Journal of ELECTRONIC MATERIALS, Vol. 48, No. 4, 2019
https://doi.org/10.1007/s11664-018-6785-5

TOPICAL COLLECTION: INTERNATIONAL CONFERENCE ON THERMOELECTRICS 2018

Effect of Electrical Contact Resistance on the Performance of Cascade Thermoelectric Coolers

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Performance of low-temperature cascade thermoelectric coolers (TECs) is analyzed with emphasis on the deterioration of electrical contact resistance. Two key characteristics are under consideration: the maximum coefficient of performance at a given temperature difference and the maximum obtainable cooling for the TECs with fixed configuration. The deterioration of these characteristics with increasing of the resistance of electrical contacts is analyzed for the TECs having from two to six stages that are optimized to achieve the temperature differences of 100–150 K with minimal power consumption. The quality of electrical contacts is a crucial factor that greatly affects the performance of the cascade TECs. To maintain the TEC efficiency at an acceptable level, a contact resistance r_c in the range from $10^{-7}\ \Omega\ cm^2$ to $10^{-6}\ \Omega\ cm^2$ should be provided, whereas with greater resistance, the TEC performance decreases dramatically, especially for the TECs with thermoelectric (TE) leg height of 0.5 mm and less. The irreversible losses caused by the resistance of the connecting metal strips are analyzed and the thicknesses that should provide an acceptably low r_c level are determined for different cascade TECs with typical TE leg dimensions and spacing.

Key words: Cascade thermoelectric cooler, electrical contact resistance, performance, measurements

INTRODUCTION

Creation of miniature thermoelectric coolers (TECs), destined for thermal management of electronic and optoelectronic components, is a mainstream of modern thermoelectric technology. The problem that researchers face along this path is the alignment of these details by their size and power, which requires further miniaturization of the TECs. It is known that the reduction of the height of a thermocouple L is a key to reducing the overall TEC dimensions with simultaneous increase in its cooling power. This approach can give a solution, but it also meets constraints: when decreasing thermocouple height, the ohmic resistance R_c of the electrical contact is comparable with that of the thermoelectric (TE) leg, and the Joule's heat release on electrical contacts becomes the limiting factor for further TEC miniaturization. The situation is especially complicated for multi-stage TECs, whose performance is highly dependent on any kind of irreversible losses. Hence, the reduction of R_c value is the necessary condition to promote advanced miniaturization of cascade TECs. Researches in this direction have been carried out since the early 1960s[1,2] and are currently activated in attempts to create thermoelectric cooling micro-devices for telecommunication and "on chip" cooling applications.[3–6]

Generally, in existing studies, the influence of contact resistance is taken into account by simply correcting the figure of merit Z of the semiconductor materials according to the formula[1,2]:

$$Z_e = Z\left(1 + \frac{2r_c}{\rho L}\right)^{-1} \tag{1}$$

(Received July 19, 2018; accepted October 30, 2018; published online November 7, 2018)

Table I. Minimum specific power required to achieve a given temperature difference in the absence of a contact electrical resistance and for a realistic case with $r_c = 10^{-6}\ \Omega\ \mathrm{cm}^2$ (in parentheses)

	Temperature difference (*K*)					
No. of stages	**100**	**110**	**120**	**130**	**140**	**150**
2	84.8 (133)	728 (2125)	–	–	–	–
3	43.6 (55.2)	106.1 (149)	369 (650)	3151 (12,677)	–	–
4	38.4 (47.1)	81.4 (107)	208 (301)	730 (1281)	4829 (13,373)	–
5	37.2 (45.1)	75.2 (96.5)	175 (242)	509 (794)	2105 (4065)	17081 (52,650)
6	37.2 (45.1)	73.7 (93.6)	165 (226)	444 (546)	1562 (2723)	8576 (19,578)

T_h = 300 K, L = 0.5 mm.

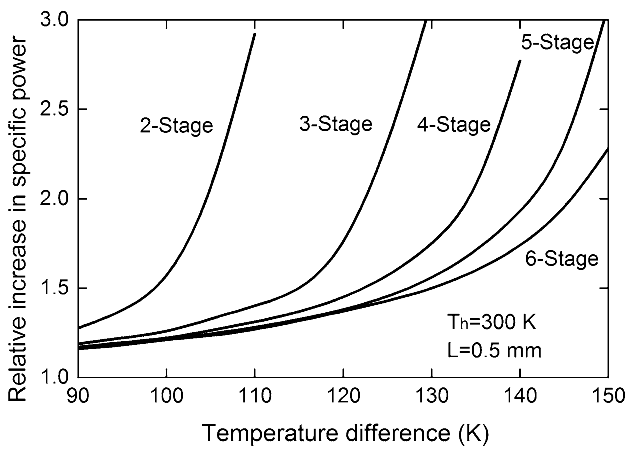

Fig. 1. Relative increase in specific power at $r_c = 10^{-6}\ \Omega\ \mathrm{cm}^2$ compared to the idealized case with $r_c = 0$.

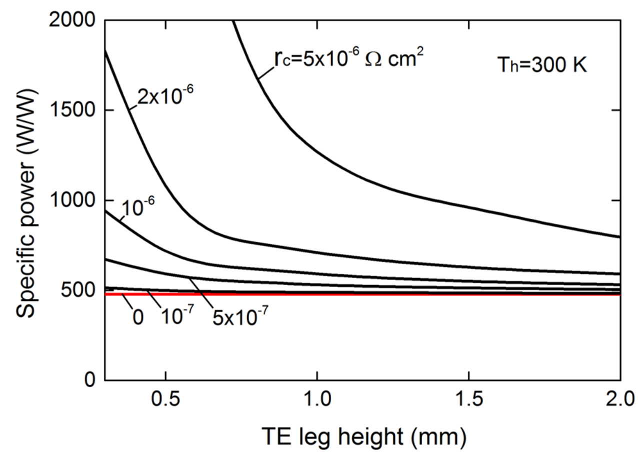

Fig. 2. Dependence of the minimal specific power on TE leg height at different r_c values. Each line is a locus of 6-stage TECs optimized to provide a ΔT of 130 K.

where Z_e is the effective value of the figure of merit, ρ is the TE material electrical resistivity, and $r_c = R_c S$ is the specific electrical contact resistance related to the unit of the contact area (S).

This approach is suitable for single-stage coolers with relatively small temperature differences. However, in the case of low-temperature-cascade TECs, the temperature variation of Z value becomes quite significant. This means that thermoelectric figure of merit loses its universality as a sole index of a TEC performance and simplified method yields unreliable results.[7–10]

In this paper, a theoretical analysis of the effect of electrical contact resistance on the performance of miniature cascade TECs is given, based on the advanced TEC model with temperature-dependent thermoelectric parameters. The model is related to our earlier publications,[8–10] so we give here its general description without mathematical details and algorithms. In general terms, the following features of the method used can be described. A TEC is considered as a thermally integrated system containing a complete set of thermoelectric cascades together with ceramic substrates at their interfaces. The method of a cascade TEC simulation and optimization is based on representing the heat transport and heat balance within the TE leg by the fundamental system of differential equations with temperature-dependent kinetic coefficients. As boundary conditions, the heat flux continuity is used, supplemented with temperature drops at the cascade interfaces, caused by the thermal resistance of the intermediate substrates. To determine the thermal resistance of the substrates, a three-dimensional model of heat spread within substrate body is used.[11]

The proposed thermal model is applied for numerical evaluation of temperature distribution separately within p-type and n-type TE legs that leads directly to heat balance at cascade interfaces and then to evaluation of the coefficient of performance (COP) for the system in a whole. The influence of contact Joule heating is accounted for by introducing these quantities into the heat balance equation at cascade junctions. To obtain necessary accuracy, a typical temperature dependence of all thermoelectric parameters is considered both for p-type and n-type bismuth telluridebased TE materials.[11]

Two different problems are solved on this basis when assessing the influence of electrical contact resistance:

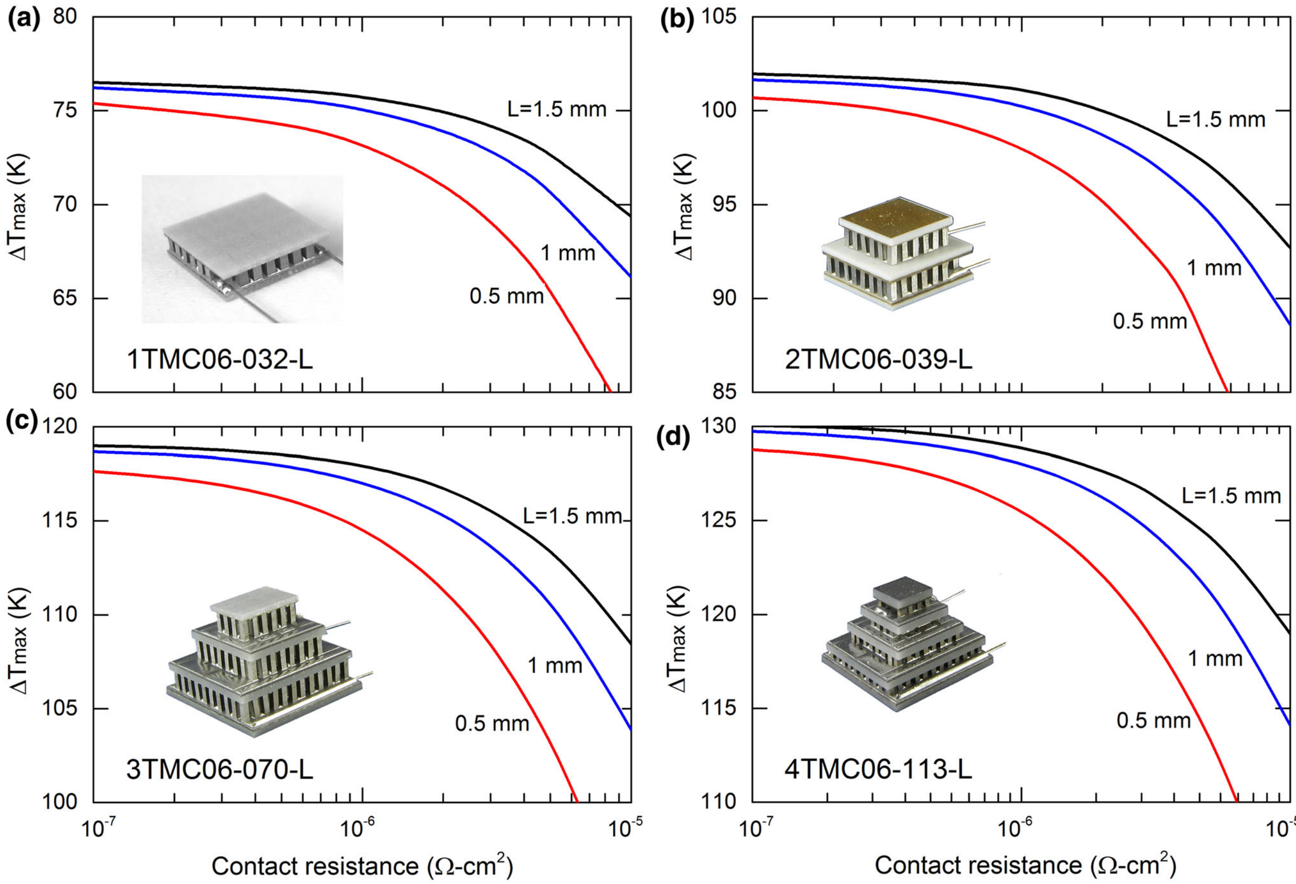

Fig. 3. Dependence of maximum temperature difference on electrical contact resistance for cascade TECs with different TE leg heights: (a) single-stage TEC; (b) two-stage TEC; (c) three-stage TEC; (d) four-stage TEC.

- Definition of the minimum electrical power that is necessary to provide a predetermined temperature difference $\Delta T = T_h - T_c$, where T_h and T_c are the hot side and cold side temperatures, respectively;
- Estimation of attainable maximum temperature difference ΔT_{max} for the TECs with a fixed configuration.

Finally, the method of indirectly estimating the r_c value is presented, based on measured dependence of the TEC performance on TE leg height. The irreversible losses caused by the electrical resistance of the connecting metal strips are analyzed and their thicknesses, which should provide an acceptably low r_c level, are determined for different cascade TECs with typical TE leg dimensions and spacing.

AFFECTED PARAMETERS

Increase in Specific Power

We will use, as a TEC performance characteristic, its power P_c that is necessary to provide a unit of cooling capacity (so-called specific power $P_c = 1/\mathrm{COP}$). It will be shown below how significant the impact of the electrical contact resistance on this parameter is. Two cases are considered for comparison: the idealized model with zero r_c value and the realistic one with contact electrical resistance of $10^{-6}\ \Omega\ \mathrm{cm}^2$. In both cases, the TEC configurations and their electrical parameters are optimized to receiving a given temperature difference with minimal specific power. The optimizing algorithm described in Ref. 8 was used in these calculations. The results are presented in Table I and Fig. 1. Table I shows the minimal specific power for both cases and Fig. 1 gives the relative increase in specific power for the real model compared with the idealized one.

It can be seen from Table I and Fig. 1 that, even for r_c value as small as $10^{-6}\ \Omega\ \mathrm{cm}^2$, the rise of minimum specific power exceeds 20% at moderate ΔT values and a real dramatic increase (by factor of 3 and more) takes place when required ΔT approaches its maximum level available with a given number of cascades. This also means that to maintain a given cooling capacity, the areas of all cascades should be increased proportionally as

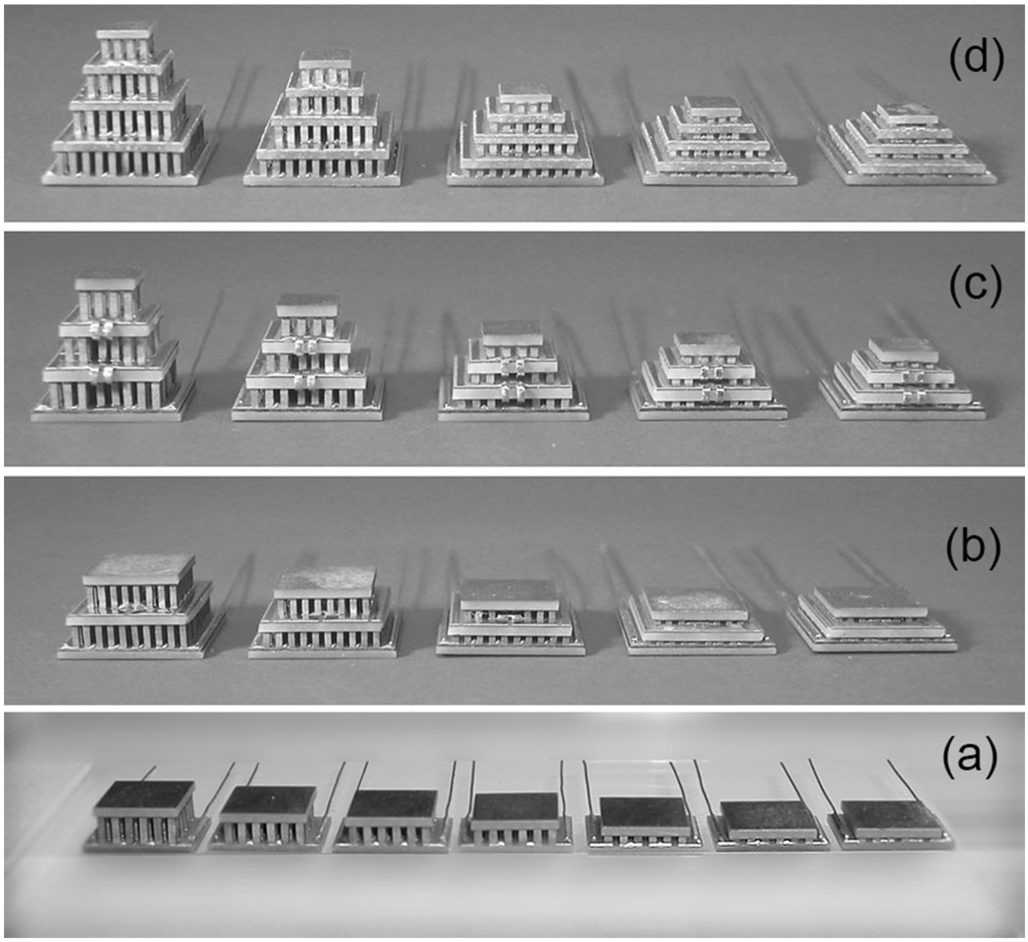

Fig. 4. Experimental samples of short-legged TECs: (a) single-stage; (b) two-stage: (c) three-stage; (d) four-stage. Reprinted with permission from Ref. 15.

Table II. Characteristics of experimental samples presented in Fig. 4

No. of stages	TEC part number[12]	No. of TE legs	TEC dimensions (mm)[a]	
			Top	Bottom
1	1TMC04-018-L	36	4.8 × 4.8	6.4 × 4.8
2	2TMC04-083-L	118 + 48	6.4 × 6.4	9.6 × 9.6
3	3TMC04-046-L	62 + 22 + 8	3.2 × 3.2	6.4 × 6.4
4	4TMC04-105-L	118 + 62 + 22 + 8	3.2 × 3.2	9.6 × 9.6

Reprinted with permission from Ref. 15. [a]For all TEC models, TE leg cross sections and their pitch are 0.4 × 0.4 mm and 0.8 mm, respectively.

compared with an idealized case. The influence of the contact resistance increases sharply with a decrease in the height of the thermocouples and at L = 0.2 mm or less, this becomes the main obstacle for further miniaturization of cascade TECs. Figure 2 illustrates this effect for 6-stage TECs whose configurations and electrical parameters are optimized to obtain ΔT = 130 K with minimal specific power.

Reduction of the Maximum Temperature Difference

Along with energy losses and growing of the TEC dimensions, the presence of electrical contact resistance can lead also to a considerable reduction of achievable temperature drop. Figure 3 shows the results of calculations of the attainable temperature differences for a series of standard Thermion TMC

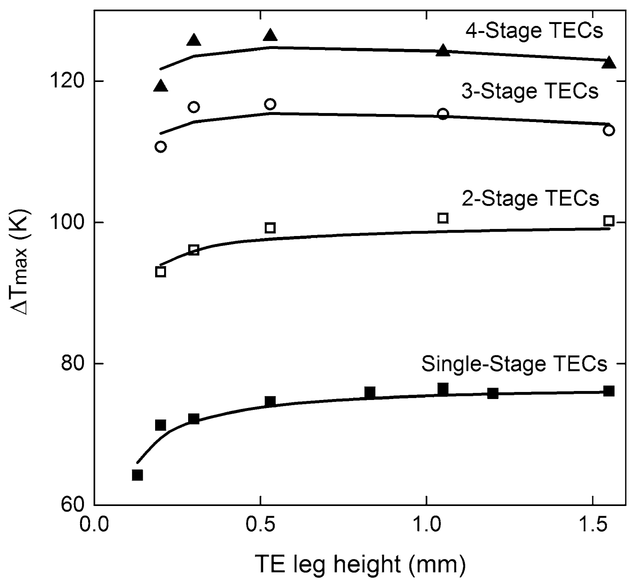

Fig. 5. Maximum temperature differences versus TE leg height.

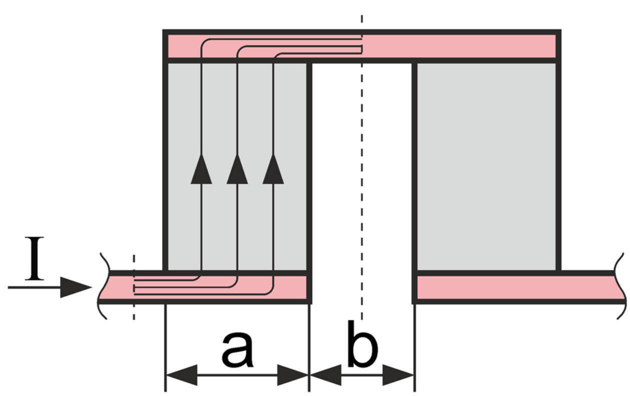

Fig. 6. Model of the thermocouple for calculating the connecting strip electrical resistance.

coolers[12] with different heights of thermocouples. The region of r_c values from $10^{-7}\ \Omega\ cm^2$ to $10^{-5}\ \Omega\ cm^2$ is under consideration. It is seen clearly that acceptable cooling can be achieved with r_c below $10^{-6}\ \Omega\ cm^2$, while at greater contact resistance, the catastrophic reduction in ΔT_{max} is observed, especially for short-legged cascade TECs.

PRACTICAL IDENTIFICATION OF THE ELECTRICAL CONTACT RESISTANCE

Direct measurement of contact electrical resistance encounters considerable difficulties due to a small measured value. This is why the data published in literature vary in a wide range from 10^{-5} to 10^{-7} [3–5] and even to $10^{-8}\ \Omega\ cm^2$.[6] In this study, we used an indirect method of r_c identification based on its deteriorative effect on a TEC's performance. Particularly, the reduction of maximum temperature difference ΔT_{max} with decreasing TE legs height was used for this purpose. To obtain reliable data, the results of TEC miniaturization are processed, which have been obtained by Thermion during recent decades.[13–17] Figure 4 illustrates the practical progress in TEC miniaturization. Three models of cascade TECs were manufactured, each one repeated in five modifications with TE legs of 1.55 mm, 1.05 mm, 0.53 mm, 0.3 mm, and 0.2 mm long. To insure the good quality of the used TE materials, the set of single-stage 18-couple TECs was also fabricated with TE leg heights reduced from 1.55 mm down to 0.13 mm. The TEC's dimensional characteristics are presented in Table II.

To avoid random errors, several duplicate modules of each dimensional type were fabricated. All the modules were tested in vacuum at 1.3×10^{-2} Pa on achieving maximum temperature difference. The test results are shown in Fig. 5. It is seen that high ΔT_{max} values comparable to those for large-geometry TECs can be retained down to the TE leg length of 0.5 mm, but below this dimension, a notable decrease in achieved ΔT is observed.

The confidence r_c value was sought as giving the best quadratic fit of all calculated data to all experimental points for all tested configurations shown in Fig. 5. The used calculation model takes into account the temperature dependence of the TE parameters of semiconductor materials and thermal resistance of the ceramic substrates at the cascade boundaries.[11] Thermal conductivity was accepted to be of 0.27 W/cm K and 1.7 W/cm K for alumina and AlN ceramic, respectively. A slight decrease in the maximum temperature difference for the three- and four-cascade TECs indicates the influence of heat inflows, which were estimated to be 5 mW and 7 mW, respectively, and these data were incorporated into the calculation algorithm. Within the framework of this model, the r_c value, as small as $6 \times 10^{-7}\ \Omega\ cm^2$, is obtained, which indicates the high efficiency of the used technology.

RESISTANCE OF CONNECTING STRIPS

Modeling of the Strip Resistance

Here we must clarify the concept of the electrical contact resistance. In the general case, one can write:

$$R_c = R_0 + R_s = (r_0 + r_s)/S \qquad (2)$$

where R_0 is the transition resistance at the metal–semiconductor interface, R_s is the resistance of the adjacent part of the metal connecting strip, r_0 and r_s are the corresponding specific resistances related to a unit of contact area $S = a^2$, and a is the TE leg side dimension.

On its physical meaning, r_s is the Joule equivalent of the strip resistance, referred to the unit of contact area. Its value is determined by formula (3) obtained with the assumption that the current

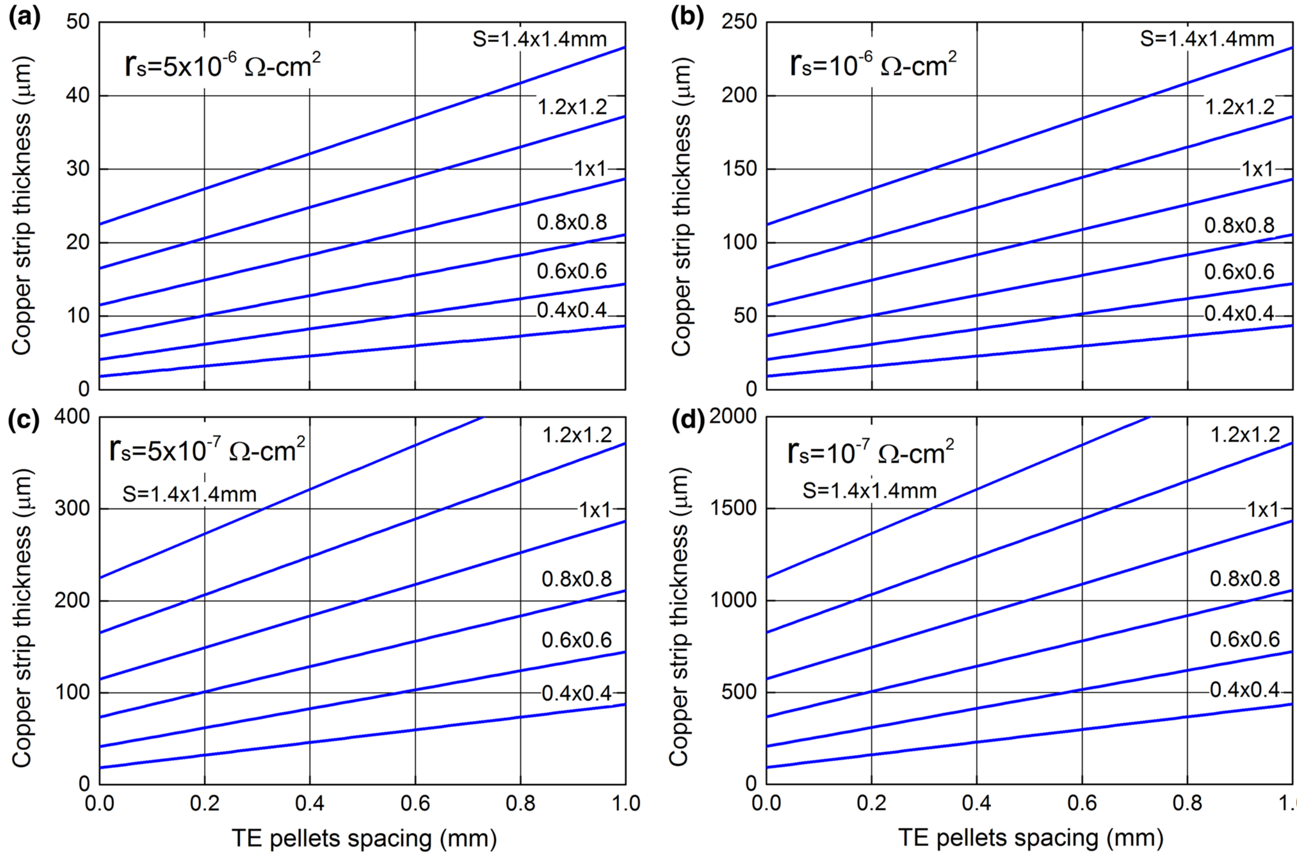

Fig. 7. Copper strip thicknesses providing a predefined electrical contact resistance versus junction area and TE pellets spacing: (a) $r_s = 5 \times 10^{-6}$ Ω cm²; (b) 10^{-6}; (c) 5×10^{-7}; (d) 10^{-7}.

density is uniform within TE leg and varies linearly along the strip[18] as shown in Fig. 6:

$$r_s = \frac{\rho_m S}{2\delta}\left(\frac{b}{a} + \frac{2}{3}\right) \quad (3)$$

where ρ_m is the metal strip electrical resistivity, b is the gap between TE legs (spacing), and δ is the metal strip thickness.

The transition component r_0 of the contact resistance at the Sb_2Te_3 and Bi_2Te_3 to metal interface is of the order of 10^{-8} Ω cm²,[6] while the measured contact resistance typically varies in the range from 10^{-5} Ω cm² to 10^{-7} Ω cm². Hence, the transition component r_0 may be neglected in further calculations.

Choice of the Strip Thickness

With given a and b values, Eq. 3 makes it possible to determine the required thickness of the plate, which should provide a predetermined contact electrical resistance. Results of calculations are given in Fig. 7. Considered are typical combinations of junction dimensions with their spacing. It can be seen that the maximum strip thickness, required to reproduce a given r_s value, varies from 50 μm at $r_s = 5 \times 10^{-6}$ Ω cm² to 2.5 mm at $r_s = 10^{-7}$ Ω cm². Two different technologies can be used for producing such connectors in ceramic substrates: so-called 'direct plated copper (DPC)' technology for depositing copper layers with thickness up to 150 μm and 'direct bonded copper (DBC)' technique for the strips with greater thicknesses.[19]

It can be seen from Fig. 7a that in order to maintain the r_s value at a level of 5×10^{-6} Ω cm², the strip thickness of 50 μm is quite enough for all studied configurations. This means that DPC technology should reliably reproduce this contact resistance at any combination of TE contact areas and their spacing within considered ranges. It can be seen also that r_s of 10^{-7} Ω cm² (Fig. 7d) is not affordable for DPC technology, and hence, DBC technique should be used to support this r_s value. Regarding the r_s range between 5×10^{-7} and 10^{-6} Ω cm² (Fig. 7b and c), the DPC or DBC technique should be selected, depending on the combination of S and b values.

CONCLUSIONS

Electrical contact resistance greatly affects cascade TEC performance. This is especially critical for the TECs with TE leg height of 0.5 mm and less. To support their high efficiency, electrical contact resistance in the range from $10^{-7}\,\Omega\,\text{cm}^2$ to $10^{-6}\,\Omega\,\text{cm}^2$ should be provided, while greater r_c values lead to a dramatic increase in required power and decreases the attainable temperature difference.

Connecting strips make the predominant contribution to the electrical contact resistance. To reproduce a desired contact resistance, the strip thickness must be accurately matched with junction size and spreading.

For miniature TECs with a contact area of less than 1×1 mm, the thickness of the copper strips in the range from 50 μm to 150 μm is sufficient to provide an r_c value of $10^{-6}\,\Omega\,\text{cm}^2$. This is quite achievable for DPC technology. For greater junction dimensions, the DBC technique should be preferred.

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