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Two-dimensional electrical modeling of thermoelectric devices considering temperature-dependent parameters under the condition of nonuniform substrate temperature distribution

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Since more aggressive thermal solutions, than would be required for uniform heating, are highly desired. Thermoelectric devices are regarded as an available thermal solution for high power electronic packages like processors. In this paper, a steady-state numerical model is derived for thermoelectric coolers (TECs) with parameters controlled by two-dimensional thermal profiles. Using the thermoelectric duality, we propose an improved electrical model with temperature-dependent parameter distribution in the presence of multi-couple pellets. Both electrical element and thermal behavior are simulated based on this improved model with TEC parameters modified according to the nonuniform temperature effects. The results demonstrate an excellent agreement with numerical calculation and the proposed electrical model. It proves that thermal profiles in the underlying silicon substrate have a linear effects on the temperature at the cold side of TECs. In addition, the optimum value of the temperature difference exhibits a negative interrelation with the electrical current flowing through TECs under a fixed hot junction temperature.

1. Introduction

The continuously rising operating frequency and power density can give rise to more and more serious heat problem for scaling CMOS devices [1]. It predicts that the peak temperature can reach 210 °C for global interconnects in worse case at 50 nm technology node, thus results in a nonuniform thermal distribution both on temporal and local scales [2,3].

The management of heat dissipation has already become one of the most challenging efforts in high performance chips. Seeking for an integrated compact cooling device with low power consumption is becoming overwhelming for the small electrical system such as MEMS to exhibit enhanced performance [4].

Due to its compactness, precision and simplicity, thermoelectric coolers (TECs) are widely used in various fields such as military, aerospace, industry, optoelectronic medical institutions [5–7]and so on. Abramzon proposed a unified numerical method to achieve the maximized cooling rate and the performance coefficient of the whole cooling system with constant material properties of a single-stage TEC [8]. By optimizing currents and cooling configurations, Zhang et al. presented an analytical method that can obtain thermal enhancements without resorting to the thermoelectric parameters and geometric details in iterative procedure [6]. Without starting from addressing material shortcoming, a distributed control strategy was proposed to improve the overall coefficient of performance in an engineering system [9]. In Ref. [5], Mitrani et al. presented both lumped and distributed parameter electrical models for TECs including the temperature dependence of material features. The proposed models limiting to one dimensional single thermocouple shows an awful disagreement with the real package on chip. Most previous theoretical models and methods carried out the numerical analysis to evaluate the performance of the thermoelectric coolers without considering the thermal effects on TECs, while only few investigations adopted thermoelectric modeling and focused on the estimation of the multi-pellet chains. In fact, due to underlying thermal gradients over the substrate and height caused by the Peltier effect, the thermal distribution is nonuniform both horizontally and vertically for multistage TECs.

In this paper, a numerical model for TECs is derived with temperature-dependent parameters considering two-dimensional thermal profiles. Also, a dynamic temperature-dependent electrical model of a TEC is presented based on the steady-state constant parameter Spice thermal model. And by cascading this model, a multi-pellet network electrical model is obtained for 10×10 series-wound TECs. Finally, the effects of linear, exponential and normal substrate thermal profiles on TEC performance are studied and comparison results between numerical model and electrical network of multi-pellet TECs are discussed.

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2. Thermoelectric cooler

TECs, small in size, easy to integrate and silent in operation, have drawn a lot of attention in cooling technology study. The basic structure unit of TECs is illustrated in Fig. 1(a). Many thermocouples consisting of p-type semiconductor and n-type semiconductor pellets are connected by Cu plates. Thermocouples connected electrically in series and thermally in parallel are integrated in packages. According to the Peltier effect, when electrical current is applied on the TECs from n-type end to the p-type end, the heat will be absorbed at the bottom of TECs and released at the top side [10]. Nevertheless, heat pumping direction will be changed subsequently if the polarity of power supply is reversed. When a temperature difference is produced by worked pellets at the two sides of plates, a Seebeck voltage will be generated to overcome the Seebeck effect. Moreover, even without electrical current flowing through it, a TEC still worked at the cooling state due to higher thermal conductance compared with the other materials around. Fig. 1(b) shows a type of chip package structure with embedded TECs covered by heat sink and chip substrate. When the TECs are applied by electric current, heating on the surface of substrate will be cooled down and the thermal due to the Peltier effect and TECs resistance will be released to the heat sink.

The cooling power of a TEC at the cold side is given by the following equation [8]:

$$Q_c = SIT_c - \frac{1}{2}I^2R - K(T_h - T_c). \tag{1}$$

here, S is the Seebeck coefficient, I is the applied electric current, R is the electric resistance, K is the overall thermal conductivity of the module, T_h and T_c represent the temperature of the hot side and cold side, respectively. It should be noted that the material parameters of p-type and n-type pellets are generally similar to each other except for opposite Seebeck coefficient [5,8]. Where, K, R and S are calculated by

$$K = 2N\frac{kA}{L}, \quad R = 2N\frac{\rho L}{A}, \quad S = 2Ns \tag{2}$$

N is the number of p–n pellets, L and A are the length and cross-sectional area of a p- or n-pellet, temperature-dependent parameters k, ρ and s are the thermal conductivity, resistivity and Seeback coefficient of a thermoelectric couple, respectively.

3. Numerical modeling with one-dimensional steady-state thermal profiles

3.1. Thermal property of pellet material

Due to the process of decalescence and heat release, the temperature distribution along the extending direction of TECs becomes non-uniformed, discretizing the values of TEC material parameters. Seifert et al. studied the temperature characteristics of bismuth antimony telluride semiconducting crystal in the temperature range from 80 K to 400 K and made an approximately polynomial fit to the experimental data $s(T)$, $k(T)$, $\sigma(T)$ [11], the results are shown in Fig. 2. It can be seen that great changes occur as the temperature rises from 80 K to 300 K, especially for $s(T)$ and $\sigma(T)$ whose maximum variations can reach up to 5 times of the minimum value. Although the variation of these material parameters will be mitigated in the high temperature range, they still play an important role in the accurate estimate of the TEC performance [11].

3.2. Numerical model of TECs

Since the n-type and p-type TEC pellets share similar material properties, we only consider p-type pellet in this paper as illustrated in Fig. 3. Ignoring conduction via the ambient, radiation and convection, we assume that the only heat transmission path is from one side of pellet to the other. For simplicity, any non-parallel electrical current and heat flow perpendicular to the flow direction of electrical can be neglected. Under the condition of a constant steady-state electrical current density J with these assumptions, Domenicali's equation in the x direction based on the energy balance to the thermoelectric element is given as follows [5]:

$$\frac{\partial}{\partial x}\left(k(x)\frac{\partial T(x)}{\partial x}\right) = JT(x)\frac{\partial s(x)}{\partial x} - J^2\rho(x) \tag{3}$$

where $s(T)$, $k(T)$, $\rho(T)$ and $T(x)$ are the Seebeck coefficient, thermal conductivity, electrical resistivity and temperature distribution in the x direction, respectively. In the simplified case where s, k and ρ are assumed to be constant, Eq. (3) can be simplified as

$$\frac{\partial^2 T(x)}{\partial x^2} = -\frac{J^2\rho}{k}. \tag{4}$$

Given suitable boundary conditions to the TEC problem, the numeric solution of TEC thermal profile can be attained by limiting the case that the temperatures at both sides of the pellet are known. Assuming the length of a single of TEC pellet is L and the temperature at the two ends to be T_c and T_h respectively, the boundary conditions can be defined as

$$T(x=0) = T_c, \quad T(x=L) = T_h. \tag{5}$$

The final temperature profile along the extending direction of TECs can be yielded by combining Eqs. (4) and (5) with the above boundary conditions.

$$T(x) = -\frac{J^2\rho}{2k}x^2 + \left(\frac{T_h - T_c}{L} + \frac{J^2\rho L}{2k}\right)x + T_c \tag{6}$$

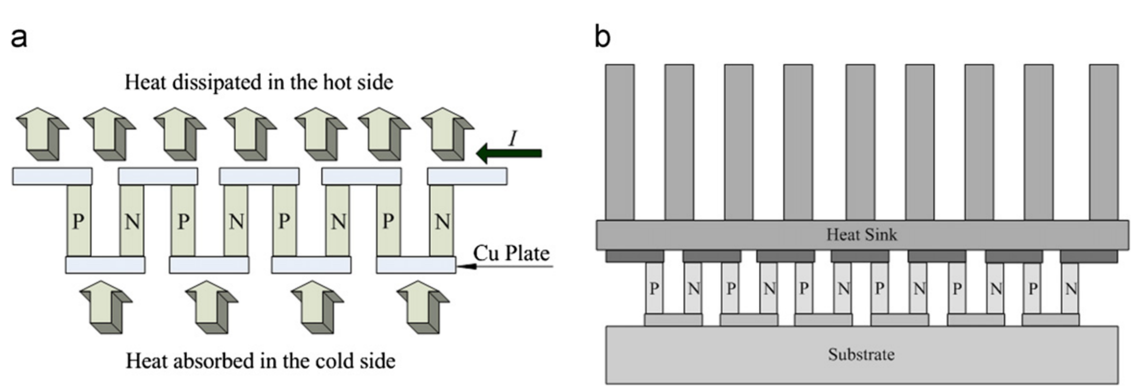

Fig. 1. Schematic of TECs module. (a) TEC devices chain with electrical current powered on and (b) Electronic package with integrated TECs.