論 文 の 内 容 の 要 旨

論文題目　Research on Ultra-Low Power CMOS Circuits for Battery Management
（バッテリーマネジメント向け超低消費電力CMOS回路の研究）

氏　　名　　染谷　晃基

The internet of things (IoT) is creating a new world where objects are connected to the internet, and we can collect much information from edge nodes easily. The IoT is expected to achieve new applications that enhance productivity and quality of our lives. In the IoT, the lifetime of IoT nodes determines the total cost and the quality of the applications. It is clear that to prolong and improve the lifetime of the IoT node is challenging issue for the future expansion of the IoT. However, the size and capacity of battery in IoT node are limited, which reduces the total amount of energy for the operation. In such situations, low-power circuit designs are essential to improve the lifetime. This study focuses on circuits that comprise battery management in an IoT node and proposes new ultra-low power techniques to reduce the power consumption of the circuits in the battery management.

This thesis is organized into six chapters. Chapter 1 describes an introduction of this thesis. Chapter 2 presents an ultra-low power CMOS voltage reference that generates a constant standard voltage for the components in the battery management. Chapter 3 proposes a programming technique to obtain appropriate standard voltages for each circuit in the battery management. In Chapter 4, voltage detectors for RF energy harvesting and for battery monitoring are presented. In Chapter 5, an ultra-low power temperature sensor for small capacity batteries is proposed. Chapter 6 concludes the research with a summary of this dissertation.

In chapter 2, a 90 pA voltage reference for ultra-low power IoT node is presented. The voltage reference generates a temperature and V_{DD} independent constant voltage that becomes a standard voltage of the analog circuits in the battery management. The 90 pA voltage reference proposed in Chapter 2 is robust to the V_{DD} change compared with conventional low power voltage references. The simulated line sensitivity and the PSRR are 21μV/V and -70dB, respectively. The voltage reference is a fundamental circuit that is applied to a programmable voltage reference in Chapter 3, a voltage detector in Chapter 4, and a temperature-to-digital converter in Chapter 5.

In Chapter 3, an ultra-low power post-fabrication programming method for a voltage reference that realizes the programmability of the reference voltage (V_{REF1}) by users, is proposed with a theoretical analysis. A multiple voltage duplicator (MVD) is newly proposed to eliminate a tradeoff between the temperature dependence of V_{REF1} and the power consumption of the programmable voltage reference. Also, a fine voltage subtraction (FVS) method is presented to achieve fine and linear programmability of V_{REF1}. The measurement results of the test chip fabricated in 250-nm CMOS process shows that the proposed programming method achieves a 6-bit, linear and monotonous programmability with the power consumption of sub-1nA and the temperature coefficient of 15.2μV/°C. The programming method is applied to a voltage detector in Chapter 4 which realizes programmability of the detection voltage by users.

In Chapter 4, voltage detectors for RF energy harvesting and battery monitoring are presented. A voltage detector (VD) watches a node voltage and once the node voltage reaches a predefined voltage (V_{DETECT}), the VD generates a signal. The proposed VD assumed to be applied to RF energy harvesting is fabricated in 250-nm CMOS process. The measured VD achieves 248 pW, glitch-free operation that the VD does not generate a glitch even though the input and supply voltage for the VD is close to 0V. Moreover, the VD has a trimming method to realize the accurate voltage detection by using the MVD in Chapter 3. These advantages open the way to realize energy autonomous applications that operate with harvested RF energy. The VD for battery monitoring enables users to program the detection voltage of the VD. The programmability mitigates the cost of VDs originated from variations of batteries, users, or applications. The programmable VD is fabricated in 250-nm. The measurement results show 6-bit programmability of the detection voltage ranging from 902 mV to 4904mV with the resolution of 62.5 mV. The resolution covers the ±1% of the charging voltage of lithium ion battery while the detection range covers operation voltages of most batteries.

In Chapter 5, an ultra-low power temperature sensor for miniature size batteries is presented. The batteries have the large cell resistances that limit the maximum supply current. Therefore, to obtain the temperature information from the batteries, the temperature sensor is designed to be ultra-low power consumption. The proposed temperature sensor uses a new principle of temperature sensing utilizing two sub-threshold nMOSFETs operating in the deep triode region and the saturation region. The ratio of two currents of the nMOSFETs shows good temperature linearity. A circuit that converts the two currents into frequencies and the ratio of the frequencies into PTAT digital output is also presented. The temperature sensor fabricated in 180-nm CMOS process achieves the inaccuracy of -0.7 °C /+1.3 °C in the temperature range of -20 °C to 80 °C with the resolution of 110 m°C. The measured power consumption is 13 nW which is the lowest power consumption in the previously published low-power temperature sensors. The temperature sensor is suitable for a battery that power is limited.

Chapter 6 gives conclusions of the thesis.