The Physics of Heat Transport in Semiconductor Lasers

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Abstract: A first study of thermoelectric and convective effects in lasers is given in addition to Joule and recombination heating. Optimized devices and thermal measurements verifying the theory are presented.

Heating in semiconductor lasers is detrimental to device performance, affecting such characteristic parameters as threshold current, efficiency, and lifetime. Previous work has identified several sources of heating (Joule heating, radiation absorption, contact heating, and non-radiative recombination) and has modeled heat transport through thermal conduction [1]. These models have neglected macroscopic heat transport mechanisms such as convection at the laser's surface and have likewise neglected several microscopic heat exchange processes such as thermoelectric effects that occur when carriers move across heterojunctions and diffuse against built-in fields. These microscopic effects have been demonstrated to produce net cooling of nearly ten degrees in bulk thin films [2], and their magnitude in (bipolar) laser diodes has been shown to be of the same order as conventional heating processes, with predicted cooling under certain bias conditions and device geometries [3].

In Fig. 1a we show measured data taken with a $25\times25\mu m^2$ NIST-calibrated microthermocouple (accurate to 10mK) on a $20\times500\mu m^2$ λ=980nm InGaP/InGaAs/GaAs laser mounted on a heatsunk copper block. A thermistor was stabilized at 17°C and was located 2mm from the laser. Temperature measurements were taken both on the laser surface and on the heat sink approximately 10μm from the bottom contact to the 100μm-thick GaAs substrate. A temperature difference ΔT was measured at zero bias, indicating the effect of convection from ambient air (21.4°C) warming the laser. This convective power is of greater magnitude than the laser's optical power, and must be included in a thermal model [4]. As the laser reaches threshold, a fraction of the electrical bias power is dissipated through light emission rather than through heat, appearing as a kink in ΔT. By carefully applying a thermal impedance model for heat conduction and by considering convection, laser surface temperature can be used to derive the optical power output without recourse to an optical detector (see Fig. 1b inset) [5]. This also provides independent verification of the measured cooling.

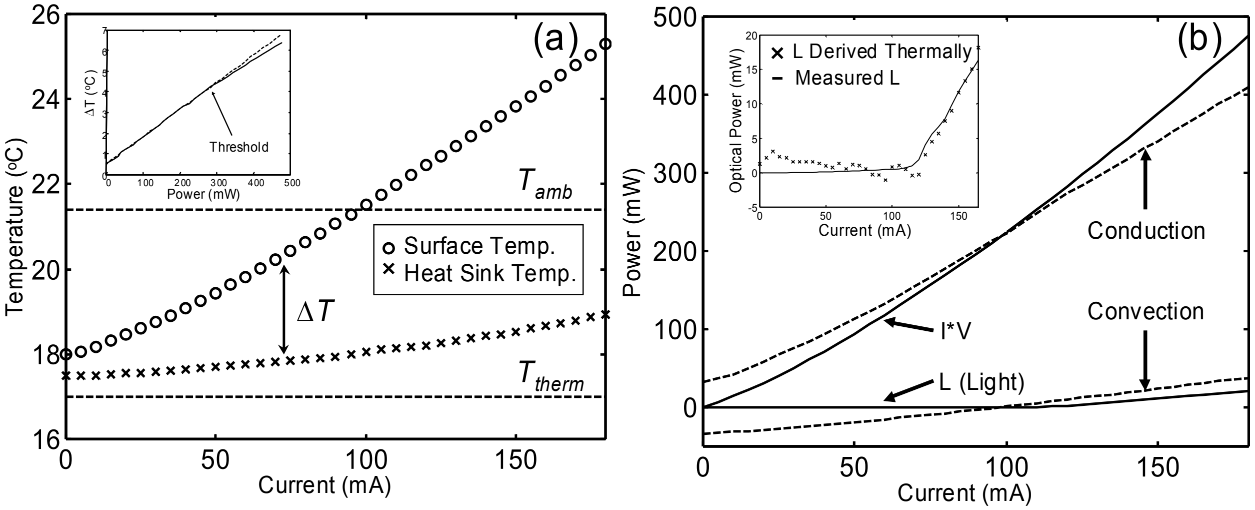

Fig. 1(a): Measured data; INSET: slope discontinuity in ΔT at threshold. **Fig. 1(b)**: Measured rates of conduction and convection compared to measured bias power and optical power; INSET: calculated / measured optical power.

This macroscopic model of heat transfer assumes a uniform temperature throughout the laser active region and waveguide that is often approximately valid for typical devices. However, if a laser has both small thermal conductivity and large band offsets (comparable to the photon energy), large internal temperature gradients can develop due to thermoelectric effects. Such is the case with GaInAsSb; Fig. 2 shows a λ=2.64μm $GaSb/Ga_{0.7}In_{0.3}As_{0.26}Sb_{0.74}/Ga_{0.8}In_{0.2}As_{0.17}Sb_{0.83}$ device in which the cladding doping has been modified to create either heating or cooling as injected carriers enter the core region [6]. These heating and cooling effects can be large with respect to other heating processes; Figure 3 shows the results of a finite-element simulation which takes into account thermoelectric effects as well as other thermal sources such as Joule heating and non-radiative recombination (contact resistance is typically very low in GaSb due to Fermi-level pinning). While leakage current (~8% in these devices) produces thermoelectric cooling in both devices, injection current cools rather than heats the optimized device, producing an overall lower temperature in the quantum well. Increased removal of heat from the contacts is expected to magnify this effect.

By examining for the first time these microscopic and macroscopic heat exchange terms, we uncover new design strategies for the internal and external cooling of lasers, as well as a new characterization tool.

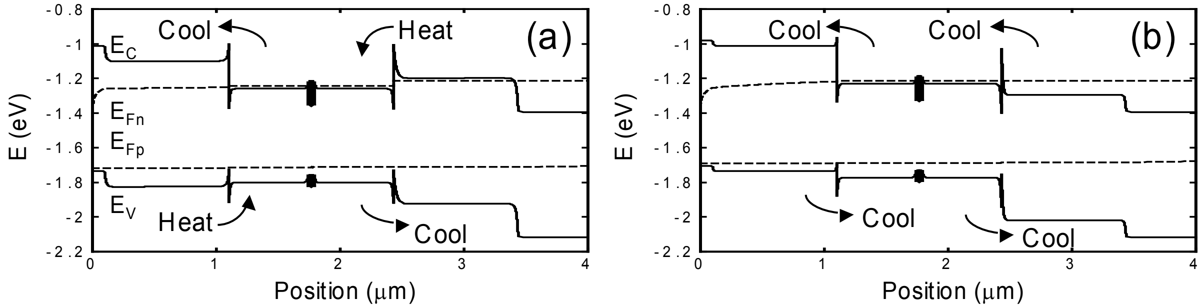

Fig. 2: Simulated band structure for GaInAsSb (**a**) conventional and (**b**) optimized laser structures biased at 475A/cm^2 (threshold), with associated thermoelectric heat exchange illustrated.

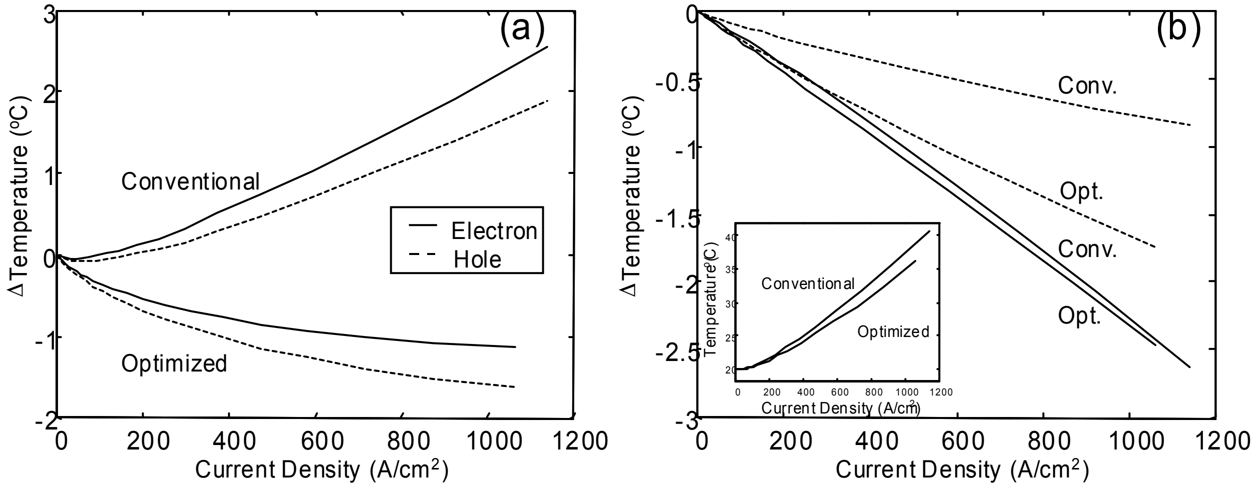

Fig. 3: Contribution by (**a**) injection and (**b**) leakage thermoelectric terms to the quantum well temperature. INSET: Overall quantum well temperature, including all thermoelectric terms as well as Joule and recombination heating.

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