$ and $V_{TH_{reg}}$ are threshold voltages of H-V_{TH} and R-V_{TH} MOSFETs, respectively. The first term in relation (3) exhibits a CTAT (complementary to absolute temperature) behavior. Second term in relation (3) is proportional to V_T and exhibits PTAT (proportional to absolute temperature) behavior for absolute temperature current. N_1, N_2 and N_3 are admittance coefficients of threshold voltage terms such that TC of I_{ref} will be close to zero.

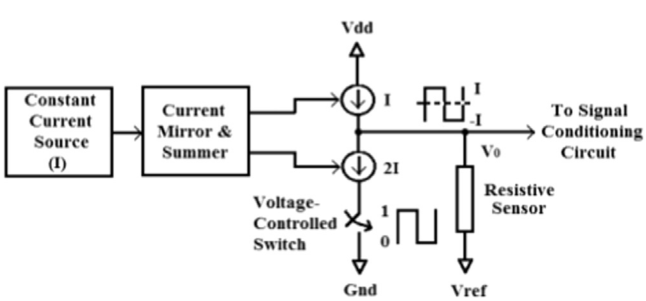

Fig. 1. Basic concept of the proposed temperature independent bidirectional current source.

This concept is used in this paper to develop a novel temperature independent current source.

3. Proposed current source circuit configuration

The idea expressed by Eq. (3) is realized by biasing CMOS transistors in subthreshold and strong inversion regions and producing a linear combination of gate source voltages. This section explains the details of the realization and the corresponding circuit configuration. Eqs. (4) and (5) can state the drain currents in strong inversion and subthreshold regions of the MOSFET, respectively [11].

$$I_{D_{inv}} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)\left(V_{GS_{inv}} - V_{TH}\right)^2 \tag{4}$$

$$I_{D_{sub}} = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_T)^2 \exp\left(\frac{V_{GS_{sub}} - V_{TH}}{\eta V_T}\right) \tag{5}$$

where V_T is KT/q and it is assumed that $V_{DS} \geq 3V_T$. From Eqs. (4) and (5), $V_{GS_{inv}}$ and $V_{GS_{sub}}$ can be rewritten as a function of threshold voltage and drain current as follows. We use combination of and to produce a temperature independent current source, which will be explained here.

$$V_{GS_{inv}} = \sqrt{\left(2I_D/\mu_n C_{ox}\left(\frac{W}{L}\right)\right)} + V_{TH} \tag{6}$$

$$V_{GS_{sub}} = \eta V_T \ln\left(I_D/\mu_n C_{ox}\left(\frac{W}{L}\right)(V_T)^2\right) + V_{TH} \tag{7}$$

3.1. Temperature independent current source

Fig. 2 shows the complete schematic of the proposed bidirectional current source circuit. This circuit is comprised of a startup circuit along with the temperature independent current source generator followed by the bidirectional current source. Eq. (3) shows the basic principle behind the proposed circuit. This equation is implemented using the main loop of the circuit, shown in Fig. 2, constituting transistors M_1 to M_3 (M_1 and M_2 operate in subthreshold region and M_3 operates in the strong inversion region) and an opamp. V_x and V_y (Fig. 2) are equal due to virtual short generated by the op-amp. M_{01} to M_{06} constitute the low power tail less op-amp [11]. Transistors M_1 to M_5 form a current source circuit and transistors. Since transistors M_1, M_2 and M_3

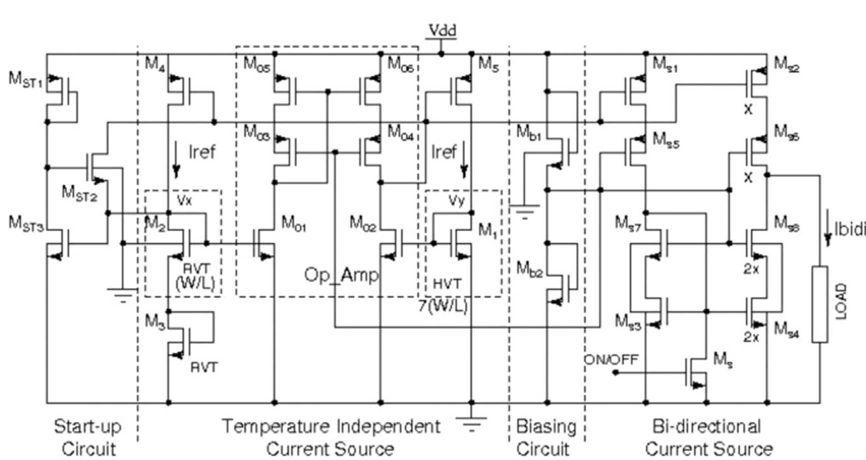

Fig. 2. Proposed CMOS current reference and bidirectional current source architecture.