LOW ENERGY THERMOELECTRIC GENERATORS

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Abstract: The paper describes the possibilities of energy harvesting using thermoelectric generators. It is shown that organic semiconductors enable a large variability of properties and some of their properties may be better than by inorganic semiconductor materials. Nevertheless they suffer from poor electrical conductivity. Because the voltage of one junction is quite low even in case of large temperature difference thermoelectric generators need integration of large number of individual thermo-junctions. Printing technologies enhance effective production of integrated thermo-generators with individual junctions connected in series.

Keywords: Organic semiconductors, thermoelectric generators Energy harvester, Low voltage DC/DC converter.

1 INTRODUCTION

Energy harvesting is becoming more feasible today because of the increased efficiency of devices used to capture, store, and produce electrical energy. However many energy harvesting transducers provide a low output voltage not sufficient for electronic devices. For DC sources, like solar cells and thermal generators, there is therefore a need to boost the voltage to a level sufficient for operation of regular converters or low voltage circuits. A simple low cost DC to DC converter was designed to boost the voltage from the level of several tenths of volt to level of about 3 V, which may be applicable to most of devices. A simple low cost thermo-generator should be prepared to feed this converter.

2 LOW VOLTAGE DC TO DC CONVERTER FOR ENERGY HARVESTING

2.1 PRINCIPLE OF OPERATION

Fundamental scheme of the converter is shown in Figure 1 A). The transistor JFET operates as a switching element. As soon as the transistor turns on the secondary winding generates a voltage pulse. Capacitor C_1 is being charged by means of this pulse.

The junction between the Gate electrode and Source of the transistor in this case operates as a rectifying diode. Because in this state the Gate-Source junction of JFET is in forward polarization the width of this junction is very small and there is very high conductivity across the transistor – it means between the electrodes S and D.

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.

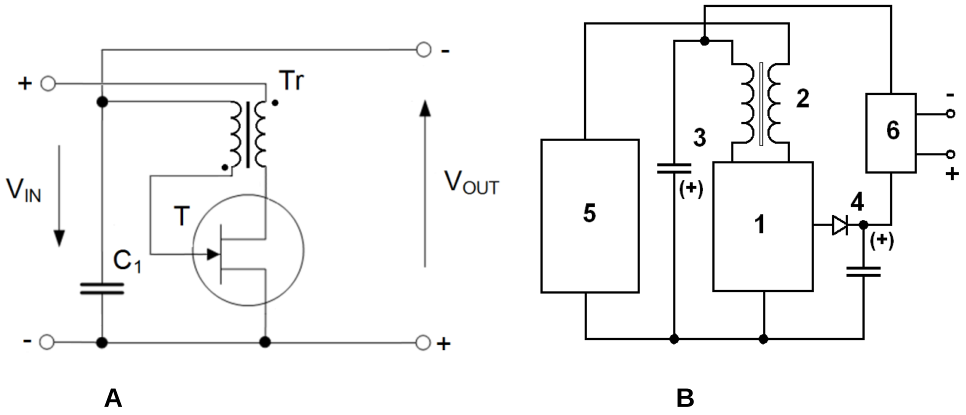

Figure 1: A) Basic scheme of the converter. B) Converter with increased output voltage.

The modified circuit shown in Figure 1 B) utilizes the energy stored in the transformer during the switch-on state. As soon as the switch-off starts a voltage pulse appears on the primary winding, which charges the capacitor C_2. This is due to the drop of magnetizing current and subsequent collapse of the magnetic field in the transformer core. With optimal settings of the circuit the positive voltage on capacitor C_2 has approximately the same size as negative voltage on capacitor C_1. The output voltage can therefore be approximately twice as large. At the same time, there will be a slight increase in efficiency. At high current consumption, however, the output voltage decreases rapidly.

It was verified that the circuit can operate in a large range of frequencies. The working frequency of the circuit is determined by the transformer. To ensure high efficiency, it is necessary that the transformer should minimize leakage inductance. Start up voltage is about 0.5 V and could be much lower by higher transformer ratio and/or when using the transistor with lower threshold voltage. However in both cases the energetic efficiency of the circuit drops.

3 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 current passes through the junction of different materials one side is cooling and the other side is 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

In almost all devices there is in energy conversion process a release of large amount of waste energy. 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 but sufficient waste heat.

The energy transfer efficiency of conventional rigid TEGs is only around 5%. Flexible TEGs are supposed to have even less transfer efficiency. Hence, in order to achieve high power output, large number of TEG devices need to be electrically connected together. Although the power output is low for a single thermocouple, the flexibility allows the screen printed TEGs to be connected in series and rolled in to a coil. Much higher power output can be achieved this way. The impediments as to why this technology has not yet found extensive application are the low conversion efficiency and high costs per watt. Then, an easy fabrication process is 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).

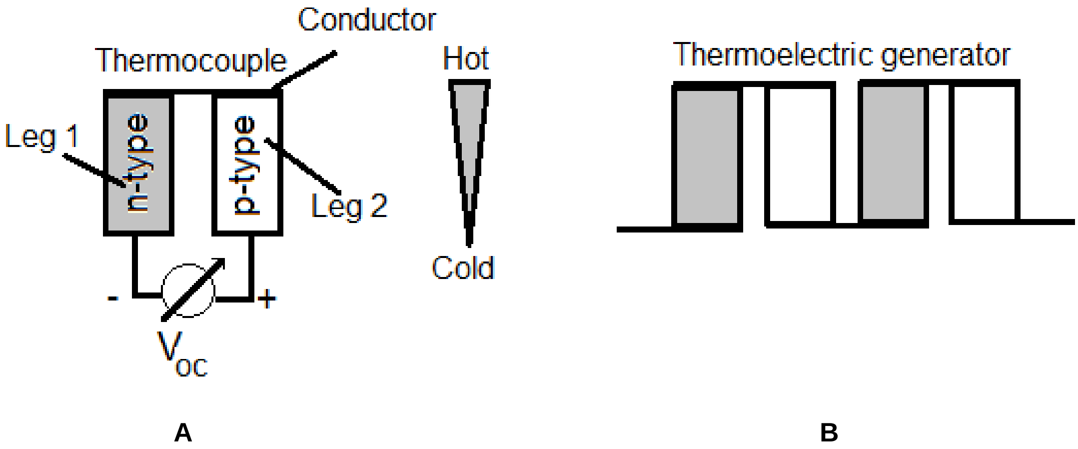

Figure 2: A) Principle of thermoelectric conversion.
B) To achieve sufficient voltage level the thermocouples are connected in series.

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 fabricating TEGs.

The materials and the parameters of printing technology need to be examined, so that an optimized workflow is set up. 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.

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].

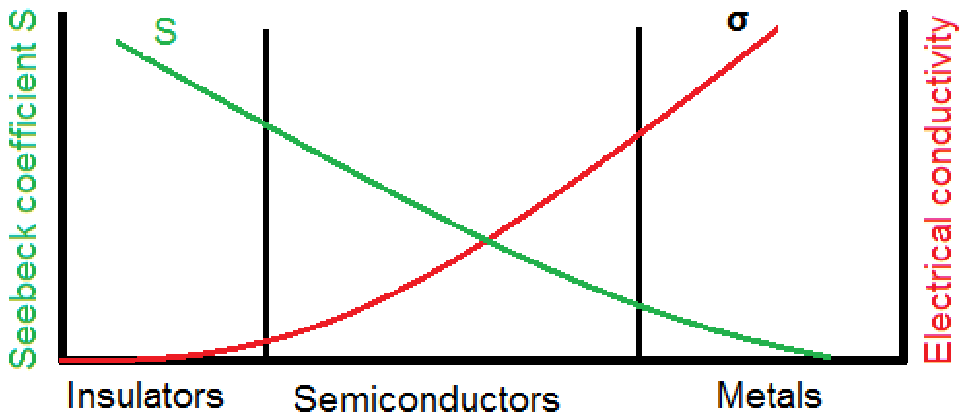

Figure 3: Seebeck coefficient and electrical conductivity for insulators, semiconductors and metals.

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 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 including polyaniline, polypyrrole, and poly (3, 4-ethylenedioxythiophene): poly (styrenesulfonate) as a thermoelectric (TE) material and organic-based TE generators have been fabricated with these elastic polymers. The polymers exhibited high flexibility and outstanding potential for use on human skin. However the organic-based TE generator shows very low output power density due to several limitations of the polymer: a low power factor, high contact resistance with a metal electrode, and very low thickness of TE materials.

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

These problems are primary concerns for practical applications. In order to achieve high output power density, the use of inorganic materials is inevitable, but in this case it becomes necessary to overcome the problem of material rigidity and optimize the design of the device structure. One of these design goals is the choice of the external substrate, which holds tens or hundreds of TE legs.

Vacuum processes like sputtering or evaporation are able to prepare a variety of thermoelectric materials and its compounds typically using only bulk materials. Printing methods need the same materials in a liquid ink or paste. Consequently more complex materials need to be considered and in printing process a more or less viscous mixture are needed.

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

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

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

The Seebeck coefficient and electrical conductivity both depend on charge carrier density and cannot be simultaneously increased. There is always an optimum charge carrier density that delivers the highest nominator (power factor) of the thermoelectric figure of merit.

Maximizing ZT requires minimal thermal conductivity. Thermal conductivity consists of two parts e.g. fonon-part and electron-part. Both can be altered more or less independently. The solution of two isovalent materials with the same crystal structure could be used to increase phonon scattering, thereby reducing thermal conductivity.

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, enabling 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.

For n-type bismuth tellurium alloy, the ratio of tellurium (Te) affects the thermoelectric performance of the device. When the atomic ratio of Te is a 64%, the bismuth tellurium alloy will have the highest negative Z value [3]. The actual formulation of this n-type semiconductor material is Bi (1.8) Te (3.2.)

However, the price of tellurium, a key component in this materials is high and increase significantly. 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.

As seen from the definition of figure of merit ZT the resistivity of the respective thermo-generator-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. 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 printed layers is isostatic pressing of the layers before curing [4].

4 CONCLUSION

DC to DC converters are to time able to operate from the voltage of few tenths of Volt and the output voltage could be in the level of several Volts. Achieved efficiency of simple DC to DC converter designed to this purpose is close to 50%. Such device is easily applicable for thermoelectric generators.

Because the voltage of one junction is quite low even in case of large temperature difference thermo-generators need integration of large number of individual thermo-junctions. Printing technologies enhance effective production of integrated thermo-generators which are connected in series.

It is shown that organic semiconductors enable a large variability of properties and some of their properties could be better than by standard semiconductor materials. This applies especially for organic semiconductors for use in thermo-generators. However its poor electrical conductivity prevents to achieve high power level. In case of inorganic materials the figure of merit could be very high but these materials usually contain high portion of tellurium which is very expensive and its price is constantly growing. Therefore further research in new promised materials as bismuth oxides and some metal sulfides is needed.

ACKNOWLEDGEMENT

The article was supported by project no. FEKT-S-17-3934, “Utilization of novel findings in micro and nanotechnologies for complex electronic circuits and sensor applications."

REFERENCES

[1] I.G. Hill at al.: “Charge-separation energy in films of π-conjugated organic molecules“, Chemical Physics Letters 327, 2000, pp181–188

[2] Bubnova O. Crispin X.: “Towards polymer-based organic thermoelectric generators”, Energy & Environmental Science, 2012, ISSN 1754-5692, Vol. 5, no 11, pp 9345-9362

[3] C. Wood: “Materials for thermoelectric energy conversion”, Phys. 51 (1988) 459-539. 580–583

[4] Z. Cao1, E. Koukharenko, R.N. Torah, J. Tudor and S.P. Beeby: “Flexible screen printed thick film thermoelectric generator with reduced material resistivity”, Journal of Physics: Conference Series 557 (2014) 01201 –55.