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Analysis of the reduced thermal conductivity in InGaAs/GaAs quantum dot lasers from chirp characteristics

Hua Tan
Electrical & Computer Engineering and Computer Science Department, University of Cincinnati, Cincinnati, Ohio 45221-0030

Kishore K. Kamath, Zetian Mi, and Pallab Bhattacharya
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122

David Klotzkin[a]
Electrical & Computer Engineering and Computer Science Department, University of Cincinnati, Cincinnati, Ohio 45221-0030

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The thermal conductivity of self-organized quantum dot (QD) active regions is estimated by measurements of wavelength chirp with injected current as a function of the current pulse duty cycle both below and above threshold. A simple model which separates out thermal and charge carrier chirps is used to estimate the thermal conductivity of the QD active region. With this model, the thermal conductivity of the InGaAs QD active region is estimated to be ~0.1 W/m K, about two orders of magnitude less than that of the bulk material. This is consistent with theoretical predictions of the reduced thermal conductivity of QD regions. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2354415]

With the great success of self-organized quantum dot (QD) fabrication, there is considerable interest in the properties of semiconductor QD lasers. QD lasers are predicted to have extremely low chirp, with a corresponding zero or negative α factor [a figure of merit for directly modulated transmission, equal to $\alpha = -(2\pi/\lambda)(dn/dg)$, with dn/dg being the change in refractive index with gain and λ the wavelength]. Many low chirp lasers with near-zero α factors based on self-organized InGaAs/GaAs QDs have been reported in recent years.[1–4] This low chirp property is extremely beneficial for directly modulated transmission.

However, QD lasers demonstrate an unusual dependence of measured chirp on current duty cycle below threshold, with redshifting observed with increasing dc and blueshifting observed with short pulse current inputs which have minimal thermal effects. This would result in negative α factors measured at dc due to thermal effects. Below threshold, laser wavelength shifts with increasing injection current are simultaneously redshifted with current injection due to heating and blueshifted due to the charge carrier chirp from increasing carrier density, with the observed wavelength shift with injected current with a combination of the two effects. Far above threshold with a clamped active region carrier density, the wavelength redshifts with increasing current due only to thermal effects.

This unusual dependence of chirp on duty cycle has been previously reported.[5] In this letter, the change in wavelength as a function of pulse duty cycle is measured both below and above threshold. From the measurements, the magnitude of thermal and charge carrier chirps are separated: from the magnitude of the change in active region temperature due to current injection (which we term "thermal impact"), the thermal conductivity of the active region is estimated using a simple model.

Multilayer ridge waveguide QD laser bars, ~400 μm long with a 3 μm wide ridge with both n- and p-metal contacts on top, are placed on a Cu heat sink mounted to a Peltier cooler. Device characteristics are fairly typical, with thresholds of 20–30 mA and differential resistances above threshold of about 5 Ω. The QD lasers, whose fabrication details and layer structures are described elsewhere,[6–8] are driven with a current input applied either continuously (dc) or in a pulsed mode, with a pulse width of 1–9 μs in a total period of 10 μs, corresponding to duty cycles from 10% to 90% at 100 kHz. The wavelength of one of the Fabry-Pérot

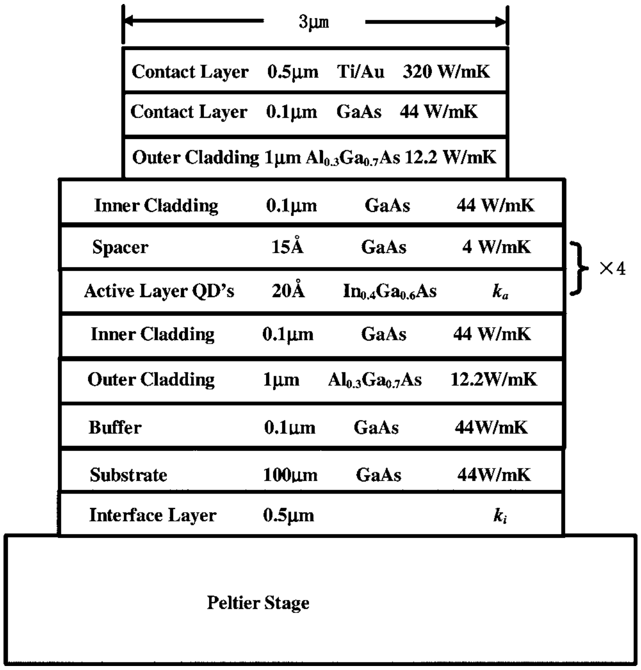

FIG. 1. Thermal model of the structure, including a 0.5 μm thick layer of unknown thermal conductivity as a model for the contact between the laser bar and the stage (V_0 is the total volume of QD active layer).

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[a] Electronic mail: klotzkdj@ececs.uc.edu

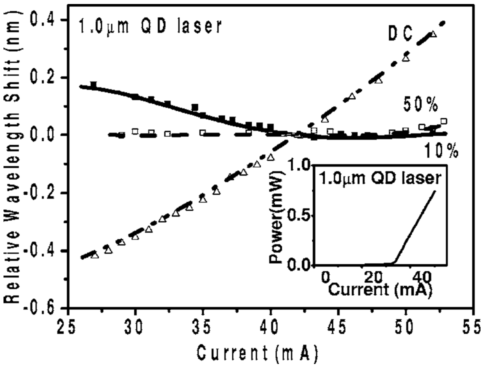

FIG. 2. Wavelength shift with current for 1.0 μm QD laser. (The % is the duty cycle of the pulse width of the measurement [100 kHz (10 μs period)].) Inset is the *L-I* curve of the laser under test.

(FP) modes is measured with an Ando 6317 spectrometer at 0.05 nm resolution as a function of pulse width. The Peltier cooler stage is controlled to be at 22.5 °C throughout the measurement. Figure 1 shows both the laser structure, thicknesses, and thermal conductivities. The contact between the bottom of the laser and the Cu-topped Peltier stage is modeled as a 0.5 μm thick layer of unknown thermal conductivity k_i, which will be discussed in more detail later. [Thermal conductivities of thin layers <10 nm are transverse quantum well (QW) thermal conductivities, while thicker regions use bulk conductivities.[9,10]]

Figure 2 shows measurements of the wavelength shift of one of the FP modes of the QD InGaAs laser as a function of pulse width, both below and above threshold. Under dc bias the QD devices show increasing wavelengths below threshold due to thermal effects. At low duty cycles of 10%–20%, QD lasers demonstrate typical QW semiconductor behavior with wavelengths decreasing with current below threshold due to charge carrier chirp.[11,12] In order to quantify this reduced thermal conductivity, the dependence of the lasing wavelength on the input current is modeled as

$$\frac{d\lambda}{dI}=\frac{\partial\lambda}{\partial I}+\frac{\partial\lambda}{\partial T}\frac{\partial T}{\partial I}, \tag{1}$$

where $d\lambda/dI$ is the measured chirp of the laser, $\partial\lambda/\partial I$ is the carrier-induced wavelength shift, and the $(\partial\lambda/\partial T)(\partial T/\partial I)$ term describes the indirect chirp which is thermally induced through change in temperature T. To separate these terms out, at the lowest measured duty cycle pulse, $\partial T/\partial I$ is assumed to be negligible and the chirp from the carrier injection can then be estimated as $\partial\lambda/\partial I\approx d\lambda/dI$. As obtained from Fig. 2, at low duty cycles below threshold, the QD laser showed charge carrier chirp of $\partial\lambda/\partial I\approx d\lambda/dI=-0.012$ nm/mA.

To estimate the $\partial\lambda/\partial T$ term, the dependence of wavelength on temperature at fixed current is measured for the devices. The device is driven at a fixed dc below threshold, and the output wavelength is measured as a function of the temperature setting on the temperature controlled Peltier cooler stage. These QD lasers have a thermal chirp of about $\partial\lambda/\partial T=0.074$ nm/K. With the measured $d\lambda/dI$ and $\partial\lambda/\partial T$ and $\partial\lambda/\partial I$, the thermal impact of current injection with dc injection $\partial T/\partial I$ is about 0.5 K/mA for the QD lasers. Alternatively, the thermal chirp may be estimated by assuming that far above threshold, the carrier density in the active region is clamped, and thus $d\lambda/dI\approx(\partial\lambda/\partial T)(\partial T/\partial I)$.[13,14] With this method, the values determined for $\partial T/\partial I$ are 0.52 K/mA, in good agreement with the prior calculation.

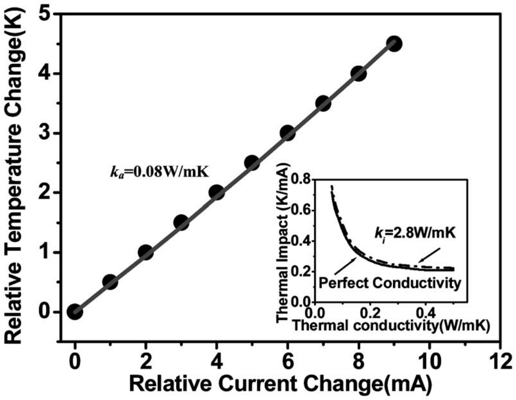

FIG. 3. Measured change in temperature of QD laser. Inset is the calculated thermal impact, $\partial T/\partial I$, as a function of active region thermal conductivity, assuming perfect thermal conductivity to the Peltier stage and best fit interface conductivity layer.

The experimentally determined thermal impact $\partial T/\partial I$ can be related to the thermal conductivities (k) of the layers through a two dimensional heat transfer model which relates the heat injected into the active region to the temperature rise of the active region. In steady state, the temperature T satisfies a differential equation,

$$k\left(\frac{d^2T}{dx^2}+\frac{d^2T}{dy^2}\right)+H=0, \tag{2}$$

where H, the internal heat generation rate per unit volume, is estimated by the power dissipated within the laser as $H=(IV-P)/V_0$, where I and V are the current and voltage on the laser, respectively, P is the output laser power, and V_0 is the total volume of the active layer (see Fig. 1). It is assumed that most of the heat is generated in the active region. The background heat developed through resistive injection, similar below and above threshold, is neglected.

The temperature versus heat relationship is modeled by assuming that the temperature of the heat stage is fixed by the Peltier cooler with adiabatic boundary conditions applied to the other exposed surfaces. Using values from literature for the thermal conductivities of the AlGaAs and GaAs materials of the laser cladding and substrate,[15–17] the temperature of the active region can be determined as a function of thermal conductivity and a temperature rise can be computed for each additional milliampere of injected current. The value for QD thermal conductivity k_a is picked to give the best fit for temperature versus current curve, with the temperature determined from the wavelength shift after accounting for charge carrier chirp. The temperature increase is consistent with a thermal conductivity of about 0.08 W/m K for the QD active region (Fig. 3). Due to the reported variation of thermal conductivity values with size, direction, and composition, these numbers are only considered accurate to within a factor of 2 or so. The analysis shows that there is about two orders of magnitude difference between the thermal conductivity of bulk material (about 5 W/m K) and the QD region.

Figure 3 (inset) shows the simulated thermal impact as a function of active region thermal conductivity k_a with the “best fit” interface layer thermal conductivity k_i of 2.8 W/m K (to be discussed below), and for comparison,

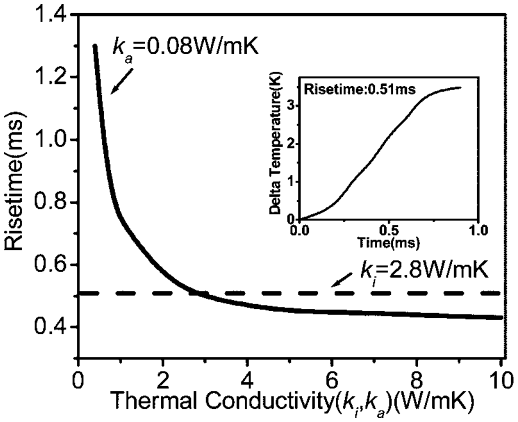

FIG. 4. Rise time (from 10% to 90% of the peak temperature) of transient thermal responses of QD lasers from simulation. Inset is the transient thermal response from experiment. Two sets of curves are shown: varying interface k_i with active region k_a fixed at the nominal 0.08 W/m K and varying active k_a with interface thermal conductivity fixed at the nominal 2.8 W/m K.

with perfect thermal conductivity and fixed bottom wafer temperature. There is a very steep increase in thermal impact with decreasing thermal conductivity below about 0.15 W/m K, but a relatively flat thermal impact with thermal conductivities above 0.2 W/m K. The steep knee of the curve suggests that this technique is much more suited to estimate lower QD thermal conductivities than higher QW thermal conductivities. For active region thermal conductivities below 0.15 W/m K, the thermal impact becomes extreme. This is fundamentally why a negligible QW effect becomes a significant factor in a QD active region.

To validate the thermal model (particularly the thermal contact of the QD laser bar to the Cu-topped Peltier cooler) and ensure that the increased thermal impact comes from the decreased thermal conductivity of the active, the heat sinking is evaluated as follows. The devices were set up in a steady state above threshold at 22.5 °C. The output of the laser was put into an Ando 6317 spectrum analyzer, configured as a monochromator with 0.05 nm resolution and tuned to one of the wavelength peaks. A step current is abruptly applied to the Peltier cooler and its top surface temperature monitored with a thermistor. As the laser temperature changes, the power through the monochromator decreases, and the power falloff can be related to the change in wavelength and hence back to the change in active region temperature. Measured active region versus stage temperatures are compared to the dynamic two dimensional differential heat transfer equation,

$$k\left(\frac{d^2T}{dx^2}+\frac{d^2T}{dy^2}\right)+H=\rho C_p\frac{dT}{dt}, \tag{3}$$

where ρ is the density, C_p is the specific heat of the material, and the other symbols as defined previously.

The laser temperature rise versus time is measured as shown in Fig. 4 (inset), and also compared to several calculations done using various values of k_a and k_i. These comparisons are shown in Fig. 4, which shows, on the same graph, the 10%–90% rise time of temperature versus k_a (with k_i fixed at the best fit value of 2.8 W/m K) and versus k_i (with k_a fixed at its nominal 0.08 W/m K value). The rise time is largely insensitive to k_a and very sensitive to k_i; as seen in Fig. 3 (inset), the thermal impact is relatively insensitive to k_i and quite sensitive to k_a, making these two measurements complementary in measuring the laser thermal properties. Experimentally, the measured results of chirp versus input pulse were quite consistent from bar to bar with varying contacts, which also suggest that with reasonable contact, the contact (interface) plays a minor part in the thermal impact.

This technique for estimation of thermal conductivity was also applied to InGaAsP QW laser bars and InGaAs packaged pump lasers, using appropriate thermal boundary conditions, in both cases yielding a thermal conductivity value of ~0.5 W/m K for the quantum well active region, which is a reasonable estimation for typical QW material.[18] These devices below threshold chirp varied minimally with duty cycle. While it is well known that thermal chirp does play a role in measurement of QW lasers, the degree which is observed here and elsewhere in QD lasers is quite extreme. From this analysis, we believe it is due to the decreased thermal conductivity of the QD active region.

This is consistent with theoretical studies on SiGe QD regions, which indicate that QDs can have a thermal conductivity two orders of magnitude lower than that of the bulk materials due to the incoherent phonon scattering by the quantum dots.[19] Typical semiconductor QW regions have a thermal conductivity one order of magnitude lower than that of the bulk materials.

This low thermal conductivity can result in measured negative α factors, which are no longer good figure of merits for high speed dynamic, directly modulated performance. In addition, operation at frequencies low enough for the carriers to thermally equilibrate with the lattice will induce this chirp into the transmitted signal. This methodology of using the difference between pulsed and dc laser performance to quantitatively evaluate the laser thermal properties may be applied to optimize device thermal performance.

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