DOI 10.5162/12dss2015/5.6

Thermoelectric Energy Harvesting from small and variable Temperature Gradients

Peter Woias
Laboratory for Design of Microsystems, Dept. of Microsystems Engineering (IMTEK),
Albert-Ludwig-University Freiburg, Freiburg, Germany, woias@imtek.de

Abstract:

Although there is a wide spectrum of potential applications, thermoelectric energy harvesting from small (typ. 1K) and highly variable (typ. on the second to minute scale) temperature gradients is not covered too much by research activities or applications today. It is obvious that this resource will not provide a wealth of thermal energy to be harvested from, compared with high-temperature resources. However, it has enough potential to provide an energy supply for wireless embedded systems in applications that will in not exhibit huge and stable temperature gradients and heat fluxes, but also no other choices for energy harvesting. This article will explain the technical problems encountered in this very specific area of thermal energy harvesting and will show design concepts for suitable energy-autonomous embedded systems. As a result it turns out that a thorough and truly application-specific system design is required to cope with size and space constraints, low output voltages of thermoelectric generators and, especially, the high temporal variability of the small temperature gradients available.

Key words: Thermoelectrics; energy harvesting; small temperature gradient; step-up converter

Introduction

Among the huge range of applications conceivable for thermoelectric energy harvesting only a few examples are found for the tapping of small and variable temperature gradients (e.g. [1,2,3]). One reason may be that the potential of this "small energy resource" is regarded as not being attractive. Also, reliability issues for the stable operation of an energy-autonomous embedded system are frequently named as a serious counter argument. On the other hand, we find a number of conceivable application areas for thermoelectric energy harvesting that provide, by their nature, only small and highly dynamic temperature gradients and heat fluxes: These are, for instance, wearable systems for humans and animals or applications in environmental and infrastructure monitoring. Here, the heat source is either regulated or limited in its thermal output, consider e.g. the thermal regulation capabilities of human skin or the thermal insulation of animal fur, and highly dynamic, e.g. through variable weather conditions or duty cycles of technical equipment. At the same time, other energy resources are not useable, small or non-predictable in many of these applications: For instance, mechanical energy harvesting from human body movements, done at a reasonable power level, requires huge seismic masses and generator structures that are not "wearable". An energy-autonomous sensor mounted at an exposed building site will not undergo vibrations to a useful degree and photovoltaic cells used at the same location may suffer from the danger of icing, snow coverage or dirt accumulation.

On the other hand, thermoelectric generators (TEGs) possess advantages for an energy harvesting from small and variable energy levels that are not found with many other generator and conversion principles:

(1) The electrical output is DC-like with the exception of - easily correctable - polarity changes due to a reversal of the temperature field. A rectification of AC currents with all associated power losses is not required. (2) The electrical properties of a TEG will remain relatively constant under variable environmental conditions, in contrary to e.g. the highly dynamic variation of parameters found in a piezoelectric vibration harvester. (3) The high robustness and reduced complexity of the thermoelectric principle opens a wider space for system design under harsh global constraints.

This overview paper will first present the basic theory for low-ΔT energy harvesting and will then demonstrate different optimization strategies with exemplary results taken from several studies performed in our lab.

System model

Fig. 1 shows the simplified equivalent circuit and system model of a TEG with connected DC-DC converter. The latter is used to boost the usually too low output voltage $U_{out,TEG}$ of the TEG to a higher voltage U_L for the system electronics modeled as resistive load R_L. The main characteristics of this step-up converter are its self-controlled start-up voltage $U_{in,min}$, power conversion efficiency η and its voltage step-up ratio S.

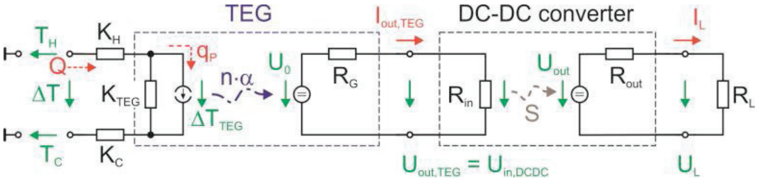

Fig. 1. Equivalent model of a TEG with its thermal interfaces and a connected DC-DC converter.

The thermal interface to the hot and cold temperatures T_H and T_C is characterized by two thermal resistances K_H and K_C, respectively. Finally, the TEG itself can be described with its Seebeck coefficient α, thermal resistance K_{TEG} and internal electrical resistance R_G. For high power applications the Peltier effect of the TEG could be taken into account via a parasitic heat flux, shown as the current source q_P in Fig. 1. This effect is, however, negligible for the following discussion of low power energy harvesting. With this simplification the basic equations for the temperature difference ΔT_{TEG}, no-load output voltage U_0 and electrical output power P_{out} at the TEG are as follows:

$$\Delta T_{TEG} = \frac{K_{TEG}}{K_H + K_{TEG} + K_c} \cdot \underbrace{\left(T_H - T_C\right)}_{\Delta T} \quad (1)$$

$$U_0 = \alpha \cdot \Delta T_{TEG} \quad (2)$$

$$U_{out,TEG} = U_{in,DCDC} = U_0 \cdot \frac{R_{in}}{R_G + R_{in}} \quad (3)$$

$$P_{out} = \eta \cdot P_{in,DCDC} \quad (4)$$

A combination of eq. (1) to (4) delivers the output power P_{out} at the load R_L as a function of the temperature difference $\Delta T = T_H - T_C$:

$$P_{out} = \left(\frac{K_{TEG}}{K_H + K_{TEG} + K_c}\right)^2 \alpha^2 \cdot \Delta T^2 \cdot \frac{R_{in}}{\left(R_G + R_{in}\right)^2} \cdot \eta \quad (5)$$

It has to be mentioned that the power conversion efficiency η of the DC-DC converter is not constant, but usually a complex function of its input and output voltages and currents. Also, several other parameters, e.g. the TEG internal resistance R_G, are not constant. Nevertheless the model given with eq. (1) to (5) delivers sufficiently accurate data for system design and optimization. A few consequences for harvesting from small ΔT with maximized output power P_{out} can easily be derived from eq. (5):

- The ratio of the thermal resistive divider will always be smaller than one and appears as a squared argument. On a first glance it should therefore be maximized by keeping K_H and K_C as small as possible with respect to the TEG thermal resistance K_{TEG} .
- The optimization of power transfer over the electrical interface follows well-known rules for voltage sources with internal resistances and resistive loads. Maximal power is transferred for $R_L = R_G$ with a drop of the TEG output voltage to $0.5 \cdot U_0$.
- The Seebeck coefficient α of the TEG should be as high as possible. Unfortunately this cannot be achieved by simply increasing the number of thermocouples as this may be accompanied by an equivalent raise of the electrical resistance R_G.

These optimization rules do appear as useful on a first glance. However, detailed examination of different applications shows that additional rules apply not obvious from eq. (5). That will be explained in the following for different optimization strategies, with practical applications as examples.

Optimization of thermal interfaces with regard to dynamic temperature variations

In a project with industrial partners [4] the application of thermoelectric energy harvesting in road and railway tunnels has been studied in detail. The duties of energy-autonomous sensor systems in a tunnel could be, for instance, environmental and climate control, traffic monitoring or the detection of accidents, fire and explosions. For all these tasks a distributed sensor system is required with the potential for an easy retrofit of existing tunnels. An energy supply via batteries or power grids can be excluded from maintenance and cost reasons, which opens room for the application of energy harvesting. For this project, initial ideas were targeting geothermal energy harvesting: A thermal

DOI 10.5162/12dss2015/5.6

conductor embedded into the tunnel wall would allow a heat flux to the wall surface with a TEG mounted in between. Although this concept could be proven to be realistic from the physical standpoint it turned out as not viable from a technical point of view: Modern construction techniques use prefabricated concrete shells to build a watertight and crack-free tunnel wall. This excludes a retrofit by drilling holes for an embedding of thermal conductors as these would form potential locations for crack formation and water penetration.

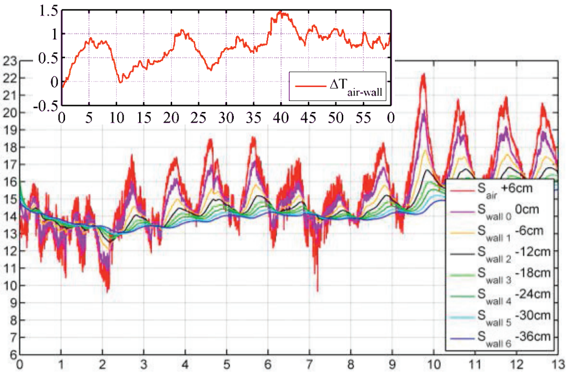

Fig. 2. Temperatures of the air (S_{air}) and tunnel wall surface ($S_{wall,0}$), and temperature profile in the wall of a road tunnel, measured over 13 days during spring; insert: temperature difference between air and wall surface for a period of 1 hour [5].

Nevertheless, meaningful measurement data could be obtained during revision of a road tunnel built in traditional concrete technique (Hugenwald tunnel close to Freiburg). For this purpose a probe shaft was designed carrying 8 equidistant PT1000 temperature sensors to measure the air temperature above the tunnel wall, the wall surface temperature and a 36 cm deep temperature profile in the wall (see Fig. 2). Results show the principal feasibility of geothermal energy harvesting in a tunnel wall, with maximal temperature differences up to 6 Kelvin between the wall surface and a depth of 36 cm. Also, daily and seasonal variations of the air temperature are found in the depth of the tunnel wall with a delay, equilibration and reduction caused by the thermal mass of the tunnel wall. Although these are promising results that may be applied for elder tunnels the technical boundary conditions described above do only allow thermoelectric energy harvesting between the wall surface and the air in the tunnel, with small (0…2K) and highly dynamic (second to minute scale) temperature gradients.

In consequence an air-solid energy harvesting system was built using a commercial TEG with a heat sink mounted on one side to establish a thermal contact to the air. The other side of the TEG was directly mounted onto the tunnel wall using heat paste for a low thermal resistance.

A more detailed investigation showed that the optimization of the air-TEG interface had to happen primarily with regard to the dynamic variations of temperature. Following equation (5) the application of a heat sink with a low thermal resistance K_H would be at premier need. However, as a consequence the thermal mass of the heat sink would also be increased leading to a higher thermal time constant of the whole system. As the output power follows $(\Delta T)^2$ such a thermal low pass would dampen and average all rapid excursions of ΔT with detrimental effects on the harvested energy.

Tab. 1: Thermal resistance K_{HS}, thermal time constant τ and harvested energy E for different heat sinks used with the same TEG [6].

Heatsink *Supplier: Fischer Elektronik, Germany*	**K_{HS} [K/W]** for ΔT = 1-10K	**τ [s]**	**E [J/day]**
1: ICKPEN45W	9.3 - 7.1	239	1.74
2: SK47550SA	10.3 - 7.6	374	1.32
3: ISKPEN3XE1	3.4 - 2.5	402	0.87
4: SK414100SA	5.6 - 4.3	416	0.68

Table 1 shows the calculated harvested energy for four different heat sinks with different thermal resistances and time constants. Input data were taken from Fig. 2. As a result, heat sink 1 with the shortest thermal time constant provides the best thermal interface, with a harvested energy almost triple in comparison to e.g. heat sink 4 with a lower thermal resistance but a much higher thermal time constant. In a practical application an optimized system has been used in the above-mentioned road tunnel to supply of a wireless temperature sensor. Starting from a temperature difference of only 1.2 K at the TEG this sensor system was able to transmit data on a reliable basis [5,13].

Optimization of thermal interfaces with regard to static temperature variations

As an example for a biological application a study on thermal energy harvesting from wildlife is currently conducted, first results have been published in [7]. The application scenario would be the realization of energy-autonomous wildlife trackers, to follow the migration paths of wildlife in biological studies, to detect unusual behavior of animals in biological or environmental studies or to monitor the position of freely grazing livestock in precision farming. For all these cases battery-powered wireless transmitters are used today, with several limitations and tradeoffs concerning battery lifetime, wireless connectivity and data retrieval. The concept of thermal harvesting from wildlife pursued in this study uses a thermoelectric generator mounted in the collar of a tagged animal, to harvest energy from the temperature differences between the fur and ambient air. Here the isolating effect of fur is a major, detrimental influence factor when mammals are considered as thermal energy source. Problems arise from the - naturally high - thermal insulation of fur and also from a high variability of its thermal resistance due to e.g. wetting, wind, air humidity, seasonal effects or individual characteristics of different animals and species. As a result, a worst-case scenario has to be taken into account for system design and strategies for a compensation of thermal insulation have to be developed.

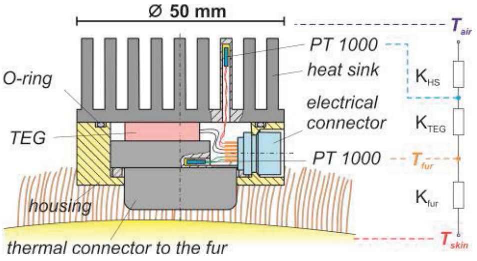

Fig. 3. Schematic cross section of a collar-mountable TEG system with a depiction of all thermal resistances and temperatures.

Fig. 3 shows the schematic cross section of a collar-mountable TEG system tested on a freely grazing sheep. Partial fur penetration is accomplished by a protruding alumina block at the bottom of the module. A commercial TEG is mounted between this block and a heat sink using heat paste. In addition, two PT1000 temperature sensors are integrated for a continuous recording of the hot side and cold side temperatures across the TEG. Exemplary measurement results are shown in Fig. 4 as taken from [7].

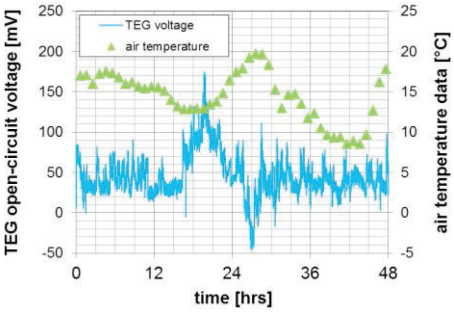

Fig. 4. Calculated TEG open-circuit voltage from a 48-hour temperature measurement on a freely grazing sheep, together with climate data from a local weather station [7].

Using the system model from Fig. 1 a thermal resistance of sheep fur close to 88 K/W could be calculated for this animal, in accordance to literature data [11]. This is an exceptionally high value when compared to the maximal thermal resistance of TEG (20 K/W) and heat sink (typ. 5 K/W). Nevertheless, with the data from Fig. 4 the TEG delivers an average power of 174 µW at maximal no-load output voltages of 170 mV. After voltage up-conversion with all effects as described below an average power of 54 µW is available at the output of the step-up converter. This is sufficient to supply a low-power wireless transmitter with a typical power consumption of 25 µW. Next steps of this study will be a further optimization of the power management electronics and a full system integration of TEG, electronic power management, wireless transmitter and, eventually, a rechargeable backup battery.

Low-voltage step-up converters

The measurement data shown in Fig. 4 give an example for the high variability of temperature gradients in low-ΔT applications. Temperature gradient and output voltage of the TEG system do even change polarity, presumably due to direct solar irradiation onto the heat sink. The low level of output voltages obtained is the range of a few 10 mV. Therefore, an electronic boost converter is mandatory, which in best case will also detect and compensate polarity changes of the TEG output voltage. As general and most important requirement step-up conversion should start at input voltages as small as possible, as all harvested energy with TEG output voltages below this threshold will be wasted. Power conversion efficiency η should be as high as possible and at least constant with variable input voltages. The voltage step-up ratio S must be high enough to supply connected electronic circuitry with a reasonable voltage and, finally, a self-powered operation from the applied low input voltages should ensure operation under worst-case conditions, i.e. without any auxiliary power from a separate battery.

At the present state-of-the-art the principle of the so-called Meissner or Armstrong oscillator is used throughout to address the problem of low-voltage start-up, see e.g. [8,9]. This circuit is a transistor oscillator with a transformer in the feedback loop (see Fig. 5). Field effect transistors [8] or depletion MOSFETs [9] are used instead of bipolar junction transistors or enhancement MOSFETs to enable current flow through the transformer's primary winding at zero gate threshold voltages and, with that, at low input voltages. For an operation as step-up converter the oscillator is operated in a non-linear mode, i.e. current flow through the transistor is periodically disrupted and enabled to generate a high periodic variation of the magnetic field in the transformer core. A drawback of this approach is, however, that magnetic field poling happens only in one direction with the danger of core saturation and corresponding energy loss. As a consequence power conversion efficiency is not constant and drops rapidly when an optimal value of the input voltage is left, see e.g. [9].

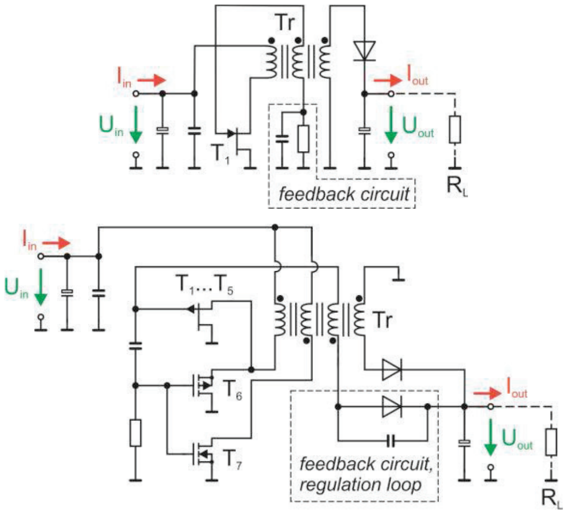

Fig. 5. Schematic of a Meissner oscillator according to [8] (top) and of a combined Meissner-forward converter [10] (bottom).

An improvement is the combination of a Meissner oscillator with a so-called forward converter (see Fig. 5). The Meissner oscillator is built from transistors T_1 to T_5 and two windings of the transformer. This circuit part ensures a start-up at low input voltages and provides an eventually increasing AC signal in the transformer's feedback winding, which also drives the MOSFET transistors T_6 and T_7. As soon as the gate threshold voltages of T_6 and T_7 are reached this circuit part starts operating as a forward converter feeding alternating currents into the two input windings of the transformer, thus generating an alternating magnetic field in the transformer core. Consequently, effects of magnetic biasing are avoided and the transformer is used to a better extent. Also, energy wasted in the feedback circuit of the traditional Meissner oscillator is directed into the output terminal.

Further details of this circuit are found in [10]. Its start-up voltage is 10 mV, compared to 20 mV found for other low-voltage step-up converters [8,9]. Power conversion efficiency reaches 35% at start-up and remains fairly constant with variable input voltages. For that the combined feedback-regulation loop shown in Fig. 5 regulates the transistor drive voltages depending on the output voltage U_{out}.

Optimization of electrical interfaces

Aside from the design of step-up converters their implementation into the TEG system is also of primary importance for an application-specific optimization. Frequently, load matching is targeted for the adaptation of a TEG to a load at is output, which would, in this case, be the input resistance R_{in} of the step-up converter. For this purpose R_{in} is made equivalent to the TEG source resistance R_G. The TEG output voltage is then given by

$$U_{out,TEG} = \frac{1}{2}\cdot\underbrace{\frac{K_{TEG}}{K_H + K_{TEG} + K_c}\cdot\alpha\cdot\Delta T}_{U_0} \qquad (6)$$

While this configuration guarantees a maximal power transfer it can be suboptimal for the start-up of a TEG system from small temperature gradients ΔT. As seen from eq. (6) the output voltage of the TEG falls to 50% of its no-load value U_0 in this case. Therefore the TEG has to provide a no-load voltage U_0 that is double the value of the step-up converter's start-up voltage, with consequences for the required minimal temperature difference at the TEG.

Optimization strategies targeting this interface are discussed in the following with a study on the automotive application of TEG systems [12]. The power grid of a mid-class passenger car has a total length of wires close to 3000 m, takes a substantial share of the car's total weight, it is installed and serviced manually and does provide a number of potential sources of failure, e.g. at electrical connectors or in harsh environments. To improve this situation energy harvesting could be used for the energy-autonomous operation of wireless, embedded sensors, to reduce the size and mass of power grids used in a car and to eliminate wire-based defect sources. In principle, the thermal energy dissipated as waste by an internal combustion engine is by far high enough to power a wealth of sensors. However, as soon as thermal energy harvesting is applied, the problem of a rapid cold-start will arise: After the start of the engine it may take several minutes until the temperature gradients at the motor block or the exhaust duct are high enough to enable start-up of a TEG system. Under normal operation, however, thermal waste energy is abundant in a car. Therefore, a deliberate electrical load mismatch can be chosen to enable an early start-up of thermal energy harvesting and thus an early availability of wireless sensors.

Fig. 6 shows results of a test drive with a TEG system mounted to the motor block of a passenger car. In this study a small TEG was chosen on purpose, with a Seebeck coefficient of only 4 mV/K. After 210 s the temperature gradient between the motor block and the air in the motor compartment is sufficient to provide 300 µW of electrical power, which is in principle high enough to run an energy-autonomous

DOI 10.5162/12dss2015/5.6

system with a power consumption of 100 µW, taking the efficiency of the step-up converter into account (typ. 33%). However, the TEG output voltage of only 17 mV at that time does not allow starting today's low-voltage step-up converters under load-matched conditions. The above-described optimized device with 10 mV start-up voltage [10] would require a TEG no-load voltage of 20 mV, others need at least 40 mV for a start-up at 20 mV [8,9].

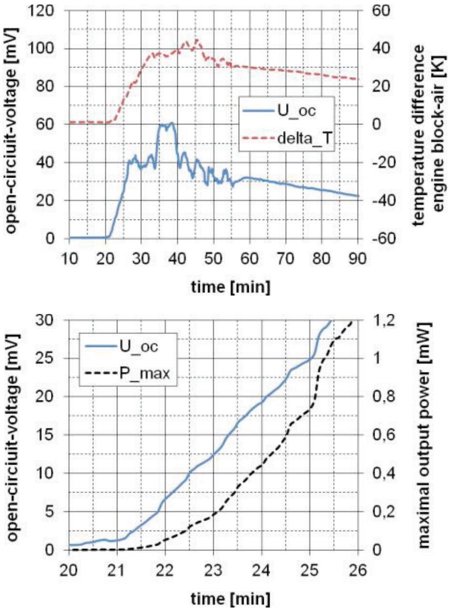

Fig. 6. Open circuit voltage U_oc and temperature difference delta_T for a TEG mounted at the motor block of a passenger car during a 35 min test drive, starting at minute 20 (top), detail of the cold-start period with U_oc and the maximal power P_max deliverable by the TEG (bottom) [12].

In consequence, as the TEG delivers enough electric power but not enough voltage, a deliberate load-mismatch can be used to reduce the start-up time of the low-ΔT TEG system while keeping the harvested power high enough. The step-up converter described in [10], although not ideal as explained below, will be taken for an explanation of this approach and its revenue:

At an input voltage around 10 mV the step-up converter has an input resistance R_{in} of approximately 1.8 Ohm. With a TEG source resistance R_G of 0.21 Ohm eq. (3) predicts that operation will start at a TEG zero-load voltage U_0 of app. 11.2 mV, instead of 20 mV required for load-matching. The respective temperature gradients at the TEG are 2.8 K and 5 K. This calculation is theoretical and idealized to highlight the proposed concept. Under realistic boundary conditions the required start-up voltage for the chosen combination of TEG and step-up converter is approximately 25 mV. The reason is a non-sufficient voltage step-up ratio of only 120 at an input voltage of 11.2 mV. With an input voltage of 25 mV the step-up ratio is 100 at an output power of 100 µW, which means a sufficiently high output voltage of 2.5V. Nevertheless, at an input voltage of 11.2 mV the step-up converter will still deliver 12 µW at a voltage of 1.2V. This would suffice to supply a boost converter for a full step-up to the required output voltage, as shown in a similar way in [8].

Discussion and conclusion

This paper has used several practical application scenarios to discuss the idea of thermal energy harvesting from low and variable temperature gradients. As one example, energy-autonomous condition monitoring in traffic tunnels has been demonstrated with temperature gradients of only 1.2K at the TEG [13]. A study on energy harvesting from wildlife shows that several 10 µW of electric power can be obtained even with a small TEG and under the boundary condition of a low heat flux [7]. Low-voltage step-up converters have been developed with a power conversion efficiency up to 35% at start-up voltages down to 10 mV [10]. Finally, the importance of optimized system design is highlighted with a study on automotive applications [12]. Next steps will be the improvement of system concepts and power management electronics for low-ΔT energy harvesting, together with the realization of additional applications of this promising technique.

References

[1] E.E. Lawrence, *Proc. 21st Int. Conference on Thermoelectronics*, 446-449 (2002)

[2] V. Leovnov, P. Fiorini, S. Sedky, T. Torfs, C. Van Hoof, *Proc. IEEE Transducers 2005*, 291-294 (2005)

[3] Y. Meydbray, R. Singh, Ali Shakouri, *Proc. 24th Int. Conf. on Thermoelectrics*, 348-351 (2005)

[4] http://www.aisis-innovation.org, retr. 05.10.2015

[5] A. Moser, PhD thesis, Albert-Ludwig-University Freiburg, 2012

[6] A. Moser, L. Rendler, M. Kratschmer, P. Woias, *Proc. PowerMEMS 2010*, 431-434 (2010)

[7] P. Woias, F. Schüle, E. Bäumke, P. Mehne, M. Kroener, *IOP Conf. Series* 557, 012084 (2014)

[8] J.M. Damaschke, *IEEE Transactions on Industrial Applications* 33 (5), 1203-1207 (1997)

[9] Linear Technology Corp., datasheet LTC 3108

[10] P Woias, M Islam, S Heller, R Roth, *IOP Conf. Series* 476, 012081 (2013)

[11] K. Cena, J.A. Clark, *Physics in Medicine and Biology* 19, 51-65 (1974)

[12] P. Woias, P. Mehne, S. Heller, M. Kröner, *Proc. MikroSystemKongress 2015*, no page numbers

[13] A. Moser, M. Erd, M. Kostic, K. Cobry, M. Kroener, P. Woias, *Journal of Electronic Materials* 41 (6), 1653-1661 (2012)