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Micro-coolers fabricated as a component in an integrated circuit

James Glover[1], **Ata Khalid**[2], **Alex Stephen**[3], **Geoff Dunn**[3], **David Cumming**[2] and **Chris H Oxley**[1]

[1] Electronic Engineering Department, Faculty of Technology, De Montfort University, Leicester, LE1 9BH, UK
[2] School of Engineering, University of Glasgow, Glasgow, G12 8LT, UK
[3] School of Engineering and Physical Sciences, University of Aberdeen, Aberdeen, AB24 SFX, UK

E-mail: choxley@dmu.ac.uk

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Abstract
The packing density and power capacity of integrated electronics is increasing resulting in higher thermal flux densities. Improved thermal management techniques are required and one approach is to include thermoelectric coolers as part of the integrated circuit. An analysis will be described showing that the supporting substrate will have a large influence on the cooling capacity of the thermoelectric cooler. In particular, for materials with a low ZT figure of merit (for example gallium arsenide (GaAs) based compounds) the substrate will have to be substantially thinned to obtain cooling, which may preclude the use of thermoelectric coolers, for example, as part of a GaAs based integrated circuit. Further, using experimental techniques to measure only the small positive cooling temperature difference (ΔT) between the anode (T_h) and the cathode (T_c) contacts can be misinterpreted as cooling when in fact it is heating.

Keywords: micro-cooler, superlattice, thermionic, GaAs, AlGaAs, III–V semiconductors

Introduction

Current trends in many areas of III–V based electronics are (i) reduced chip area with more functionality and (ii) increased device RF output power per unit area. Both will result in higher thermal flux densities requiring improvements in thermal management.

It is well established that improvements in chip performance and reliability can be obtained if the generated heat can be efficiently removed. A possible solution for very small area devices where heat flux density can be high is the use of thermoelectric cooling. This has been explored particularly with reference to laser diodes where heat flux densities can be several kW cm^{-2} in the active region giving rise to increases in junction temperature leading to a wavelength shift, reduced power, and reliability [1]. In most examples the micro-cooler has been fabricated from materials with a high figure of merit ZT $= \frac{S^2 \sigma T}{k}$ (S is the Seebeck coefficient, σ is the electrical conductivity, T is the absolute temperature, and k the thermal conductivity) and the device is epoxy attached to the micro-cooler. A more elegant solution would be to manufacture the device with an integrated micro-cooler. Unfortunately and particularly for devices fabricated using III–V based materials (for example gallium arsenide (GaAs) and indium phosphide (InP)) the ZT figure of merit is poor giving rise to low cooling performance [2]. For example, experimental work published by Zhang [3] on an AlGaAs/GaAs cooler has indicated a cooled contact temperature of 0.8 °C below the hot contact temperature, at an ambient temperature of 25 °C. This was obtained for an ideal experimental set-up where the hot contact was bonded to the metal heat-sink of the cooler. In an integrated circuit solution the cooler and chip will both be fabricated on a semi-insulating substrate and therefore the hot contact is no-longer in direct contact with the metal heat-sink. Further, most published analysis data on the micro-cooler assumes that ohmic heating only occurs at the top contact and there is no ohmic heating at the bottom contact as it is part of the ideal heat-sink. This paper considers an extension of the

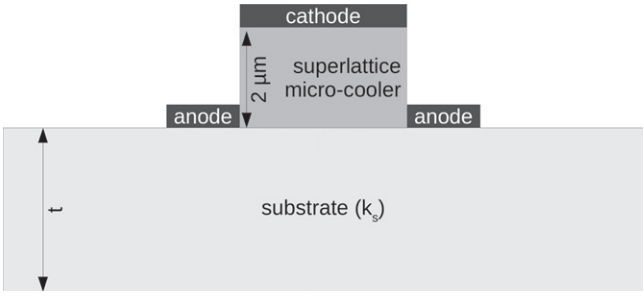

Figure 1. Schematic of micro-cooler on a semi-insulating substrate.

simple model to include the effect of the substrate and ohmic bottom contact heating and therefore is more representative of an integrated micro-cooler.

Analysis

To analyse the above integrated cooler it was assumed the cooled cathode contact was separated from the hot anode contact by a super-lattice with negligible electrical resistance and a thermal resistance of θ_c. The structure was fabricated on an electrically insulating substrate with a thermal resistance of θ_s and thickness t. Figure 1 shows a schematic diagram of the integrated cooler.

The analysis also included top (cathode) and bottom (anode) ohmic contact resistances of R_t and R_b respectively; the Seebeck coefficient for the structure was assumed to be S. A potential V was applied between the anode and cathode contacts giving rise to an electron current I, flowing from the cathode to the anode transporting heat from the cold cathode T_c to the hot anode T_h contact. The power P_c being delivered to the micro-cooler was IV watts.

The equations describing the micro-cooler are given below:

$$\Delta T = T_h - T_c, \tag{1}$$

$$\Delta T = \theta_c\left(S\ I\ T_c - I^2 R_t\right), \tag{2}$$

$$P_c = S\ I\ T_c + I^2\left(R_t + R_b\right), \tag{3}$$

$$T_h = T_a + P_c\theta_s. \tag{4}$$

Manipulating equations (1)–(4) the temperature difference, ΔT, was found to be a function of I, S, θ_c, θ_s, R_t, R_b, and T_a, where T_a is the ambient temperature.

$$\Delta T = \frac{\theta_c\ S\ I\ T_a + \theta_c I^2 R_t\left[\theta_s S\ I - 1\right] + \theta_c\theta_s S\ I^3 R_b}{1 + \theta_c S\ I - \theta_c\theta_s S^2 I^2}. \tag{5}$$

The Seebeck coefficient, S, in particular for III–V compounds is relatively small and therefore in a normal operating range of currents it was assumed that $\theta_c\theta_s S^2 I^2$ tends to zero and expression (5) reduces to:

$$\Delta T = \frac{\theta_c\ S\ I\ T_a + \theta_c I^2 R_t\left[\theta_s\ S\ I\ - 1\right] + \theta_c\theta_s\ S\ I^3 R_b}{1 + \theta_c\ S\ I}. \tag{6}$$

For an ideal device where the micro-cooler is fabricated directly on an infinite ideal heat-sink, θ_s will tend to 0 and equation (6) reduces to $\Delta T = \frac{\theta_c\left[S\ I\ T_a - I^2 R_t\right]}{1 + \theta_c\ S\ I}$, the classic equation for cooling of the cathode contact [4], when the infinite ideal heat-sink is at an ambient temperature T_a. The equation can be re-arranged as follows:

$$\Delta T = \theta_c S\ I\left(T_a - \Delta T\right) - \theta_c I^2 R_t. \tag{7}$$

For a non-ideal device where the micro-cooler is fabricated on a heat-sink with thermal impedance (θ_s), equation (6) can be re-arranged as follows:

$$\Delta T = \frac{\theta_c\ S\ I\ T_a + \theta_c\ S\ I\left[\theta_s I^2 R_t + \theta_s I^2 R_b\right] - \theta_c I^2 R_t}{1 + \theta_c S\ I}. \tag{8}$$

$\Delta T_l = \theta_s I^2\left(R_t + R_b\right)$, can be considered the temperature rise at the top face of the substrate ($\theta_s >> \theta_c$) due to self-heating from the top and bottom contacts of the micro-cooler. Therefore, equation (8) can be re-written in a similar form to equation (7) as:

$$\Delta T = \theta_c\ S\ I\left(T_a - \Delta T + \Delta T_l\right) - \theta_c I^2 R_t. \tag{9}$$

Equation (9) predicts four ΔT regions:

(1) ΔT increases ($T_h > T_c$) cooling, $\Delta T > \Delta T_l$ and $\theta_c\ S\ I\left(T_a - \Delta T + \Delta T_l\right) > \theta_c I^2 R_t$.
(2) ΔT decreases ($T_c > T_h$) self-heating $\Delta T > \Delta T_l$ and $\theta_c I^2 R_t > \theta_c S\ I\left(T_a - \Delta T + \Delta T_l\right)$.
(3) ΔT increases ($T_h > T_c$) no cooling $\Delta T_l > \Delta T$ and $\theta_c S\ I\left(T_a - \Delta T + \Delta T_l\right) > \theta_c I^2 R_t$.
(4) ΔT decreases ($T_c > T_h$) self-heating $\Delta T_l > \Delta T$ and $\theta_c I^2 R_t > \theta_c S\ I\left(T_a - \Delta T + \Delta T_l\right)$.
Conditions (1) and (2) represent cooling of the micro-cooler.
Conditions (3) and (4) represent heating of the micro-cooler.

The third and fourth conditions in particular can occur if the cooler has been fabricated as part of an integrated circuit on a substrate with high thermal impedance. The thermal resistance, θ_s, of the substrate and the top and bottom contact resistances therefore become important parameters of the cooling capability of the micro-cooler. To obtain maximum cooling, ΔT_1 needs to be minimized requiring the supporting substrate to have low thermal impedance and the micro-cooler structure a low bottom and top contact resistance. Most microwave and optical integrated circuits will be fabricated on semi-insulating gallium arsenide (GaAs) or indium phosphide (InP) substrate and therefore to minimize the thermal resistance the substrate will require to be thinned. The topology of the integrated micro-cooler in the schematic (figure 1) will also not easily enable fabrication of a low resistance bottom contact.

The above analysis was used to investigate an integrated AlGaAs/GaAs micro-cooler with a radius of 60 μm (area 11 000 μm^2). Initially it was assumed the micro-cooler was fabricated on (i) an infinite ideal heat-sink, (ii) a 50 μm thick semi-insulating GaAs substrate inserted between the micro-

Table 1. No semi-insulating substrate (cooling).

I (A)	ΔT (°C)	ΔT_1 (°C)
0.01	0.03 (cooling)	0
0.05	0.13 (cooling)	0
0.1	0.25 (cooling)	0
0.15	0.35 (cooling)	0
0.20	0.44 (cooling)	0
0.25	0.52 (cooling)	0
0.30	0.58 (cooling)	0
0.35	0.62 (cooling)	0
0.40	0.66 (cooling)	0
0.45	0.67 (cooling)	0
0.50	0.67 (cooling)	0
0.55	0.66 (cooling)	0
0.60	0.64 (cooling)	0
0.65	0.59 (cooling)	0
0.70	0.54 (cooling)	0
0.75	0.47 (cooling)	0
0.80	0.38 (cooling)	0

cooler and an infinite ideal heat-sink, and (iii) a 600 μm thick semi-insulating GaAs substrate inserted between the micro-cooler and an infinite ideal heat-sink. Throughout the analysis, the ambient temperature of the infinite ideal heat-sink was assumed to be 80 °C.

The structure of the AlGaAs/GaAs micro-cooler consisted of a top ohmic contact layer (cathode), graded aluminium gallium arsenide (AlGaAs), 100 periods of superlattice (of total thickness of 2 μm) followed by a graded AlGaAs layer, and a bottom ohmic contact layer (anode). The superlattice acted as a thermal block by reducing phonon transport thereby preventing heat flow back towards the cooled top cathode contact. The thermal conductivity of the superlattice was assumed to be 0.06 W cm^{-1} K^{-1} [5, 6] and its electrical conductivity infinite. The Seebeck coefficient was assumed to be 270 μV K^{-1} [6], which corresponded to 50 nm layer of graded AlGaAs. The top cathode contact of the micro-cooler was ohmic with an assumed contact resistance of 0.1 Ω [6].

The analysis (i) was carried out assuming the micro-cooler was fabricated on an ideal infinite heat-sink and therefore the bottom contact resistance R_b was 0 Ω and $\theta_s = 0$ W °C^{-1}. Equation (8) was used, and for all operating currents $\Delta T > \Delta T_l$, see table 1. From the analysis cooling was taking place at the top cathode contact and the calculated ΔT showed a very similar trend to Zhang's [3] published experimental results for an AlGaAs/GaAs cooler on a metal heat-sink.

The same micro-cooler structure was analysed (ii) on a 50 μm thick GaAs semi-insulating substrate between the micro-cooler and an infinite ideal heat-sink. The thermal conductivity, k_s, of the semi-insulating GaAs was assumed to be 0.45 W cm^{-1} K^{-1} (at an ambient of 350 K) [7] giving a thermal resistance $\left(\theta_s = \frac{t}{\pi r^2 k_s}\right)$ of 96 °C W^{-1} for the substrate. It was assumed that the bottom contact resistance, R_b, was 0.1 Ω. Equation (8) was used to calculate ΔT and was compared with ΔT_1 in table 2.

Table 2. 50 μm substrate (cooling/heating).

I (A)	ΔT (°C)	ΔT_1 (°C)
0.01	0.03 (cooling)	0.0002
0.05	0.13 (cooling)	0.05
0.1	0.25 (cooling)	0.19
0.15	0.36 (heating)	0.43
0.2	0.44 (heating)	0.76
0.25	0.52 (heating)	1.2
0.3	0.58 (heating)	1.7
0.35	0.63 (heating)	2.4
0.40	0.67 (heating)	3.1
0.45	0.68 (heating)	3.9
0.50	0.69 (heating)	4.8
0.55	0.69 (heating)	5.8
0.6	0.67 (heating)	6.9
0.65	0.64 (heating)	8.1

Table 3. 600 μm sustrate (heating).

I (A)	ΔT (°C)	ΔT_1 (°C)
0.01	0.03	0.03
0.05	0.13 (heating)	0.59
0.1	0.25 (heating)	2.36
0.15	0.38 (heating)	5.31
0.20	0.46 (heating)	9.44
0.25	0.55 (heating)	14.75
0.3	0.63 (heating)	21.26
0.35	0.7 (heating)	28.96
0.4	0.77 (heating)	37.76
0.45	0.84 (heating)	47.8
0.5	0.90 (heating)	59
0.55	0.96 (heating)	71.4
0.6	1.02 (heating)	85
0.65	1.1 (heating)	101

The analysis indicated that the micro-cooler only provided cooling at very low currents where $\Delta T > \Delta T_l$, above a current of 0.15 A and although ΔT was still positive, the analysis indicated an overall heating effect.

The cooler was re-analysed (iii) on semi-insulating GaAs substrate of thickness 600 μm, the estimated thermal resistance was approximately 1200 °C W^{-1}, the bottom contact resistance was again 0.1 Ω, and the results are tabulated in table 3.

For the range of bias current supplied to the micro-cooler ΔT was a positive number, however $\Delta T_l > \Delta T$ indicating no cooling. Also ΔT increased with increasing current over the chosen range of current and showed no signs that self-heating from the cathode contact would start to dominate.

The three analysis results were plotted as figure 2, however only analysis (i) (table 1) represented consistent cooling where $T_c > T_h$; analysis (ii) (table 2) cooling only occurred for a small range of currents from 0 to 0.15 A, while analysis (iii) (table 3) no cooling occurred. It is interesting to note that in all cases ΔT was positive and small. If the above analysis was repeated but experimentally, then very accurate differential temperature, ΔT, measurements would be required

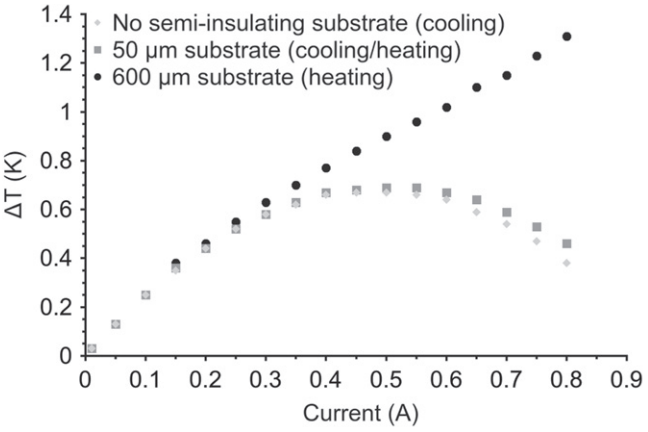

Figure 2. Micro-cooler performance as a function of substrate thickness.

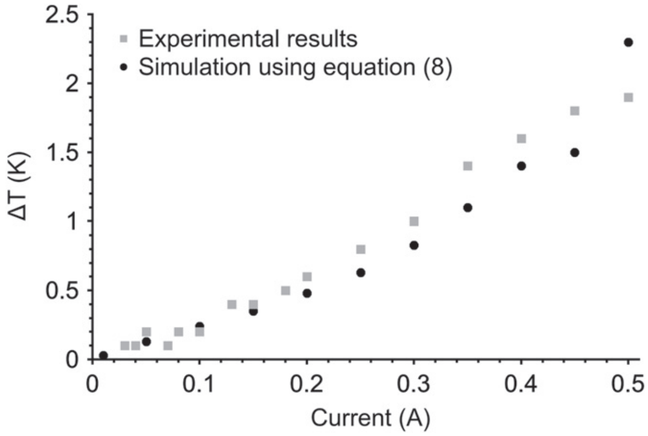

Figure 4. Comparison between experiment and equation (8).

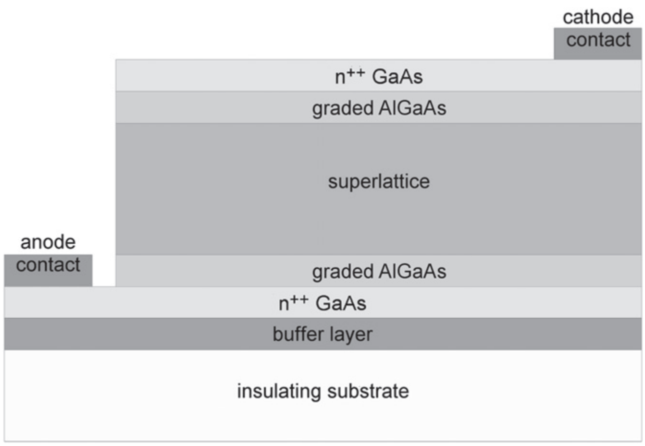

Figure 3. Layer structure of fabricated micro-coolers with anode and cathode contacts.

and the measurement of ΔT alone would not determine if cooling was taking place.

Experimental integrated AlGaAs/GaAs micro-coolers were fabricated on a 620 μm thick semi-insulating GaAs wafer, which was mounted on a Peltier heat-sink to maintain an ambient temperature of 80 °C. Micro-coolers with a diameter of 230 μm (area ~41 500 μm^2) were selected for measurement, and consisted of 300 nm n^{++} GaAs contact layer, 50 nm graded aluminium gallium arsenide (AlGaAs), 100 periods of superlattice, 10 nm $Al_{0.1}Ga_{0.9}As$/10 nm $Al_{0.2}Ga_{0.8}As$ periods, giving a total thickness of 2 μm, followed by 50 nm graded AlGaAs layer, and 300 nm n^{++} GaAs anode contact layer. The layers were grown by molecular beam epitaxy. The 50 nm graded region corresponded to a Seebeck coefficient, S, of approximately 270 $\mu V K^{-1}$ [6]. Transmission line matrix test cells were also included on the wafer to enable measurement of the contact specific resistance (~$3 \times 10^{-5}\ \Omega\ cm^2$) of the metallization layers making up the top (cathode) and bottom (anode) ohmic contacts of the micro-cooler. The measured total resistance of the micro-coolers was approximately 2 Ω and using the measured specific resistance the top contact resistance was estimated to be 0.2 Ω. For simplicity the bottom contact resistance was, therefore, assumed to be 1.8 Ω, which is consistent with the geometrical layout of the cooler as shown in figure 3.

The temperature difference $\Delta T = T_h - T_c$ between the anode and cathode contacts was expected to be small and required an accurate temperature measurement with minimum thermal loading, therefore the novel infra-red (IR) micro-sensor technology [8] was used. The IR micro-sensor is a spherical probe with a diameter of ~5 μm fabricated from a material with a high emissivity which approximates to a blackbody and the emitted radiance can be directly calibrated against temperature. The sensor ensures minimum thermal loading and the temperature measurement is independent of the surface emissivity of the contact material. Two sensors were manipulated into position on the anode and cathode contacts respectively of the micro-cooler and as they were in isothermal contact with the surface, accurate point temperature measurements were made. The field of view of the IR microscope allowed the temperature of both sensors to be measured together giving the differential temperature, $\Delta T = T_h - T_c$. The micro-particle sensors can be removed from the micro-cooler after the thermal measurements without damaging the micro-cooler.

The micro-cooler was operated at an ambient temperature of 80 °C and biased using dc micro-probes. The temperature of the micro-particle sensors on both anode (T_h) and cathode (T_c) contacts were simultaneously measured with increasing dc current. The experimental results showed that ΔT increased with current and at current of 0.35 A the apparent cooling was 1.1 °C. Using equation (8) ΔT was calculated using the measured parameters of the micro-cooler and plotted as a comparison with the measured results in figure 4. It was found that $\Delta T_l > \Delta T$ for all current values indicating that ΔT represented heating of the cathode contact. This would also explain the large values of ΔT when compared with published experimental cooling figures on similar area (14 000 μm^2) AlGaAs/GaAs micro-coolers [3] bonded to a metal heat-sink. Figure 4 also shows at low currents the ΔT values are positive and small and could be experimentally misinterpreted as cooling of the cathode electrode.

Conclusions

The simple micro-cooler analysis has been extended to include the micro-cooler fabricated on a semi-insulating substrate as would be found in an integrated circuit. The analysis indicated that the cooling ability, ΔT, of the micro-cooler was strongly influenced by the thermal resistance of the substrate, and the bottom (anode) and top (cathode) contact resistances. For integrated coolers fabricated using materials having a low figure of merit, for example III–V compounds, to obtain useful cooling the substrate will have to be substantially thinned which may preclude the micro-cooler as an integrated component on a monolithic integrated circuit. Further, if ΔT of an integrated micro-cooler is experimentally measured it may be possible to misinterpret the small changes in ΔT as cooling when in fact they are due to overall heating of the micro-cooler structure.

Acknowledgments

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