Printed thermoelectric generators

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Anotace:
Článek popisuje možnosti získávání energie pomocí termoelektrických generatorů. Protože termoelektrické generátory mají velmi nízké výstupní napětí potřebují integraci velkého počtu jednotlivých termočlánků. Tiskové technologie umožňují zvýšit efektivnost výroby s jednotlivými články zapojenými do série. Laterální uspořádání termočlánků umožňuje snadný způsob tisku, ale účinnost je snížena velkým odporem dlouhých přívodů. V případě vertikálního uspořádání článků je celkový odpor menší, ale účinnost je omezena tepelnou vodivostí použitých materiálů. Kombinovaná konstrukce s bočním uspořádáním krátkých vývodů termočlánku umístěných v dvojvrstvovém tepelném izolátoru a tepelným tokem kolmým na matrici termočlánků spojuje výhody obou typů.

Abstract:
The paper describes the possibilities of energy harvesting using thermoelectric generators. Because of very low output voltage thermoelectric generators need integration of large number of individual thermo-junctions. Printing technologies enhance effective production with individual junctions all connected in series. Lateral structure require an easy process to print nevertheless it suffers from the internal resistance of the thermoelectric materials. In case of vertical design, the total resistance is smaller but the efficiency is limited by thermal conductivity of used materials. A combined structure with lateral arrangement of short thermo-coupler legs placed in double-layer of thermal insulator and the heat flow perpendicular to the thermo-coupler matrix brings together advantages of both types.

INTRODUCTION

Although the thermoelectric phenomena are used for measurement of temperature and cooling applications quite extensively, thermo-generation of electricity starts to grow only in recent years. Such energy sources are well predictable because they are based on stable operation of respective devices. Thermoelectric Generators (TEGs) are therefore very attractive for possibility of harvesting of waste thermal energy in many applications.
The TEG devices have advantages such as silent operation, no moving parts and high reliability. Its use is advantageous in locations where there are poor levels of illumination. There are also some perspective applications as solar and thermoelectric energy harvesting in one device, or use of thermoelectricity produced in household to charge mobile phones and different types of small devices.
Use of waste thermal energy in industry and transport applications has very large potential but it needs thermoelectric converters able to work in high temperature range and often in corrosive environments or with increased safety demands.
A large number of car companies have been developing thermoelectric waste heat recovery systems with expectations of 3-5% in fuel economy and the power generated reaching up to 1 kW. Nevertheless the electrification of vehicles and change of conditions for thermoelectric generation in cars give not optimistic view to this application. Wireless sensors are to time probably the largest area for TEGs in environments with stable temperature difference. This way battery lifetime and reliability problems are eliminated. In most cases wired sensors are replaced by radio-frequency or optoelectronic coupling.
However all thermoelectric energy harvesting transducers typically provide a low output voltage not sufficient for electronic devices. Therefore, for DC sources based on thermal generators there is a need to boost the voltage to a level sufficient for operation of regular converters or low voltage circuits.

THERMOELECTRIC TRANSDUCERS FOR ENERGY HARVESTING

Thermoelectric modules work on two basic principles which are related one to another:

Seebeck effect. This effect creates potential difference across the connection of two materials module by heating one side of the module and cooling the opposite.

Peltier effect. When the electric current passes through the junction of different materials one side is being cooling and the other side is being heating. Peltier cells are to time routinely used for cooling. Consequently, when we will deliver thermal energy to this junction we may produce electricity.

Thermoelectric power conversion

The reasons why this technology has not yet found extensive application there are very low conversion efficiency and high costs per watt.

The energy transfer efficiency of conventional rigid TEGs is only around 5%. Flexible TEGs are supposed to have even less transfer efficiency. In order to achieve high output voltage large number of TEG devices need to be electrically connected together. An easy fabrication process is therefore essential to low-down the cost. Several papers have already reported use of different large-scale fabrication technologies (e.g. dispenser printing, photolithography and electrochemical deposition).

The modular generators could be inkjet printed on flexible substrates, including natural and synthetic fabrics, and manufactured using inexpensive roll-to-roll techniques. By placing the polymer dots closer together, the interconnect length decreases, which in turn lowers the total resistance and results in a higher power output from the device.

Screen printing is a low-cost process that is well suited for large area fabrication. It involves the deposition of synthesized thermoelectric inks that consist of thermoelectric material powders in a binder and solvent matrix. After printing only a curing process is required. The simplicity and low energy consumption is quite attractive for such production of TEGs. Unfortunately, commonly used thermoelectric materials are not available as printing inks so there is a need for complex design of new types of pastes and inks.

Vacuum technologies are to time able to prepare a large variety of different thermo-electric materials but the coating processes mostly use only bulk materials. Printing methods need the same or similar materials in a liquid ink or in paste. More complex materials need to be considered and consequently in printing process more or less viscous mixture are needed.

Organic materials

For electronic properties of organic materials there is crucial the existence of conjugated bond system where carbon atoms covalently bond with alternating single and double bonds. Hydrocarbon electrons delocalize and form a delocalized bonding π orbital with a π* antibonding orbital [1],[2].

The delocalized π orbital is the highest occupied molecular orbital (HOMO), and the π* orbital is the lowest unoccupied molecular orbital (LUMO). In organic semiconductor physics, the HOMO takes the role of the valence band while the LUMO serves as the conduction band. The energy separation between the HOMO and LUMO energy levels is considered to be the band gap of organic electronic materials and is typically in the range of 1eV to 4 eV [1],[2].

Many researchers have focused on conducting polymers as polyaniline, polypyrrole, and poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) as a thermoelectric (TE) material. However the organic-based TE generators show very low output power density due to several limitations of the polymer, e.g. a low power factor, high contact resistance with a metal electrode and very low thickness of TE materials.

Inorganic materials

A combination of Bi_2Te_3 (n-type; negative sign of Seebeck coefficient) and Sb_2Te_3 (p-type; positive sign of Seebeck coefficient) semiconductive materials is to time the best performance option for TEGs, having high Seebeck coefficient, high electric conductivity and low thermal conductivity.

The screen printable thermoelectric pastes contain thermoelectric materials Bi_2Te_3 and Sb_2Te_3 in form of alloy powders. The paste contains basic compound of the layer (Bi_2Te_3 and Sb_2Te_3), epoxy binder system and solvent. The adjacent particles are stuck to each other and adhered onto the substrate by the epoxy binder system. The solvent is added into the paste to adjust the viscosity to a screen printable level. The pastes are fully dried after printing and then cured in appropriate temperature depending on the type of paste.

However, the price of tellurium, a key component in these materials is high. The other materials used for higher operating temperatures also use tellurium for example PbTe for n-type and GeTe for p-type semiconductors. Due to increasing tellurium costs, it is necessary to find alternative materials that have comparable figures of merit. Very promising low-price-candidates are bismuth oxides and some metal sulfides

Performance of thermoelectric materials

To evaluate the performance of a thermoelectric material we use the coefficient ZT called figure of merit, which is defined as:

$$ZT = \boldsymbol{S^2(\sigma/\lambda)T} \qquad (1)$$

where **S** is the Seebeck coefficient, **σ** is the electrical resistivity, **λ** is the thermal conductivity and **T** is the temperature.

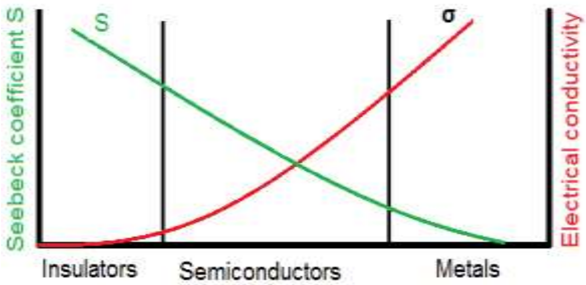

Fig. 1: Seebeck coefficient and electrical conductivity for insulators, semiconductors and metals.

Typical dependence of Seebeck coefficient and electrical conductivity for different materials is shown in Fig.1. The Seebeck coefficient and electrical conductivity both depend on charge carrier density and cannot be simultaneously increased. There is always an optimum that delivers the highest nominator (power factor) of the thermoelectric figure of merit [3].

As seen from the definition of figure of merit ZT the electrical conductivity of the respective thermoelectric material is the bottle neck that limits the power output of the thermo-cells. Here is of great importance the density of printed layers which is influenced by composition of the layer and the amount of solvent used to control the viscosity of the paste or liquid ink. Low content of the solvent yields the layers with higher density but prevents good printing process. One possibility how to improve the conductivity of the screen printed layers is isostatic pressing of the layers before curing [4].

LAYOUT OF THERMOGENERATOR MADE BY PRINTING TECHNOLOGY

There are two critical factors for efficient thermoelectric power conversion. Firstly, the amount of heat flux must be successfully moved to the module. Secondly, the thermal conductivity of module material between hot and cold side must be as low as possible. High thermal conductivity is a problem by almost all inorganic semi-conductive materials. Organic semiconductors could have the thermal conductivity almost one order lower. In any case the basic parameters there are the difference in work functions and Seebeck and Peltier coefficients [1][2].

Long lateral structures provide a good spatial separation of the heat source and sink and require an easy process to print, but in this case the internal electrical resistance of materials used for the thermocouple legs causes a high total electrical resistance of the TEG. This leads to a low power delivered by the generator.

Moreover, in this case, the heat flow is transmitted along the length of the thermoelectric converter, and the heat flow capture area is therefore very small. This can be overcome by parallel arrangement of foils containing thermoelectric transducers or, in the case of elastic films, by rolling them into spiral shapes. However, such a mechanical arrangement is complicated.

If the length of the legs is reduced such as with the vertical design, the total resistance is smaller but the efficiency is limited by thermal conductivity of used materials. Contrary to the lateral arrangement, there is an advantage in a substantially larger area of the thermoelectric converter since the heat flow being processed passes through the entire surface of the transducer as shown in Fig. 2.

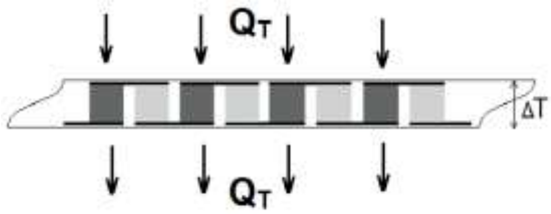

Fig. 2: Vertical design. Heat flow passes through the entire surface of TEG transducer.

A substantial increase in heat transfer area is possible in the lateral arrangement of thermocouples in the structure shown in Fig.3. Individual thermocouples are printed on a material with low thermal conductivity. The same material also thermally insulates thermocouples from the top. Copper electrodes with high thermal conductivity ensure that there is approximately the same temperature difference between thermocouple ends as the temperature difference across the thermoelectric transducer.

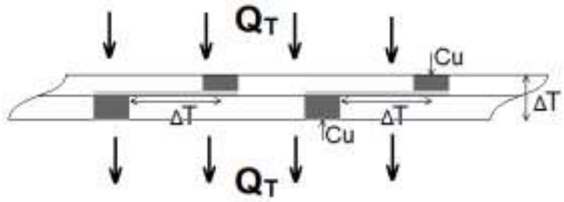

Fig. 3: Combined design. Copper electrodes ensure large temperature difference between thermocouple ends.

In order to achieve high output power density, the use of inorganic materials is inevitable, but in this case in many applications it becomes necessary to solve the problem of material rigidity. One of the design goals is therefore the choice of the external substrate, with optimal combination of low thermal conductivity and mechanical properties.

DC TO DC CONVERTER WITH LOW INPUT VOLTAGE

The serial connection of individual thermocouple cells usually yields the output voltage much less than 1 V. Therefore, a low cost DC to DC converter is needed to boost the voltage from the level of several tenths of volt to the level of approximately 3 V, which may be applicable to most devices.

Single JFET DC to DC converter

Very simple circuit to boost the voltage of the TEGs to standard voltage level is based on a single JFET circuit. The scheme of the converter [5] is given on the Fig. 4. As soon as the transistor turns on the secondary winding generates a voltage pulse and Capacitor C_1 is being charged. The junction between the Gate electrode and Source of the transistor in this case operates as a rectifying diode.

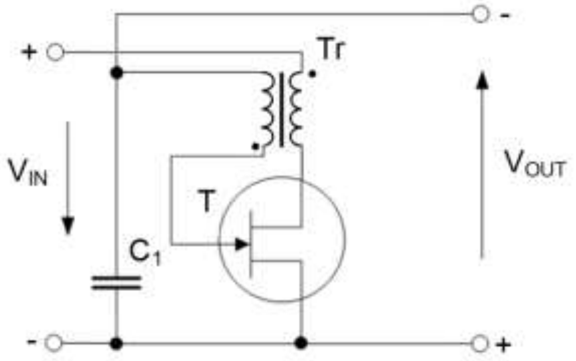

Fig. 4: Basic scheme of the low-voltage converter

Once the transformer core becomes saturated the voltage on the secondary winding starts to drop. Due to the positive feedback given with actual polarity of primary and secondary windings the transistor closes. With a negative voltage on the capacitor C_1, JFET is maintained in a closed state until the next part of the cycle where it passes into the on-state and consequently the whole process is repeated. The voltage on the capacitor C_1 is at the same time output voltage of the converter as a whole.

The working frequency of the circuit is in the range from few kHz until few hundreds of kHz and is determined by the transformer. To ensure high efficiency, it is necessary that the transformer design should minimize leakage inductance. Start up voltage is about 0,5 V and cut-off voltage is about 0,3 V. Both (start-up and cut-off) voltages could be even much lower in dependence on the transformer ratio and the threshold voltage of driving transistor. Efficiency of the circuit could be slightly more than 50%.

CONCLUSIONS

Thermoelectric Generators (TEGs) are very attractive in many applications and have advantages such as silent operation, no moving parts and high reliability but need integration of large number of individual thermo-junctions. Printing technologies enhance effective production of such structures with individual junctions connected in series. Organic semiconductors could be good candidate for such devices but to time suffer from low electrical conductivity and low Seebeck coefficient.

Both lateral and vertical printed structures need to balance between low thermal conductivity and high electrical conductivity of the respective structures and the area of heat flow surface. A combined structure with lateral arrangement of short thermo-coupler legs placed in double-layer of thermal insulator could ensure good balance between electrical and thermal conductivity and enhance a large heat flow perpendicular to the matrix of thermo-couplers, which contributes to higher power output and higher conversion efficiency.

TEGs usually provide low output voltage and for DC sources based on TEGs there is a need to boost the voltage to a level sufficient for operation of standard converters or low voltage circuits. Simple circuit to boost the voltage of the TEGs is based on single JFET circuit. Start up voltage is about 0,5V and cut-off voltage is about 0,3V with efficiency close to 50%. Start-up and cut-off voltages could be even much lower with high transformer ratio.

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