論文の内容の要旨

論文題目　Circuit Design for Sub-0.5V DC-DC Converter
（0.5V 以下動作の DC−DC コンバータに向けた回路設計）

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The self-powered power management circuit applying energy harvester for battery-free portable electronics is attracting a lot of attention. These harvested voltages are usually lower than the threshold voltages (V_{TH}) of standard CMOS technologies. Therefore, a step-up DC-DC converter is required to convert the harvested energy to usable outputs. There are many challenges when implementing such a low input voltage DC-DC converter, including startup mechanism, low conversion efficiency, and process variation. This thesis proposes several techniques to solve these problems to develop an extremely low input voltage DC-DC converter.

This thesis is organized into 6 chapters. The first chapter describes the motivation and contribution of this thesis. Harvesting energy from the environment by using the thermoelectric generator (TEG) or the photovoltaic cells provides a solution for battery-free sensor networks or electronic healthcare systems. New startup mechanisms without using mechanical switch or large off-chip transformer could achieve low startup voltage while the circuit topologies could remain the same in operation mode. This means that we could apply all the developed control schemes to realize the DC-DC converter with high efficiency and good regulation performances.

Chapter 2 introduces two basic types of step-up DC-DC converters. The first type is capacitive step-up converter called “charge pump” and the other type is inductive step-up converter called “boost converter”. These converters perform different characteristics and can be used in different application. We will also introduce the prior works on low-voltage startup mechanism. Both the operation principles and drawbacks of these circuits will be described.

Chapter 3 presents the implementation of 0.18-V startup step-up DC-DC converter. It applied an on-chip charge pump as a startup mechanism in startup mode to reduce the startup voltage of the boost converter significantly. In operation mode, the converter uses boost converter as the main DC-DC converter to achieve the high conversion efficiency and high output power. In the developed charge pump, all the switch transistors are forward body biased by using the inter-stage/output voltages. Therefore, the conduction loss can be reduced without large area overhead. To verify the circuit characteristics, the conventional zero body bias charge pump and the proposed forward body bias charge pump were fabricated with 65nm CMOS process.

Chapter 4 describes a 95-mV startup-voltage step-up DC-DC converter. Two techniques are applied to reduce the startup voltage. One is capacitor pass-on scheme and the other is fixed-charge V_{TH}-tuned oscillator. Capacitor pass-on scheme solve the limitation of startup voltage in chapter 2. The fixed-charge V_{TH}-tuned oscillator compensates for the die-to-die process variation by post-fabrication V_{TH} trimming. This technique can make sure the clock generator can provide the clock signal to charge pump at low supply voltage.

Chapter 5 shows a low startup-voltage and fast startup dual-mode boost converter, which further improves the converter introduced in chapter 4. Comparing with the previous work, the startup-time, the minimum startup voltage, and the program time are greatly improved. (1) A startup by the boost converter instead of a charge pump reduced the startup-time to 4.8ms which is reduced to 1/56 and the shortest to date. (2) The proposed sub-1nW charge-pumped pulse generator (CPPG) enabled the lowest startup voltage of 80mV to date without mechanical switch. (3) The proposed threshold-voltage-tuned oscillator with hot-carrier injection (HCI) for CPPG to compensate for the die-to-die process variations reduced the program time to 3min which is 1/20 of previous version, thereby reducing the test cost.

Usually, the control circuit and switch driver in DC-DC converter are supplied either by input voltage or by output voltage. In energy harvesting applications, sometimes both the input/output voltages are both too small. If there is any process variation, the conduction loss changes dramatically and decreases the conversion efficiency. To compensate the conduction loss variation caused by process variation, we developed an adaptive local boost DC-DC converter. It adaptively changes the supply voltage of driver circuit to fix the voltage drop in power switches. Another merit of this technique is the conversion efficiency improvement over a wide output load. It achieves higher conversion efficiency comparing to conventional approaches. The circuit design and design methodologies of the adaptive local boost DC-DC converter are presented in chapter 6.

Finally, the thesis concludes in chapter 7.