New high density micro structured thermogenerators for stand alone sensor systems

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Abstract

Thermoelectric thin film micro-devices with high packing densities of thermoelectric legs are of high demand in micro-systems for self-standing and so called waste energy self-powered sensor systems for wireless data transfer. One technical solution for such micro-devices is offered by the Micropelt technology.

The recent development status of the Micropelt micro thermogenerators will be presented. The Micropelt platform technology now allows devices with up to ~8000 p-n-couples per cm^2. Open circuit voltages achieved so far were about 2.3 V at 10 K temperature difference. Maximum power output was measured to be 2.8 mW. Thus they are suited as power supplies for harvesting energy in stand alone sensor systems for wireless data transmission. An evaluation setup to perform first level tests for the efficiency of harvesting waste energy using the microstructured thermogenerators will be presented.

Introduction

The need for ubiquitous electronics is rapidly growing with increasing features and possibilities of modern mobile terminal devices. One important drawback is the demand for power supplies that allow unlimited operating and stand-by times. One solution to tackle this problem relies on devices and systems which transform otherwise lost energy, mainly of industrial equipment and in addition of human power into electricity.

There are several approaches to the energy harvesting scenario. The most common are electromagnetic, electrostatic or piezoelectric and in particular thermoelectric generators. The major challenge of these energy autarkic systems lies in the optimization of the energy harvesting source parameters as a function of the provided heat power. Additionally, it is essential to match the generator to the load and to consume the transferred energy in an economical manner.

Sensor systems can be powered by thermoelectric energy harvesting. A self-standing sensor system powered by waste energy needs miniaturized thermoelectric devices with overall device height of a few 100 µm and some hundreds leg pairs integrated into few mm^2 areas. Thus a manufacturing of thermoelectric devices similar to microelectronics fabrication is required to address the expected industrial high volume quantities of reliable products described above.

For applications around ambient temperature the use of the bismuth telluride (V-VI) related compounds as conversion material are self-evident [1]. Consistent with those purposes the Micropelt concept for thermoelectric devices with typical thin film thermoelectric layers in common vertical architecture on silicon substrates were successfully invented [2] and developed [3, 4, 5, 6].

Due to the Micropelt silicon-wafer based and MEMS-like production process devices with a total thickness of less then 500 µm can be customized in a wide size range from dimensions of less than 1 mm^2 to ~1cm^2.

The recent development status allows the production of micro-devices with up to a few thousand p-n-couples per cm^2 achieving enough output power for wireless data transmission systems.

Micropelt – Technology: State-of-The-Art for Thermogenerators

The Micropelt technological approach for a common vertical architecture of thermoelectric devices is based on a up to 6” two wafer technology separately for n- and p-type V_2-VI_3-based material. Details of the technology are reported elsewhere [4].

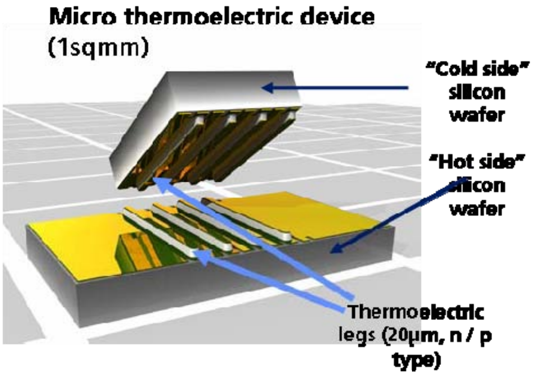


Figure 1: Micropelt device: schematic drawing of the two wafer concept with the thermoelectric legs on the individual wafers before the soldering process, Photo: Micropelt©.

Figure 1 shows a schematic drawing of a Micropelt device before the final soldering process. The “two-wafer” concept is indicated by the individual n- and p-type parts with their thermoelectric legs.

The so called power factor $\sigma * S^2$ [7] is taken for thermoelectric quality control. For n-material a power factor of ~30µW/cmK^2 and for p-type material ~40µW/cmK^2 power factors have been achieved by appropriate annealing processes.

Recently, a novel preparation technique for nanometer-scale sputtered thermoelectric material with power factors of ~50µW/cmK^2 for p-type materials was presented [8].

The definition of the individual n- and p-type legs is done using dry etching techniques [4]. Figure 2 [9] is a SEM picture of a new design for micro thermogenerators proving the feature size of ~35µm square. Figure 3 [9] shows the corresponding picture of one of the recent Peltier-cooler designs with a bar length of ~600µm for comparison

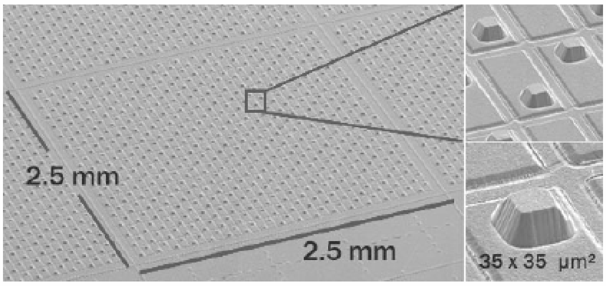


Figure 2: SEM picture: typical micro-thermogenerator design with a feature size of ~35µm square, Photo: Micropelt©.

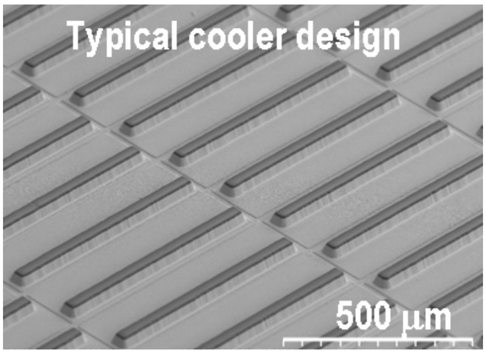


Figure 3: SEM picture: Typical micro-Peltier-cooler design with a feature size of ~600µm length, Photo: Micropelt©.

The Micropelt platform technology enables flexibility concerning device sizes. Currently available devices feature areas from 0.5 mm^2 up to 25 mm^2, figure 4 [9] in comparison to some important coins-.

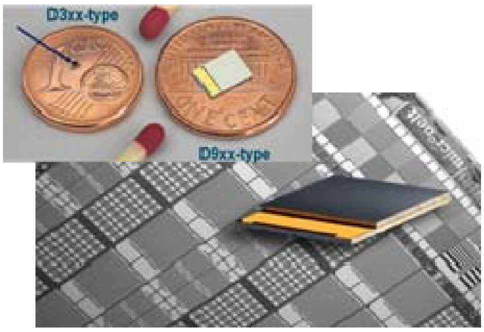


Figure 4: Individual miniaturized Micropelt© devices, upper part: comparison to coins lower part: side view in front of a wafer with different Micropelt designs, Photo: Micropelt©.

Properties of the micro Thermogenerators

Table 1 [9] summarizes some features of the available types of the micro-generators including dimension, number of leg pairs thermal resistance and mean electrical resistance. 1800 leg pairs, type MPG-D901, integrated on an area of ~5mm^2, corresponds to ~75 leg pairs per square mm.

Table 1: Some features of the currently available types of the Micropelt micro-generators including dimension, number of leg pairs thermal resistance and mean electrical resistance. See also Micropelt data sheet (www.micropelt.com).

Type	Dimensions [mm] Top side Bottom side	Number of leg pairs	Thermal resistance [K/W]	Electrical resistance [Ω]	Subtrates Type	Thickness [µm]
MPG-D601	2.47 x 2.47 2.47 x 3.34	578	13.0	416	Silicon	500
MPG-D602	2.47 x 2.47 2.47 x 3.34	450	9.6	189	Silicon	500
MPG-D603	2.47 x 2.47 2.47 x 3.34	200	21.1	79	Silicon	500
MPG-D901	4.97 x 4.97 4.97 x 6.72	1800	2.4	757	Silicon	500
MPG-D902	4.97 x 4.97 4.97 x 6.72	1152	1.7	236	Silicon	500

Output voltage (open circuit) and the matched electrical power output for the micro-generator types MPG D601 and MPG D602 are displayed in figure 5. At 10 K temperature difference 2.3 V (open circuit voltage) and 2.8 mW (load matched) are available from MPG-D901.

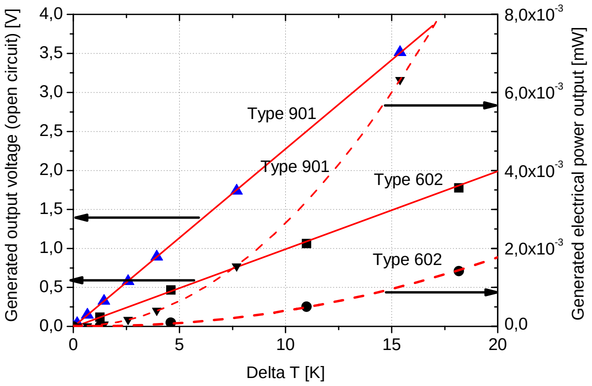


Figure 5: Open circuit voltage and matched electrical power output for the micro-generator types MPG D901 and MPG D602.

From the data in figure 5 it can be calculated, taking into account the thermoelectric properties of the sputtered n- and p-layers, that further improvements are possible. With ~220µV/pair the type MPG-D602A achieves approximately 60% of the “theoretical” open circuit voltage. The main reason for this difference can be explained by losses of the applied temperature difference within the silicon substrates.

The currently achievable packing density of up to 100 thermoelectric leg pairs/mm^2 is to our knowledge the highest leg pair density for industrial manufactured thermoelectric devices.

Evaluation Kit

The naked devices, figure 4, are not suitable for an easy evaluation of remote sensing applications by harvesting different types of waste energy. Based on the micro-generator type MPG-D602 a robust evaluation setup was developed which allows easy first level tests. In figure 6 the different parts of this setup are illustrated. The left part of figure 6 shows the base equipped with two MPG D602 devices in series fixed with a high thermoconducting solder onto the aluminium base. The middle part of figure 6 is an engineering drawing of the heat sink-“aluminium tower”- with thermally decoupled screws and ball-shaped spacers for a pressure-less mounting of the generator between ground plate and heat sink. The ground plate is equipped with additional holes for an easy mounting to any heat source. The right part in figure 6 is the final hardware configuration. It should be mentioned, that the assembly is not optimized for maximum generated voltage and power. The robust design allows outdoor energy harvesting and even the use in harsh environments.

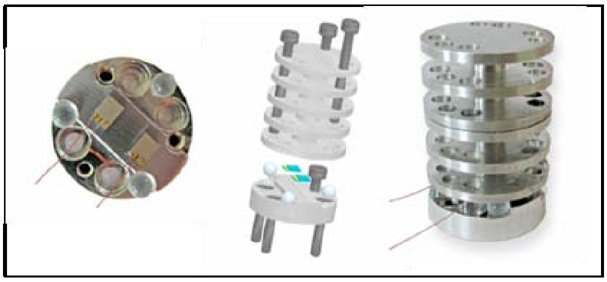


Figure 6: MPG-D602 evaluation setup which allows easy first level evaluation; left: aluminium base with two thermogenerators; middle: engineering drawing of the whole set-up; right: complete assembly, Photo: Micropelt©.

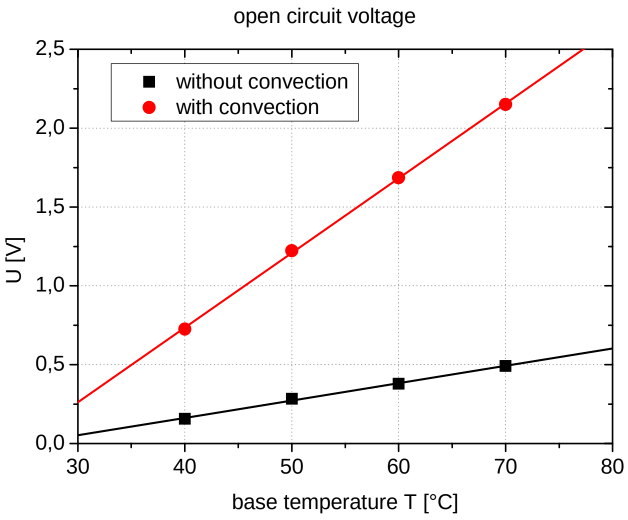


Figure 7: Open circuit voltage of a MPG-D602 evaluation kit for natural convection and forced convection.

The utilisability of this setup was analyzed for natural convection in an ambient environment (temperature was 24°C) and under forced convection. To simulate forced convection a fan at 5 cm distance to the kit was used. In figure 7 the generated open circuit voltage is plotted for both methods.

The effect of the forced convection is obvious. This results in a significant increase of the output voltage by factor ~4. So even for small temperature differences (hot side temperature 37°C e.g. human body) a remarkable voltage of ~250mV was measured for forced convection. This is more than enough to start step-up dc-dc converters for wireless communication systems [10].

In the same manner the characteristic diagrams voltage versus current at different load resistances, figures 8, 9, were measured. The thermogenerator resistance is around 400Ω, table 2. The respective max. (matched) output powers depicted from figures 8 and 9 is summarized in figure 10.

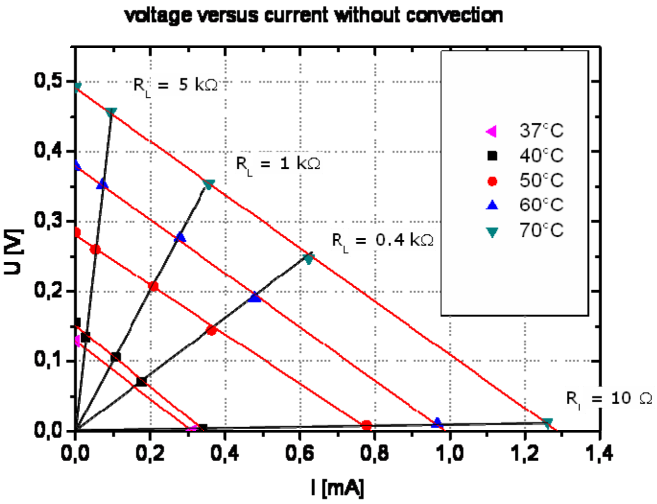


Figure 8: Characteristic diagram voltage versus current at different load resistances for natural convection of a MPG-D602 evaluation setup. The thermogenerator resistance is around 400Ω, table 2.

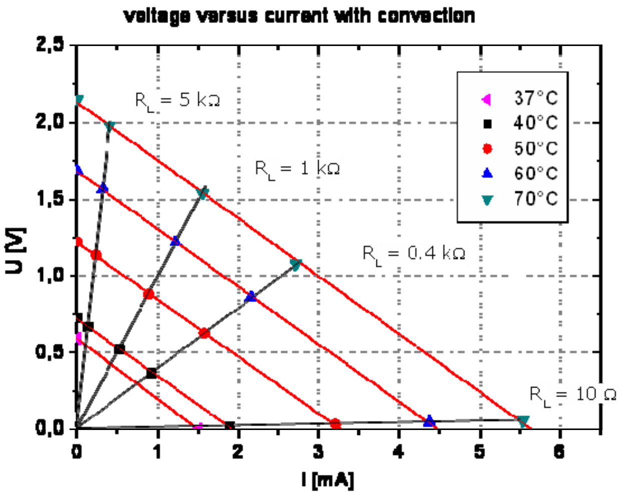


Figure 9: Characteristic diagram voltage versus current at different load resistances for forced convection of a MPG-D602 evaluation setup. The thermogenerator resistance is around 400Ω.

The lines for 37°C in figures 8 and 9 were derived from the extrapolated open circuit voltages, see figure 7. Accordingly the max. (matched) power for a "hot" side temperature of 37°C was calculated from figures 8 and 9 and inserted in figure 10. Although the thermogenerator power for a base temperature of 37°C is quite low the generated power would exceed the power requirement for wrist watches by far.

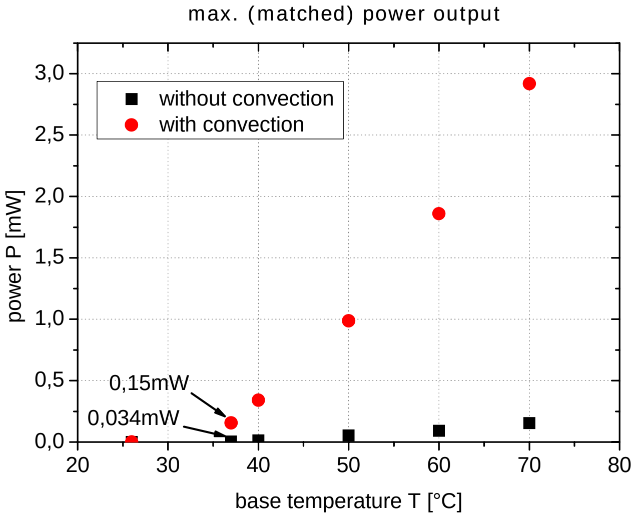
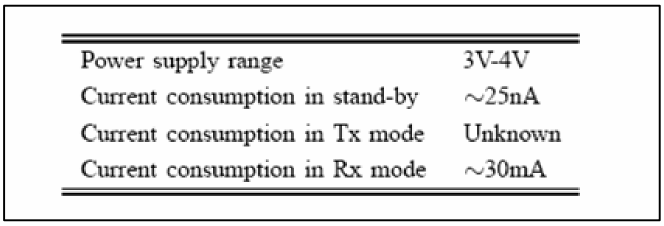


Figure 10: Matched output power of a MPG-D602 evaluation kit for natural convection and forced convection.

The enormous ratio, factor 20, of the matched output power between natural convection and forced convection highlights the relevance of an appropriate heat sink with a low thermal resistance.

Based on the example in table 2 it is clear, that these devices outperform the requirements of communication modules of different suppliers like EnOcean [10], table 2, and Nordic [10], if the thermogenerator is connected to a step-up dc-dc converter which is also described in [10].

Table 2: Power requirements for the EnOcean communication module, Tx: transmission mode, Rx: receiver mode



Power supply range	3V-4V
Current consumption in stand-by	~25nA
Current consumption in Tx mode	Unknown
Current consumption in Rx mode	~30mA

Conclusion

The Micropelt technology for the manufacturing of miniaturized thermoelectric generators enables now the integration of up to 100 thermoelectric leg pairs on 1mm^2.

The devices can easily be incorporated into an evaluation setup for converting waste heat into electrical energy also in harsh environments. The converting performance exceeds by far the requirements needed for remote sensing in wireless data transfer systems.

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