A 0.04mm^3 16nW Wireless and Batteryless Sensor System with Integrated Cortex-M0+ Processor and Optical Communication for Cellular Temperature Measurement

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Abstract

This paper demonstrates a complete wireless sensor node for accurate cellular temperature measurement that includes a fully programmable Cortex-M0+ processor, custom SRAM, optical energy harvesting, 2-way communication, and a subthreshold temperature sensor. The temperature resolution is 0.034°C RMS, and the transmit distance extends to 15.6cm. The 0.04mm^3 (~500× smaller than a grain of rice) fully assembled cellular temperature sensing system (CTS) is 24× smaller than prior programmable sensing systems [3], enabling implantation in a cluster of cells or large egg cells for biological studies.

Introduction

Monitoring cellular temperature, as an indicator of cellular metabolism, is highly beneficial for disease study and drug discovery, as many diseases (e.g., cancer) are characterized by abnormal metabolism. Recently scientists have achieved passive temperature mapping inside living cells using fluorescent materials [1] with limited accuracy of 1.3°C and 0.58°C resolution. This method nevertheless lead to the discovery that mitochondria are 10°C higher than in other parts of a cell [2]. Silicon implementation of accurate, autonomous sensor systems for cell cluster temperature measurement is lacking and can facilitate further biological discoveries. Direct measurement of such cellular temperatures is extremely challenging since it requires highly localized measurements. Cellular sensor size cannot exceed 0.1 mm^3 to achieve good spatial resolution, making prior miniature implantable sensor systems (typically several mm^3) [3-5] impractically large.

This aggressive size constraint for cellular sensor systems (<0.1mm^3) creates two major design challenges: 1) Efficient wireless communication to program the processor and retrieve data is very difficult given the sub-mm area constraint. RF antenna efficiency degrades quickly with antenna size, forcing very high carrier frequencies (and correspondingly high power circuits and mm TX distance [6]). The proposed CTS uses optical communication since transmitter and receiver elements (LED and PV diodes) readily scale to tens of µm without efficiency loss. 2) Temperature-independent frequency and voltage references are critical for communication synchronization and high accuracy temperature sensing. However, crystals are far too large and bandgaps too power hungry for a sub-mm sensor. Hence, CTS uses a base-station generated clock reference encoded with the optical link, enabling reliable communication over 15.6cm and temperature measurement using a subthreshold oscillator to achieve a high accuracy of +0.11/-0.08°C and 0.034°C RMS resolution.

Cellular Temperature Sensing System

Fig. 1 shows the CTS, which integrates a commercial Cree LED for optical transmission, custom 50 x 50 µm AlGaAs diode for optical reception, and 180 x 230 µm custom AlGaAs diode for power harvesting on the top layer. The bottom layer of CTS is a custom chip (360×400×150µm) in 55nm CMOS (MIFS C55DDC) including a M0+ processor with full programmability, subthreshold oscillation based temperature sensor [7], TX and RX circuits, LED drivers, and custom SRAM. A Photomultiplier Tube (PMT) in the base station senses transmitted data from the sensor node (Fig. 1) and includes an optical filter to remove self-interference. Since cellular-level temperature measurement is typically performed in a controlled laboratory environment, lighting conditions can be restricted to wavelengths that limit interference. The always-on base station supplies modulated light (615nm) to power the battery-less sensor node and supply an accurate clock. CTS operates at 3klux with 16nW system power consumption (including TX and temperature sensor). We verified full autonomous, wireless system operation with the complete stack shown in Fig. 1. Its measured system operation (Fig. 3) shows boot-up, default program operation, wireless programming by the base station, temperature measurement with on-chip recovered accurate clock, transmission of temperature codes through sensor node LED, and successful demodulation of the correct packet at the base station (Fig. 3).

Figs. 2-3 show the CTS architecture and captured operation sequence. When the base station sends only DC light, CTS enters a power-on mode in which it executes a default program stored in a register file. To program the CTS, the base station sends Manchester-coded modulated light, which is received by the integrated photodiode, canceled for ambient light, and demodulated [8]. Once CTS recognizes the password, it shifts its system clock source to the recovered accurate base station clock. The system then stores the received program in a 4Kb SRAM optimized for static power reduction and activates the M0+ processor for program execution. Our sensors were programmed to take temperature measurements, store them and then transmits data with pulse position modulated light signals via the integrated LED at 180pJ/bit (simulated) using energy accumulated on 100pF on-chip capacitor C1.

Circuit Block Implementation

Fig. 4 shows the transmitter circuit implementation. A charge pump accumulates charge harvested from the photovoltaic (PV) cell on the on-chip capacitor C1, which then supplies energy to the LED with regulated current and accurate timing dictated by a PPM modulator. Each LED flash sends out a 2-bit symbol. Regulated LED current is optimized for minimum energy per bit. A voltage regulation loop controls VLED_Anode on C1 to prevent voltage overshoot. As shown at the bottom of Fig. 4, the regulation loop divides the voltage on VLED_Anode with a charge-sharing voltage divider and compares the divided voltage Vcs with the on-chip generated reference voltage Vref. The charge pump is clock gated when Vcs>Vref.

A key design consideration for the IC layer is light exposure as coating with a light blocking epoxy is not feasible in the required form factor. This led to different design decisions than in other ultra-low power systems, e.g., the voltage divider in Fig. 4 uses capacitive charge sharing instead of a conventional diode stack divider to avoid inaccuracies introduced by photo-generated current from parasitic P-N junctions in diode stacks under light exposure. Similarly, the voltage reference providing Vref is sized to have a bias current larger than the photogenerated currents to ensure robust operation under light.

CTS senses temperature (Fig. 5) by converting subthreshold current, which is exponentially dependent on temperature, to frequency, which is measured relative to the accurate reference clock. We employ a sensing oscillator structure similar to [7] due to its low line sensitivity created by a stacked native NMOS header that serves as a supply voltage regulator. This supply voltage invariant temperature sensor greatly relaxes supply regulation requirements in the system, enabling batteryless operation without voltage regulation even under modulated light intensities, improving power and area efficiency.

Measurements

The proposed CTS circuit exhibits +0.38/−0.33°C average error (2-point calibration) for five chips across 10−60°C (Fig. 6), which is a wider range than required for biological measurements. Line sensitivity is 0.6%/V, corresponding to 0.17°C/V. Heating effect of the base station on the sensor was measured to be negligible (<0.1°C in 3hrs). In addition, heating effect from sensor LED can be mitigated by delayed read-out after experiment, thanks to the integrated processor and memory. A fully assembled CTS stack is measured using the setup in Fig. 7, demonstrating successful wireless programming and accurate sensing using clock recovery (Fig. 3). Fig. 8 shows temperature readings received wirelessly from a fully assembled CTS stack across 10−50°C, showing 0.034°C RMS resolution and +0.11/−0.08°C error. Table 1 compares this work to other small sensing platforms [3-6].

References

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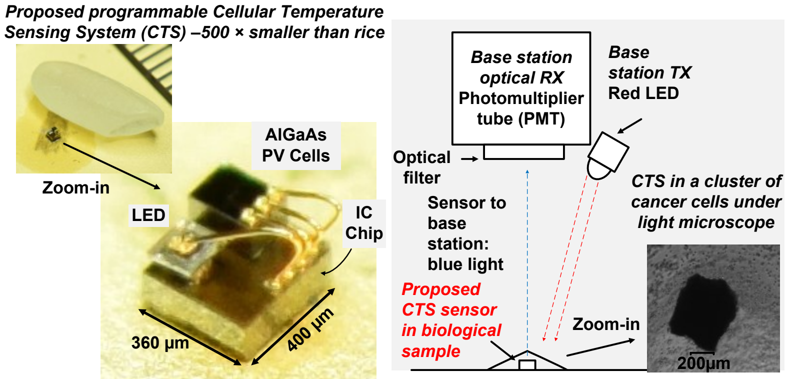

Figure 1. CTS encased with bio-compatible material and implanted in a cluster of homogeneously dispersed HS5 human bone marrow stromal cells

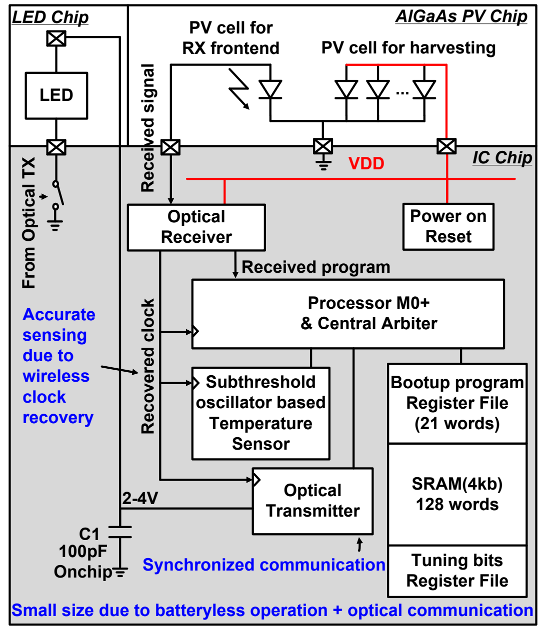

Figure 2. System architecture of CTS

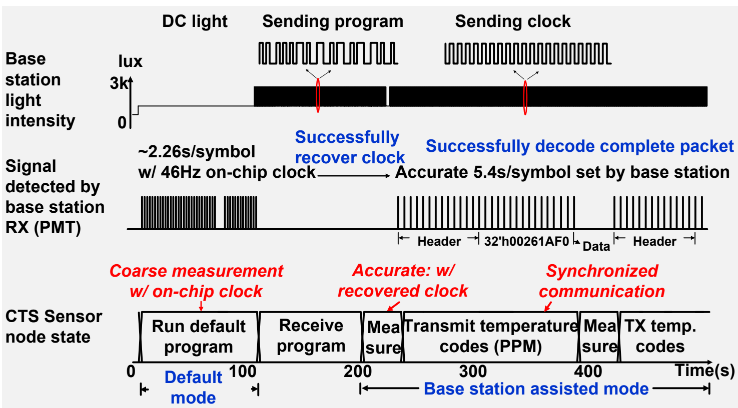

Figure 3. Measured waveform with fully assembled CTS system

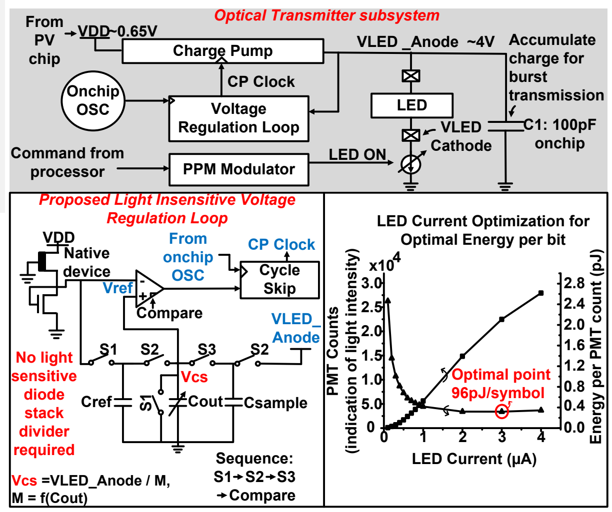

Figure 4. Circuit implementation of optical transmitter subsystem

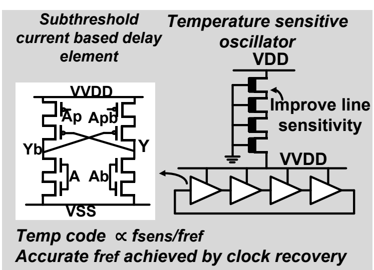

Figure 5. Implementation of temperature sensor

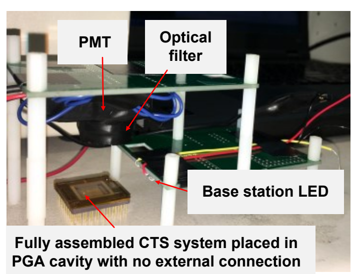

Figure 7. Testing setup showing CTS stack in use with base station

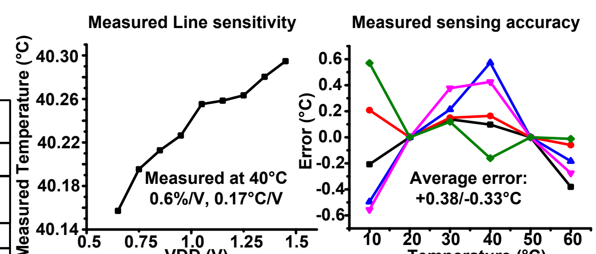

Figure 6. Measured temperature sensing performance

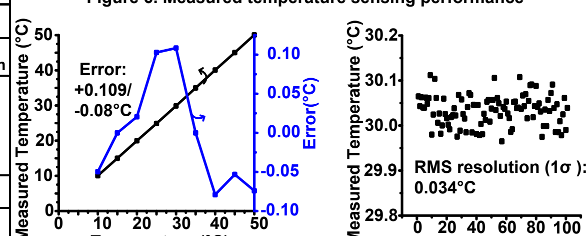

Figure 8. Sensing error and RMS resolution measured wirelessly with fully assembled CTS stack

Table 1. System performance comparison

	This work	[3] JSSC-2013	[4] ISSCC 2017	[5] Nature Bio. 2012	[6] RFIC 2017
Technology	55nm	0.18µm,0.13µm	0.18µm	0.18µm	65nm
System Dimension	360 x 400 x 280µm	1.1 x 2.21 x 0.4mm	2.8mm diameter, 200µm thick	11 x 9 x 0.2mm *	200 x 200 x 100µm
System Volume	0.04mm^3	0.97mm^3	0.38mm^3 **	19.8mm^3	0.004mm^3
System Power	16nW	11nW (standby) 20µW (active)	48.9µW	1.12nW	63nW
Integrated Processor	Yes	Yes	No	No	No
Sensor	Temperature	Temperature	Pressure	Endocochlear potential	Glucose concentration
Sensor Performance	Error +0.38/-0.33°C Line sensitivity 0.17°C/V RMS resolution 0.034°C	RMS resolution: 0.51°C	Pressure sensitivity: 0.67mmHg	RMS error: 0.45mV	--
Communication	Optical	RF/Optical	RF	RF	RF/Optical
TX/RX Area	0.07mm^2	0.168mm^2	4.52mm^2	12mm^2	0.04mm^2
Transmit Distance	15.6cm	10cm	20cm	1m	2mm

*System thickness is estimated from paper **Not including volume enclosed by powering coil