Monolithic Integration of Solid State Thermionic Coolers with Semiconductor Lasers

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ABSTRACT: We examine the cooling requirements and temperature stabilization needs of semiconductor lasers. Monolithic integration of thin film solid state thermionic coolers for laser applications is proposed and experimental results on an integrated structure are discussed.

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Monolithic Integration of Solid State Thermionic Coolers with Semiconductor Lasers

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Many types of semiconductor lasers such as vertical cavity surface emitting lasers (VCSEL's) or distributed feedback (DFB) lasers can generate large heat power densities on the order of kW/cm^2 over areas as small as 100μm^2 [1]. Under these conditions, the active region can reach temperatures greater than 70°C above the heat sink temperature. It is desirable in many applications to control the operating temperature in order to tune the operating characteristics such as emission wavelength or to enhance the performance such as increasing the output power. Conventionally, thermoelectric (TE) coolers are used to manage temperature, however since they are not easily integrated with semiconductor devices [2], the packaging can be costly. Moreover, the TE device usually determines the reliability and lifetime of a packaged laser module [3].

An alternative to traditional TE coolers is heterostructure integrated thermionic coolers. These thin film coolers use the selective emission of hot electrons over a heterostructure barrier layer from emitter to collector resulting in an evaporative cooling of the electron gas beyond what is possible with the Peltier effect [4]. Thermionic coolers fabricated in the InGaAsP material system have demonstrated cooling on the order of several degrees over one-to-two micron thick barriers (see fig.1) and cooling power densities of over 100 W/cm^2 [5,6]. This cooling power density is approximately an order of magnitude greater than what is possible with TE coolers. The InGaAsP material system is important for long wavelength semiconductor lasers used in long haul and other high-speed optical communication systems. By using the same material system for the laser and cooler growth, monolithic integration is possible.

The proposed structure for the integration of a cooler and laser is shown in fig. 2. The growth was performed with metal organic chemical vapor deposition (MOCVD) on a n-InP substrate. The thermionic cooler structure was composed of a 1 μm thick superlattice barrier (25 periods of 10nm InGaAs and 30nm InGaAsP, λ=1.3μm) surrounded by n+ InGaAs emitter and collector layers that were 0.3μm and 0.5μm thick respectively. The laser structure consisted of a 2 μm thick n-InP cladding layer, an undoped InGaAsP active region consisting of five quantum wells (λ=1.64μm) with a 0.3μm thick confinement layer (λ=1.15μm) above and below, a 1.5μm thick p-InP cladding layer, and a 0.15μm thick p-InGaAs contact layer. During the design of the structure, a two-dimensional waveguide simulation [7] was used to predict the necessary thickness of the lower n-InP cladding region to eliminate mode leakage into the layers comprising the cooler. A thickness of two microns was determined to confine the mode sufficiently. The ridge widths were varied from 20 to 50 μm, and the metal contacts to the cooler were 50 μm wide and 10 μm from the edge of the laser mesa. The lasers were cleaved to various lengths (100-300μm), mounted on fabricated silicon packages, and wire bonded for testing. Two current sources were used to independently control the current through the laser and cooler sections.

The lasers were first tested with no current to the cooler section (fig.3). Comparing to similar laser structures grown without the extra cooler layers, the lasers operated as expected under pulsed conditions indicating that the addition of the thermionic cooler structure did not significantly impact the quality of the growth. The emission wavelength was around 1.55μm and the temperature sensitivity was measured to be approximately 0.1 nm/°C. This was then used to monitor the temperature change of the laser versus cooler current. It was determined that the laser would only heat for either current bias direction. To explain the observed experimental results, a commercial laser diode simulator [8] was used to model the laser/cooler device. Simulation results indicated that the current injected from the cooler contact was not spreading underneath the laser mesa negating any thermionic cooling effects (fig. 3). It was also determined that the InGaAs region between the laser and cooler was not sufficiently thick enough to prevent a substantial amount of laser current to penetrate into the cooler structure. In addition, no bulk thermoelectric cooling effect was observed which may be due to the high doping of the epi layers and substrate. Further simulations are currently being examined to improve the laser/cooler integration. While the absolute cooling of the thermionic coolers is currently only a few degrees, the large cooling power density provided should allow for the laser to operate close to the heat sink temperature. In addition, the temperature tuning time constant of this structure is expected to be much faster than previously possible with conventional thermoelectric devices.

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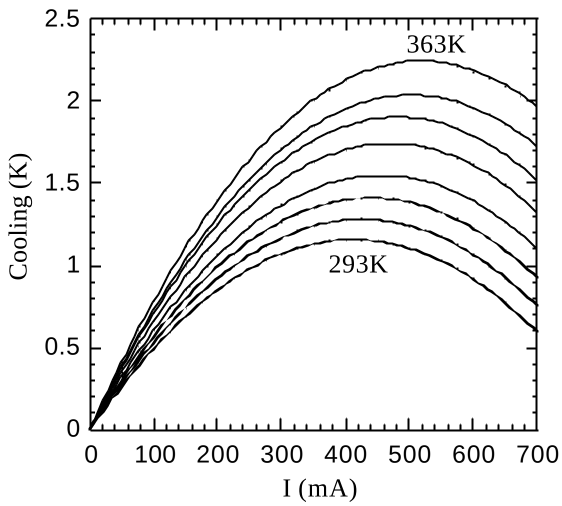

Figure 1. Thermionic cooling versus current bias for heat sink temperatures of 293-363K in 10K increments. Data is shown for a 50x100mm^2 cooler.

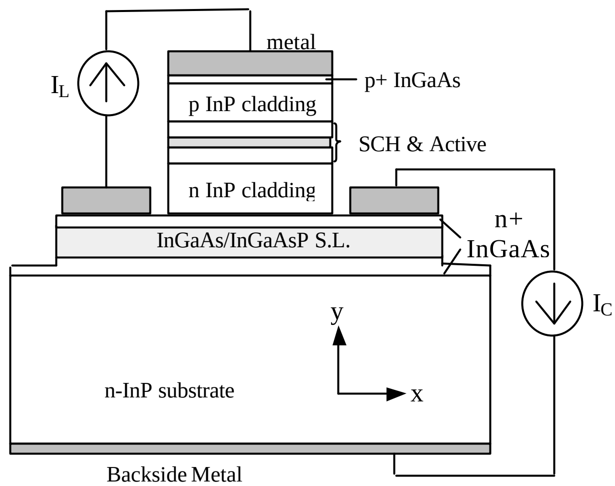

Figure 2. Schematic of thermionic cooler integrated with a ridge waveguide laser showing the laser (I_L) and cooler (I_C) bias.

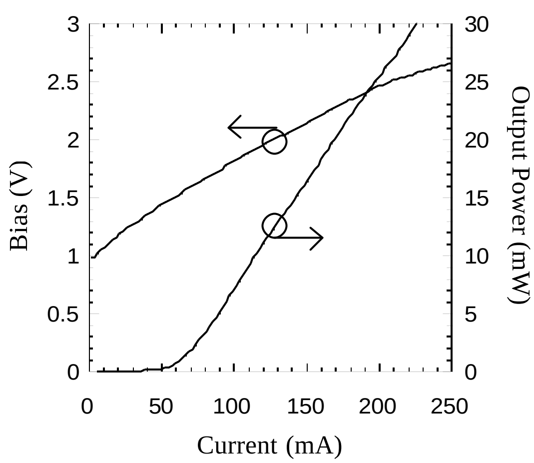

Figure 3. L-I-V characteristics of ridge waveguide laser integrated with a thermionic cooler. Data is shown for a 100 mm long cavity with a 20 mm wide ridge.

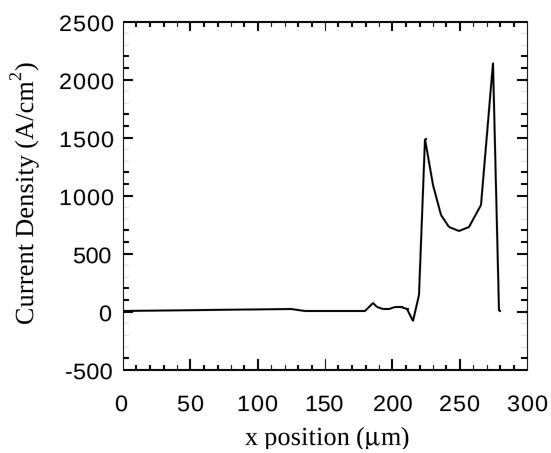

Figure 4. Simulation of current density perpendicular to the cooler at the interface of the lower n-InP cladding and InGaAs layers. The current does not spread underneath the laser mesa.