

## A STUDY ON THE HOT SPOT COOLING USING MICRO THERMOELECTRIC COOLER

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### ABSTRACT

An experimental apparatus to show the hot spot cooling of an IC chip using a thermoelectric cooler (TEC) is developed. The spot heating in very small area is achieved by applying CO<sub>2</sub> laser source and temperatures are measured using miniature thermocouples. The active effects of thermoelectric cooler on the hot spot cooling system such as rapid heat spreading in the chip and lowering the peak temperature around the hot spot region are investigated. The experimental results are simulated numerically using the TAS program, which the performance characteristics, such as Seebeck coefficient, electrical resistance and thermal conductivity of the thermoelectric cooler are searched by trial and error. Good agreements are obtained between numerical and experimental results if the appropriate performance data of the thermoelectric cooler are given.

### INTRODUCTION

Heat dissipation problems of high performance micro-electronic chips are still a "hot issue" and many researches to resolve this problem have been conducted for many years [1-3]. According to these researches, maximum junction temperature should be lower than 100°C, but localized heat flux (hot spot) on the chip is very high and thus is considered as a dominant challenge. Thermoelectric cooling to manage the hot spot cooling in the chip level using the thin film technique is tried by many researchers [4-6]. They showed the micro thermoelectric cooler could get very high cooling power density such as 600 W/cm<sup>2</sup> [4] or 1250 W/cm<sup>2</sup> [5] and provide the enhanced effective thermal conductivity resulted in 50% of temperature reduction in the hot spot [6].

Recently, Micr<sup>o</sup>Pelt [7] commercialized the micro TECs using the two wafer MEMS technique and reported that a net cooling of about 56 K with 2 A in the vacuum atmosphere. Our research team is also developing a micro TEC using the co-sputtering method [8]. Thermion, [9] also supplied the very

small sized, micro TECs, having extremely short TE leg of order: 0.2 mm and 0.3 mm.

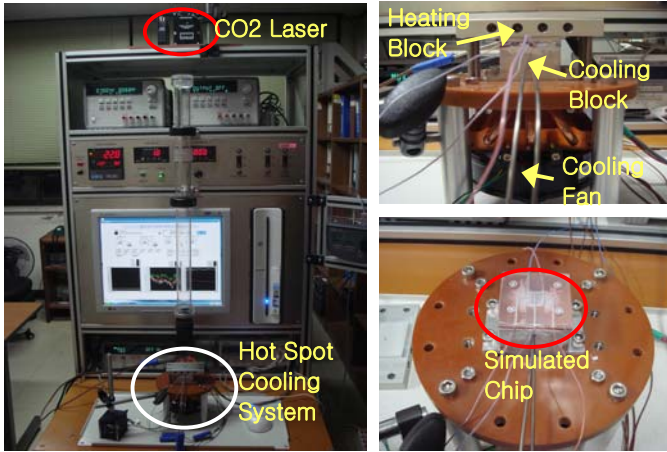
In this paper, in order to investigate the potential availability of the micro sized TEC for hot spot cooling systems, an experimental study using CO<sub>2</sub> laser source as a hot spot heating and chip cooling system with imbedded TEC is carried out. A numerical analysis by using the commercial software TAS [10] – based on the finite element method – is also conducted. The results from the experiment and numerical analysis are compared and the active effects of thermoelectric cooler on the hot spot cooling are investigated in detail. An estimation of performance according to the thermoelectric characteristics of the TEC on the cooling system is also explored and its limitations are discussed.

### EXPERIMENT: HOT SPOT COOLING

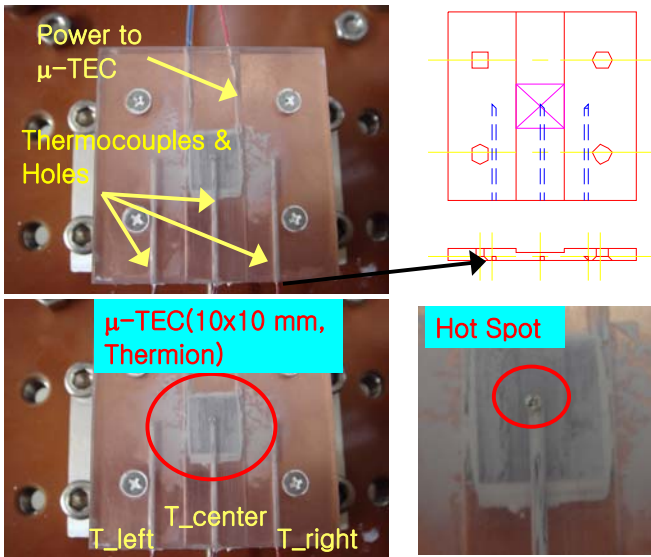
#### Experimental set-up

The experimental set-up to show the hot spot cooling of an IC chip using a micro TEC is shown in Figure 1. A CO<sub>2</sub> laser system (SYSRAD, Model 48-1) with a 10 W average output power is used to create a hot spot and its power was regulated by a controller (SYNRAD, Model UC-2000). The invisible laser light is introduced to the hot spot hole of 1.5 mm diameter through a reflecting mirror and a convex lens with 110 mm focal length. This laser light is finally reached at the hot spot area of 0.6 mm diameter.

An acrylic plate is chosen to simulate the computer IC chip and a very small sized thermoelectric cooler (Thermion, Model IMC04-060-02) is attached on the center of the plate using a liquid thermal compound (CASMOPLY HC-300). Four electric resistance heaters are inserted in the aluminum heating block and the temperature of the block is measured using thermocouple at the center of the block and adjusted by a PID controller (Yokogawa, UT550) and a voltage regulator (Sanup Electronic, SPR Pro).



**Figure 1** Overview of experimental set-up



**Figure 2** View of simulated chip, micro TEC, and thermocouples

Heat from resistance heaters and hot side of the TEC is dissipated to the surroundings through the air cooling system, composed of an aluminum block, heat pipes, and a fan. Precision power suppliers, Model E3634A and E3633A (Agilent) are used to supply DC power to the cooling fan and the TEC respectively. Type T miniature thermocouples are inserted to holes of 0.9 mm diameter in the acrylic plate to measure temperatures as shown Figure 2.

The detail locations and names of the thermocouples are shown in Figure 2. The thermocouple, T-center is positioned under the hot spot. The thermocouples, T-left and T-right are installed at the left and right side, with a 5 mm distance apart from the hot spot respectively. Therefore these two thermocouples are located on the outside area of the TEC as shown Figure 2. All thermocouples are installed at 0.85 mm below from the chip's surface as shown in the right upper part in Figure 2. Therefore, thermocouple, T-center is not located at

the exact point of the hot spot, but its location is called as hot spot in this paper.

Table 1 shows the specifications of the experimental set-up and the thermo-physical properties from the literature [11] are also shown. The copper back plate in the Table 1 is used for rapid heat spreading of heat from the laser and the TEC. The thickness of the TIM is not measured but determined by trial and error. This result will be explained later. The temperatures of the heating block and chip, level of laser power, and supplied power to the TEC are set and recorded by a personal computer using the Labview [12] program.

### Experimental procedure

A very important step to carry out the experiment is focusing the laser source to the same hot spot in the chip plate. Therefore, the focusing was checked using sensitive paper before measurement.

After setting the temperature of the heating block and DC power of the cooling fan, the chip is heated until all temperatures are steady. Then hot spot heating, using the laser, is started and DC power is supplied to the TEC subsequently.

The temperatures of the chip are measured and analyzed according to the levels of the laser power and DC voltage of the TEC. The range of laser power is varied from 3% to 5% of average output and the DC voltage of the TEC is supplied from 0V to 5V. For each pair of laser power and TEC voltage, three consecutive measurements are carried out. If losses from the laser are neglected, 3%, 4%, and 5% of average laser output can be equivalent to 106 W/cm<sup>2</sup>, 141 W/cm<sup>2</sup>, and 176 W/cm<sup>2</sup> of heat flux in the hot spot area respectively.

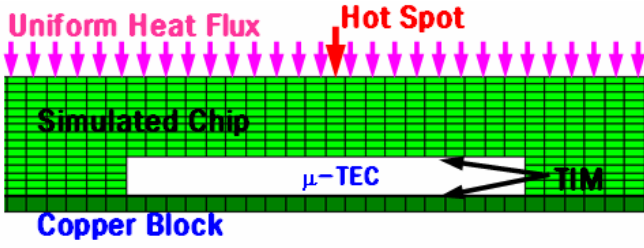
### NUMERICAL MODELING OF HOT SPOT COOLING

The numerical model of the hot spot cooling system using an imbedded a micro TEC, is shown in Figure 3. Heat from the heating block and TEC is transferred to the ambient through convection. The measured temperature and forced-convection-heat-transfer-coefficient are given as boundary conditions for the upper and lower part of the model respectively. Natural convection boundary condition is applied to the side wall of the model.

Hot spot heating is simulated by applying heat flow to a center node and the thermal contact resistances between the chip and TEC interface are included in the effective thermal conductivity of the TEC material and the thickness of the TIM as given in Table 1.

**Table 1** Specifications of experimental set-up

	Geometry (L x W x H) (unit : mm)	Material or Model	Thermal conductivity (W/m-K)
Chip	40 x 40 x 3.0	Acrylic	0.2
TEC	8 x 9.6 x 0.8	1MC04-060-02	0.35
Back Plate	40 x 40 x 2.0	Cu	380
TIM	0.1	HC-300	0.84
Hot Spot	0.6 (diameter)	CO <sub>2</sub>	-



**Figure 3** Numerical model of hot spot cooling system

The following general equations built in the TAS software are used to calculate the performance of the micro TEC.

$$Q_h = 2N[SIT_c + ((I^2r)/(2G))] \quad (1)$$

$$V = 2N[(((Ir)/G) + (S\Delta T))] \quad (2)$$

$$i_{\max} = (kG/S)[(1 + (2ZT_h))^{0.5} - 1] \quad (3)$$

Where,

$i_{\max}$  Maximum current

$T_h$  Hot side temperature

$T_c$  Cold side temperature

$\Delta T$   $T_h - T_c$

$G$  Area/length of TE element

$N$  Number of TE pairs

$I$  Current

$S$  Seebeck Coefficient

$r$  Electrical resistivity

$k$  Thermal conductivity

$Z$  Thermoelectric figure-of-merit of material

The detail specifications and thermoelectric properties of the micro TEC obtained from the previous research [8] and the company [9] are shown in Table 2. As explained in the previous section, the thermal properties of the TEC material and thickness of TIM are determined by trial and error method, which shows the best agreement between calculated and experimental results of no hot spot and not working TEC case.

The thermoelectric properties such as Seebeck coefficient, electrical resistivity and thermal conductivity of the micro TE column can be expressed by the polynomial function of temperature. About 130,000 nodes are created for the entire system and 0.02 ~ 0.2 mm space resolution can be obtained.

## RESULTS AND DISCUSSIONS

### Experimental results

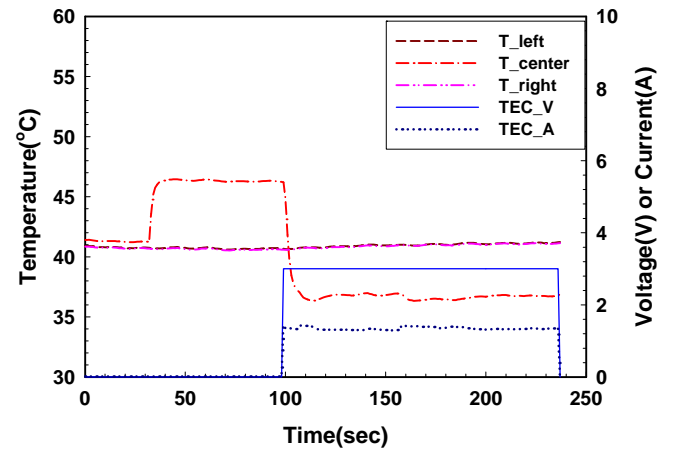
Figure 4 shows the temperature variations of the chip when the temperature of the heating block is maintained at 50 °C and the variations of applied power, voltage and ampere, to the TEC are also shown. In this case, 3% of average laser output is

applied to the hot spot area, which means about 106 W/cm<sup>2</sup> heat flux.

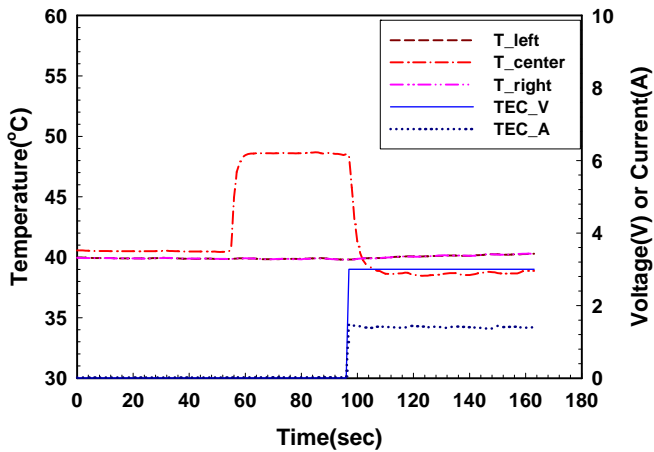
The hot spot's temperature is abruptly increased due to spot heating and decreased as the TEC is operated. Meanwhile, the temperatures at the outside of the TEC are not affected and changed because the acrylic plate has very low thermal conductivity. This result shows that the phenomena of hot spot heating and cooling only occur at the location of the TEC. As 3% of laser average output is applied to the hot spot, about 4.5 °C temperature rise is obtained and about 9.5 °C temperature drop occurred as 3 voltages of DC power is applied to the TEC. This large temperature drop means that the temperature of the hot spot point can be maintained lower than the temperature of other parts of the chip even though locally high heat flux existed. For the cases of increased laser power with the same supplied voltage to the TEC, is shown in Figure 5 and Figure 6. As laser power is increased, the temperature of the hot spot is increased. About 6 °C and 11 °C temperature rise is shown in Figure 5 and Figure 6, respectively. But almost the same temperature drop is obtained for each case because same power is applied to the TEC. Figure 6 shows that the hot spot temperature cannot be maintained under the temperature of other areas of the chip due to very high heat flux and indicates that more power to the TEC is required.

**Table 2** Specifications or properties of micro TEC

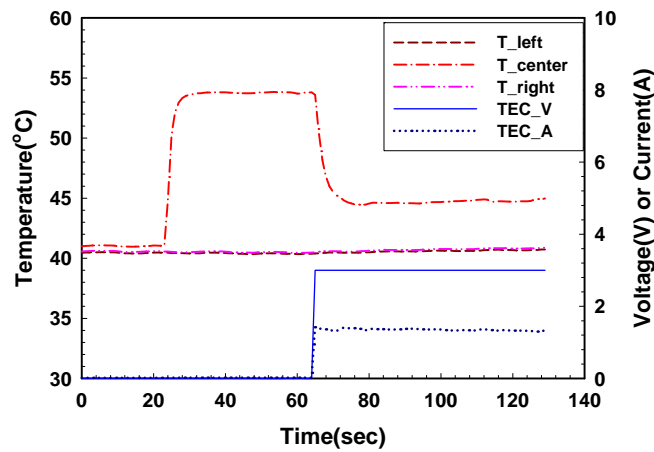
Specifications or Properties	Unit	Values
$S$	V/K	$170 \times 10^{-6}$
$r$	$\Omega$ -m	$1.04 \times 10^{-5}$
$k$	W/ m-K	1.5
$G$	m	$3.8 \times 10^{-3}$
Substrate thickness	mm	0.3
Area	mm <sup>2</sup>	100
Number of pairs	-	60



**Figure 4** Variations of temperature, voltage and current with time (laser power 3%)



**Figure 5** Variations of temperature, voltage and current with time (laser power 4%)

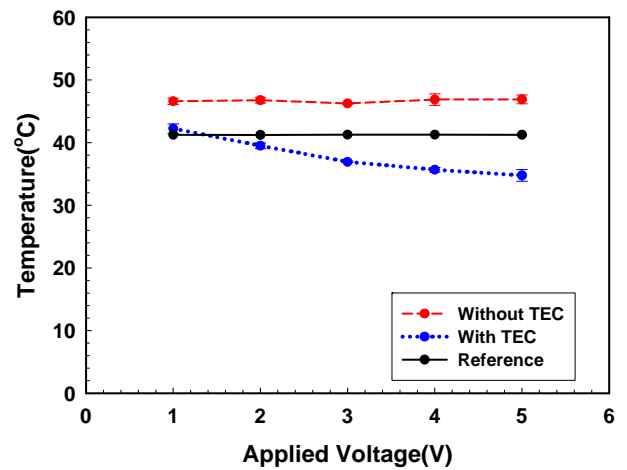


**Figure 6** Variations of temperature, voltage and current with time (laser power 5%)

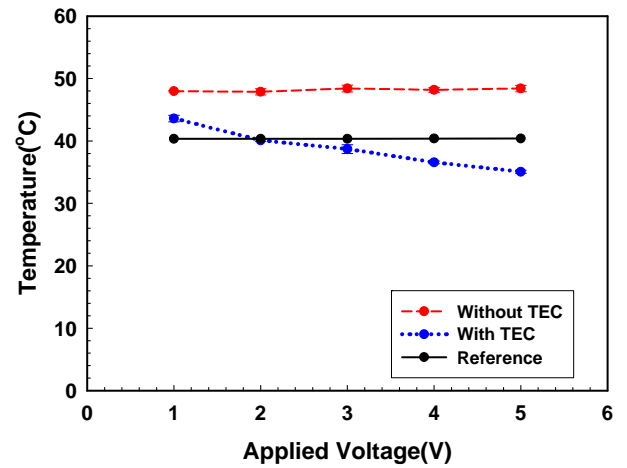
Figure 7 through Figure 9 shows the temperature drop in the hot spot for all ranges of applied laser power and TEC voltage. In the Figures, the reference means the temperature of the chip without hotspot heating and TEC cooling. And three measurement results are expressed as error bar with a symbol. In case of low heat flux, the hotspot temperature can be lower than the reference throughout all ranges of TEC voltage applied as shown in Figure 7 and Figure 8. But in case of high heat flux, relatively high voltage of the TEC is required to maintain the temperature of the hot spot.

### Comparison of experimental and numerical results

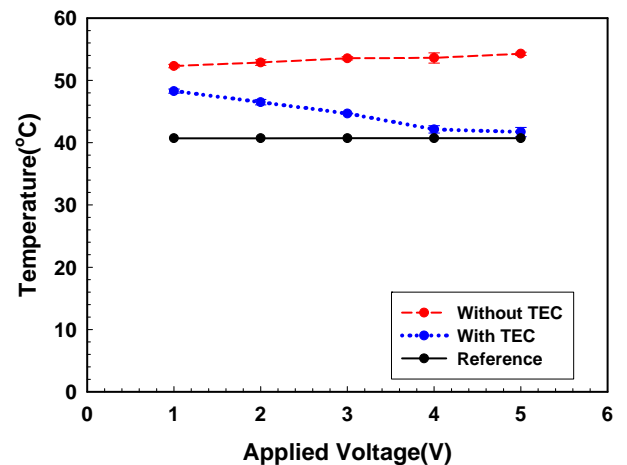
Comparison of temperature drop obtained from experiment and numerical analysis is conducted and the results are shown in Figures 10 through Figures 12. Good agreements are obtained between numerical and experimental results throughout the applied voltage range except for a low voltage range. Therefore thickness of the TIM, including contact thermal resistance effects in Table 1 and thermal conductivity of the TEC in Table 2, are well assumed.



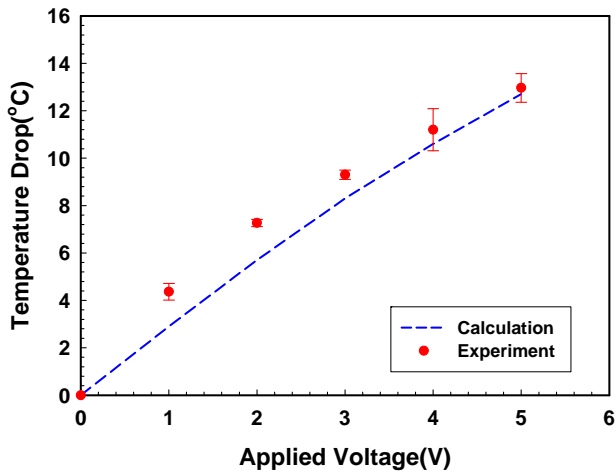
**Figure 7** Temperature drop in the hot spot point according to TEC voltage (laser power 3%)



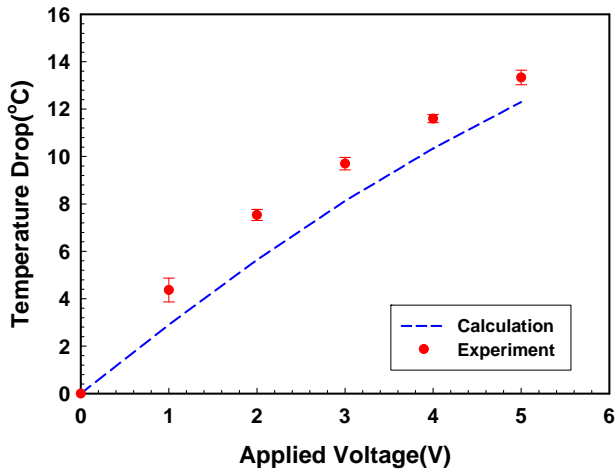
**Figure 8** Temperature drop in the hot spot point according to TEC voltage (laser power 4%)



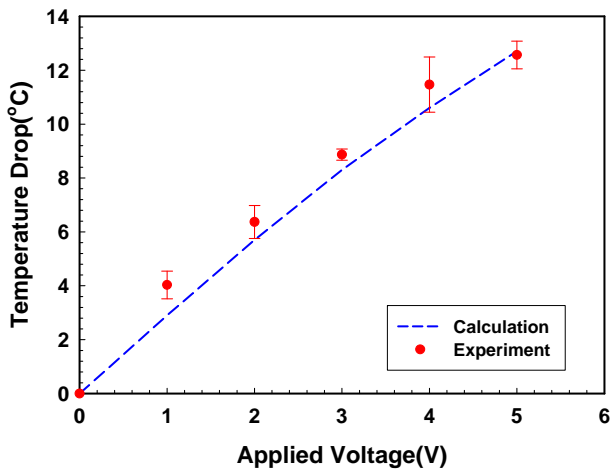
**Figure 9** Temperature drop in the hot spot point according to TEC voltage (laser power 5%)



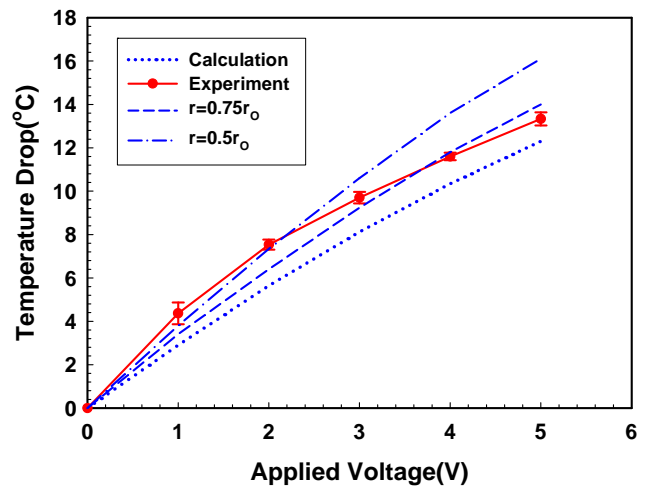
**Figure 10** Comparison of temperature drop in the hot spot according to TEC voltage (laser power 3%)



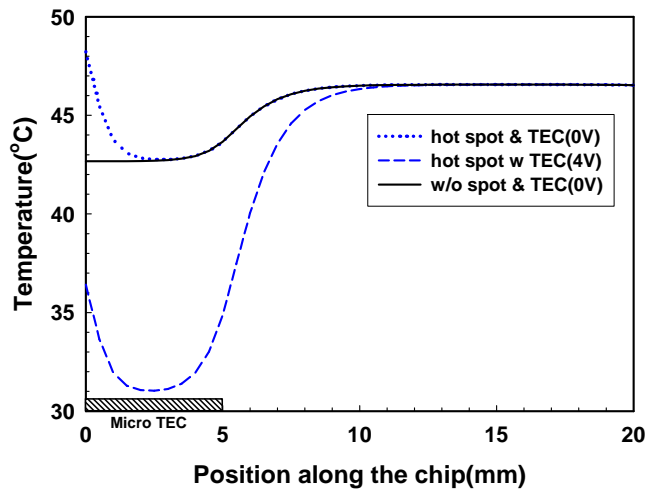
**Figure 11** Comparison of temperature drop in the hot spot according to TEC voltage (laser power 4%)



**Figure 12** Comparison of temperature drop in the hot spot according to TEC voltage (laser power 5%)



**Figure 13** Comparison of temperature drop in the hot spot according to applied TEC voltage with variation of electrical resistivity (laser power 4%)



**Figure 14** Comparison of temperature profiles along the chip (laser power 4%)

This results shows that thermo-physical properties, such as contact thermal resistance and thickness of liquid TIM, which measurement is difficult, can be estimated by numerical analysis.

To improve the estimation accuracy in low voltage range, temperature drop in the hot spot is calculated according to the variations of thermoelectric properties of the TEC. Because the values of thermoelectric properties shown in Table 2 are adapted on the bases of the thin film form of the thermoelectric leg, which these properties can be enhanced if the bulk thermoelectric leg is used, as shown in the literature [13]. Among the properties, variation of electric resistivity can bring the best agreements between calculation and experiment results as shown Figure 13. In the Figure,  $r_0$  means the original electric resistivity of Table 2 and  $0.75r_0$  and  $0.5r_0$  indicate 25% and 50% reduction of resistivity, respectively. But there are still

differences between two results in the low voltage range, which mean that an exact estimation of thermal contact resistance and thermoelectric properties is difficult and limited.

Finally, the temperature profiles along the chip are compared in Figure 14. Due to symmetry, only half of the chip is shown in the Figure. Very sharp temperature rise is anticipated in the hot spot but the active cooling by the micro TEC occurred at the entire area of TEC. These are due to the low conductivity of the TEC substrates which can't effectively spread the heat horizontally. Therefore, a smaller sized TEC with the substrate made by high conductivity material is necessary to the sharp peak temperature reduction.

## CONCLUSION

The experimental and numerical study is carried out to investigate the availability of micro TEC for hot spot cooling of an IC chip. It is found that an acrylic plate integrating with a copper plate and imbedded micro TEC represents good hot spot cooling of the IC chip when a CO<sub>2</sub> laser is used for hot spot heating. Effective active local cooling phenomena by the TEC are well investigated by this experiment. The measured temperature drop in the hot spot is compared to numerical results using the TAS program in every case. Numerical results show a good agreement with the experiment using some appropriate thermal and thermoelectric properties of TEC and TIM obtained by trial and error. Measurement of thermo-physical properties such as contact thermal resistance and thickness of liquid TIM is difficult but can be estimated by numerical analysis.

## ACKNOWLEDGMENTS

This research is implemented as a part of the project "Technology Development of Advanced Cooling System" managed by Korea Research Council for Industrial Science & Technology. The authors gratefully appreciate the support.

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