D14-037

High-Accuracy, High-Speed, Low-Power Consumption Time-Domain Smart Temperature Sensor with Voltage Calibration

高精度、高速、低功耗具電壓校正之時域智慧型溫度感測器

隊伍名稱

溫贏耶!!! / Winner!!!

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作品摘要

在高度科技化的現代社會裡，眾多感測器陸續被開發、使用。除了強調高精度、低功耗、小面積與低成本以符合節能減碳之趨勢外，更講求功能最佳化與嚴控品質穩定度，以契合市場發展所需。其中，溫度感測器擁有龐大的市場潛力，高性能、低功耗及低成本的溫度感測器需求與日俱增，重要的應用包含：環境溫度監控、感應火災及煙霧探測系統、平面顯示器溫度補償、背光系統溫度管理、可攜式或移動式消費電子溫度控制系統、輪胎溫度監測系統…等等應用。

傳統溫度感測器採用BJT充當感溫元件，產生一與溫度成正比（PTAT）之訊號以及另一低溫度之帶差參考電壓/電流訊號，

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再藉由類比至數位轉換器（ADC）轉出數位輸出。利用ADC將與溫度相關訊號轉成數位輸出之溫度感測器（電壓域溫度感測器）具有高精準度，但電路結構複雜且採用動態元件匹配（DEM）、斬波（Chopping）…等技術來消除製程不匹配，致使轉換速度變慢。為此，我們提出一利用時間至數位轉換器（TDC）為核心之溫度感測器架構（時域溫度感測器）來取代電壓域的架構以降低電路架構複雜度、提高轉換速度。我們採用MOSFET當作感溫元件來產生與溫度成正/反比（PTAT/CTAT）之輸出電壓，再藉由低溫敏之電流在此二電壓區間對電容充放電，以產生高溫敏之輸出脈衝寬度，再利用TDC將它轉換成數位輸出。此時域感溫器之精度雖較電壓域者稍差，但全然符合當下絕大部分之工業與民生要用之要求，且架構簡單、每次轉換所需之功耗遠低於電壓域之對手。

無論電壓或時域的溫度感測器，為了克服製程變異的影響通常需要單點或雙點恆溫校正以達到足夠之精度。與電壓跟電流相比，溫度的傳導速度非常慢，因此需等候相當長之穩定時間（Setting Time）才能讓待測晶片之溫度與校正溫度趨於一致，才能進行校正，致使量產成本飆升。為此，本設計傾全力讓時域溫度感測器擺脫定溫校正之桎梏，並同時兼顧功耗、速度、精度，為時域溫度感測器奠定重要研發基礎。

本次參賽作品乃是全球第一顆採用電壓校正之時域智慧型溫度感測器，可大幅壓低量產成本。主要架構採一數位可調弛張振盪器，其電壓振盪範圍為上述具曲率補償之PTAT與CTAT兩溫敏電壓，用以產生與溫度相依且高線性度之輸出脈衝，再透過TDC轉出數位輸出，更重要的是，該弛張振盪器之製程變異可透過電壓校正加以去除。本溫度感測晶片使用TSMC 0.18-μm CMOS標準製程來實現，操作速度高達486k S/s，晶片總面積僅為0.122mm^2，-40℃至120℃範圍之三個標準差（3σ）誤差只有±1.5℃，其性能甚至優於以往一些需要單點或雙點校正之溫度感測晶片！終於為時域智慧型溫度感測器立下擺脫定溫校正桎梏之嶄新里程碑。

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研究領域

類比 / 混合訊號 IC 設計與佈局、驅動 IC 與電源管理 IC 設計。研發項目以時域訊號處理電路為主，包含：溫度感測器、PLL、DLL、DCC、TDC、DTC 與 DPWM…等。

Abstract

Low cost but high performance temperature sensors are extensively applied to the following applications:1) ambient temperature monitoring for home or office electronics;2) thermal sensing for fire and smoke detection systems;3) thermal compensation for flat panel displays; 4) temperature management for backlight systems and power electronics; 5) temperature control in portable or mobile consumer electronics products such as personal computers and domestic appliances ; 6) tyre monitoring systems and 7) combing integrated temperature sensors with Radio Frequency Identification (RFID) tags.

Conventional temperature sensor digitizes a proportional to absolute temperature (PTAT) signal according to temperature-independent bandgap reference signals. A corresponding ADC is utilized for digital output coding. The ADC-based temperature sensor (commonly known as voltage-domain temperature sensor) has high accuracy, but the corresponding architecture is usually complicated and possesses slow conversion rate due to chopping, dynamic element matching (DEM) and/or auto-zeroing to suppress 1/f noise and offset for excellent accuracy [2-3]. One feasible way for reducing structure complexity and speeding up operation is to process the sensed signal mainly in time- instead of voltage-domain. The sensor converted the test temperature into a time signal with a thermally sensitive width first and then utilized a time-to-digital convertor (TDC) which could be much simpler and more power efficient than ADC for output coding. However, the expense was comparatively poor accuracy.

Regardless of voltage- or time-domain design, the sensors usually needed one- or two-point thermal calibration to get enough accuracy. Compared to voltage or current calibration, the temperature of test chips needs much more time to be stabilized and thus the mass production cost is hard to be reduced.

To overcome the calibration and mass production problem, this thermal sensor presents the first voltage-calibrated CMOS time-domain smart temperature sensor to reduce the cost of mass production. A digitally adjustable relaxation oscillator designed as the temperature sensor vibrates between CMOS-based CTAT, PTAT voltage references with mutual curvature compensation to generate linear temperature-dependent output pulses. Voltage instead of temperature calibration is adopted to alleviate the impact of process variation and TDC is used for output coding. Fabricated in a TSMC 0.18-μm standard CMOS process, the proposed sensor is able to operate at a high speed of 486k Samples/sec. Moreover, each sample consumes only 535pJ. The active area is merely 0.122 mm^2, resolution is 0.26 ℃ and inaccuracy is measured to be ±1.5 ℃ (3σ) for 15 test chips in a wide temperature range of -40 ℃ to 120 ℃. The performance is even superior to some chips with one- or two-point temperature calibrations. A milestone is established for time-domain smart temperature sensor to get rid of the heavy burden of fixed-temperature calibration with reason error budget.

With the help of SAR, the temperature-insensitive variable current source is fine-tuned to compensate for the process variations faced by the oscillator under voltage calibration to get rid of the need of any fixed calibration temperature. Monte Carlo simulation is adopted for the critical device sizing of the VPTAT and VCTAT generator to ensure acceptable spread for all 5 process corners. Even voltage-calibrated over a wide temperature range of 0 ℃ ~ 80 ℃, the proposed sensor still achieves an inaccuracy approximately ±0.8 ℃ along with a linear master curve. Ensured by the experimental results, the proposed sensor has great potential to exploit the most popular low cost market with ±1℃ error tolerance.

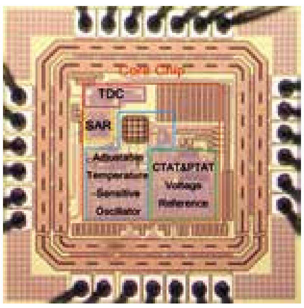

Fig.1 > Chip microphotograph