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Thermoelectric microstructures of Bi_2Te_3/Sb_2Te_3 for a self-calibrated micro-pyrometer

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Abstract

The fabrication of thermopiles suitable for thermoelectric cooling and energy generation using Bi_2Te_3 and Sb_2Te_3 as n- and p-type layers, respectively, is reported. The thin-film thermoelectric material deposition process, thin-film electronic characterization and device simulation is addressed.

The thermoelectric thin-films were deposited by co-evaporation of Bi and Te, for the n-type element and Sb and Te, for the p-type element. Seebeck coefficients of −190 and +150 $\mu V K^{-1}$ and electrical resistivities of 8 and 15 $\mu\Omega$ m were measured at room temperature on Bi_2Te_3 and Sb_2Te_3 films, respectively. These values are better than those reported in the literature for films deposited by co-sputtering or electrochemical deposition and are close to those reported for films deposited by metal-organic chemical vapour deposition and flash evaporation.

A small device with a cold area of 4 mm × 4 mm^2 and four pairs of p–n junctions was fabricated on a Kapton® substrate, showing the possibility of application in Peltier cooling, infrared detection and energy generation.

Small devices fabricated on a polyimide (Kapton®) substrate and micro-devices fabricated on a silicon nitride substrate were simulated using finite element analysis. The simulations show the possibility of achieving near 20 K cooling over 1 mm^2 areas.

Keywords: Thermoelectric; Thin-film; Pyrometer; Peltier; Micro-cooler; Bi_2Te_3

1. Introduction

Thermoelectric cooling is widely employed in electronics to stabilize the temperature of devices, decrease noise levels and increase operation speed. And since Peltier devices are reversible, they can also be used as electrical generators, converting thermal into electrical energy. Commercial Peltier devices are usually fabricated on a transversal (cross-plane) configuration (Fig. 1). In theory, this configuration could be reduced for micro-device fabrication, but the conventional fabrication processes are not scalable to the micrometer range. Using a lateral (in-plane) configuration (Fig. 2), thin-film techniques can be used to scale down the thermoelectric coolers and generators to micro-device dimensions [1]. In the present work, planar thin-film technology will be used to fabricate such devices.

The thermoelectric performance of the thermoelectric materials is characterized by the dimensionless figure of merit parameter (ZT):

$$ZT = \frac{\alpha^2}{\rho\lambda} T \quad (1)$$

Where α is the Seebeck coefficient, ρ the electrical resistivity, λ the thermal conductivity and T the temperature [2]. While the search for thermoelectric materials with higher figures of merit is going on [3] (with higher Seebeck coefficients, lower electrical resistivities and lower thermal conductivities), efforts are currently made to achieve compatibility with state-of-the-art electronic materials and in particular with silicon-wafer technology [4]. In this paper, the possibility of integration with next-generation flexible electronic devices is also demonstrated.

Tellurium alloys (Bi_2Te_3 and Sb_2Te_3) are well-established low-temperature thermoelectric materials and are widely employed in conventional thermoelectric generators and

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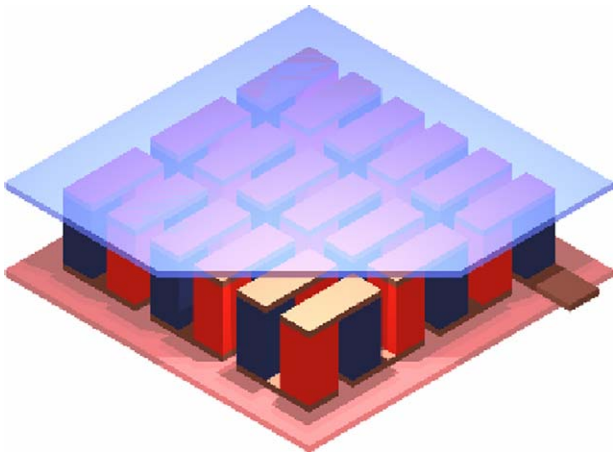

Fig. 1. Cross-plane (transversal) Peltier cooler.

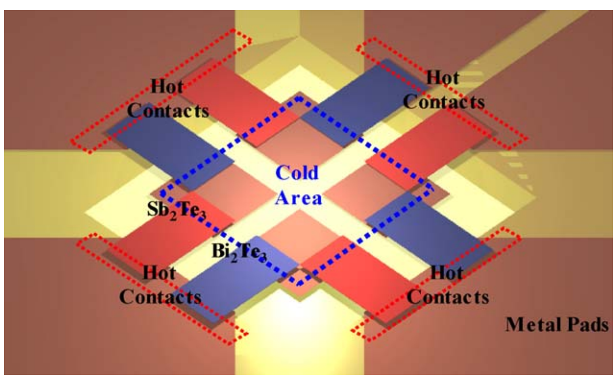

Fig. 2. In-plane (lateral) Peltier cooler.

coolers [2]. Different deposition techniques can be used to obtain Bi–Sb–Te thin-films. Thermal co-evaporation [5], co-sputtering [6], electrochemical deposition [7], metal-organic chemical vapour deposition [8] and flash evaporation [9] are some examples. In this work, thermoelectric energy converters are addressed, from simulation and performance prediction, to materials deposition and optimization and device fabrication. A Peltier cooler and a thermopile in a single device to implement a self-calibrated micro-pyrometer, operating in the 20–100 °C measuring range, is the final goal of this work.

2. Simulation

Each p-n thermoelectric pair of the Peltier cooler can be modelled [1] by Eq. (2).

$$\Delta T = \frac{1}{K_{\rm eq}}\left[(\alpha_{\rm p} - \alpha_{\rm n})T_{\rm c}I - \frac{1}{2}R_{\rm eq}I^2 - Q_{\rm LOAD}\right] \qquad (2)$$

ΔT is the maximum temperature difference achieved by the cooler, $\alpha_{\rm n}$ and $\alpha_{\rm p}$ are the Seebeck coefficients of the n- and p-type materials, $T_{\rm c}$ is the cold side temperature, I is the current injected in the device and $Q_{\rm LOAD}$ is the sum of all thermal loads applied. $R_{\rm eq}$ and $K_{\rm eq}$ are the equivalent electrical resistance and thermal conductance of n- and p-type elements, including the effect of substrate and contact resistances, calculated with Eqs. (3) and (4):

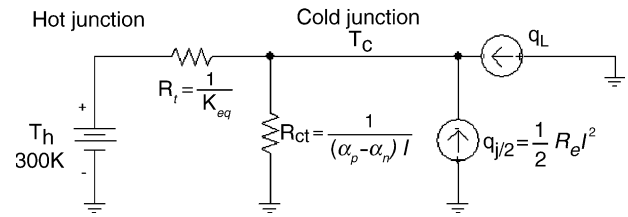

Fig. 3. Schematic model of a Peltier cooler.

$$R_{\rm eq} = \rho_{\rm n}\frac{L_{\rm n}}{W_{\rm n}H_{\rm n}} + \rho_{\rm p}\frac{L_{\rm p}}{W_{\rm p}H_{\rm p}} + 2\left(\frac{\rho_{\rm cn}}{L_{\rm c}W_{\rm n}} + \frac{\rho_{\rm cp}}{L_{\rm c}W_{\rm p}}\right) \qquad (3)$$

$$K_{\rm eq} = \lambda_{\rm n}\frac{W_{\rm n}H_{\rm n}}{L_{\rm n}} + \lambda_{\rm p}\frac{W_{\rm p}H_{\rm p}}{L_{\rm p}} + \lambda_{\rm m}\frac{W_{\rm m}H_{\rm m}}{L_{\rm m}} \qquad (4)$$

where W is the width, H is the height, L is the length, the indexes n, p, m and c stand for n-type leg, p-type leg, membrane and contact, respectively, ρ is the electrical resistivity and λ is the thermal conductivity. Eq. (2) assumes that the hot side of the cooler is connected to a highly thermally conductive material and to a heat sink, capable of keeping the hot side of the device at room temperature. This can be achieved in a micro Peltier cooler for example by the use of a silicon substrate as the heat sink. For convenience of the simulation, Eq. (2) was implemented by the schematic shown in Fig. 3 using electrical simulation software.

For more complex structures, the use of more powerful finite element analysis tools is required. Two device types were simulated using finite element analysis:

- A small device (Figs. 2 and 9), with a cold area of 4 mm × 4 mm. This mini-device rests on a 25 μm-thick Kapton® membrane and has 4 p–n pairs of thermoelectric legs, each with dimensions of 2 mm × 1 mm × 10 μm.
- A micro-device (Figs. 4 and 10), with cold area smaller than 1 mm^2, supported by a 1 μm-thickness silicon nitride air-gap bridge, cooled by three pairs of thermoelectric legs, with dimensions of 100 μm × 200 μm × 4 μm each. This device will be used to cool down a radiation sensor and a thermopile in a self-calibrated micro-pyrometer, as described below.

Results of the simulations show the possibility to obtain 18 K temperature difference with the mini-device and 10 K with the micro-device, after considering conduction, radiation and convection losses. Fig. 4 shows the temperature map simulated for a micro-cooler device.

The performance of the Peltier cooler is largely affected by the thickness and thermal conductivity of the supporting membrane used as substrate. This is shown in Fig. 5 where the temperature achieved with a thermoelectric cooler was simulated using Eqs. (2)–(4) and plotted as a function of the current injected in the device, for different material composition and thickness of the substrate membrane.