TWO STAGE MONOLITHIC THIN FILM COOLERS

Chris LaBounty, Ali Shakouri*, Patrick Abraham, and John E. Bowers

Department of Electrical and Computer Engineering
University of California - Santa Barbara
Santa Barbara, CA 93106-9560, USA
Phone: (805) 893-4235
Fax: (805) 893-7990
labounty@opto.ucsb.edu

*Jack Baskin School of Engineering
University of California - Santa Cruz
Santa Cruz, CA 95064-1077, USA

ABSTRACT

Optoelectronic devices such as vertical cavity surface emitting lasers (VCSEL's) generate large heat power densities on the order of 100's of W/cm^2. A novel device structure consisting of a two-stage monolithically integrated thin film thermionic and thermoelectric cooler is proposed to accommodate these cooling requirements. By optimizing the geometry of each stage, improved heat spreading can be achieved resulting in an increase of the cooling power density. The two-stage, three terminal structure is investigated experimentally. Cooling power densities of 100's W/cm^2 have been demonstrated in III-V semiconductor material systems proving that the integration of these coolers with optoelectronic devices should be possible.

KEY WORDS: integrated; thermionic; thermoelectric; refrigeration

NOMENCLATURE

I	current, A
Q	cooling power, W
S	Seebeck coefficient, V/K
T	temperature, K
e	electron charge, C
k	Boltzmann's constant, J/K

Greek symbols

β	heating coefficient (K/A^2)
ϕ	heterojunction barrier height (J)

Subscripts

B	barrier
SUBST	substrate
TE	thermoelectric
TI	thermionic

INTRODUCTION

Temperature stabilization and control for laser sources, switching/routing elements, and detectors in high speed and wavelength division multiplexed optical telecommunication systems is typically accomplished with thermoelectric (TE) coolers. Since optoelectronic devices are not easily integrated with TE coolers[1], the cost of packaging is high. In addition, the TE cooler usually limits the reliability and lifetime of a packaged module [2]. An alternative to conventional TE coolers is heterostructure integrated thermionic coolers (HIT). These thin film coolers use the selective emission of hot electrons over a heterostructure barrier layer from cathode to anode resulting in evaporative cooling [3]. Cooling on the order of several degrees over one-to-two micron thick barriers has been demonstrated in conventional material systems such as InGaAsP [4] and SiGe [5]. This corresponds to a cooling power density approaching 1000 W/cm^2.

A limitation in these thin film devices is the thermal resistance of the substrate on which the epitaxial films are grown [6]. This thermal resistance between the hot side of the cooler and the heat sink can cause much of the heat to flow back to the cold side of the cooler. Several methods for transferring the epitaxial films to surrogate substrates with high thermal conductivity are possible, but they complicate considerably the processing and packaging. A simpler way of effectively reducing the substrate thermal resistance is to use the substrate itself as a thermoelectric cooler. This concept has been successfully employed in the tuning of in-plane and vertical cavity lasers by changing the current through a metal-substrate contact [7,8]. The first experimental demonstration of using thermionic and thermoelectric coolers in a multistage, three-terminal configuration is presented, and the effects of the device geometry are discussed.

DEVICE STRUCTURE

A 2 μm thick superlattice barrier (80 periods of 18 nm InGaAs and 7 nm InP) surrounded by n+ InGaAs cathode and anode layers was grown by metal organic chemical vapor deposition (MOCVD). The cathode and anode layers were 0.3 μm and 0.5 μm thick respectively. Ohmic metal contacts (Ni/AuGe/Ni/Au) were deposited for the contact on the top n+ cathode region, and mesas of different areas were etched down to the lower anode region using dry etching techniques. Metal contacts were again deposited on the lower n+ InGaAs region to define the TE cooler stage. The substrate was thinned to 125 μm before the backside metal was deposited. Figure 1 shows the complete device structure. The coolers were then cleaved, packaged, and wire bonded for testing. Two different bottom contact geometries were used to study their effects on the cooling performance. In one case a rectangular contact (80x200 μm^2) is placed 20 μm away from the mesa, and in the second case a 60 μm wide ring contact surrounds the mesa on all sides with the closest edge 20 μm away. In the first case the thermoelectric contact area was constant with varying thermionic cooler size, while in the second case it scales with the thermionic cooler size.

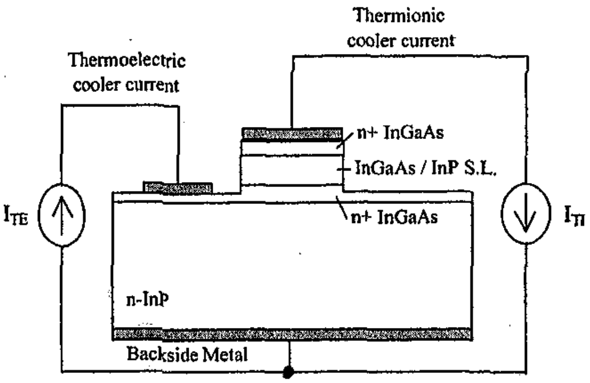

Fig.1 Device structure and geometry. The superlattice barrier is 2 μm thick (80 periods of 18 nm InGaAs and 7 nm InP) while the top and bottom n+ InGaAs regions were 0.3 μm and 0.5 μm thick respectively. Positive currents I_{TE} and I_{TI} are shown.

EXPERIMENTAL RESULTS & DISCUSSION

A micro-thermocouple is used to measure the cooling on top of the mesa as a function of thermionic (I_{TI}) and thermoelectric (I_{TE}) currents. The temperature on top of the mesa if first measured as a function of I_{TE} with I_{TI} set to zero, $T(I_{TE})$. Next I_{TE} is set to zero, and the temperature is measured as a function of I_{TI}, $T(I_{TI})$. Then I_{TE} is set to various constant values, and the measurement of cooling is repeated as a function of I_{TI} resulting in a temperature on top of the mesa that is a function of both currents, $T(I_{TI},I_{TE})$. Thermionic and thermoelectric cooling, Q_{TI} and Q_{TE} respectively, are both proportional to current and can be expressed as:

$$Q_{TE} = S \bullet T \bullet I_{TE}$$

$$Q_{TI} = (\phi_B + 2k_BT/e) \bullet I_{TI}$$

where S is the Seebeck coefficient, T is temperature, ϕ_B is the heterojunction barrier height, k_B is Boltzmann's constant, and e is the charge of an electron. The expression for thermionic cooling is valid in the limit of Boltzmann statistics [3]. Since the cooling is proportional to current and Joule heating is proportional to the square of current, the experimental data can be fitted with a second order polynomial (Table 1). From Table 1 the coefficients for thermoelectric cooling can be seen to be substantially smaller than those for the thermionic case. This is due in part by the fact that the thermoelectric cooling action is occurring further away from the top of the mesa than that of the thermionic cooling, and in part due to the inherently smaller thermoelectric cooling properties of InGaAs and InP compared to the thermionic effects.

Intuitively when both currents are biasing each section of the multistage cooler, it is expected that the resulting temperature, $T(I_{TI},I_{TE})$, would be the sum of the two independent measurements, $T(I_{TI}) + T(I_{TE})$, however this is not the case. Figure 2(a) illustrates this point graphically by plotting the *cooling on top of the thermionic cooler for constant* thermoelectric currents of 100 mA, 0 mA, and -100 mA. If superposition applied, then the three curves would look identical with only a vertical shift due to the constant thermoelectric current. This is obviously not the case as any two curves cross each other at some observable point. Figure 2(b) plots the corresponding linear and quadratic fitting coefficients versus I_{TE}, and shows that while the heating coefficient remains approximately constant, the linear coefficient is changing linearly with thermoelectric current.

Table 1. The linear and quadratic fitting coefficients for some of the various current configurations of I_{TI} and I_{TE}. The data listed is for a 40 x 80 μm^2 thermionic cooler with a surrounding metal contact around the base of the mesa that is 60 μm wide and 20 μm away.

Thermionic Current (mA)	Thermoelectric Current (mA)	linear coefficient (K/mA)	quadratic coefficient (K/mA^2)
0	independent variable	0.0015	-0.00000675
independent variable	0	0.0085	-0.00003450
independent variable	100	0.0100	-0.00003740
independent variable	-100	0.0083	-0.00003850

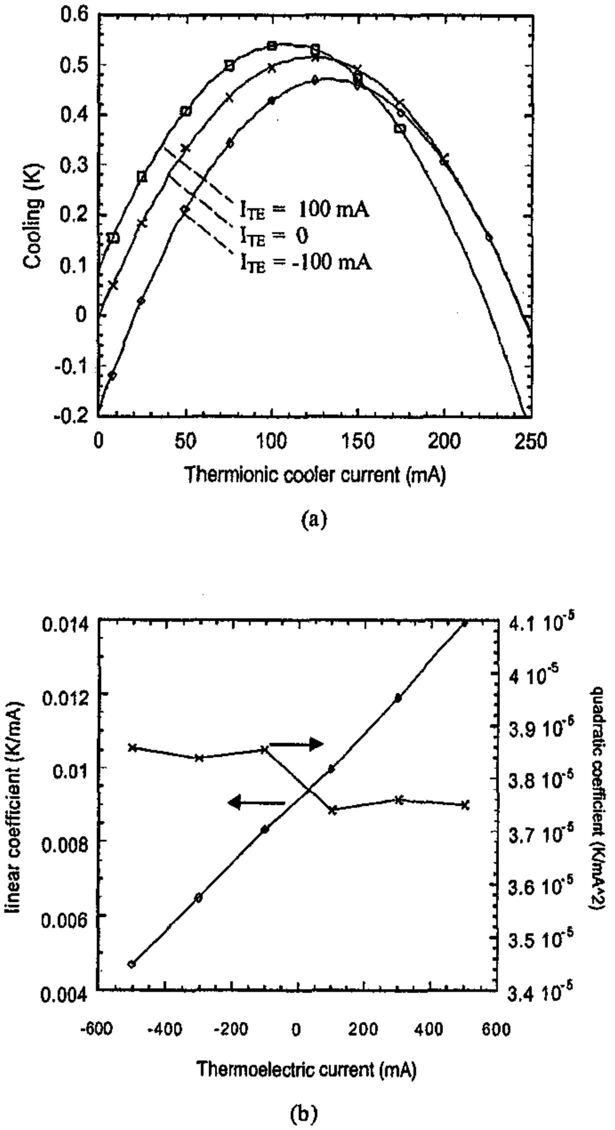

Fig.2 (a) Cooling versus thermionic cooler current for three different thermoelectric currents. The points refer to experimental data while the lines are 2^{nd} order polynomial curve fits. (b) The corresponding linear and quadratic coefficients versus thermoelectric current.

Therefore the constant thermoelectric current not only adds or subtracts a constant amount of cooling, but it also changes the magnitude of the overall cooling term. The reason for this I_{TE} - dependent linear coefficient is due to both I_{TI} and I_{TE} superimposing in the substrate region. If the substrate region has a heating coefficient β_{SUBST}, then the quadratic term in that region is multiplied by the square of the sum of the currents flowing through it, $-\beta_{SUBST}(I_{TI} + I_{TE})^2$. Expanding this expression yields the normal heating terms, $-\beta_{SUBST}I_{TI}^2$, $-\beta_{SUBST}I_{TE}^2$, and a cross term $-2\beta_{SUBST}I_{TE}I_{TI}$. This cross term can be used to further enhance the overall cooling of this two-stage device. From the slope of the linear coefficient in figure 2(b), β_{SUBST} is measured to be 4.57×10^{-6} K/mA^2, which corresponds to only 12 percent of the total quadratic coefficient measured. This result is expected since it is believed that most of the heating is caused by the contact resistance of the metal-semiconductor contacts and from the current carrying wire bonds (see reference 6). An interesting result of this cross term is that it originates from the heating effects in the substrate. Therefore even with no additional cooling from the thermoelectric stage, there exist optimum currents I_{TI} and I_{TE} for which the cooling is maximized.

CONCLUSIONS

The first two stage, three terminal monolithic thin film cooler has been demonstrated through the use of the thermoelectric effect in the substrate as a thermoelectric cooling stage by means of a metal-semiconductor interface. While the electrical current distributions for each cooler stage obey superposition, the resulting temperature distribution does not, and this non-linearity has been examined. The linear coefficient of the temperature versus thermionic current has been shown to linearly depend on the current in the thermoelectric stage due to regions shared by the two current distributions. This non-linear effect can be used to enhance the cooling performance of multi-stage devices.

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