A self-startup DC-DC boost converter for thermal energy harvesting in a 0.35 µm CMOS process

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ABSTRACT

In this paper a self-startup DC-DC boost converter for thermal energy harvesting applications is presented. A startup circuit boosts an internal supply voltage using a low voltage generated from a thermoelectric generator to operate the internal circuitry of the converter. To reduce power dissipation, the startup circuit is disabled after the startup operation is finished. A boosted output voltage is obtained by alternating an auxiliary converter for the internal supply voltage and a main converter for the output voltage. The converter has been implemented in a 0.35 µm complementary metal–oxide–semiconductor (CMOS) process. Measurement results shows that the designed converter is capable of generating an output voltage close to 3V from an input voltage of 200 mV, and can provide a maximum output power of 278 µW with an end-to-end power efficiency of 46.5%. It occupies an active area of 0.36 mm^2.

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1. INTRODUCTION

Recently, there is increasing interest in renewable energy sources and their applications. A lot of research and development is in progress on micro-energy harvesting technology to drive low-power electronic systems by harvesting energy from the environment. Compared to the technology using light energy [1]–[6] or vibration energy [7]–[11], the technology using thermal energy [12]–[22] is somewhat slow in research and development due to the technical difficulty that the voltage level extracted from a thermal energy transducer is small. However, since the thermal energy is suitable for application to living organisms including humans, it is possible to create a variety of application fields such as health care systems.

A commonly used thermoelectric generator (TEG) is a bismuth telluride type of thermoelectric element that uses p-n legs, generating a very small voltage of tens of mV (@10 cm^2) per 1 degree of temperature [23]. When these devices are applied to the body of a living organism, the temperature difference applied to the TEG is 2-3 degrees. It is difficult to drive application circuits directly because the voltage generated from the TEG is very small. Therefore, a startup circuit and a boost converter are required to provide the supply voltage needed to power the electronics.

In the early stages of development, several startup techniques have been reported to lower the input voltage required for the converter operation by utilizing a pre-charged battery [13], [14], [18], a mechanical switch [15], an off-chip transformer [17], [20]. Because of the use of bulky external devices or batteries, these techniques are not suitable for system miniaturization or integration. The technique proposed in [16] cannot be applied to standard complementary metal–oxide–semiconductor (CMOS) processes as it requires post-fabrication threshold voltage adjustment to start the system at an input voltage as low as 95 mV. As such, these techniques, which require additional off-chip devices or post-process trimming, are not suitable for self-powered, miniature-sized systems.

Recently, fully integrated cold start techniques for completely electronic startup without additional external components have been proposed [24]–[28]. These techniques focus on operating ring oscillators and charge pumps at as low a voltage as possible. A 5-stage conventional ring oscillator with forward body biasing and five series connected 20-stage Dickson-type charge pumps are used to achieve cold start at 60 mV [24]. Alternatively, inverters with a new structure for realizing low-voltage ring oscillators are proposed, such as selective schmitt trigger (ST) inverters [25], redundant inverters [26], stacked inverters [27], and low-leakage ST inverters [28]. In addition, to obtain a boosted voltage from a low input voltage various charge pump structures are used as follows: six parallel connections of 24-stage cross-coupled charge pumps [25], 3-step cross-coupled charge pumps with clock boosting [26], and cross-coupled complementary charge pumps with gate voltage boosting [27]. In these techniques, expensive advanced processes with various options are utilized for low-voltage startup. As the number of stages of the charge pump increases, the buffer stage of the ring oscillator for driving it also increases, thereby increasing the chip area.

In this paper, an inexpensive standard 0.35 μm n-well CMOS process is used to implement a self-startup DC-DC boost converter for thermal energy harvesting. Due to limited process options such as triple-well, and low-V_t transistors, there is a limit to realizing low voltage characteristics, so the target minimum input voltage is 200 mV. Section 2 describes the overall structure of the proposed DC-DC converter and the design of the component blocks. Experimental results are presented in section 3, and conclusion are shown in section 4.

2. PROPOSED DC-DC BOOST CONVERTER

2.1. Overall circuit description

The architecture of the proposed DC-DC boost converter for thermal energy harvesting is shown in Figure 1. It consists of a TEG, a startup circuit, a control block, and a main DC-DC boost converter. The startup circuit serves to boost the internal supply voltage (V_{DD}) from the low output voltage of the TEG to the voltage at which the control block can operate (e.g. 1.3 V). When V_{DD} is boosted by more than 1.3 V by the startup circuit, the control block generates a signal EN to disable the startup circuit. Also, it generates a CHG_V_{OUT} signal for the boosting operation of the main DC-DC boost converter (DCDC_V_{OUT}), while maintaining V_{DD} of 2V or more after the startup circuit is disabled.

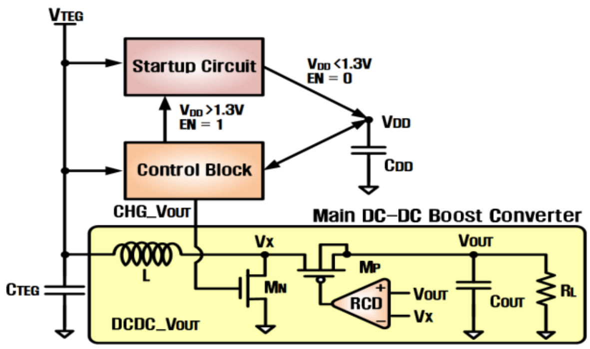

Figure 1. Block diagram of the proposed DC-DC boost converter

2.2. Startup circuit

Figure 2 shows the low-voltage startup circuit proposed in this paper, which consists of an oscillator (OSC), a charge pump, a pulse generator (pulse GEN), and a negative (NMOS) switch, M_{NS}. The OSC generates clocks CLK1 and CLK2 for the step-up operation of the charge pump, and the charge pump boosts the input voltage above the threshold voltage of the transistors and supplies the boosted voltage V_{CP} to the pulse generator. The pulse generator generates a pulse V_{PG} for turning on/off the power switch to boost V_{DD}.

The threshold voltage of a typical MOSFET provided in the 0.35 μm process used in this design is about 750 mV, while the TEG outputs a much lower voltage than this. Therefore, to operate the startup circuit at such a low voltage, the OSC, buffer and charge pump are designed using native n-type MOSFETs with a threshold voltage of about 100 mV provided by the process. Figure 3 is the OSC circuit designed in the form of a 3-stage ring oscillator. In the process, only NMOS is supported for native devices, so the positive (PMOS) transistors of the OSC are replaced with resistors. In order to minimize current consumption, EN switches and evolved node B (ENB) switches are added to disable the startup circuit when the startup operation is finished. EN and ENB signals are generated by the voltage detector in the control block. The 12-stage Dickson-type charge pump as shown in Figure 4 is used, and the pulse generator is composed of a 3-stage CMOS inverter.

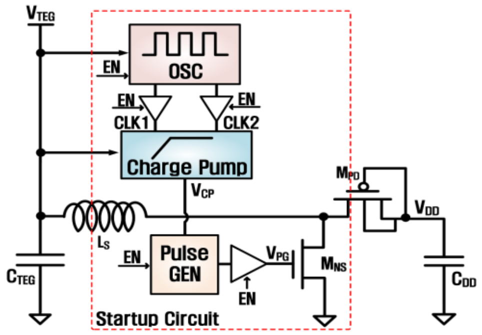

Figure 2. Proposed startup circuit

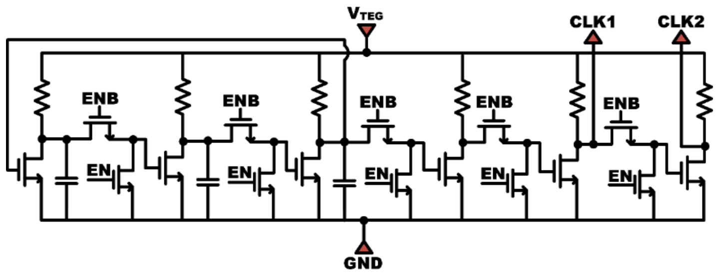

Figure 3. 3-stage ring oscillator (OSC)

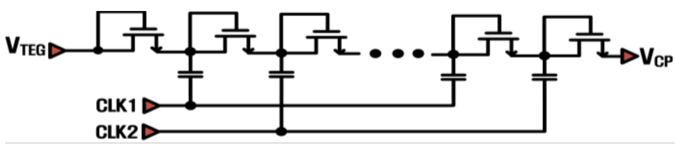

Figure 4. 12-stage Dickson-type charge pump

2.3. Control block

The control block shown in Figure 5 is composed of an auxiliary DC-DC boost converter (DCDC_V_{DD}) that boosts V_{DD} and a controller that controls the operation of the entire circuit. When V_{DD} is boosted by more than 1.3 V by the startup circuit, the controller starts to operate and outputs the EN signal to disable the startup circuit. In addition, the controller monitors V_{DD} and alternately supplies a signal CHG_V_{DD} to maintain V_{DD} above 2V and a signal CHG_V_{OUT} to boost output voltage V_{OUT} to the auxiliary DC-DC boost converter and the main DC-DC boost converter, respectively.

The controller consists of a voltage detector (VD), a reference voltage generator (REFGEN), a clock generator (CLKGEN), and a comparator (CMP). As a voltage detector to detect the V_{DD} level, the ultra-low-power structure proposed in [16] is adopted as shown in Figure 6. As a result of simulation at five corners (SS, TT, FF, FS, and SF), the detection voltage of the designed VD has a value in the range of 1.0 to 1.4 V. It consumes a maximum of 65 nA when the output state changes and consumes little current in the steady state.

The reference voltage generator generates a reference voltage and supplies it to the comparator. To minimize current consumption, it consists of only MOSFETs and resistors [29] instead of the conventional bandgap circuit using BJTs. As shown in Figure 7, REFGEN contains a start-up circuit [30] that consumes no power after startup. Simulation results show that the designed reference circuit produces a stable output voltage V_{REF} at V_{DD} above 1.1 V and exhibits a V_{DD} sensitivity of 0.85%/V and a temperature coefficient of 17 ppm/ºC over the range of -20 ºC to 80 ºC. The reference circuit outputs 857 mV and consumes 820 nA at a supply voltage of 2 V.

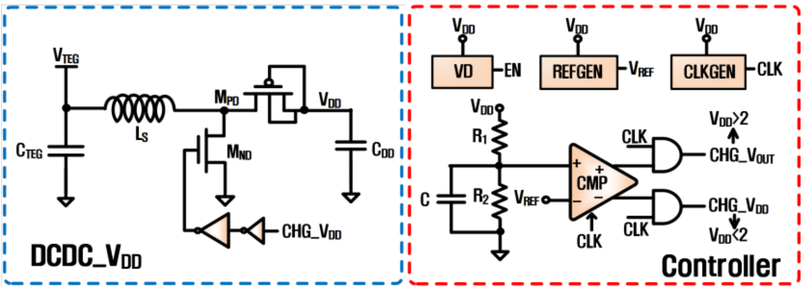

Figure 5. Control block

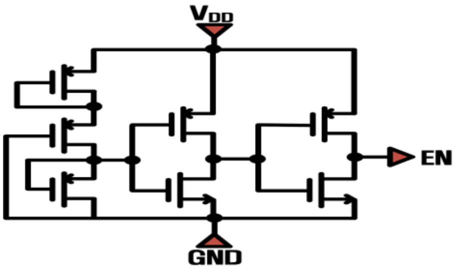

Figure 6. Voltage detector

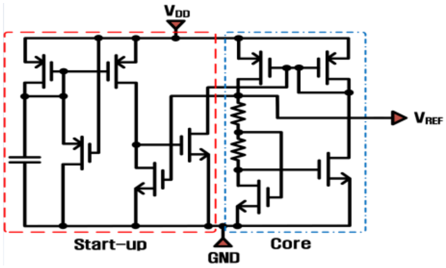

Figure 7. Reference voltage generator

The clock generator is a five-stage ring oscillator that supplies the clock (CLK) required for comparator operation. As shown in Figure 8, the comparator is implemented using a clock-driven regenerative structure to reduce current consumption. The divided value of V_{DD} is compared with V_{REF} and if it is higher, the comparator sends the CHG_V_{OUT} signal to DCDC_V_{OUT} to boost V_{OUT}. Otherwise, the CHG_V_{DD} signal is delivered to DCDC_V_{DD} and V_{DD} is boosted. The designed comparator consumes 2.25 µA at a supply voltage of 2 V.

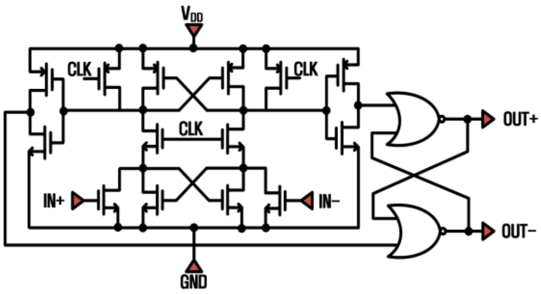

Figure 8. Comparator

2.4. Main DC-DC boost converter

The main DC-DC boost converter in Figure 1 boosts the low voltage generated from the TEG by 2 V or more and supplies it to the load. The power NMOS switch M_N is turned on/off by the CHG_V_{OUT} signal output from the control block. To prevent reverse current from flowing from V_{OUT} to the inductor L, a reverse current detector (RCD) is employed to control the power PMOS switch M_P. Figure 9 is the circuit diagram of the RCD used in this design [31]. The RCD circuit compares the inductor voltage (V_X) with the output voltage V_{OUT}, and outputs a V_{RCD} signal if V_{OUT} is greater to turn off the PMOS switch.

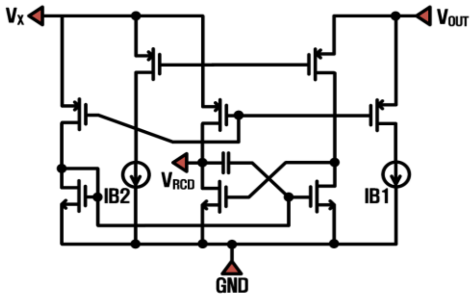

Figure 9. Reverse current detector

3. RESULTS AND DISCUSSION

The DC-DC boost converter for thermal energy harvesting proposed in this paper was designed and fabricated in a standard 0.35 μm n-well CMOS process. Figure 10 is a photograph of the fabricated chip, and the chip area is 1 mm×0.36 mm excluding the pads. Figure 11 shows the experimental setup for measuring the fabricated chip. As a thermoelectric element, TEC1-12706 from Thermonamic was used. A temperature-controllable hotplate (MSH-20D, daihan scientific) was used to apply heat to one side of the TEG, and a general CPU cooling fan/heat sink was used for the opposite side (cold side). Using these devices, one side of the TEG was set at 35 °C and the other at 25 °C so that the TEG outputs an open circuit voltage of 200 mV. The values of the passive elements used for the measurement are: $L=L_S=47$ μH, $C_{TEG}=100$ nF, $C_{DD}=1$ nF, $C_{OUT}=47$ μF, and $R_L=10$ kΩ.

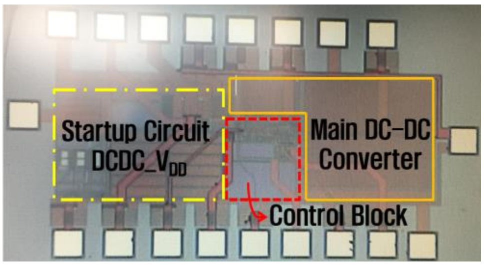

Figure 10. Die photograph

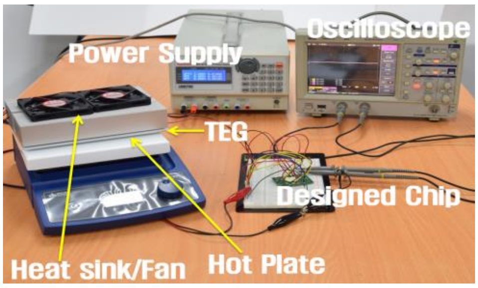

Figure 11. Experimental setup

Figure 12 shows the measurement results of CLK, CHG_V_{DD}, CHG_V_{OUT}, V_{DD}, and V_{OUT}. The clock CLK generated by CLKGEN has a frequency of 220 kHz and a duty cycle of 66%. It can be seen in Figures 12(a) and (b) that the comparator CMP alternately outputs CHG_V_{DD} and CHG_V_{OUT} based on CLK according to the V_{DD} value. In Figures 12(c) and (d), it can be seen that V_{DD} maintains an average of 2.3 V by DCDC_V_{DD} operation by CHG_V_{DD} signal and V_{OUT} maintains 1.5 V by DCDC_V_{OUT} operation by CHG_V_{OUT} signal.

Figure 13 shows the summary of V_{OUT} values according to load resistance changes. The designed DC-DC boost converter outputs a voltage of 2 V or more at a load resistance of 20 kΩ or more from the TEG that outputs an open circuit voltage of 200 mV. When the output is open, the output voltage is at its maximum, 2.97 V.

The input/output power and power efficiency according to the load resistance are shown in Figures 14 and 15, respectively. The proposed DC-DC boost converter for thermal energy harvesting shows a maximum power efficiency of 46.5% at a load resistance of 4.3 kΩ. At this time, an average of 600 μW of power is output from the TEG, and a maximum of 278 μW of power is supplied to the load. The measured power efficiency shows a reduction of up to 16% compared to the simulation results. The main cause is that after deactivation, the startup circuit draws more current than expected. This is because the leakage current in the native MOSFETs used to operate the startup circuit at low voltage is larger than expected. If an advanced process is used, this problem can be solved, and starting at lower voltages is also possible.

Table 1 compares the performance of the proposed circuit and the conventional thermal energy harvesting DC-DC boost converters. In the case of converters using an inexpensive process (0.35 um) [13], [15], [18], external devices such as batteries and mechanical switches were used for low-voltage operation, whereas the circuit proposed in this paper can start itself without additional external devices. Compared with self-starting converters using advanced processes [24]–[27], the pro posed circuit has a rather large minimum input voltage, but it has the advantage of high price competitiveness because it can be implemented with a small chip area using an inexpensive process.

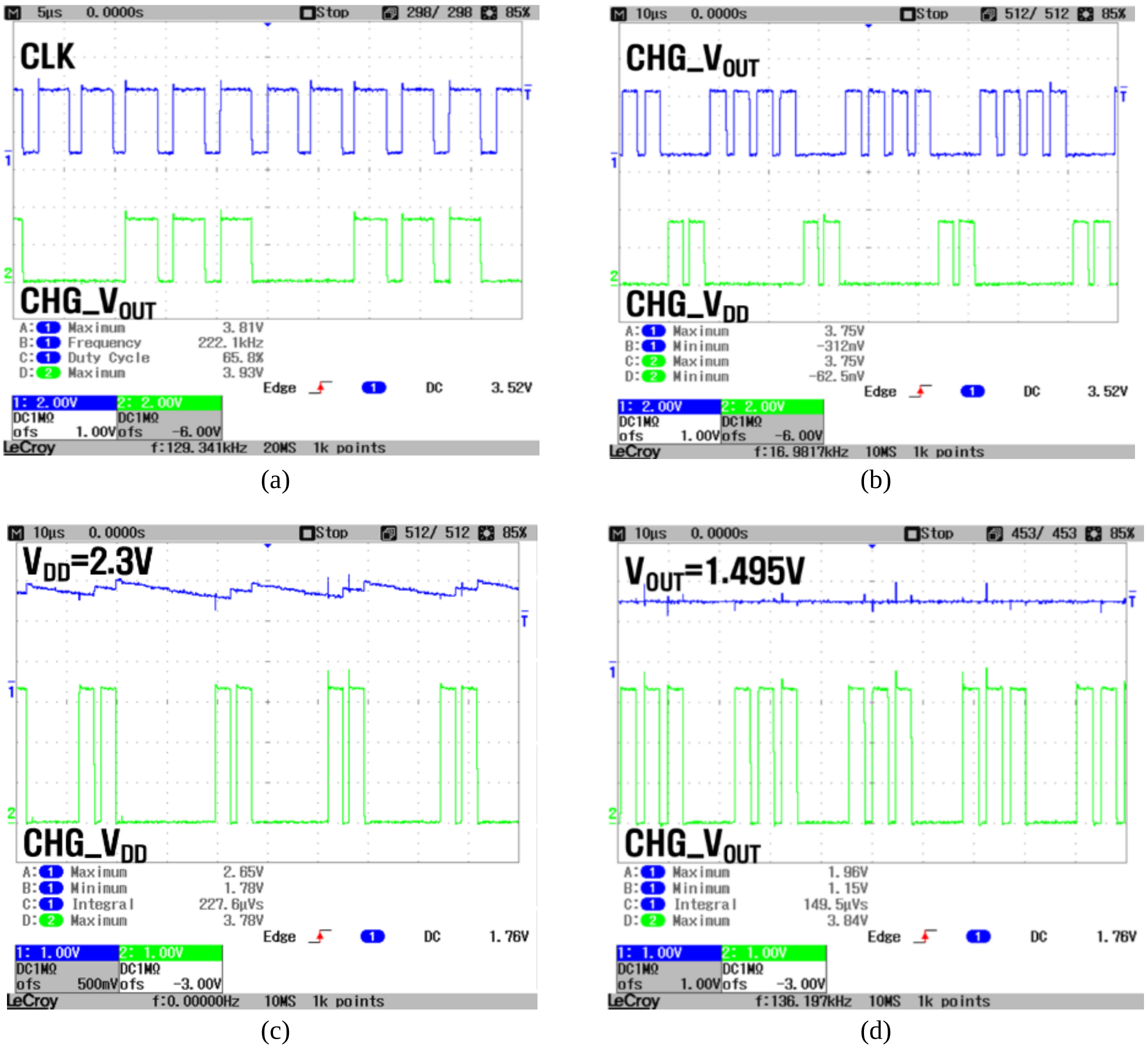

Figure 12. Measured waveforms at steady state when R_L=10 kΩ, (a) CLK and CHG_V_{OUT}, (b) CHG_V_{OUT} and CHG_V_{DD}, (c) V_{DD} and CHG_V_{DD}, and (d) V_{OUT} and CHG_V_{OUT}

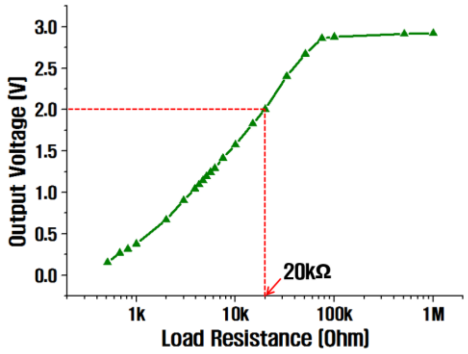

Figure 13. V_{OUT} versus R_L

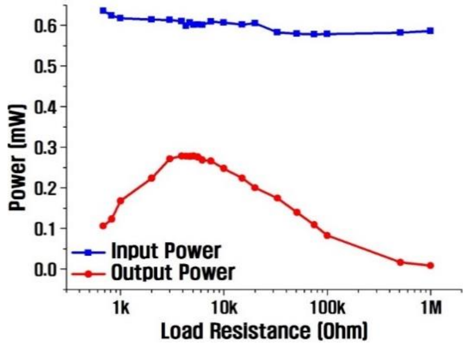

Figure 14. Input and output power versus R_L

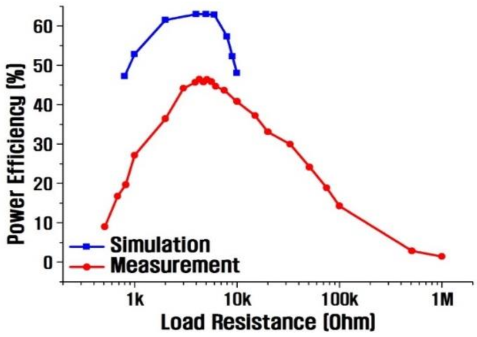

Figure 15. Measured power efficiency versus R_L

Table 1. Comparison of DC-DC boost converters for thermal energy harvesting

Parameter	[13]	[15]	[18]	[24]	[25]	[26]	[27]	This work
Process	0.35 um	0.35 um	0.35 um	0.18 um	0.13 um	65 nm	0.18 um	0.35 um
Minimum input voltage	600 mV	35 mV	70 mV	60 mV	70 mV	210 mV	57 mV	200 mV
Output voltage	~2V	1.8V	3~5.8	1~3	1.25V	1.0V	~1.8V	~2.9V
Startup mechanism	External voltage	Mechanical switch	External voltage	Charge pump	Charge pump	Charge pump	Charge pump	Charge pump
DC-DC conversion principle	Charge pump	Inductive boost converter	Inductive boost converter	Inductive boost converter	Inductive boost converter	Inductive boost converter	Inductive boost converter	Inductive boost converter
Number of inductors	-	3	1	2	1	1	1	2
MPPT	Hill climbing	Fixed frequency	FOCV	Yes	No	FOCV	No	No
Max. output power	N/A	N/A	N/A	N/A	17 uW	229 uW	N/A	278 uW
Peak efficiency (%)	70 (boost converter)	58 (end-to-end)	72.2 (boost converter)	48 (end-to-end)	58 (end-to-end)	71.5 (end-to-end)	20 (end-to-end)	46 (end-to-end)
Active area (mm^2)	3.06	1.6	1.9	Simulation	0.6	4.58	1.6	0.36

4. CONCLUSION

This paper presented a self-startup DC-DC boost converter for thermal energy harvesting implemented in an inexpensive standard 0.35 µm n-well CMOS process. The designed converter starts-up at an input voltage of 200 mV without additional external devices, and generates an output voltage of 2 V or more at a load resistance of 20 kΩ or more. Measurement results shows that the maximum output power is 278 µW and the end-to-end power efficiency is 46.5%. The proposed circuit occupies a relatively small active area of 0.36 mm^2 and can be implemented with an inexpensive process, which is advantageous in terms of price.

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