Microelectronics Journal 42 (2011) 772–777

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

Optimal design of a microthermoelectric cooler for microelectronics

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ARTICLE INFO

Article history:
Received 1 October 2010
Received in revised form
24 January 2011
Accepted 25 January 2011
Available online 16 February 2011

Keywords:
Microthermoelectric cooler (μ-TEC)
Finite element methods (FEM)
Taguchi Methods

ABSTRACT

In this paper, performance analysis using finite element methods (FEM) was carried out to develop a microthermoelectric cooler (μ-TEC) for maintaining the chip temperatures under the operating limitation. The performance evaluation process using the Ansys FEM software is described. The effects of the geometries of the thermoelectric columns and the thicknesses of connecting electrodes were investigated. The governing equations for the μ-TEC element were developed and the analytical solutions of the heat absorbed at the cold side of a single μ-TEC element were obtained using the derived equations. The FEM calculation results agreed well with the analytic solutions. Based on these results, the geometries and dimensions of the μ-TEC element were optimized using Taguchi Methods for maximizing the heat absorbed at the cold side of the μ-TEC. The experimental plan using an Orthogonal Array L_9 (3^4) is described in detail. Nine different μ-TEC models were simulated using FEM and the design parameters were optimized. The optimal width to depth ratio (width/depth) was found to be 3.6 (600 μm/167 μm) and the optimized thicknesses of the thermoelectric column and the gold electrode were 25 and 2 μm, respectively. The obtained optimal distance between the P-type and the N-type columns was found to be 35 μm. Finally, the absorbed heat of the optimized μ-TEC was calculated. The obtained value was 72.1 mW, which agreed well with the predicted value of 75.7 mW. At the end, the electrical contact resistance was considered and the calculated performance was 72.2 mW, which is a little smaller result than the analytic solution of 72.5 mW without the contact resistance.

1. Introduction

As the feature sizes of microelectronic devices decrease, the thermal management in maintaining the temperatures of the integrated chips under their operating limits has become a crucial issue to ensure their performances and reliabilities [1]. Recently, much efforts have been made to develop microcoolers which have high heat dissipating abilities, while being simple in structure and small in volume. Among these, a microthermoelectric cooler (μ-TEC) is considered to have major potential for providing cooling in localized chip surfaces, since it does not have any mechanical moving parts and can be easily integrated on microelectronic chips [2,3]. Furthermore, the thin-film thermoelectric module can be fully fabricated with current semiconductor surface micromachining technologies. Alley et al. [3] reported an embedded thermoelectric cooling (eTEC) device, which can dissipate a heat up to 227 W/cm^2. The device size is 3.0×3.5 mm^2 with the thickness of 125 μm and they have 42 p- and n-types couples. Micropelt has also developed a micro-structured thin-film Peltier cooler, which cooling power density is 60 W/cm^2 [4]. The p- and n-types materials are bismuth telluride (Bi_2Te_3) based compounds and they are fabricated with microelectromechanical system (MEMS) technologies.

In microscale systems design, Taguchi Methods can be effectively used [5]. By adopting Orthogonal Array, time and effort can be reduced. Recently, researches related to microscale Taguchi optimization were reported elsewhere [6,7].

In the current research, the performance analysis using finite element methods (FEM) was carried out to develop a μ-TEC cooler for maintaining the temperatures of electronic chips under their operating limits. The performance evaluation is performed using the Ansys FEM software and it is fully explained in the paper. The effects of the geometries of the thermoelectric columns and the thicknesses of the connecting electrodes were investigated. The governing equations for the μ-TEC element are derived. Geometries and dimensions are optimized using Taguchi Methods for maximizing the heat absorbed at the cold side of the cooler. The experimental procedures using an Orthogonal Array L_9 (3^4) are described in detail and nine different μ-TEC models are simulated using FEM so that the design parameters can be optimized. Finally, the absorbed heat of the optimized μ-TEC device is calculated.

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0026-2692/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mejo.2011.01.007

2. Performance modeling

A single μ-TEC device is composed of P-type and N-type semiconductors connected together by a metal plate. When a voltage is applied to the ends so that a current flows, the thermocouple cools on one side by the Peltier Effect, while heating up on the other side. At this stage, the contact resistance between thermoelectric elements and metal electrodes was not considered. After μ-TEC is optimized, it will be taken into account in the modeling again. Heat absorbed at the cold side of a μ-TEC (Q_c) can be obtained from following equation [8]:

$$Q_c = \alpha T_c I - \frac{1}{2} I^2 R_t - \frac{1}{2} I^2 R_e - K\Delta T \quad (1)$$

where α is the Seebeck coefficient, T_c is the temperature at the cold side, I is the current, R_t is the electrical resistance of the thermoelectric columns, R_e is the electrical resistance of the electrodes, K is the thermal conductance, and ΔT is the temperature difference between the top and bottom sides. The $(1/2)I^2R_t$ and $(1/2)I^2R_e$ terms denote Joule heating from the thermoelectric columns and the metal electrode, respectively. In addition, the required power (P) can be described by the following equation:

$$P = \alpha \Delta T I - I^2 R_t - I^2 R_e \quad (2)$$

Finally, the Coefficient of Performance (COP) (β) is given by:

$$\beta = Q_c / P \quad (3)$$

3. Geometry analysis

3.1. Analysis model

To investigate the effect of geometries such as the width to depth ratio (width/depth), the thermoelectric column thickness, and the electrode thickness, three-dimensional (3D) steady-state thermal-electric FEM analysis was performed. A single couple of μ-TEC was modeled to perform an analysis and a meshed model is shown in Fig. 1. It is comprised of a P-type and an N-type thermoelectric column, forming a couple which occupy an area of 0.1 mm^2. The material of the P-type was Bi_2Te_3 and the N-type was antimony telluride (Sb_2Te_3). The top and bottom part of each column is electrically connected in series through a gold (Au) electrode. Usually, when fabricating a thermoelectric element layer with a Si substrate, a solder layer is needed for bonding, but in this analysis, it was not considered to simplify the analysis.

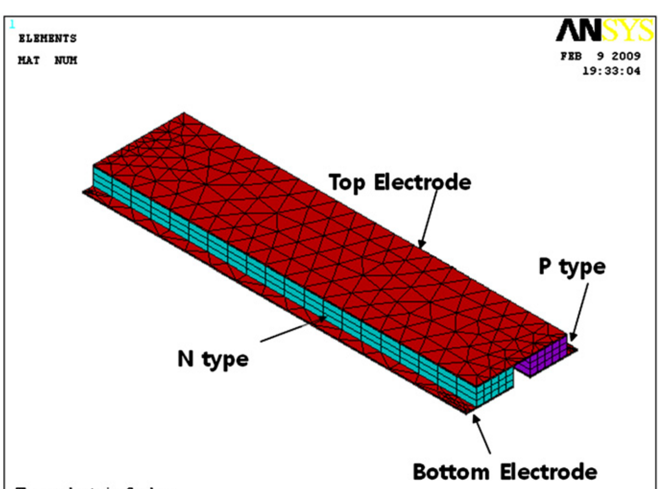

Fig. 1. Structure of the meshed μ-TEC analysis model.

The whole μ-TEC module is composed of 100 thermoelectric couples on an area of 10 mm^2, which has dimensions 3.3×3.3 mm^2.

The element type of the thermoelectric columns was SOLID 226 (3D 8-node coupled-filed solid) and the element type of the electrode was SOLID 227 (3D 10-node coupled-filed solid). The properties for the analysis are listed in Table 1. The hottest and coolest temperatures were given as boundary conditions, which were 70.0 and 55.0 °C, respectively. It was assumed that there is no air around the analysis model, therefore, there is no conduction heat loss to the surrounding environment. In addition, no convection heat loss was assumed. To make the analysis simpler, the contact resistance between thermoelectric elements and metal electrodes was not considered. The applied load at the electric terminal of the p-type column side was set to be the ground, 0 V. After giving a current of 1.27 A, the problem was solved to find Q_c that can maintain the hot and cold temperatures as 70.0 and 55.0 °C, respectively. When calculating, the Joule heating from the thermoelectric columns and the metal electrode was considered. In the following analyses, all the boundary conditions and the loads are same except the geometry dimensions.

3.2. Effect of the width to depth ratio

The effect of the width to depth ratio was simulated with seven different analysis models as shown in Fig. 2. The width to depth ratio (width/depth) was changed from 0.7 (260 μm/385 μm, #1 model) to 6.4 (800 μm/125 μm, #7 model), while the overall module areas were constrained to an area of 0.1 mm^2. Same boundary conditions and the loads from the Section 3.1 were applied and Q_c was obtained by giving the current of 1.27 A. Fig. 3 illustrates the heat absorbed at the cold side of the μ-TEC (Q_c) versus the width to depth ratio for these seven models, which agree well with the calculated values using the derived governing equations. The heat Q_c absorbed at the cold side increases rapidly until the width to depth ratio reaches 3.0. Considering the fabrication process and the overall layout, the width to depth ratio of 3.6 (600 μm/167 μm, #2 model) would be optimal, which shows Q_c to be 65.8. In Fig. 4, the temperature profile of the #2 model is shown.

3.3. Effect of the thermoelectric column thickness

Then the effect of the thermoelectric column thickness was analyzed and the results are presented in Fig. 5. In this analysis, boundary conditions and loads were also same as explained in the Section 3.1. And Q_c was solved when the current was 1.27 A. The results agreed well with the calculated values using the derived governing equations. Similarly, Q_c also increases continuously up to a thickness of 30 μm. But our film deposition equipment only allows a maximum thickness of 25 μm to be realized, consequently, the optimization range was up to 25 μm.

Table 1
Thermoelectric properties for the analysis.

	Seebeck Coefficient, α (μV/K)	Resistivity, ρ (μ Ω m)	Thermal conductivity, W/(m K)
N-type Bi_2Te_3 [2]	−210	9.0	1.5
P-type Sb_2Te_3 [2]	110	3.5	1.5
Au electrode		2.4	316.0