Ultra-low-power circuit techniques for mm-size wireless sensor nodes with energy harvesting

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Abstract: This paper describes circuit techniques for energy-harvesting technology in millimeter-size ultra-low-power batteryless wireless sensor nodes as a front end for BigData, IoT, M2M, and ambient intelligence. Power generated by energy harvester becomes as small as the nanowatt level when the size of a sensor node becomes millimeter-size. First, technical trends in low-power circuits and the portfolio of energy harvesting and circuit technology are discussed from the viewpoints of technical and application issues. Then, circuit techniques for nanowatt level wireless sensor nodes—a zero-power vibration sensing circuit, power management with MEMS switch, and an intermitted RF transmitter—are explained.

Keywords: wireless sensor node, low power, sensing circuit, power management, RF transmitter, energy harvesting, MEMS

Classification: Integrated circuits

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1 Introduction

Wireless sensor node technology with an energy harvester has become attractive recently, and wireless sensor networks (WSNs), which obtain various sensing data and transmit the data to the Internet, are advocated to advance the ubiquitous society [1]. Irrespective of such expectations, WSNs have actually not become as widespread as ICT (Information and Communication Technology), which has spread dramatically. This is because of restrictions on the size and battery life of sensor nodes and also because of the lack of key applications. However, the situation could abruptly change with the explosive popularity of smartphones in recent years. Smartphones pre-install the GPS function, Wi-Fi, Bluetooth, and accelerometers, which provide a basic platform for sensor nodes. Furthermore, we are seeing the start of huge data processing with Cloud technology, which enables the extraction of useful information and returns it to society or users, which is called BigData. An infrastructure that connects all devices and sensors to the
Internet, which is called IoT (Internet of Things), M2M (Machine to Machine), or ambient intelligence, is becoming a reality. In such a situation, there is a growing demand for a self-consistent sensor node that harvests minute amounts of energy from the environment. In order to embed sensor nodes in everything and without the need for node maintenance, further technical innovations are required. Therefore, millimeter-size batteryless sensor nodes with an energy harvester will be desired as shown in Fig. 1.

In this paper, first, trends in circuit technology for energy harvesting are described. Next, the architecture and operation of the nanowatt level sensor node we developed are explained. Furthermore, as ways to achieve nanowatt level operation, a zero power vibration sensing circuit combined with a variable MEMS capacitor, a power management circuit using a MEMS switch, and an intermittent RF transmitter are explained in detail.

2 Trends in circuit technology and energy harvesting

The relationship between the size of the energy harvester and the power it generates is shown in Fig. 2 [2]. The generated power is proportionally reduced as the size of energy harvester decreases. The energy generated by vibration is larger than that by
light in room conditions. In this case, the generated energy is limited to under 100 µW in the size of a centimeter-order (100 mm³, 100 mm²) and to under 1-µW in the size of a millimeter-order (1 mm³, 1 mm²). We have been working to develop millimeter-size batteryless sensor nodes. So, the target of the power consumption of the sensor nodes is the nanowatt (nW) level.

Fig. 3 plots the change in power consumption of low-power LSI chips reported from 2007 to 2014 at ISSCC and VLSI Circuits [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37], which are the most popular international conferences in the semiconductor industry. It is found that there are three domains: milliwatt, microwatt, and nanowatt. Low-power processing is located at the milliwatt level. On the other hand, the power consumption of LSI chips for sensor nodes and mobile applications has been reduced to the microwatt level. In recent years, some circuit chips with power consumption below the microwatt level have appeared. Furthermore, circuit techniques for millimeter-size sensor nodes have been developed and power consumption at the nanowatt level of them has been achieved.

The technical trends in power generation of energy harvesters and power consumption are reflected in the research portfolio for energy harvesting and circuit techniques, as shown in Fig. 4. As for technical requirements, there is the viewpoint of “power generation,” or how to generate electric power efficiently from restricted energy sources, and the viewpoint of “ultra-low power,” or how to reduce the power consumption of circuits that operate with limited electric power. It functions as a system when these technologies harmonize. Moreover, since it is difficult to adapt them to all the applications, the trend is for technical development customized for applications. The applications, in terms of the handling of sensing data, can be classified into continuous-monitoring and event-driven applications. Continuous monitoring requires a battery to be charged. For event-driven applica-
tions, batteryless operation is preferable. Therefore, there are four research areas wherein key technologies are combined: energy harvesters, ultra-low power circuits, continuous-monitoring applications and event-driven applications.

From Fig. 4, we see that the portfolio is concentrated on power generation. Specifically, many companies have been developing piezoelectric/electret devices that increase power-generation efficiency by vibration and dye-sensitized solar cells suitable for indoor light-power generation. These developments assume TPMS (tire pressure monitoring system) and the telemetry system of a plant, etc. The size of the sensor node is centimeter order and generated power is between microwatts and milliwatts. In this case, in order to achieve stable continuous monitoring, it is necessary to mount a battery. On the other hand, EnOcean has put wireless switches into practical use in buildings. Electric power is generated when a person pushes the switch, and a radio signal is transmitted by using the generated power without a battery. With these switches, wiring for indoor lighting switches can be eliminated. In this application, the lack of a battery is the most important feature.

The other approach is to make power consumption as small as possible. The University of Michigan is furthering research and development of a millimeter-size health care application implanted inside the body as one target [38]. For such an application, size restriction is the most important issue. Therefore, generated power is also restrained. It operates by electric power supplied by radio and charging a battery. So, a processor that operates below microwatts is needed. As the source of this technology trend, it is well known that a UCB team has advocated micro sensor nodes in the form of “smart dust” for military use [39]. Aiming at an application of WSNs as a front end for BigData, a research group at NTT has been developing event-driven millimeter-size sensor nodes without a battery [17, 22, 31, 40, 41]. In the event-driven world, we think a self-consistent mechanism exists. In conventional continuous monitoring system, power is consumed even if an event does not occur. So, it has to hold batteries to keep operation and there is limit in operating time. This is not self-consistent system. If we can use only the energy caused by the event for operating a sensor node, self-consistent batteryless sensor nodes could be
realized. This would enable us to attach sensor nodes to places we haven’t been able to.

Therefore, ultra-low-power circuit techniques are needed because the generated power is extremely low, such as at the nanowatt level. In the next section, sensor node technology that enables nanowatt level operation is described.

3 Nanowatt batteryless sensor node techniques

3.1 Sensor node architecture

In order to achieve nanowatt level operation, not only the circuit technology but also a system level design and heterogeneous integration, such as MEMS and circuits, are needed. The basic concept of a sensor node with functions for energy accumulation is shown in Fig. 5. The node contains function blocks for the energy harvester, power management, sensing circuit, and radio. The power-management block accumulates energy to the accumulation capacitor, which is large enough for radio. When the voltage monitor detects that the voltage of the accumulated energy has reached the voltage needed for radio, the sensing block is activated. Then, the radio block transmits the sensed data when an event occurs. In this mode of operation, the voltage monitor for controlling the switch should operate with subnanowatt-level power consumption because the monitor operates continuously during energy accumulation. Moreover, the power for sensing needs to be reduced to the subnanowatt level since the sensing function needs to be active after energy accumulation. To reduce the power consumption of the RF circuit dramatically, an RF receiver is not included in the sensor node, and we have developed an intermittent transmitter circuit for nanowatt level WSNs. In what follows, we describe the key techniques for the nanowatt level wireless sensor node: a zero-power sensing circuit, power management with a MEMS switch and ultra-low-power impulse OOK (on off keying) transmitter.

![Architecture of nanowatt level wireless sensor node.](image)

3.2 Zero-power vibration sensing circuit

The principle of zero-power sensing circuit operation is described. Fig. 6 shows the vibration-sensing circuit configuration [17]. The configuration consists of a capacitance-change-integrating (CCI) circuit connected to a transducer (vibration) and of a ramp-detection circuit. The supply voltage of these circuits is provided by the power-management circuit. The CCI circuit contains three diode-connected MOSFETs and its output voltage $V_{CI}$ is first set to a voltage depending on the
threshold voltage of the diode-connected MOSFETs. When vibration is generated as a result of an event occurrence, capacitances $C_1$ and $C_2$ formed in the movable structure of the vibration sensor, which is fabricated with a MEMS structure, changes alternately. This results in a charge-pump operation in diode-connected MOSFETs and voltage $V_{ci}$ increases. The ramp-detection circuit has two threshold circuits that have different logic threshold voltages and an exclusive-OR gate. The threshold circuit consumes subnanoampere current [17]. The ramp of increasing $V_{ci}$ is detected as the PWM (pulse width modulation) signal.

In the CCI circuit, the power consumption during a charge-pump operation is zero theoretically. There is no DC current when a vibration does not occur. Moreover, the sensing circuit is able to start the sensing operation without a wake-up circuit when the vibration occurred. The total power of this circuit is composed of discharge current from the capacitor in the CCI circuit and the subnanoampere level current in the ramp detection circuit.

To confirm the effectiveness of the circuit techniques, we fabricated a test chip using a 0.35-µm CMOS process. The power consumption of the vibration-sensing circuit with the time-to-digital converter is shown in Fig. 7. The x-axis is the interval of the sensing operation, what we call the event interval. The power

![Fig. 6. Principle of zero-power vibration sensing circuit.](image)

![Fig. 7. Power consumption of zero-power vibration sensing circuit.](image)
consumption of the circuit, calculated by using the measured energy for the converting mode (360 pJ) and the measured current for waiting mode (620 pA), is 0.7 nW in a range of more than a 3-s event interval. A previously reported circuit with a low-power sensor interface [42] consumes 450 nW independently of the vibration-occurrence frequency. Our circuit consumes 1/600 of the power of the reported one.

As mentioned above, the vibration sensing circuit based on the co-design of the MEMS structure and sensing circuit achieves nanowatt level power consumption by utilizing external vibrational energy for sensing operation.

3.3 MEMS-switch-based power management

The power management scheme using a MEMS switch is shown in Fig. 8. The voltage monitoring does not consume any power and off-state leakage is much smaller compared with that of a MOS switch. The power generator charges the accumulation capacitor, which generates electrostatic force in the MEMS switch. When the voltage of the capacitor reaches the threshold voltage of the MEMS switch, the capacitor is connected to the sensing circuit. The MEMS switch has hysteresis for the threshold voltage like a hysteresis comparator, since the contact point sticks to the electrode. When the voltage of the accumulation capacitor is lowered due to the discharge by the transmitter, the MEMS switch turns off and capacitor charging is restarted. The threshold voltages of the hysteresis are designed to meet the LSI supply voltage (e.g., 3.3 V) by making the air gap 1 µm and adjusting the stiffness of the beam in the MEMS structure [43].

Power management using the MEMS switch was confirmed in the test circuit [22]. The MEMS switch was fabricated by using the MEMS process [43]. The LSI chips were fabricated by using the 0.35-µm CMOS process. From the measurements, the charge holding time on the accumulation capacitor is estimated to be more than 125 days from the measured leakage current of less than 0.1 pA.

Therefore, by applying the MEMS switch to the power management circuit, we can achieve performance that we cannot attain only with CMOS technology.

![Fig. 8. Power management with MEMS switch.](https://example.com/fig8.png)
3.4 Nanowatt-level RF transmitter

Fig. 9 shows the configuration of the RF transmitter and its waveform. The RF transmitter consists of a pulse generator with a ring oscillator (RO) and an asynchronous pulse counter for generating impulse OOK signal. When the ID signal is set to “1”, the 300-MHz RO starts to generate pulses. The pulse counter counts the number of pulses and when the count becomes 16, the pulse generator stops wireless circuits and consumes no power. The on-off rate of RF circuits is 1 to 20 in a symbol. The RO is advantageous for its rapid start-up time of less than 1 ns and realizes such intermittent driving. It is also used as a 1-MHz baseband clock, and consumes little power during start-up. Compared to the continuous driving system, the power consumption is 1/20 and start-up power consumption becomes negligible.

Fig. 10 shows the configuration and a photograph of the wireless sensor node we developed. Solar energy is charged to a capacitor, which is good for low-current charging from a small solar battery. When a vibration is detected, the charged energy is supplied to the wireless IC. The IC generates and transmits the ID signal. Thus the sensor node can detect motion events such as something being dropped or lifted. Each device is mounted on two 5 × 5 mm printed circuit boards. The devices are stacked three dimensionally to reduce total volume [41]. The wireless IC was fabricated in a 0.18 µm CMOS process. The current consumption becomes ∼3 mA when the pulse signal is generated and ∼100 µA when it stops. Thus the energy efficiency is 625 pJ/bit. When we transmit 100 bits per second, the total power consumption is less than 62.5 nW. Therefore, the RF transmitter based on pulse OOK achieves nanowatt-level power consumption.
4 Conclusions

Circuit techniques for energy harvesting for millimeter-size wireless sensor nodes were described. Generated power is reduced dramatically because of the small size of a sensor node, and it reaches nanowatt level by millimeter-size. Low-power techniques for microwatt levels have been developed for applications of the wireless sensor nodes, and ultra-low-power techniques for nanowatt levels have been reported for millimeter-size sensor nodes.

Based on these technology trends, the portfolio of energy-harvesting technology and circuit techniques was shown, and we described that there are four categories: power generation, ultra-low-power circuit techniques, and the use or nonuse of a battery, depending on the application. Moreover, circuit techniques for nanowatt-level wireless sensors node we have developed— a zero-power vibration sensing circuit, power management with MEMS switch, and an intermitted RF transmitter— were explained. These techniques achieve nanowatt level power consumption, which enables us to use a millimeter-size energy harvester.

The above energy-harvesting and circuit technology will pave the way for the next-generation of sensor networks as a front end for BigData, IoT, M2M, and ambient intelligence.

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