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Temperature Sensors and Interface For Ultra-Low Power Microsystems

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Abstract: Ultra-low power Microsystems find their application in areas such as environmental monitoring, asset tracking, medical and control equipments. Proper choice of sensors and interface can play vital role in increasing power efficiency of such systems. This work studies and discuss various type of CMOS temperature sensors and their interface that can be chosen to improve the overall power consumption. MOSFET based temperature sensors due to their low power operations are preferred over conventional BJTs based temperature sensors. The paper discuss various topologies of MOSFET based temperature sensors and their readout interface. For low power operation, Frequency -digital conversion can be used instead of ADCs. Different type of data Convertors are discussed. Differentially Cross coupled VCO design is found to be most suitable with simulation results showing power consumption of 2~3 nW. A superior 2-T sensing element is implemented in 150nm which produce an absolute output value of 140mV with temperature coefficient of 500uV/C having power consumption of 4 nW for temperature range of -5°C to 40°C.

Keywords: Ultra low Power, Sub-threshold, PTAT, Temperature Sensor.

I. INTRODUCTION

Power Consumption stands as one of the most critical bottle neck in the design of ultra-low power Microsystems, which find their applications in areas such as , RFIDs , Implantable Medical Devices (IMDs) [1], wireless sensor networks and monitoring systems [2]. Temperature sensor is one of the most commonly used sensor in such Microsystems which makes it an important design element.

Also several type of convertors are used to digitize the output of these sensors for further processing/logging. A large portion of the power is consumed these conversion blocks. Thus careful design and choice of this constituent holds a key in improving the overall power efficiency of these systems.

This work studies the suitability of MOSFET based temperature sensors over BJTs in low power Microsystems, a comparison of different topologies of MOSFET based sensing elements is provided. The work also discusses the use of frequency-to-digital convertor instead of traditional ADCs as way of reducing the power consumption.

The paper is organized in five sections. Section II discusses BJT and MOSFET based CMOS temperature sensors, Section III discusses different type of data convertors. Section IV shows simulation results of a MOSFET based 2-T sensing element, and Differential Cross Coupled (VCO). Finally section V concludes the work.

II. CMOS TEMPERATURE SENSORS

Most Commonly used CMOS temperature sensors are based on substrate PNP bipolar junction transistors (BJTs) [3]. These sensors uses two BJTs biased at different values of stable bias current. , since the saturation current (Is) has a positive temperature coefficient, the base-emitter junction voltage V_{BE} shows complimentary-to-absolute-temperature(CTAT) behavior as can be seen in Eq. (1).

$$V_{BE} = \frac{KT}{q}\ln(\frac{I_C}{I_s}), \tag{1}$$

The difference between the base-emitter voltages of these two BJTs (ΔV_{BE}) shows proportional-to-absolute -temperature (PTAT) behavior as in Eq. (2).

$$\Delta V_{BE} = \frac{KT}{q}\ln(\frac{I_{C1}}{I_{C2}}), \tag{2}$$

Temperature can be measured by comparing these two temperature dependent characteristics . BJT based temperature sensor can achieve resolution as high as 0.003°C [4] and operate linearly for up to about 200 °C . However Saturation Current (I_s) has strong process dependencies resulting in errors and show power consumption in micro-Watt making them unfit for ultra low power Microsystems.

As CMOS process have shifted towards deep submicron process the MOSFET based temperature sensor are preferred [5]. When MOSFETs are biased in the sub-threshold region, the drain current (I_D) and the gate-source voltage VGS have an exponential relationship:

$$V_{GS} - V_{th} = \frac{\eta KT}{q} \ln(\frac{I_D}{I_o}) \quad (3)$$

where Io is a process-dependent parameter and η is the sub-threshold slope factor. This Eq. (3) is very similar to Eq. (1) which shows that BJT can be replaced with MOSFETs in sub threshold region that requires only a few nA current for operation.

A conventional 2-T sensing element uses two different MOSFETs (having different threshold voltages) [6]. as shown in Fig. 1.

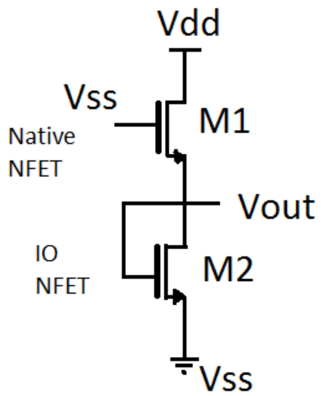

Fig. 1 A conventional 2-T MOSFET based Temperature sensing Element

Same current is flowing through M1 and M2, so equating I_{d1} and I_{d2} an mathematical expression for V_{out} can be expressed as:

$$V_{out} = \frac{\eta_1\eta_2}{\eta_1 + \eta_2}(V_{th2} - V_{th1}) + \frac{\eta_1\eta_2}{\eta_1 + \eta_2} V_t \ln(\frac{\mu_1 C_{ox1} W_1 L_2}{\mu_2 C_{ox2} W_2 L_1}) \quad (4)$$

The threshold Voltages (V_{th}) have CTAT characteristic while thermal Voltage (V_t) is PTAT in nature. With proper sizing , output voltage can be made either PTAT or CTAT. However due to the difference of threshold voltages this topologies have a large process coefficient, also the absolute value of Vout is hundreds of mili-volts, thus increasing in power consumption.

A new type of sensing element [7] uses same type of MOSFET for both devices in 2-T sensing element as shown in Fig. 2. The use of same of devices greatly minimizes threshold voltage dependent variation in Eq (4), neglecting the body effect and Drain Induced Barrier Lowering for long channel device gives output voltage as :

$$V_{out} = \frac{\eta_1\eta_2}{\eta_1 + \eta_2} V_t \ln(\frac{\mu_1 C_{ox1} W_1 L_2}{\mu_2 C_{ox2} W_2 L_1}) \quad (5)$$

Eq. 5 shows that output voltages does not depend on threshold voltages, and carrier mobility can be canceled . Thus output voltage will have low sensitivity to process variation, and a low absolute value for the output voltages will improve the power consumption. This topology is chosen to be simulated in section IV.

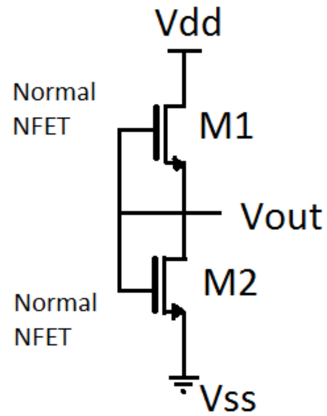

Fig. 2 A 2-T Sensing element with same type of transistors

III. DATA CONVERTORS

The output from Sensors is converted in to digital codes for transmission, logging and processing in computers. Traditionally Analog-to-Digital-Convertors (ADC) are used in Microsystems, several architecture of ADCs have been developed such as Flash[8], Successive-Approximations-Register (SAR)[9] and Integrating ADC[10], each offering trade-offs between speed, area, power consumption , resolution and accuracy. But even the most optimal designs consume power in uW range [11]. For low power operations time-to-digital [12], [13] or frequency-to-digital convertors [14], [15] can be used instead of Analog-to-Digital convertors minimizing the area and power consumption to a few Nano-W, which also reduce accuracy and resolution.

Delay cells with sub threshold current biasing , in ring VCO configuration [7],[16] ensures nWatt operation. The VCOs can be designed to oscillate at low frequency to minimize the switching losses. The frequency from such an Oscillator can be compared with the frequency of a reference Oscillator to obtain the digital code. One such configuration [16] shown in Fig. 3, the DCC delay cell is composed of a differential NMOS input pair, with cross coupled PMOS transistors, which are used as a negative resistance load. The ring VCO is designed using three DCC delay cells. The current passing through the delay cells is controller through a current mirror in the tail. A low Current in the tail , along with careful transistor sizing enables the sub-threshold operation of this DCC cell. The cross-coupled pair uses the same current passing through the main NMOS pair , thus using the same current for both the pairs, a small change in tail current can achieve a larger delay variation improving the sensitivity.

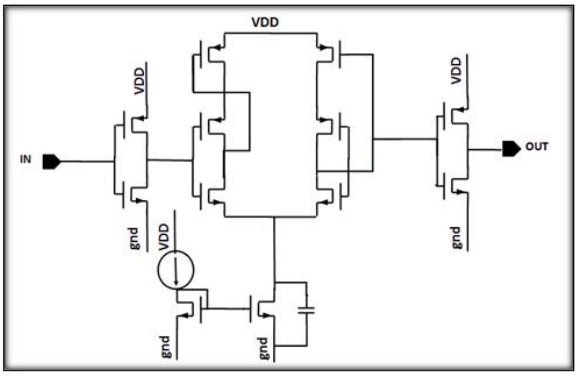

Figure 3 Differentially Cross Coupled VCO

IV. SIMULATION RESULTS

The MOSFET based 2-T is implemented in .15um CMOS process, the simulation is done in Cadence Virtuoso, as shown in Fig.4. Fig.5 shows the simulation results of the sensing element, it produces a PTAT voltage in its output with a sensitivity of 500uV/°C across all process corners FF, FS, SF and SS. The absolute output value is around 140 mV at 1 volts Vdd, and changes only 5% across corners with power consumption up to 4nW at Fast Corner. The output voltage has supply sensitivity of only ±2% for a supply change of ±10%. Proper sizing can achieve a lower absolute value of output improving the supply tolerance and power consumption.

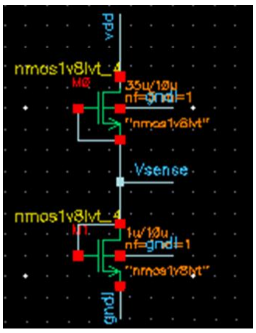

Figure 4 Simulation of 2-T sensing element in Cadence Virtuoso

The DCC VCO is also simulated for different Process corners, temperature and Supply voltages. The transient simulation for typical process corner at 5C is shown in Fig.6. DCC-VCO has moderate temperature sensitivity of (0.6%/°C), and good supply sensitivity of (0.4 % /mV) while consuming only 2-3nW power in its operation. Table 1 shows the performance in simulation across PVT corners. The interface can be made PVT tolerant by using a reference VCO with similar architecture and comparing their frequency to generate the digital code.

Table 1 VCO performance across PVT corners

Corner	Frequency	Temperature Coefficient
SS	990 Hz	0.5% / ^{0}C
FF	1.1 KHz	0.6% / ^{0}C
SF	995 Hz	0.5% / ^{0}C
FS	1.05KHz	0.6% / ^{0}C

Fig. 6 shows the output of VCO at 5°C at Typical process corner and Vdd = 1V.

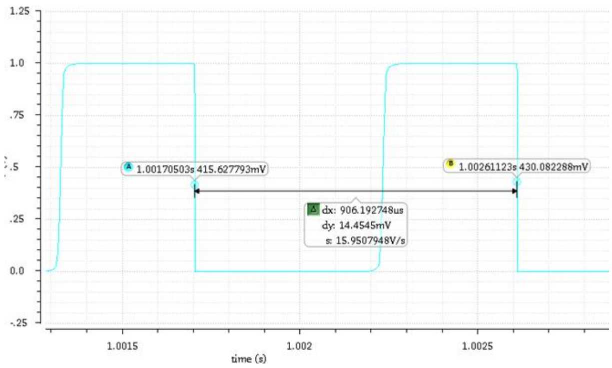

Figure 6 VCO simulation For typical corner at 5°C

V. CONCLUSION

Research into smart temperature sensors is currently driven by the requirements of key applications such as : RFIDs , WSNs and environmental monitoring systems. while most of the research in this area emphasize to manage the utilization power by the constituents of

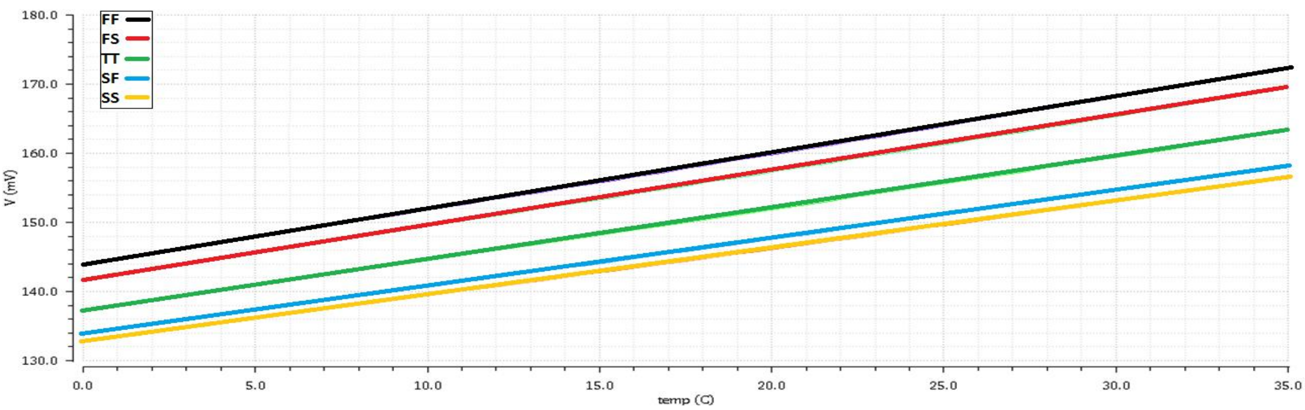

Figure 5 Simulation results of MOSFET based 2-T temperature sensing element

the sensor, the choice of right design and architecture of these components can have a large impact on overall power consumption. The simulation of 2-T MOSFET based temperature sensors with frequency-to-digital convertors readout shows power consumption of less than 10nW with sensitivity up 500uV/C and good supply tolerance thus proving it highly suitable for sub-nW operation.

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