

Planar thermocouples, thermopiles, and thermoelectric microgenerators

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The first thermoelectric phenomenon – the Seebeck effect – was discovered more than 200 years ago, in 1821. This effect refers to the creation of an electromotive (also called thermoelectric) force whenever there is a temperature gradient in a circuit containing two different materials (conductors, semiconductors, or insulators). Under open-circuit conditions, where there is no internal current flow, the thermoelectric force is directly proportional to the gradient in temperature.

The Seebeck effect is the basis for the operation of various thermoelectric devices - thermocouples, sensors of physical and chemical quantities, and thermoelectric generators/microgenerators. The first mention of commercial thermocouples being available for temperature measurement appeared in a Cambridge Instrument Company catalogue of 1898, but the manufacture of them did not begin until 1902, when special stocks of platinum (Pt) and platinum-rhodium (Pt-Rh) alloy were purchased from Johnson Matthey and marketed in suitable porcelain tubes. Probably the first information in the open literature about thick-film thermocouples appeared in 1976 [1] and the first information about thick-film thermoelectric generators was published in 1980 [2].

Analyzing research in the field of thermoelectricity at the Faculty of Electronics, Photonics and Microsystems and its predecessors, it should be stated that the first paper on thin-film thermoelectric transducers comes from 1980 [3], while the first report related to the characterization of thermocouples and thick-film thermopiles was published in 2000 [4].

The aim of this presentation is to discuss the thermoelectric properties of various films, structures, sensors, and microgenerators implemented using thin-film, thick-film or mixed techniques, with reference to the global trends and achievements.

Research on thin-film thermoelectric structures and devices was related to:

- fabrication as well as electrical and structural characterization of thin-film thermocouples and thermopiles based on such semiconductors, such as Ge doped with Au (Ge:Au), Ge:Sb, Ge:V, Ge:Sb:V, Ge:Ta:Sb, recrystallized Ge, Si:B [5],
- fabrication as well as electrical and structural characterization of thin-film metallic thermocouples and thermopiles based on Fe, Ni, Cu, NiCr and NiCu [6].

In the case of thermoelectric structures and devices prepared in thick-film technology:

- values of Seebeck coefficient were determined for many commercial and self-made conductive and low-resistive compositions; this allowed for development and characterization of thick-film thermo-couples, eg. for measurement of temperature changes on the microprocessor surface as a function of their operation speed, as well as insolation and laser power sensors [7-9]
- the influence of the substrate (alundum ceramics, LTCC ceramics) on the properties of sensors based on the Seebeck effect or thermoelectric microgenerators was examined [8],
- multilayer planar thermoelectric microgenerators were developed using LTCC technology [8,10],
- non-standard deposition methods (using photosensitive pastes and/or laser shaping) were used to produce thermopile/microgenerator arms [10,11],
- analyzes and simulations of the properties of microgenerators were carried out, taking into account material and geometric factors, with particular emphasis on the thermal conductivity of substrates as essential elements of planar thermoelectric devices.

Many thermoelectric structures (sensors or microgenerators) were prepared in mixed, thin- and thick-film technology, which allowed to expand the set of available materials to include thin semiconductive films with Seebeck coefficients of 150-200 $\mu\text{V/K}$ or constantan [12].

Cooperation with the Jožef Stefan Institute from Ljubljana enabled to develop the planar thick-film microgenerators with one arm made of *p*-type calcium cobalt oxide [13]. Cooperation with the Fraunhofer Institute for Ceramic Technologies and Systems IKTS from Dresden resulted in the development of thick-film constantan-silver and constantan-copper thermopiles with a mean Seebeck coefficient value above 40 $\mu\text{V/K}$ (one of the highest for planar metallic thick-film thermopiles) [14].

Last part of seminar will present our own results on the preparation of thermoelectric composite materials for flexible and wearable electronics applications [15].

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