Energy Efficient Design and Energy Harvesting for Energy Autonomous Systems

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***Abstract*— Energy autonomy enabled by the energy efficient design and the energy harvesting is the one of the top requirements for maintenance-free IoT sensor nodes and wearable/implanted devices. In this paper, energy efficient ultra-low voltage (< 0.5V) circuits are shown. Energy autonomous wearable healthcare devices using the flexible, large-area, and distributed organic electronics are also shown.**

I. Introduction

Requirements for IoT sensor nodes, wearable healthcare devices, and implanted medical devices are the wearing-unconsciousness and the maintenance-free operation as shown in Fig.1. To enable the wearing-unconsciousness, mechanically flexible or small-size devices with the wireless connection are required. To enable the maintenance-free operation, energy autonomous devices are required. The energy autonomy is achieved by both the energy efficient operation and the energy harvesting. In this paper, energy autonomous systems with the energy efficient design and the energy harvesting are shown.

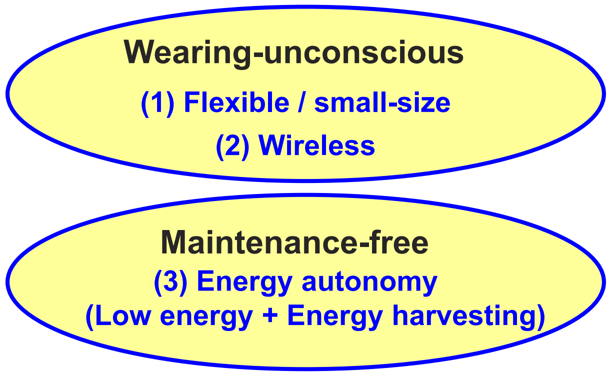

Fig. 1. Requirements for wearable/implanted devices.

II. Energy Efficient Design

The energy efficient operation is achieved by a near-threshold operation and a temporal-spatial fine-grained control. Fig. 2 shows the simulated power supply voltage (V_{DD}) dependence of power, delay, and energy. Compared with the nominal operation at V_{DD} = 1.2V, the energy of the near-threshold operation at V_{DD} = 0.3V is reduced to one-tenth of that at V_{DD} = 1.2V. Fig. 3 shows the temporal-spatial fine-grained control [1]. In the conventional design, the clock frequency (f_{CLK}), V_{DD}, and the threshold voltage (V_{TH}) of transistors are common within a chip. In contrast, in the state-of-the-art design, many different f_{CLK}'s, V_{DD}'s, and V_{TH}'s are used within a chip and they are dynamically changed to minimize the energy. Such temporal-spatial fine-grained control includes the dynamic voltage scaling [2], the dynamic frequency scaling [3], the power gating, the clock gating, the body biasing, the local gate overdrive [4], and the quick wake-up circuits [5].

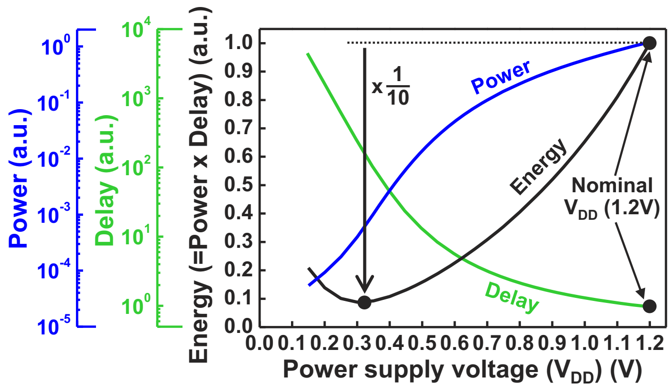

Fig. 2. Power supply voltage dependence of power, delay, and energy.

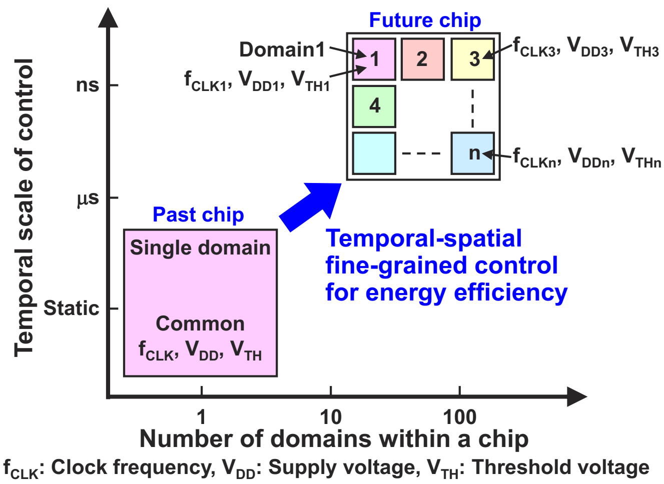

Fig. 3. Temporal-spatial fine-grained control.

Fig. 4 shows a block diagram of extremely low power 0.5V SoC for IoT sensor nodes. The voltage obtained from the energy harvester is regulated by the power management circuits [6-7] and many different V_{DD}'s are given to A/D

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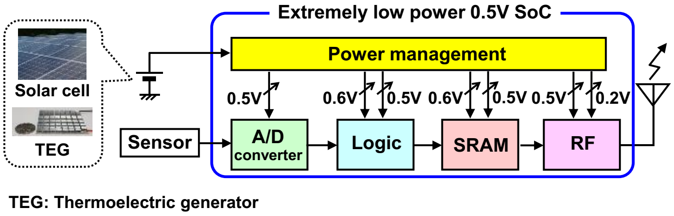
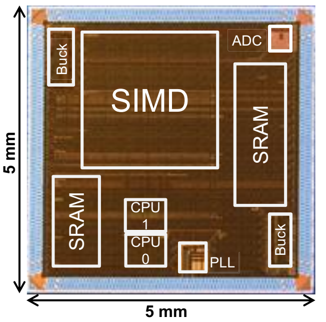


Fig. 4. Block diagram of extremely low power 0.5V SoC for IoT sensor nodes.



Technology	40 nm CMOS		
Die size	5 mm x 5 mm		
Number of Transistors	31 M (Logic : 16 M, SRAM : 15 M)		
Logic cores	CPU	32 bit	
	SIMD	4 bit, 320 PE	
SRAM	CPU	Inst.	1 Mbit
		Data	256 kbit
	SIMD	Inst.	512 kbit
		Image	128 kbit x 4
		Work	64 Byte x 320 (2port)
Frequency	10 MHz		
Supply voltages	V_{LOGIC}	0.5 V	
	V_{CLK}	0.6 V	
	V_{SRAM1}	0.8 V (1 port)	
	V_{SRAM2}	0.6 V (2 port)	
Power	9 mW		
SIMD performance	559 GOPS/W (5.73 mW@10 MHz) Max. 563 GOPS/W (4.26 mW@7.5 MHz)		

Fig. 5. 0.5V image processor [3].

converter, logic circuits, SRAM, and RF circuits for the temporal-spatial fine-grained control to minimize the energy. Fig. 5 shows an example of 0.5V SoC [3]. The 0.5V image processor with 563 GOPS/W SIMD and 32bit CPU includes an all digital PLL (ADPLL), an A/D converter, and buck converters.

III. Energy Autonomous Wearable Flexible Devices

The organic electronics enables flexible, large-area, and distributed sensor and/or actuator array and is suitable for the wearing-unconscious devices. Several energy autonomous wearable healthcare devices using the organic electronics have been proposed [8-9].

Fig. 6 shows a photograph of a fever alarm armband (FAA) [10] integrating fully flexible solar cells, a piezoelectric speaker, a temperature detector, and 12V organic complementary FET circuits. FAA is a flexible energy autonomous healthcare device with the wireless interface. FAA is looped around an upper arm of a patient in a hospital room, and the temperature detector monitors the underarm temperature of the patient. 220-µm thickness amorphous silicon solar cells attached outside of the upper arm generate the power. When high fever is detected, a 52-µm thickness piezoelectric speaker with polyvinylidene difluoride (PVDF) makes a sound to alarm a nurse. Organic circuits and the temperature detector are fabricated on a 50-µm thickness flexible polyimide film, and the solar cells and the speaker are attached on it. Fig. 7 shows a block diagram of FAA. An active

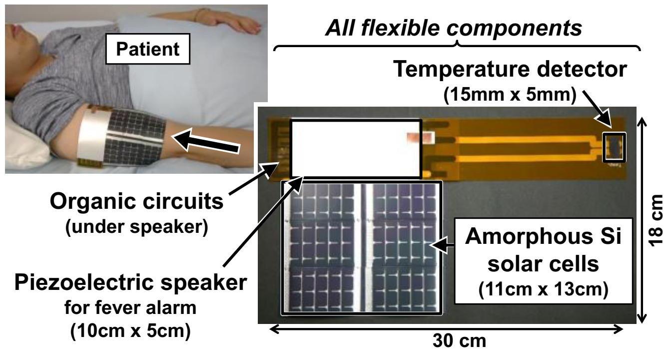


Fig. 6. Fever alarm armband [10].

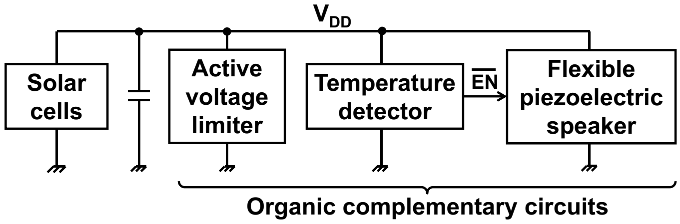


Fig. 7. Block diagram of fever alarm armband [10].

voltage limiter regulates V_{DD}. When the measured temperature is higher than the preset threshold temperature, a ring oscillator starts oscillation and the speaker makes a sound.

Acknowledgment

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