Development and optimization of high power density micro-thermoelectric generators

Wenhua Zhang¹, Juekuan Yang² and Dongyan Xu¹

¹ Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong Special Administrative Region, China
² School of Mechanical Engineering and Jiangsu Key Laboratory for Design and Manufacture of Micro-Nano Biomedical Instruments, Southeast University, Nanjing 211189, China
dyxu@mae.cuhk.edu.hk

Abstract. This paper presents the design, fabrication, characterization, and optimization of micro-thermoelectric generators. The micro-thermoelectric generators are fabricated by a bottom-up approach combining pulsed electroplating and microfabrication techniques. This paper shows a complete set of experimental results of four prototypes and also reports on theoretical analysis that provides design guidelines for optimizing the power density of the prototypes.

1. Introduction
Thermoelectric generators (TEGs) are promising for harvesting waste heat from the environment to power wireless sensor networks in smart buildings. Despite of low energy conversion efficiency, TEGs have many advantages including high reliability, long lifetime, and environmental friendliness. Especially, compared to conventional heat engines, TEGs are compact, scalable, and can be easily driven by small temperature differences. Recently, several high-performance non-flexible and flexible TEGs are reported in the literature [1-3].

Electroplating is commonly used to fabricate TEGs on non-flexible substrates [2, 3]. In comparison with other techniques, electroplating has a number of advantages including efficient usage of raw materials, compatibility with microfabrication processes [4], and low contact resistance. In this work, we developed four non-flexible micro-TEG prototypes by combining pulsed electroplating and microfabrication techniques. Our TEGs demonstrate very low internal resistance and high power density, which can be attributed to the low parasitic contact resistance and high packing density of thermoelectric pillars [3].

2. Design and Fabrication of Micro-thermoelectric Generators
In this work, we designed and fabricated four cross-plane micro-TEG prototypes including TEG27, TEG355, TEG127, and TEG495. The micro-TEGs are fabricated by a bottom-up approach. Figure 1 shows the schematic of the fabrication process. The fabrication was conducted on silicon chips with 300 nm SiO₂ on both sides. First, bottom interconnectors and thin connecting lines are fabricated by sputtering, photolithography, and wet etching (Fig. 1a). Next, a 10 µm thick SU-8 layer is fabricated by photolithography with two open holes patterned on each bottom interconnector (Fig. 1b). One set
of holes are covered by photoresist and n-type Bi$_2$Te$_3$ is deposited in open holes by the pulsed electroplating (Fig. 1c). Then, another layer of photoresist is used to cover the deposited n-type materials and p-type Sb$_2$Te$_3$ is deposited in the rest of open holes (Fig. 1d). Next, top interconnectors are formed by electroplating in a temporary photoresist mold (Fig. 1e-i). After that, the chip is soaked in acetone to remove the photoresist and then partial connecting lines are chemically etched away to break external electrical connections. Then, the micro-TEG is bonded with the top cover.

![Figure 1](image1.png)

**Figure 1.** (a-j) The schematic of the fabrication process for the micro-TEGs. (k) The photograph of the TEG27 prototype.

The photograph of TEG27 is shown in Fig. 1k and those of other prototypes are given in Fig. 2. The dimensions of thermoelectric pillars, total number of pairs, and the room temperature internal resistance of all the prototypes are listed in Table 1.

![Figure 2](image2.png)

**Figure 2.** The photographs of the micro-TEG prototypes: (a) TEG127; (b) TEG355; and (c) TEG 495.
Table 1. Dimensions of thermoelectric pillars, total number of pairs, and internal resistance of four micro-TEG prototypes

|                | TEG 27 | TEG 355 | TEG127 | TEG495 |
|----------------|--------|---------|--------|--------|
| Diameter × Thickness | 500 µm × 10 µm | 100 µm × 10 µm | 200 µm × 10 µm | 200 µm × 10 µm |
| Number of Pairs  | 27     | 355     | 127    | 495    |
| Internal Resistance | 45.2 Ω | 180.2 Ω | 13 Ω   | 114.5 Ω |

3. Device Performance

The open circuit voltage and the maximum power output of each prototype are characterized by using a home-made setup at different temperature differences and the testing results are summarized in Fig. 3. TEG27 and TEG355 demonstrate very low power output, which is mainly due to the large electrical resistance of thin bottom interconnectors (100 nm Au) and thus large internal resistance as shown in Table 1. In TEG127, bottom interconnectors are thickened by depositing 1.5 µm Au layer via DC electroplating. Meanwhile, thermoelectric properties of both n-type and p-type materials are further optimized. As a result, TEG127 produces a maximum power of 3 mW at ΔT = 52.5 K, corresponding to a power density of 9.2 mW/cm², which is the highest value reported for the electroplated TEGs [3]. TEG495 demonstrates a maximum power of 4.4 mW at ΔT = 50 K, which is larger than the counterpart of TEG127 but not as high as we expected. As can be seen in Fig. 3a, the open circuit voltage of TEG495 is 1.36 V at ΔT = 50 K, ~3.4 times the value of TEG127. However, the maximum power of TEG495 at ΔT = 50 K is only ~47% higher than that of TEG127 because of the abnormal increase of the internal resistance as shown in Table 1. The large internal resistance of TEG495 might be caused by the nonuniform current density during the pulsed electroplating, which might lead to larger electrical resistivity of thermoelectric materials.

Figure 3. The open circuit voltage (a) and maximum power (b) of four micro-TEG prototypes at different temperature differences.

4. Design Optimization

TEG127 demonstrates the largest power density, which can be attributed to the low parasitic contact resistance and high packing density of the thermoelectric pillars [3]. To explore the possibility of further enhancing the power density of TEG127, we conducted theoretical analysis for this prototype using the model in Fig. 4. The simulation results are given in Fig. 5. Our theoretical analysis shows...
that the maximum power density of TEG127 might be further enhanced by optimizing the diameter (290 \( \mu \)m) and the thickness (11 \( \mu \)m) of thermoelectric pillars and decreasing the side length of the area containing the thermoelectric pillar.

![Figure 4](image1)

**Figure 4.** Schematic diagram of a micro-TEG (a) and one pair of n-type and p-type thermoelectric pillars embedded in the filling materials (b).

![Figure 5](image2)

**Figure 5.** Variation of the calculated maximum power density with diameter of thermoelectric pillars (a), side length of the area containing one pillar (b), and thickness of thermoelectric pillars (c).

5. Conclusions

In summary, we developed four micro-TEG prototypes by combining pulsed electroplating with microfabrication techniques. TEG127 demonstrates the largest power density, \( \sim 9.2 \text{ mW/cm}^2 \) at a temperature difference of 52.5 K. Theoretical analysis reveals that it is possible to further enhance the power density of this prototype by optimizing the design parameters.

Acknowledgments

The authors acknowledge the financial support from the Research Grants Council under Theme-based Research Scheme (T23-407/13-N) and the Innovation and Technology Commission (ITS/020/16FP) of the Hong Kong Special Administrative Region, China.

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