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CMOS Temperature Sensor Using a Modified Bandgap Reference Voltage Circuit with a Low-Temperature-Coefficient Resistor Structure

Ruey-Lue Wang[1], Jian-Liang Shi[1], Yi-Fan Hao[1], Kai-Bau Lee[1], Xiang-Jing Yang[1], Wei-De Wu[1], Hsin-Hao Liao[2], Hann-Huei Tsai[2] and Ying-Zong Juang[2]

[1] National Kaohsiung Normal Univ.
No.62, Shenjhong Rd., Yanchao District, Kaohsiung City 824, Taiwan
Phone: +886-7-7172930ext 7916 E-mail: rlwang@ms22.hinet.net
[2] National Applied Research Laboratories
National Chip Implementation Center
Chimei Bldg., 7F, No.1, Ta-Hsuch Rd., Tainan 701, Taiwan

Abstract

A CMOS temperature sensor with a highly linear proportional-to-absolute-temperature (PTAT) output current is presented. A modified bandgap reference voltage circuit, in which diode-connected MOSFETs are used to replace commonly-used diode-connected BJTs and the resistor with a PTAT voltage drop is replaced by two resistors with opposite-sign temperature coefficients, is used as the core circuit of the temperature sensor. The current flowing through the resistors in series connection exhibits a PTAT characteristic with high linearity of 99.998% at least for a temperature range from -20 to 100ºC. The PTAT current is mirrored to an added current controlled oscillator which output pulse frequencies have also a PTAT characteristic. The plot of measured pulse frequencies against temperature shows the sensitivity of 14.2 Hz/ºC with linearity of 99.992%.

1. Introduction

Highly linear voltage or current with respect to temperature can be obtained by mathematically dealing with nonlinear temperature characteristic of voltage, current or resistance [1, 2]. A bandgap voltage reference, which produces a temperature-insensitive constant voltage, is generally based on BJT devices and resistors. Under the bias of matched currents by a current mirror, the difference ΔV_{EB} between two emitter-base voltages of two pnp BJTs with different device sizes is quite accurately proportional to absolute temperature (PTAT) and the ΔV_{EB} is designed to be across a resistor by virtual grounding between two matched MOSFETs. A PTAT current can be generated because the $\Delta V_{EB}(T)$ is across the resistor R. However, the $\Delta V_{EB}(T)/R$ does not really exhibit a highly linear temperature dependence since R depends on temperature [3].

Polysilicon resistors with and without silicidation process have positive temperature coefficient (PTC) and negative TC (NTC), respectively. The two resistors connected in series may have a much smaller TC due to the cancellation of opposite-sign TCs. In this work, the low-TC resistor structure is substituted for the single resistor in the bandgap voltage reference. Hence a highly linear PTAT current can be generated. The bandgap temperature sensor has successfully been implemented by the TSMC 0.18 μm process.

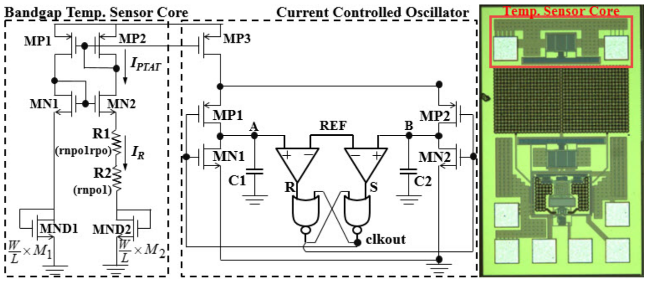

Fig. 1 The circuit schematic and chip photograph of the proposed temperature sensor with pulse output.

2. Sensor Design and Measurement Results

Fig.1 shows the circuit schematic and chip photograph of the designed temperature sensor. The temperature core is a modified bandgap voltage reference circuit, in which the diode-connected BJTs are replaced by n-type MOSFETs, i.e., MND1 and MND2. The MOSFET in subthreshold region, i.e., $V_{GS}<V_{TH}$, exhibits an exponential dependence on V_{GS} and can be substituted for BJTs in a bandgap voltage reference. The subthreshold current can be expressed as [4]

$$I_D = I_0 \exp(\frac{V_{GS} - V_{TH}}{\zeta V_T})[1-\exp(-\frac{V_{DS}}{V_T})] \quad (1)$$

where $\zeta>1$ is a nonideality factor and $V_T=kT/q$. I_0 is proportional to the W/L ratio of device channel. For V_{DS} greater than about 200 mV, eq. (1) is similar to the exponential I_C-V_{BE} relationship in a BJT. Fig. 2 shows the simulated temperature dependence of the V_{GS} of the diode-connected MOSFET, MND2, of the modified bandgap temperature sensor in which a single ideal resistor of 11.8 kΩ with zero TC is used. The V_{GS} is smaller than 300 mV for the temperature range of -20 to 100 ºC. The threshold voltage V_{TH} of the MOSFET in the 0.18 um process is larger than 400 mV and hence the diode-connected MOSFET actually operates in the subthreshold region. The current flowing and the voltage across the ideal resistor are also shown in Fig.2. They actually exhibit PTAT temperature characteristics. The linearity are 99.998 % and 99.999 %, respectively.

In Fig. 1, the resistors R1 and R2 are polysilicon resistors without and with silicidation process, respectively, and are connected in series. To demonstrate the effect of the reducing temperature dependence of resistance on the enhancement of the linearity of PTAT current across the resistor, two additional bandgap voltage reference circuits in which the resistor is implemented by a single polysilison resistor without silicidation process. The low-TC series-connected resistor structure (R_NTC+PTC) and the two single NTC resistors (R_NTC1 and R_NTC2) have resistance of 11.8, 9.5 and 22.6 kΩ, respectively, at room temperature. The R_NTC1 is the NTC component of the R_NTC+PTC. Fig. 3 show the simulated temperature characteristics of the real modified bandgap voltage reference circuits. The R_NTC+PTC indeed exhibits low TC. The I_R exhibits a sensitivity of 2.76, 4.27 and 1.82 nA/ºC and linearity of 99.998%, 99.908%, and 99.9166%, respectively. The series-connected low-TC resistor structure indeed enhances the linearity of resulting PTAT current

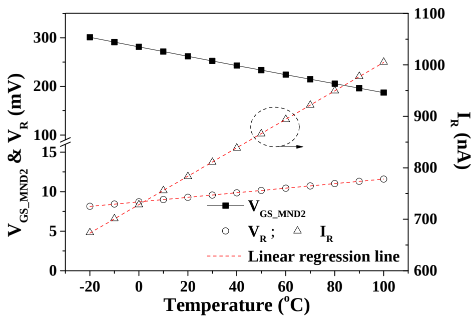

Fig. 2 Simulated temperature characteristics of V_{GS_MND2}, V_R, and I_R for bandgap temperature sensor using an off-chip ideal resistor.

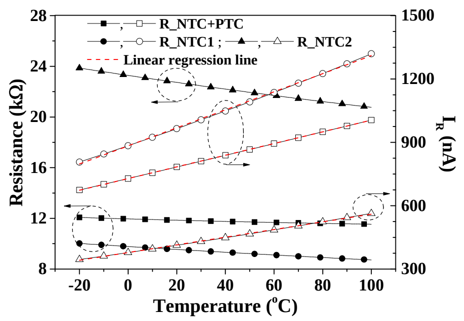

Fig. 3 Simulated temperature characteristics of resistance and I_R for bandgap temperature sensors using on-chip R_NTC+PTC, R_NTC1, and R_NTC2, respectively.

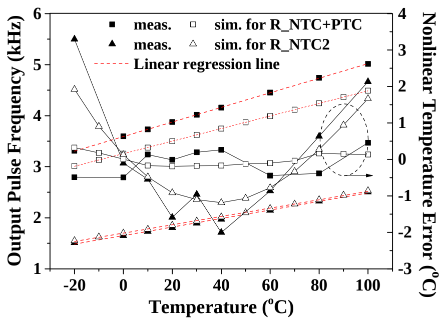

Fig. 4 Simulated and measured pulse frequencies against temperature, its linear regression line and nonlinear temperature error.

Because the linear resolution of output current is the order of nA, the measurement setup can be difficult. Therefore, the PTAT current is inputted to a current controlled oscillator by a current mirror, as shown in Fig.1, in order to generate voltage pulses [2]. Fig.4 shows simulated and measured pulse frequencies, which exhibit PTAT characteristics indeed. Equivalent temperature errors resulting from nonlinear deviation of the pulse frequencies are also shown in Fig.4. For the case using a single R_NTC2 resistor, the oscillator has simulated and measured sensitivities of 8.2 and 8.4 Hz/ºC with linearity of 99.924% and 99.798% at the V_{ref} of 0.7V, respectively. Temperature error range is from -1.18 to 1.92 ºC and from -2.0 to 3.29 ºC, respectively. For the case using series-connected resistors, the simulated and measured sensitivities are 12.3 and 14.2 Hz/ºC with linearity up to 99.998% and 99.992%, respectively. Temperature error range is from -0.19 to 0.32 ºC and from -0.49 to 0.45 ºC, respectively. The simulated and measured results are similar. The current of the temperature sensor core is less than 3 μA under the supply voltage of 1.8 V. The whole circuit consumes only about 0.2 mA. The sensor core occupies an area of 103×295 μm^2.

3. Conclusions

A temperature sensor with a high-linearity PTAT current has been successfully implemented by a modified bandgap voltage reference circuit in which diode-connected BJTs are replaced by MOSFETs. The two polysilicon resistors without and with silicidation process, respectively, are connected in series and are used to replace the resistor with a PTAT voltage drop, which is the difference voltage between two biasing voltages of two different-size diode-connected transistors under the same biasing current. The simulated results shows that the series-connected low-TC resistor structure indeed enhances the linearity of the resulting PTAT current up to 99.998 % at least for a temperature range of -20 to 100 ºC. The PTAT current is mirrored to control a current controlled oscillator. The simulated and measured sensitivities are 12.3 and 14.2 Hz/ºC with linearity up to 99.998% and 99.992%, respectively.

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