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Design of a Novel Ultra-Low Power Time-Domain Temperature Sensor

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***Abstract*—This paper proposed a novel ultra-low power time-domain temperature sensor. It consists of two current generators including one constant-with-temperature (CWT) current reference generator, relaxation oscillator, separation circuit and digital circuit system. Both of current generators are used to drive the oscillator to produce a signal whose high level duration is complementary to absolute temperature, and low level duration is temperature-independent. The separation circuit is used to separate the high level duration and low level duration. The digital circuit system can quantify the separation circuit output and make a subtraction, and therefore obtain digitized temperature information. The temperature sensor is designed using a standard 0.18μm CMOS process. The simulation results show that it can measure temperature from 0℃ to 60℃. The power consumption of the complete system is 86.79 nW at 25℃. The maximum conversion speed is 52 Sa/s under 1V voltage supply.**

Keywords—current generators, relaxation oscillator, ultra-low power, temperature sensor, subthreshold conduction

I. Introduction

IoT sensors develop towards ultra-low power, because it will extend the sensor life, or even can be self-powered by the energy harvested from environment. The ultra-low power temperature sensor is of vital importance in a number of applications including health care, environmental monitor, IoT and so on [1]. Temperature sensors usually consist of two parts, the temperature sensing part and quantification part. As for the temperature sensing part, there are two main ways by using BJT and MOSFET in weak inversion respectively. As far as BJT to be considered, the voltage of the base-emitter V_{BE} is complementary to absolute temperature, and the difference between two V_{BE}, that is ΔV_{BE}, is proportional to the absolute temperature as shown in (1): [2]

$$\Delta V_{\mathrm{BE}} = \frac{kT}{q} ln(p) \tag{1}$$

where p is the emitter current density ratio, k is Boltzmann's constant, q is the electron charge, and T is temperature. Although the temperature sensor based on BJT can provide high precision, the power consumption is large and it is not suitable for ultra-low power applications. And compared with the BJT-based temperature sensor, MOSFET-based temperature sensor is not so accurate, but its power consumption is low because of its operation in weak inversion region. And as for the quantification part, there are three main methods including ADC, TDC [3], and FDC [4].

This work proposes a novel ultra-low power time-domain temperature sensor. Two simple current generators produce two kind of current respectively to drive the relaxation oscillator. Then the high level duration and low level duration of the oscillator output is separated by the separation circuit. Finally, separation output is quantified by the digital circuit system. The block diagram of the temperature sensor is shown in Fig. 1. The structure of the paper is as follows: section II describes the temperature sensor circuit implementation. Section III gives the conclusion.

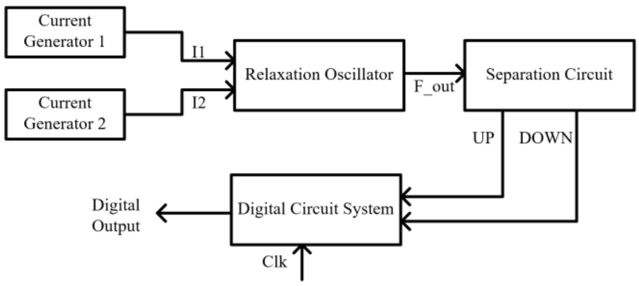

Fig. 1. The block diagram of the proposed temperature sensor.

II. Temperature Sensor Circuit Implementation

As shown in Fig. 1, Current Generator 1 produces current I1 which is constant with temperature to control the the relaxation oscillator, so that the low level duration of the output of the oscillator F_out is constant with temperature. The Current generator 2 is used to generate current I2 to control the oscillator so that the high level duration of F_out is complementary to the absolute temperature (CTAT). Then F_out is sent into the separation circuit to separate the high level duration and the low level duration, which means F_out generates two waveforms UP and DOWN. The high level duration of UP waveform is equal to the high level duration of the F_out, and meantime the high level duration of DOWN waveform is equal to the low level duration of the F_out. Then the UP and DOWN signals are fed to the digital circuit system and quantified. We get two digital signals. One is independent to the absolute temperature, the other is

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CTAT. After subtraction, the final digital output value is linear to the absolute temperature.

A. Subthreshold Conduction

Fig. 2 shows the vertical view of an NMOS. As shown in Fig. 2(a), when the gate-source voltage $V_{gs}=0$, there are two opposite PN junctions between the drain and source. There is no conductive channel and no drain current. When the gate-source voltage $V_{gs}>0$, we can see that the gate-SiO_2-P-substrate is similar to a capacitor as shown in Fig. 2(b). Because the gate is connected with positive pole, there are positive charges accumulating on the gate. And the positive holes in the P-substrate are repelled by the positive charge of the gate, resulting in negative ions left near the interface between the P substrate and SiO_2. So a depletion layer is formed. And with the further increase of V_{gs}, as shown in Fig. 2(c), The depletion layer is widened and the free electrons in the N+ diffusion regions are attracted into the depletion layer, forming an N-type conductive channel called the inversion layer, which connect the source and drain. When the conductive channel is formed, $V_{gs}=V_{th}$, which is called the threshold voltage.

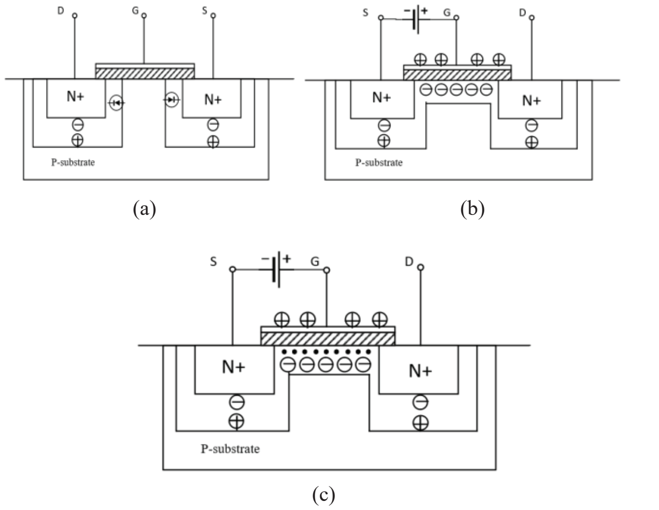

Fig. 2. The vertical view of an NMOS, (a) $V_{gs}=0$, (b) The formation of depletion layer, (c) The formation of inversion layer.

Generally, when $V_{gs}<V_{th}$, we consider that the MOSFET is off, and the current flowing from drain to source is zero. But in fact when $V_{gs}\approx V_{th}$, MOSFET does not shut down immediately, instead, there is a weak inversion layer and the drain to source current exists. Even when $V_{gs}<V_{th}$, the drain to source current is not infinitesimal, but has an exponential relationship with V_{gs}, this effect is called subthrehsold conduction. The current in the subthreshold region can be expressed as in (2) [5]. In most situations, the drain to source current of MOSFET working in the weak inversion can be nA or pA.

$$I_{\text{sub}} = \mu C_{\text{ox}} \frac{W}{L}(m-1)V_T^{\,2} \exp\left(\frac{V_{\text{gs}}-V_{\text{th}}}{mV_T}\right)\left(1-\exp\left(\frac{-V_{\text{ds}}}{V_T}\right)\right) \tag{2}$$

where μ is mobility, C_{ox} is oxide capacitance, W is transistor width, L is transistor Length, m is subthreshold slope factor, V_T is thermal voltage.

B. Current Generators

As discussed above, current generator 1 produces temperature-independent current. The circuit is shown in Fig. 3. The transistor M1, M2, M3, M4, M8, M9, M10 work in the subthreshold region. The M1 current I1 is equal to Vx divided by M7 turn-on resistance. Vx is actually the difference of Vth (ΔVth) of M3 and M4. It is known that Vth is proportional to the temperature for the first order approximation, so ΔVth is also proportional to the temperature. The temperature coefficient of ΔVth depends on the size of M3 and M4. While M7 turn-on resistance is proportional to the temperature too. We carefully size each of transistors, so that temperature coefficients of ΔVth and M7 turn-on resistance are nearly cancelled each other. Therefore we get M1 current which is nearly independent to the temperature.

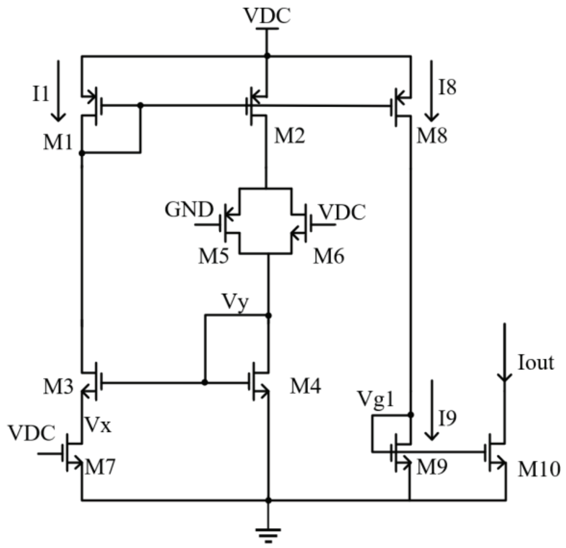

Fig. 3. The schematic of current generator 1.

Fig. 4 shows the simulation result of M1 current. We can see that the maximum value of current is 606.3pA, and the minimum value of current is 602.4pA, the variation of current is only 3.93pA, and its average value is 605.1pA. The temperature coefficient of the M1 current is 108.2ppm/℃. M1 current is mirrored to M8. M8 current is the same as M9 current and it is mirrored to M10, which is the current generator 1 output current. It will drive relaxation oscillator.

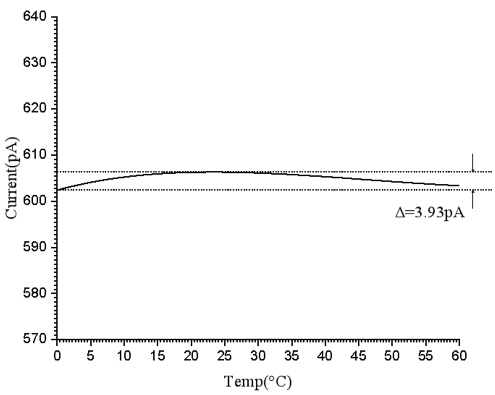

Fig. 4. The simulation result of I1 current flowing through M1.

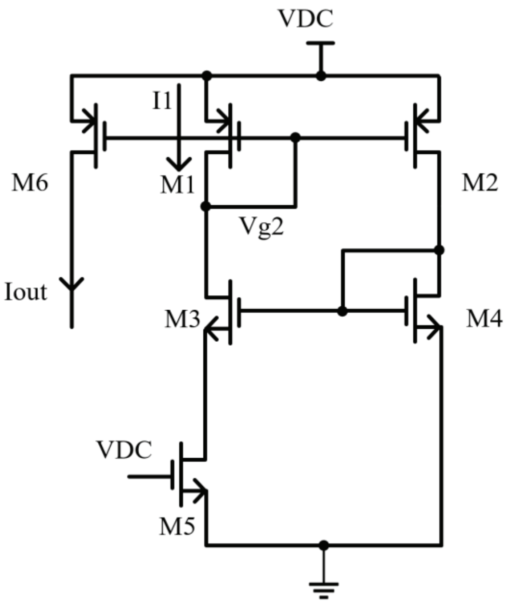

Fig. 5. The schematic of current generator 2.

As we mentioned before, current generator 2 is used to generate current I2. The schematic of current generator 2 is shown in Fig. 5. It is slightly different from current generator 1, but the working theory is the same. At this time, the temperature coefficients of ΔVth and M5 turn-on resistance are not cancelled. we carefully size each of transistors and make M1 current with positive temperature coefficient. The simulation result of M1 current of generator 2 is shown in Fig. 6. The I2 is used to control the relaxation oscillator to generate a waveform whose high level duration is complementary to absolute temperature.

C. Relaxation Oscillator

Relaxation oscillator is controlled by I1 and I2. And it outputs F_out whose high level duration is complementary to the absolute temperature and low level duration is constant with temperature. Its circuit is shown in Fig. 7. [6] The circuit has two branches, and by charging and discharging the capacitor, each of the branch controls half an oscillation period respectively. The node vg1 and vg2 are connected to the vg1 node in Fig. 3 and the vg2 node in Fig. 5 respectively. This means the M3 current is equal to generator 1 output current and M5 current is equal to generator 2 output current.

A cross-coupled inverter-based latch is used to keep the state of V1 node stable. M6 and M2 are used to stop charging or discharging the capacitors. For example, if V1 is high, M2 is on and C1 is discharged by generator 1 current through M3. At the same time, M6 is off and M7 discharges the capacitor C2 to the ground immediately. If V1 is low, M6 is on and C2 is charged by generator 2 current through M5. At the same time, M2 is off and M1 is on. The capacitor C1 is charged to VDC immediately. The relaxation oscillator structure is very simple. It consists of only a few of NOT gates and several MOSEFET. Compared with other oscillators, it can save a lot of power.

The oscillator works as follows: Supposing the initial state of V1 is zero, then M7 is off and M6 is on. M5 begins to charge capacitor C2. During the charging process, V2 is low and so V4 is low. It causes M8 is off and V5 is high. So V1 keeps zero. When the C2 voltage reaches the threshold voltage of the inverter INV2, the state of V3 changes from high to low. After several gate delays, it causes V1 becomes high. At this time, M7 is on and it will clear the charge on the capacitor C2, then the first half period is completed. So the low level time of V1 corresponds the charging time of C2 by generator 2 current. Because this current increases with temperature, the charging time is complementary to the temperature. After INV1, the low level time of V1 becomes the high level time of F_out. Similarly, from the upper branch, we get the high level time of V1 corresponds the discharging time of C1 by generator 1 current, which is independent with temperature. So the low level time of F_out is constant with temperature.

The simulation result of the relaxation oscillator output F_out is shown in Fig. 8. This waveform is only under 25℃ temperature. With different temperatures, it is found that the high level duration of the waveform is complementary to absolute temperature and the low level duration of the waveform is constant with temperature.

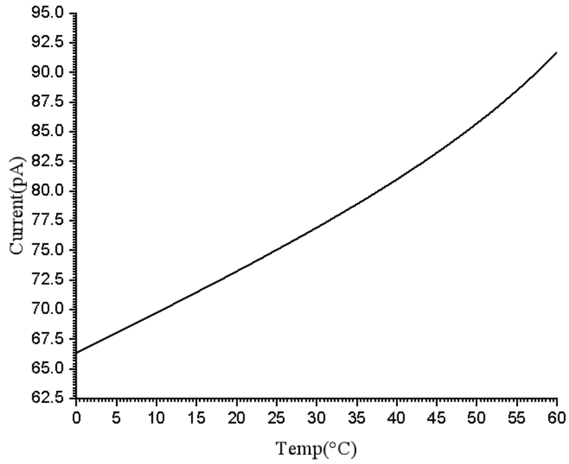

Fig. 6. The simulation result of current flowing through M1 of current generator 2.

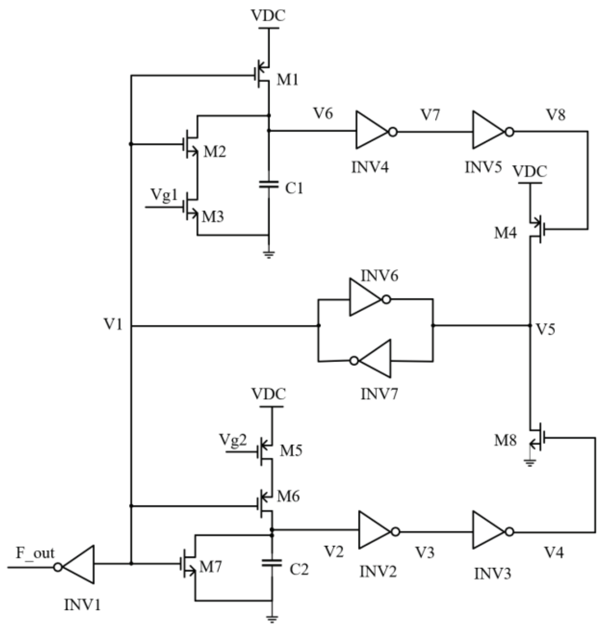

Fig. 7. The circuit of relaxation oscillator.

D. Separation Circuit and Digital Circuit System

This circuit is used to separate the high level duration and low level duration which means transforming the F_out into two signals UP and DOWN. The positive pulse width of DOWN signal is equal to the low level width of F_out, that is, it is temperature-independent. The positive pulse width of UP signal is equal to high level width of F_out, that is, it is complementary to the absolute temperature. The circuit can be realized by a D-flip flop and some logic gates. Fig. 9 shows the simulation results of the separation circuit. It can be seen that the positive pulse width of UP signal is equal to the high level duration of F_out, and the positive width of DOWN signal is equal to the low level duration of F_out.

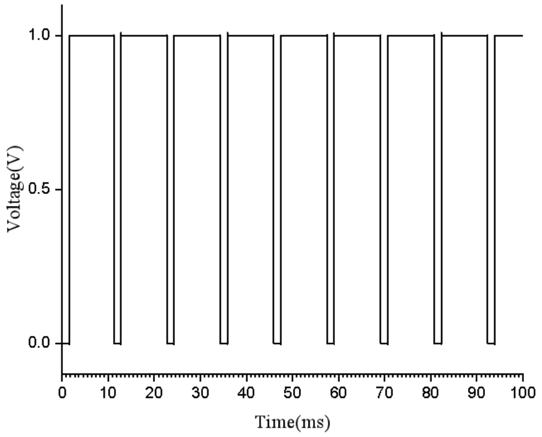

Fig. 8. The simulation result of the relaxation oscillator output F_out.

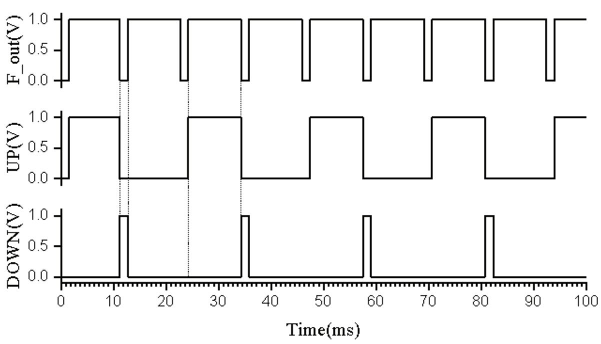

Fig. 9. The simulation results of the separation circuit.

The signals UP and DOWN are fed to digital circuit system to be quantified. We use counters to compute the positive pulse width of the two signals. Then a subtractor is used to get the difference of the two counter outputs. Therefore the digital circuit system output is a signal complementary to temperature. Fig. 10 shows the simulation results of the complete temperature sensor system. It represents the quantified value of the subtraction of the high level duration and low level duration of F_out. We simulate the complete temperature sensor system from 0℃ to 60℃ with the step of 5℃, so there are 13 points in the figure. It can be seen that the final digital output value is linear to the absolute temperature, therefore the proposed system could be used for temperature measurement. Because the high level of UP is complementary to the absolute temperature, the high level decreases while temperature increases. When the temperature is 60℃, the period of the UP waveform is down to minimum value of 19.2ms, so the maximum conversion speed is 52 Sa/s. According to the simulation results, the total power consumption of the complete system is 86.79 nW at 25℃. Such a low power could be scavenged from environment. The proposed ultra-low power temperature sensor could be used in a self-powered sensor system for IoT applications.

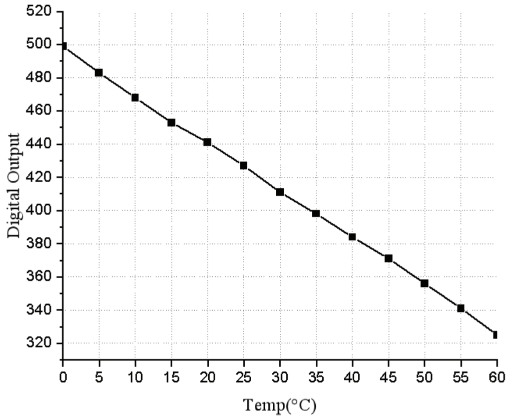

Fig. 10. The simulation results of the complete temperature sensor system.

III. CONCLUSION

This paper proposed a novel ultra-low-power temperature sensor. It works in time-domain and uses MOSFET working in the subthreshold region to achieve ultra-low power operation. Two simple current generators produce two current. They are utilized to control a relaxation oscillator to generate a signal, whose high level duration is complementary to absolute temperature and low level duration is constant with temperature. Then the signal is sent to a separation circuit and digital circuit system. Finally, a digital output is generated which is complementary of temperature. The total power consumption is 86.79 nW at 25℃ with the maximum conversion speed of 52 Sa/s.

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