Novel High Performance Thermoelectric Microcoolers with Diamond Substrates

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Abstract

The concepts discussed in previous papers [1-3] have been implemented in novel miniature thermoelectric coolers (TECs) with diamond substrates. Micromodules with TE legs 0.2mm long and 0.4×0.4mm^2 in cross-section were developed. A maximum temperature difference of 67K was obtained, a value comparable to the ones obtained for commercial TECs with TE leg length of 1mm and higher. Heat flux densities of 70W/cm^2 at cold junctions were achieved. Taking into consideration the hot side thermal resistance, the minimum TE leg length was calculated. It was found that using high thermal conductivity substrates allows miniaturization of the TE legs near its lower theoretical limit defined by electrical contact resistance only. Cold side heat flux densities in excess of 100W/cm^2 can be attained in such coolers. This makes them ideal to solve thermal problem of high density localized heat sources such as power amplifiers, microprocessors and other power electronic devices which are already operating at the edge of their reliability.

Introduction

Many electronic components need active cooling for safe operation. The thermal issues are particularly severe for high power devices such as power amplifiers, microprocessors, semiconductor lasers and other electronic and electro-optic devices which act as high density localized heat sources. To maintain control of their operating temperature, TECs with exceptionally high cooling capacity must be developed. It is well known that heat flux densities q_0 and q_1 at the TEC cold and hot junctions increase in inverse proportion to TE leg length l. With l=0.1mm, for instance, q_0 values can exceed 100W/cm^2. Thus, developing extremely short-legged TEC is required to meet the cooling requirement of high density heat sources. However, hot side heat rejection issues must also be resolved because q_1 values can reach 250-350 W/cm^2. For alumina substrates, which are commonly used, the resulting hot side temperature gradient can be more than 30K. So the use of substrates from high thermal conducting materials, such as diamond, is the most promising trend for extremely short-legged TECs development.

Theoretical maximum of cooling capacity

Heat flux densities at the TEC cold and hot sides are bound by the following system of equations (1), where α, ρ, κ are the Seebeck coefficient, electrical resistivity and thermal conductivity of TE materials, i is the input current density, T_c and T_1 are the temperatures of cold and hot junctions respectively, T_e is the temperature of environment, r_c is the contact electrical resistance referred to junction area unit, R_t is the TEC hot side thermal resistance defined as the ratio of the temperature drop to the hot side heat flux density.

$$\begin{aligned} q_0 &= \alpha T_c i - \frac{1}{2} i^2 (\rho l + 2r_c) - \frac{\kappa}{l}(T_1 - T_c) \\ q_1 &= \alpha T_1 i + \frac{1}{2} i^2 (\rho l + 2r_c) - \frac{\kappa}{l}(T_1 - T_c) \\ T_1 &= T_e + R_t q_1 \end{aligned} \quad (1)$$

(1) gives the $q_0(i,l)$ dependence in indirect fashion. For any fixed l value the set of equations (1) determines the maximum of $q_0(i)$ as a function of current density. The calculated maxima for different R_t values are given in Fig.1. One can see that for a fixed contact resistance optimal l values corresponding to absolute maximum of cooling capacity can be determined. Such l values are the minimum acceptable TE leg lengths since smaller values result in simultaneous q_0 and COP reductions. This dramatic degradation in TEC performance is mostly due to catastrophic superheating of the TEC hot side.

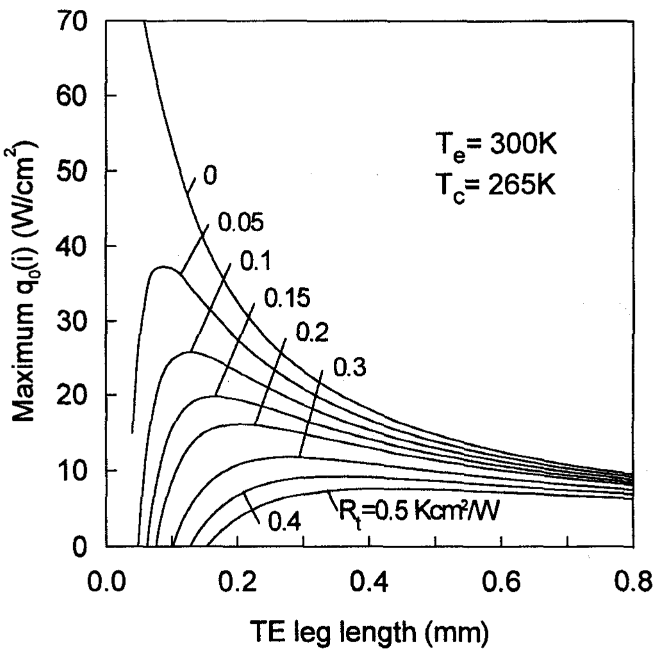

Figure 1: Maximum (by current density) cold side heat flux density versus TE leg length for different R_t values.

Fig.2 shows the variations of l_{min} and q_{0max} with increasing R_t values and highlights the importance of using high heat conducting substrates. For alumina substrates (thermal conductivity of 0.2W/cmK) R_t values are usually of the order of 0.1-0.2Kcm^2/W, minimum TE leg lengths range from 0.1 to 0.7mm, depending strongly on the operating temperature difference $\Delta T = T_e - T_c$. This gives q_{0max} values considerably below 50W/cm^2 for ΔT>20K.

Because of the much higher thermal conductivity of diamond substrates (12 to 18W/cmK), the thermal resistance practically vanishes. This enables reducing l_{min} to its theoretical limit defined by electrical contact resistance only (estimated here as $1.5 \cdot 10^{-6}$ Ωcm^2). Lower l_{min} values means that q_{0max} values can be increased to over 150W/cm^2.

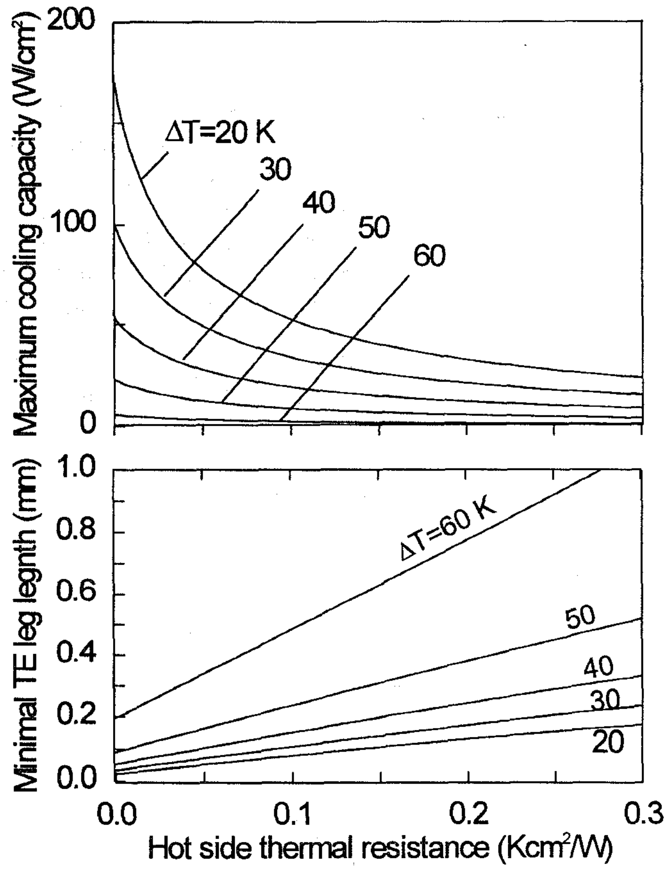

Figure 2: Minimal TE leg length and maximum cold side heat flux density versus hot side thermal resistance.

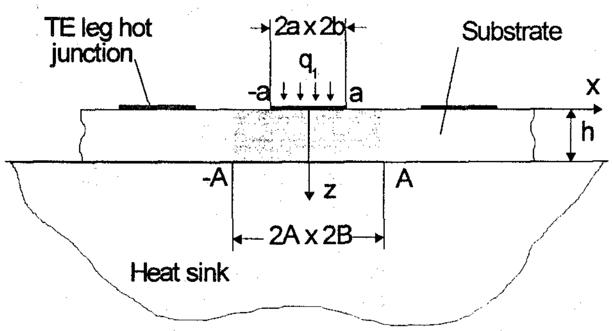

Figure 3: Scheme of TEC hot side substrate.

In real devices however, the hot side TEC thermal resistance also depends on the heat sink thermal resistance, R_{hs} for a total value of $R_t = R_{ts} + R_{hs}$. To estimate the TEC characteristics, separate modeling of the substrate and heat sink thermal resistances must be conducted.

Substrate thermal resistance

Let us consider a substrate section related to a TEC junction (Fig. 3) with dimensions $2A \times 2B$ and thickness h. Heat is generated in a junction area $2a \times 2b$ with uniform density q_1 and flows three-dimensionally into the highly conductive sink having zero temperature. Other top and side surfaces of this section are adiabatically insulated. The substrate thermal resistance is defined as the ratio of the mean integral temperature at the junction area to the heat flux density q_1. A solution of Laplace's equation for the temperature $T(x,y,z)$ within the substrate element leads to the following equation for R_{ts}:

$$R_{ts} = \frac{h}{\kappa_s} \Phi\left(\frac{a}{A}, \frac{b}{B}, \frac{h}{A}, \frac{A}{B}\right) \tag{2}$$

where

$$\Phi = \beta \left(1 + 2S_1 + 2S_2 + 4S_3\right) \tag{3}$$

Φ is a form factor characterizing the influence of TE leg spacing, and S_1, S_2 and S_3 are expressed as:

$$S_1 = \sum_{n=1}^{\infty}\left(\frac{\sin(\lambda a)}{\lambda a}\right)^2 \frac{\tanh(\lambda h)}{\lambda h}$$
$$S_2 = \sum_{m=1}^{\infty}\left(\frac{\sin(\mu b)}{\mu b}\right)^2 \frac{\tanh(\mu h)}{\mu h} \tag{4}$$
$$S_3 = \sum_{n=1}^{\infty}\left(\frac{\sin(\lambda a)}{\lambda a}\right)^2 \sum_{m=1}^{\infty}\left(\frac{\sin(\mu b)}{\mu b}\right)^2 \frac{\tanh(\alpha h)}{\alpha h}$$
$$\lambda = \frac{n\pi}{A}, \qquad \mu = \frac{m\pi}{B}, \qquad \alpha^2 = \lambda^2 + \mu^2$$

where $\beta = ab/AB$ is the TE leg packing density and κ_s is the substrate thermal conductivity.

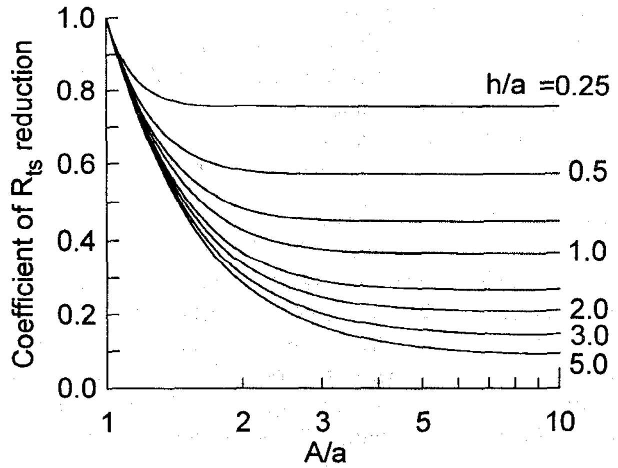

Figure 4: Reduction of substrate thermal resistance with TE legs spacing.

Fig.4 shows the dependence of the form factor Φ on TE legs spacing. In a boundary case when the packing density is unity ($a=A$, $b=B$), one has $\Phi=1$ and $R_{ts}=h/\kappa_s$, which corresponds to the one-dimensional heat flow. Increasing leg spacing considerably reduces substrate thermal resistance, the effect being particularly significant for high values of h/a ratio. It is also clear that increasing legs spacing to $A/a > 3$ does not result in any significant additional gains.

Thermal resistance of a heat sink

Let us consider the physical model of a heat sink in a form of semi-infinite section with a rectangular heat source at its surface. Heat flow from the substrate with dimensions of $2A_s\times2B_s$ enters uniformly into heat sink, heat flux density being of $q_s=q_1\beta$. The supporting surface is adiabatically insulated and the heat sink temperature at infinity is zero. The thermal resistance of such heat sink, defined as the ratio of the integral mean temperature at the substrate bottom area to heat flux density q_1, can be expressed as:

$$R_{hs}=\frac{\beta}{\pi\kappa_{hs}}\left\{A_s\ln\frac{R+B_s}{R-B_s}+B_s\ln\frac{R+A_s}{R-A_s}-\frac{2}{3}\frac{R^3-A_s^3-B_s^3}{A_sB_s}\right\} \quad (5)$$

where $R=\sqrt{A_s^2+B_s^2}$ and κ_{hs} is the heat sink thermal conductivity. If $A_s=B_s$, (5) can be reduced to the formula:

$$R_{hs}=0.947\,\beta A_s/\kappa_{hs}\,. \quad (6)$$

Results show that the heat sink thermal resistance is proportional to the substrate linear dimensions. So for fixed q_1 and β values, hot side substrate superheating increases linearly with increasing module edge dimension. For example, using a substrate with dimensions $A_s=B_s=10$ mm and $\beta=0.25$, the calculated thermal resistance of a copper heat sink is 0.06 Kcm^2/W. This resistance approaches the value obtained for 0.5mm thick alumina substrates but is much larger than the one achieved for diamond substrates. A heat flux of $250 W/cm^2$ can result in a 15K temperature gradient at the substrate-heat sink interface. This additional superheating by no means can be eliminated in such a model. It must be noted that the temperature decrease in the direction of the heat sink depth is rather slow. Even at a depth equal to the substrate edge dimension, the calculated overheating is close to half the maximum temperature rise which occurs at the center of the sink surface. Thus, heat sink thin plate geometry combined with intensive heat removal from its bottom surface are highly desirable for cooling short-legged TECs. Another alternative is a heat sink with a two-phase heat pipe embedded under the substrate bottom and directly in the zone of maximum superheating. To estimate R_{hs} for this model equations (2)-(4) can be used with A_s and B_s as a and b respectively.

Experimental details

Self-standing diamond films were produced by CVD technique and used as substrates for short-legged TECs. Similar TE modules with alumina substrates were also fabricated to provide a baseline. Some details of these TECs arrangement are given in Table 1.

Table 1. Characteristics of experimental samples

Parameter	TECs with diamond substrates	TECs with alumina substrates
Number of TE legs	120	120
TE leg length (mm):	0.2	0.2
TE leg cross-section (mm):	0.4×0.4	0.4×0.4
TE leg spacing (mm)	0.4	0.4
Top substrate thickness (mm):	0.56	0.5
Top substrate are (mm):	10.4×14.1	9.6×8
Bottom substrate thickness (mm):	0.56	0.5
Bottom substrate area (mm):	10.4×14.1	9.6×9.6
metallized and patterned area Substrate dimensions (mm)	9.2×7.6	9.2×7.6
Substrate thermal resistance per unit area (Kcm^2/W)	1.5×10^{-3}	0.1

The modules were tested in vacuum, operating with no load operation (ΔT_{max}) as well as with heat load at the cold side (Q_{max}). The hot side of the modules was maintained at 303K using ultra thermostat with heat-transfer liquid. The temperature-sensitive micro resistor mounted at the heat sink close to the bottom substrate edge was used for hot side temperature control.

The dynamic thermal behavior of the TECs after switching the DC source on was also studied. Using thermocouples from copper and constantan wires 0.03mm in diameter, the cold side temperature was recorded as a function of time.

Results and discussion

Fig. 5 plots the variations in temperature gradient at the TECs hot and cold junctions as a function of the input electrical current and under zero thermal load conditions.

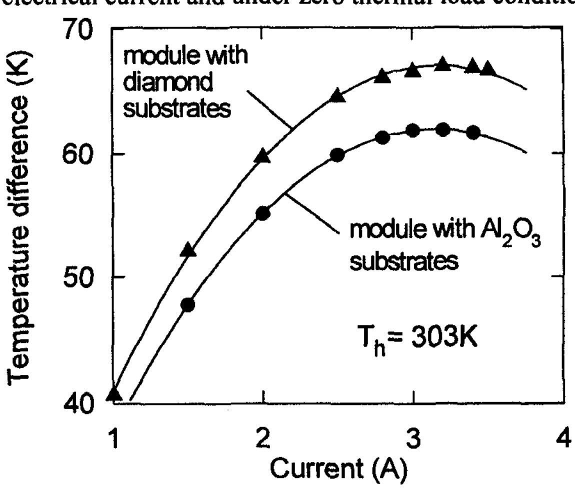

Figure 5: Dependence of TEC temperature difference with input electrical current.

In spite of extremely short TE legs, a maximum temperature difference of 67K was obtained for the cooler with diamond substrates, a result comparable to the performance of commercial coolers with TE leg length of 1mm and higher. Because of the hot side substrate superheating, a lower ΔT_{max} of 62K only was measured for the alumina-based module.

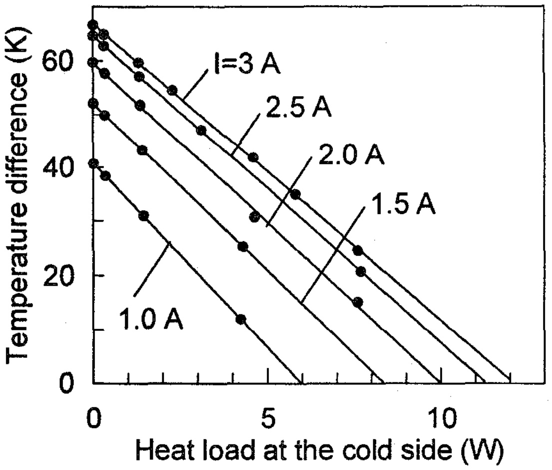

Figure 6: Heat load characteristics of TE microcooler with diamond substrate (measured).

It should be noted that the preliminary configuration of the diamond-based microcoolers was far from optimal because their substrate area substantially (more than twice) exceeded the patterned area (see Table 1), resulting in increased heat losses at the cold side. Thus, the potential for further performance improvement exists and can be realized in future. Fig. 6 plots the variations of ΔT with different heat loads at the cold side for the diamond-based microcoolers. One can see that the device can maintain a ΔT of 25K even with a heat load of up to 8W. This makes it possible to use such devices for cooling solid state power amplifiers in spacecraft applications [2]. When ΔT is completely suppressed the module has a cooling capacity of more than 12W which corresponds to a heat flux density of 65W/cm^2 at the cold junctions.

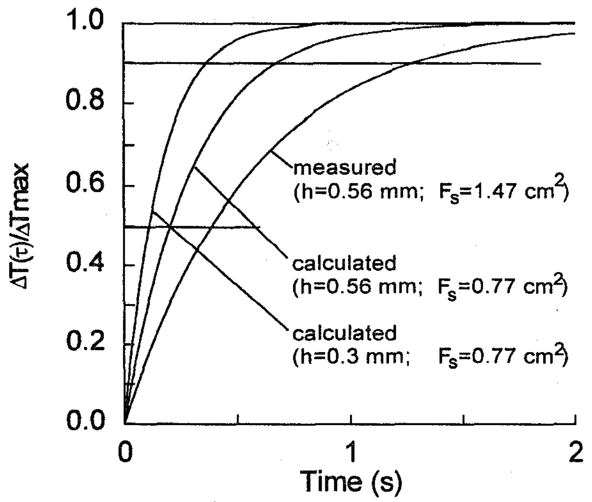

Figure 7: Dynamic characteristics of experimental sample.

The recorded dynamic characteristic of the experimental module with diamond substrates is displayed in Fig.7. The calculated characteristics for optimal top substrate dimensions are also presented here. The results are treated in the form of $\Delta T/\Delta T_{max}$ time dependence and show that the device required about 2s to achieve its ΔT_{max}. Much better results should be achieved when superfluous parts of the top substrate are removed and its thickness is diminished. Corresponding data are shown in Table 2. For TEC with substrate thickness of 0.3mm the time to achieve $0.9\Delta T_{max}$ is expected to be reduced to only 0.36s only.

Table 2. Time to achieve specified ΔT (s)

Top ceramic dimensions (mm)	Specified temperature difference (K)		
	$0.37\Delta T_{max}$	$0.5\ \Delta T_{max}$	$0.9\ \Delta T_{max}$
h=0.56, F_s=10.4×14.1	0.25	0.4	1.3
h=0.56, F_s=9.6×8	0.13	0.20	0.67
h=0.3, F_s=9.6×8	0.07	0.11	0.36

Conclusion

Use of diamond substrates in short-legged TE microcoolers resulted in near complete elimination of the undesirable superheating at the TEC hot side. A maximum temperature difference of 67K was demonstrated in TECs with TE legs 0.2mm long, a value approaching ΔT_{max} for commercial samples with TE leg length of 1mm and higher. Cold side heat flux densities over 60W/cm^2 can be reached by such coolers under maximum cooling power conditions. This makes them ideal to solve thermal issues related to high density localized heat sources, such as power electronic devices. Moreover, 50% shorter cool down time have been obtained in diamond-based coolers compared to alumina- or berilla-based coolers, because of shorter TE legs and lower substrate specific heat.

References

[1] Vladimir A. Semeniouk, Tatyana V. Pilipenko, Grant C. Albright, Leonid A. Ioffe, William H. Rolls, "Miniature Thermoelectric Coolers for Semiconductor Laser", Proc. of the XIIIth Int. Conf. on Thermoelectrics (ICT'94), Kansas City MO, USA, 1994, AIP Conf. Proc. 316 (1995) 150.

[2] Jan W. Vandersande, Richard Ewell, Jean-Pierre Fleurial and Hylan B. Lyon, "Thermoelectric Devices and Diamond Films for Temperature Control of High Density Electronic Circuits", Proc. of the XIIIth Int. Conf. on Thermoelectrics (ICT'94), Kansas City MO, USA, 1994, AIP Conf. Proc. 316 (1995) 174.

[3] Jan W. Vandersande and Jean-Pierre Fleurial, "Thermal Management of Power Electronics Using Thermoelectric Coolers", Proc. of the XVth Int. Conf. on Thermoelectrics (ICT'96), Pasadena, CA, USA, 1996, IEEE (1996) 252.