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LOW TEMPERATURE TEHRMOELECTRIC COOLERS FOR INFRARED DETECTORS

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Low temperature thermoelectric coolers for infrared detectors

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ABSTRACT

The solid state reliability and convenience of thermoelectric coolers make them an attractive solution to cooling detectors. We present evidence that the temperature difference of thermoelectric Bi_2Te_3 coolers can be increased by optimizing the device parameters. Computer modeling of multistage coolers was used to analyze the parametric effects on their performance. Experimental coolers were constructed on the basis of modeling results and tradeoffs between performance and size. A heat treatment was applied to the Bi_2Te_3 elements, reducing their resistivity to about 25% of that of untreated elements. The performance of radiation shielded coolers in vacuum was investigated, with the heat sink temperature maintained at 293 K. Without field enhancement, the temperature difference measured for a six-stage cooler was 137 K in presence of a thermal load of 10 mW. To compensate for the increase of the stage dimensions in seven-stage coolers, the thermal resistance of the stage surface was reduced by means of solder coating. For the best seven-stage device, a difference of 166 K could be achieved for a thermal load of 20 mW. For the parameter values used in the experiment, the cooldown time was typically 500 sec regardless of the supplied voltage. The measured ratio of temperatures of adjacent stages varied negligibly, indicating that the coefficient of performance of the studied cooler is close to the optimum value. The good agreement found between experimental and computer modeling data suggests that the developed model may be suited for further performance prediction.

Key words: thermoelectric cooler, BiTe, infrared detector

1. INTRODUCTION

The detection range and spectral coverage of many classes of infrared detectors increase with decreasing operating temperature. The solid state reliability and convenience of thermoelectric coolers, not pertaining to mechanical coolers, make them an attractive solution to cooling detectors. At low temperatures the coefficient of performance of thermoelectric coolers is low but adequate for cooling of small thermal loads, such as infrared detectors.[1, 2] These coolers are also used where other issues are more important than efficiency. For instance, their use allows for operations in high-*g* levels in any orientation or for a high resistance to shock and vibration. In addition, they are maintenance free and inexpensive.[3] A limitation of thermoelectric coolers is that their ultimate temperature is rather high. The purpose of this work is to develop devices intended for operation at temperatures below 160 K.

Considerable effort has been devoted to achieving low temperatures in thermoelectric coolers. One approach consists in raising the figure of merit (Z) of thermoelectric materials. Thermoelectric coolers are usually composed of pairs of Bi_2Te_3 blocks. One of the block in each pair is made of a heavily doped *n*-type material and the other block a heavily doped *p*-type material. Although Bi_2Te_3 alloys are available and inexpensive, their Z value decreases rapidly at low temperatures.[4] Smith and Wolfe investigated the thermoelectric properties of semimetal and semiconductor alloys of BiSb.[5] At temperatures below 220 K, it was shown that *n*-type $Bi_{95}Sb_5$ alloys have a Z value larger than that of Bi_2Te_3. Despite the lack of a matching *p*-type material, computation results suggested that the low temperature performance of a pair of *n*-type $Bi_{95}Sb_5$ and *p*-type Bi_2Te_3 blocks exceeds that of a pair of Bi_2Te_3 blocks. The figure of merit of BiSb could further be enhanced by means of Sn doping [6] or application of a magnetic field [7]. The other approach focuses on mini-

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mizing irreversible effects that impede the coefficient of performance of the cooler. For example, the amount of convective heat transferred to the cooler could be reduced by means of vacuum insulation. As an alternative, the use of a gas filled (Freon and Xenon) dewar as a replacement of the vacuum dewar was proposed by Angebault *et al.*[3] Jeong and Smith studied the temperature staging that results in minimum entropy generation in a multistage cooling cycle. These authors showed that, at low temperatures, a multistage cooler with equal temperature ratio for adjacent stages has a larger coefficient of performance as compared with a cooler having equal temperature difference for adjacent stages.[8]

In this work the theoretical design of multistage Bi_2Te_3 coolers was performed by means of computer modeling. Experimental coolers of up to seven stages were constructed on the basis of modeling results and tradeoff between performance and size. During the construction of these coolers we investigated means to reduce their excess thermal load. A heat treatment was applied to the Bi_2Te_3 elements to reduce their resistivity and hence, the inherent joule heating. The inner walls of the housing were coated with a thin Au film in order to reduce the amount of radiative heat from the walls. The thermal resistance of the surface of each stage was further reduced by means of solder coating. In the following we present the method and results of the computer modeling and performance characteristics of the constructed coolers.

2. MODELING METHOD AND RESULTS

The computer modeling of the multistage cooler was developed as a performance prediction tool for a given device configuration. In this section we report on the modeling method and results.

A mathematical model was first introduced for a two element thermoelectric cooler. This model served as the basis of the computation for the multistage coolers. Figure 1 shows the schematic of a two element cooler. To reduce the length of the computing time the following simplifying assumptions were made. The heat flow and electric current flow are one dimensional function of the position, x. The p- and n-type elements have equal cross sectional areas ($A_p = A_n$), resistivities ($\rho_p = \rho_n$), and junction temperatures (at $x = 0$ and $x = L$). The temperatures T_p and T_n of the elements are function of position x and time t.

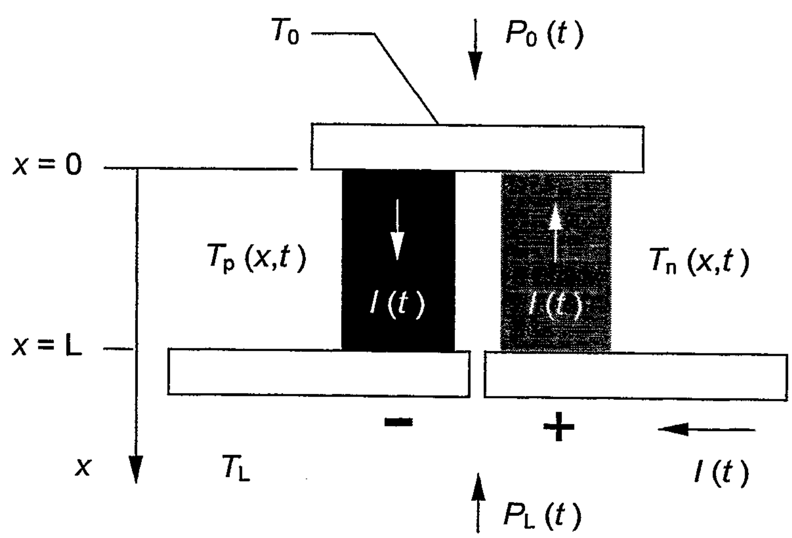

FIG. 1. Schematic of a basic two element thermoelectric cooler. The parameters used in the mathematical model for the cooler are shown.

The thermal equilibrium of a thermoelectric material under an applied electric current I can be expressed as:

$$\nabla.(k\,\nabla T) - T\,(J.\,\nabla \alpha) = -\rho\,J^2, \tag{2.1}$$

where k is the thermal conductivity, α is the Seebeck coefficient, and $J = I / A$ is the current density. According to the postulated one dimensional dependence, equation (2.1) is as follows for the p-type and n-type elements:

$$(\partial / \partial x)\,[k_p\,A_p\,(\partial T_p / \partial x)] + \tau_p\,I\,(t)\,(\partial T_p / \partial x) = -\rho_p\,I^2\,(t) / A_p, \tag{2.2}$$

$$(\partial / \partial x)\,[k_n\,A_n\,(\partial T_n / \partial x)] + \tau_n\,I\,(t)\,(\partial T_n / \partial x) = -\rho_n\,I^2\,(t) / A_n, \tag{2.3}$$

where $\tau = T\,(\partial \alpha / \partial T)$ is the Thomson coefficient. Using the available data of $\alpha\,(T)$, $\rho\,(T)$, and $k\,(T)$, the values of $T_p\,(x)$ and $T_n\,(x)$ for a given value of I could be obtained by solving the above equations. The cold end and hot end temperatures, T_0 and T_L, could then be determined using the energy balance equations:

$$P_L\,(t) + P_0\,(t) - V\,(t)\,I\,(t) = \mathrm{d}W / \mathrm{d}t, \tag{2.4}$$

where $W\,(t)$ is the energy stored in the device at time t, and the input power at the device junction represents that removed by the Peltier effect and by the heat conduction:

$$P_0\,(t) = -\alpha_0\,T_0\,(t)\,I\,(t) - k_p\,A_p\,(\partial T_p / \partial x)\,|_{x=0} - k_n\,A_n\,(\partial T_n / \partial x)\,|_{x=0}, \tag{2.5}$$

$$P_L\,(t) = -\alpha_L\,T_L\,(t)\,I\,(t) - k_p\,A_p\,(\partial T_p / \partial x)\,|_{x=L} - k_n\,A_n\,(\partial T_n / \partial x)\,|_{x=L}. \tag{2.6}$$

The above mathematical model was extended further for the computation of the parameters of the multistage cooler. Figure 2 shows the schematic of a multistage cooler used for the computation. Only three stages are shown for simplicity. N_i and Q_{ci} are respectively the number of element pairs and the thermal load

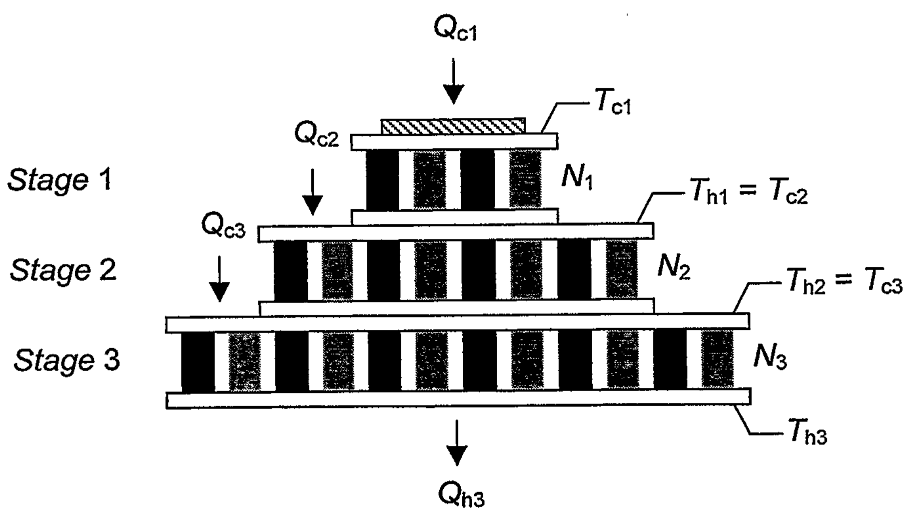

FIG. 2. Schematic of a multistage thermoelectric cooler. Only three stages are shown for simplicity. The parameters used in the computer modeling are shown.

for stage i, where $i = 1, 2, 3$. Q_{c1} is the pumping power of the device and is assumed to be constant. The sum of the thermal load and joule heat for a given stage i yields the thermal load for the stage $i+1$. The sum of the thermal load and joule heat for the final stage yields the thermal output Q_{h3}, also representing the dissipation to be removed by the heat sink. The hot end temperature, T_{h3}, is assumed to be constant.

The details of the computation were reported elsewhere.[9] Briefly, a cold end temperature T_{c1} was first assumed for a given value of current I. Using these inputs and thermal load Q_{c1}, the hot end temperature T_{h1} and the joule heat were computed for the first stage. The thermal load for the second stage, Q_{c2}, could be obtained by adding the joule heat to Q_{c1}. The cold end temperature for the second stage, T_{c2}, was set equal to T_{h1}, and the hot end temperature T_{h2} and the joule heat were computed for this stage. This process was repeated until a computed hot end temperature, T_{h3}, was obtained for the final stage. If T_{h3} was larger than a fixed heat sink temperature, a new value of T_{c1} (larger than the one previously used) would be assumed. The computation was repeated until T_{h3} is equal to the fixed heat sink temperature.

The computer modeling was used to determine the effect of different parameters of the cooler on its performance. In particular, we examined the effect of different sets of N_i for each stage. To keep the cooler size reasonably small, a limited range of N_i values was used and the number of stages was limited to $i \leq 7$.

An illustration of the modeling results is shown in Fig. 3. In this figure plots of T_{c1} are displayed against I for three different seven-stage coolers. The sets of N_i selected for the composition of the coolers were: {8, 12, 18, 25, 32, 72, 128}, {8, 16, 32, 72, 128, 257, 512}, and {8, 32, 64, 144, 384, 771, 2048}. The thermal load and heat sink temperature of all coolers were set to be 20 mW and 300 K respectively. The three plots exhibit a common feature. When I was increased the heat pumping rate rose, resulting in a decrease of the value of T_{c1}. However, because the amount of joule heat also rose with increasing I, T_{c1} started to increase when I was increased beyond a threshold value. The results obtained showed that lower values of T_{c1}

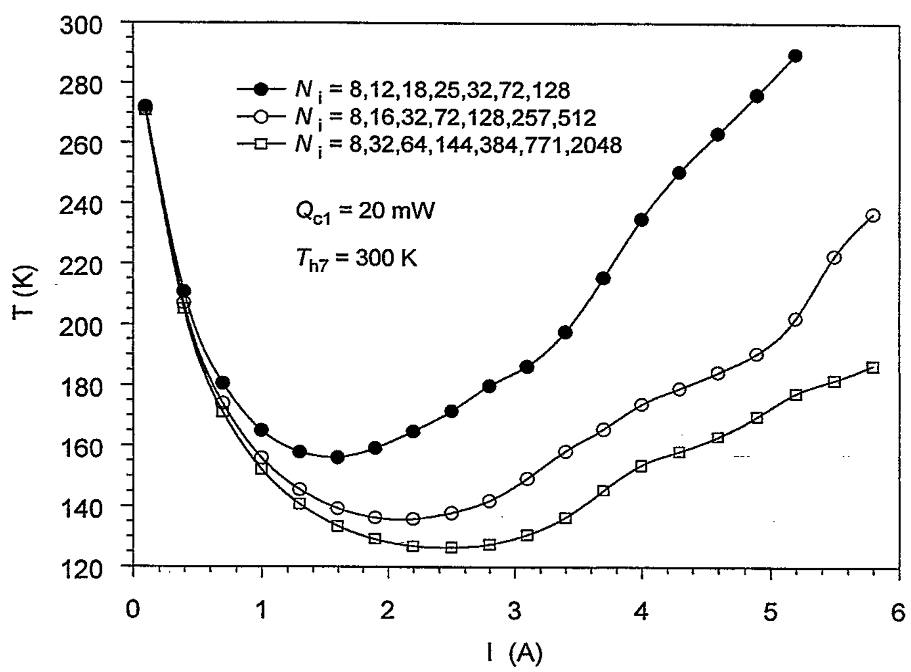

FIG. 3 - Computed cold end temperatures of three different seven-stage coolers as a function of supplied current. The thermal load was assumed to be 20 mW. The solid lines are provided as visual aids.

could be reached in the cooler with a larger number of elements in the hot stages. A theoretical ultimate temperature lower than 140 K could be achieved in the two larger coolers. However, despite an important difference in size of the two coolers (N_7 = 512 versus 2048), their ultimate temperatures do not differ significantly. It was further seen that the larger the cooler size, the higher the current level needed to achieve the ultimate temperature. Hence, in this illustration the cooler with N_7 = 512 appears to be a better candidate for systems with constraints in size, weight, and power consumption.

3. PERFORMANCE CHARACTERISTICS

We have constructed different experimental coolers on the basis of modeling results and tradeoff between performance and size. In this section the details and performance characteristics of a six-stage cooler and a seven-stage cooler are presented and discussed.

The set of numbers of Bi_2Te_3 element pairs selected for the construction of the six-stage cooler was N_i = { 2, 8, 18, 32, 72, 128}. The parameter values for these elements are shown in Table I. The Bi_2Te_3 elements were heat treated at 350 °C for more than 48 hours in Ar. The resistivity of the heat treated elements was measured using the four probe technique and is shown as a function of temperature in Fig. 4. The resistivity of the treated elements was found to decrease to ~ 25 % of the resistivity of the untreated elements. The cooler was thermally anchored to the base of a vacuum housing unit with optical access via a quartz window. A photograph of this cooler is shown in Fig. 5. The inner walls of the unit were coated with an Au film to reduce the amount of radiation heat from the walls. The thickness of the Au film was ~ 0.2 µm. The feedthroughs for electrical connection and an evacuation outlet were included in the base of the unit. Prior to the temperature measurement, the unit was evacuated until a base pressure of 5 x 10^{-7} Torr was reached. It was subsequently vacuum sealed and attached to an Al heat sink.

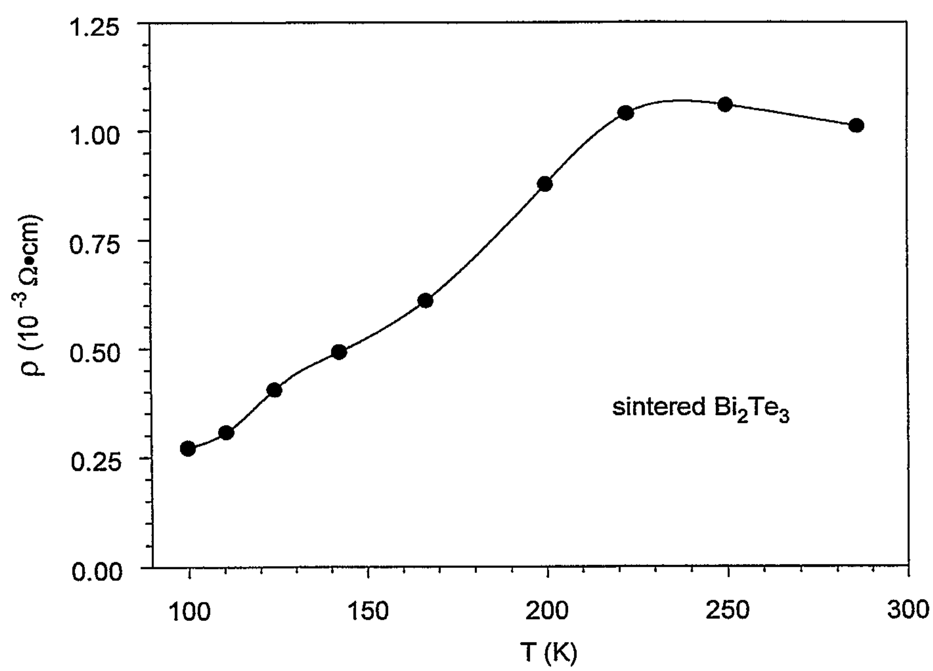

FIG. 4. Temperature dependence of electrical resistivity of a heat treated Bi_2Te_3 element.

TABLE I. Parameters for the Bi_2Te_3 elements used in the construction of multistage coolers

Parameter	Symbol	Value
Length	L	2.3 mm
Cross-sectional area	A_p, A_n	1.3 x 1.3 mm^2
Thermal conductivity	k_p, k_n	3.2 W / m.K (T = 300 K)
Seebeck coefficient	α_p	280 μV/K
	α_n	-300 μV/K (T = 300 K)

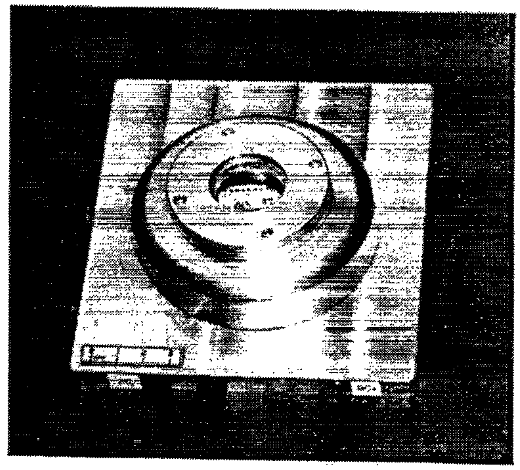

FIG. 5. A six-stage thermoelectric cooler.

The measurement of the stage temperature was performed using a type-J thermocouple attached to the platform of the stage. The electrical leads of the thermocouple were thermally adhered to the successive stages to reduce the amount of conduction heat. A Ni-Cr film resistor was used to simulate a thermal load of ~ 10 mW at the first stage. During the measurement, the temperature of the heat sink was maintained at ~ 293 K. Figure 6*a* shows the temporal characteristics of temperature obtained for different stages when a voltage of 14 V was supplied to the cooler. The temperatures stabilized after a period of ~ 500 sec from the initial cooldown. In Table II the temperatures measured at various stages are compared with those predicted by the modeling. It can be seen that, except for the first stage, the discrepancy between these data is relatively

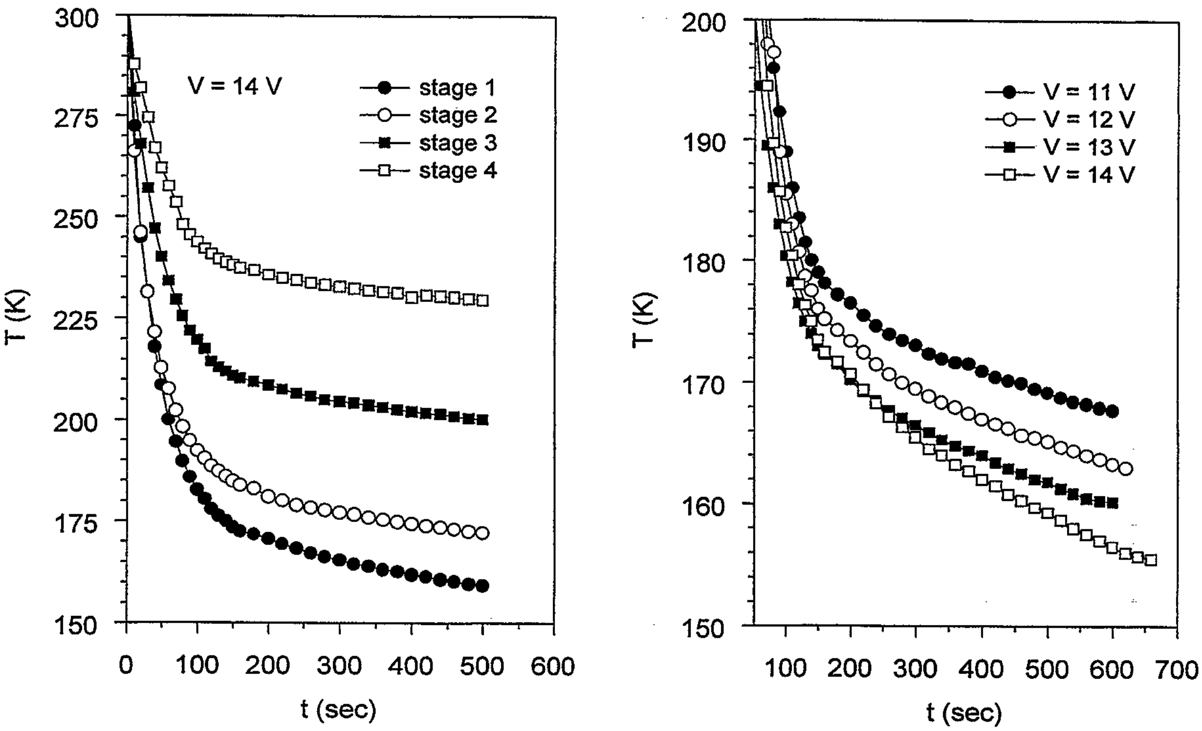

FIG. 6. Temporal characteristics of temperature for an experimental six-stage cooler: (*a*) measured at stages 1 to 4 for V = 14 V ; and (*b*) measured at stage 1 for different supplied voltages. The thermal load used is 10 mW. The temperature of the heat sink is 293 K. The pressure of the vacuum housing is ~ 10^{-6} Torr.

TABLE II. Computed and measured temperatures of different stages for a six-stage cooler and for a seven-stage cooler.

	six-stage cooler			seven-stage cooler		
i	computed T_i	measured T_i	measured T_{i+1}/T_i	computed T_i	measured T_i	measured T_{i+1}/T_i
1	142.9	156	1.10	134.9	127	1.13
2	165.2	172	1.17	152.5	143.8	1.14
3	193.1	201	1.13	169.2	163.6	1.11
4	218.8	228		187.1	181.1	1.13
5				209.8	204.7	

small (~ 4%). The ratio of the temperatures of adjacent stages, T_{i+1} / T_i, varies only negligibly, suggesting that the coefficient of performance of the studied cooler is close to the optimum value.[8] The effect of the supplied voltage on the ultimate temperature is depicted in Fig. 6*b*. When V was increased from 11 to 14 V, the temperature of the first stage decreased to the lowest value, 156 K. The ultimate temperature rose when V was increased further. The effect of supplied voltage on the cooldown time appears to be negligible.

The seven-stage cooler was designed and constructed on the basis of the computed results shown in Fig. 3. The selected numbers of element pairs were N_i = {8, 16, 32, 72, 128, 257, 512}. This combination can yield a theoretical ultimate temperature of less than 140 K. However, because of the large dimensions of the stages, the thermal resistance along the stage surface was large. To compensate for this effect, surfaces of

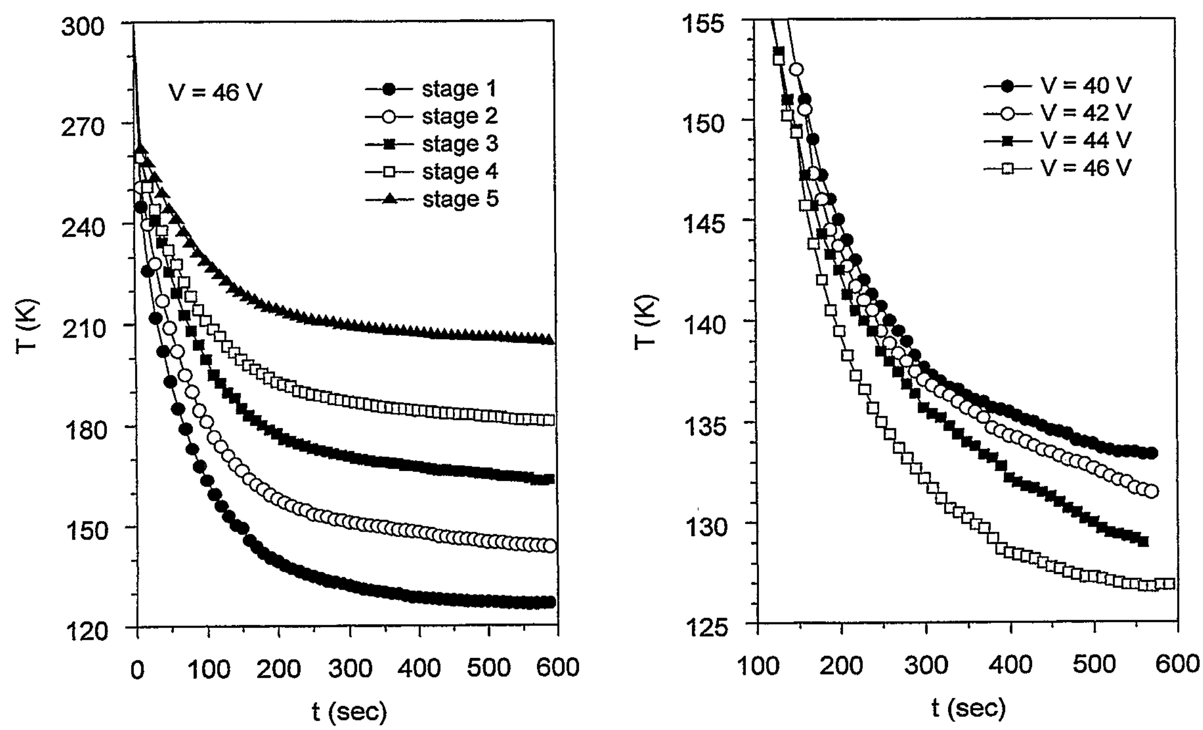

FIG. 7. Temporal characteristics of temperature for an experimental seven-stage cooler: (*a*) measured at stages 1 to 5 for V = 46 V; and (*b*) measured at stage 1 for different supplied voltages. The thermal load used is 20 mW. The temperature of the heat sink is 293 K. The pressure of the vacuum housing is ~ 10^{-6} Torr.

the various stages were coated with a layer of good thermal conductor. A thermal load of 20 mW was used during the temperature measurement. The other details of the seven-stage cooler are similar to those of the six-stage cooler.

Figure 7*a* displays the temporal characteristics of temperature measured at various stages when a voltage of 46 V was supplied to the cooler. The temperatures stabilized after a period of ~ 600 sec from the initial cooldown. The values of experimental and computed temperatures for various stages are shown in Table II. It is seen that the discrepancy between these data varies only from 2.5 % to 6 %. Again, the ratio of temperatures of adjacent stages varies negligibly, suggesting a nearly optimum coefficient of performance. The effect of the supplied voltage on the ultimate temperature is shown in Fig. 6*b*. When *V* was increased from 40 to 46 V, the temperature of the first stage decreased to the lowest value, 127 K. As for the six-stage cooler, the effect of supplied voltage on the cooldown time of the seven-stage cooler is negligible.

4. CONCLUSIONS

It was shown that large temperature differences can be achieved in thermoelectric Bi_2Te_3 coolers by optimizing the device parameters and reducing the excess thermal load of the device. The theoretical design of multistage coolers was performed by means of computer modeling. Experimental coolers were constructed on the basis of modeling results and tradeoffs between performance and size. A heat treatment was applied to the Bi_2Te_3 elements, reducing their resistivity to about 25% of that of untreated elements. The inner walls of the housing of the cooler were coated with an Au film to reduce the amount of radiation heat from the walls. The temperature difference measured for a six-stage cooler was 137 K in presence of a thermal load of 10 mW. To compensate for the increase of the stage dimensions in the seven-stage coolers, the thermal resistance of the stage surface was reduced by means of solder coating. For the best seven-stage device, a difference of 166 K could be achieved for a thermal load of 20 mW. For the parameter values used in the experiment, the cooldown time was typically 500 sec regardless of the supplied voltage. The measured ratio of temperatures of adjacent stages varied negligibly, indicating that the coefficient of performance of the studied cooler is close to the optimum value. The good agreement found between experimental and computer modeling data suggests that the developed model may be suited for further performance prediction.

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