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Temperature invariant lasing and gain spectra in self-assembled GaInAs quantum wire Fabry–Perot lasers

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GaNAs quantum wire (QWR) heterostructures have been grown by molecular beam epitaxy using the strain-induced lateral-layer ordering (SILO) process. Broad-area Fabry–Perot QWR lasers have been fabricated from this material. The lasing wavelength from the QWR laser shifts at a rate of 0.9 Å/°C between 77 and 300 K compared to 4.6 Å/°C for a quantum well laser control sample. Furthermore, the gain spectra of the QWR laser are derived from the amplified spontaneous emission spectra at 77 and 300 K using the Hakki–Paoli method. The gain peak is also stabilized against temperature changes indicating that temperature stable lasing behavior seen in SILO grown GaInAs QWR Fabry–Perot laser diodes is due to a temperature stable band gap. © 2001 American Institute of Physics. [DOI: 10.1063/1.1350629]

The band gap of a III–V semiconducting crystal decreases with increasing temperature as demonstrated by the Varshni equation.\textsuperscript{1} As such, the peak lasing wavelength from a semiconductor laser diode, as well as the wavelength of the gain peak, increase with increasing temperature. A temperature stable gain peak, however, is desirable for device applications. For instance, vertical-cavity surface-emitting lasers (VCSELs) suffer from low output powers due to a detuning of the gain peak from the reflectivity spectrum. The thermally induced detuning occurs because the gain peak of VCSELs shift at a rate of 3–9 Å/°C (depending on the material system)\textsuperscript{2,3} due to the temperature dependence of the band gap.\textsuperscript{2} Where, on the other hand, the reflectivity spectrum of the distributed Bragg reflector (DBR) mirror shifts at a rate of ~1 Å/°C.\textsuperscript{3} To solve this problem, researchers have designed VCSELs with intentionally broad gain spectrums\textsuperscript{4} and have fabricated structures with gain/DBR reflectivity spectra offsets.\textsuperscript{3} An alternative approach would be to employ an active region with a temperature stable band gap. Self-assembled GaInAs quantum wires (QWRs) grown by the strain-induced lateral-layer ordering (SILO) process\textsuperscript{5} have demonstrated temperature stabilized photoluminescence (PL) emissions of less than 1 Å/°C in the 1.55–1.62 μm wavelength region for temperatures ranging between 77 and 350 K.\textsuperscript{6,7} In this letter we use GaInAs QWRs to demonstrate temperature stabilized lasing and gain spectra from a simple broad-area Fabry–Perot laser diode.

GaNAs QWR separate confinement heterojunction (SCH) lasers were grown on S-doped (n+ ~ 3 × 10\textsuperscript{18} cm\textsuperscript{-3}) (100)-InP substrates by molecular beam epitaxy. The schematic diagram of the QWR laser structure is shown in Fig. 1. The active region consists of five QWR layers where each layer contains eight pairs of a (GaAs)\textsubscript{2}/(InAs)\textsubscript{2.2} short-period superlattice (SPS) for a total thickness of 100 Å. Each QWR layer is separated by 75 Å thick Al\textsubscript{0.24}Ga\textsubscript{0.76}In\textsubscript{0.52}As barriers. During the deposition of the SPS, the QWRs are created \textit{in situ} by the SILO process. The formation of QWRs using the SILO process has been previously discussed at length.\textsuperscript{8} A conventional quantum well (QW) SCH laser of similar structural configuration with lattice-matched Ga\textsubscript{0.47}In\textsubscript{0.53}As QWs has been fabricated for comparison.

Stripe-geometry Fabry–Perot lasers with 60 μm wide stripes and 500 μm long cavities were fabricated. Contact stripes were defined along the [110] direction to take advantage of the lower threshold current density when the stripes are perpendicular to the QWRs.\textsuperscript{9} Lasing and amplified spontaneous emission spectra were measured at 77 and 300 K under pulsed conditions using a pulse width of 1 μs and a repetition rate of 1 kHz. The Hakki–Paoli method\textsuperscript{10} was used to derive gain spectra from the amplified spontaneous emission spectra. Samples were also examined by PL spectroscopy using an Ar\textsuperscript{+} laser tuned to 5145 Å. The PL was detected with a liquid-nitrogen cooled Ge detector using the lock-in technique.

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FIG. 1. Schematic diagram of a broad-area GaInAs QWR Fabry–Perot laser diode grown using the SILO process. Notice that the contact stripe is perpendicular to the long axis of the QWRs.
The measured lasing wavelength of the GaInAs QW laser diode is 1.433 μm at 77 K and 1.535 μm at 300 K as seen in Fig. 2. The corresponding threshold current density ($J_{th}$) is 260 A/cm² at 77 K and 1.4 kA/cm² at 300 K. Also in Fig. 2, lasing spectra of the GaInAs QWR laser diode is shown at 77 and 300 K. The lasing wavelength at 77 K is 1.695 μm with a $J_{th}$ of 200 A/cm². At 300 K, the lasing wavelength is 1.715 μm which corresponds to a $J_{th}$ of 1 kA/cm². From these values it is clear that the temperature dependent lasing-wavelength shift of the QW laser diode between 77 and 300 K is ~4.6 Å°C, which is a typical value seen in this material system. Conversely, the net wavelength shift seen in the GaInAs QWR laser diode in the same temperature range is only ~0.9 Å°C. This is similar to the wavelength-shift rate seen in this structure using PL spectroscopy. In fact, temperature stabilized PL wavelengths are well documented for GaInAs QWRs grown by the SILO process. It has been shown that this effect is due to the temperature dependence of the multiaxial strain that exists in SILO grown QWRs and that this strain results in a temperature invariant band gap for GaInAs QWRs grown under the proper conditions.

Other effects, however, could cause the emission wavelength dependence on temperature to deviate from what is considered normal behavior. For example, Walther et al. has also demonstrated a temperature stable lasing wavelength in a strained GaInAs/GaAs QWR laser formed on a patterned substrate. The wavelength was shown to be stable for temperatures between 80 and 150 K. This effect was attributed to a weak mode selectivity from the etched-and-regrown QWR grating which had a period of 2500 Å. The QWR array for SILO grown QWRs, however, is rather nonuniform and has a small average periodicity of 300 Å, which would inhibit any mode selectivity that could be created due to the optical field interacting with the alternating index of refraction along the [110] direction. In addition, the peak wavelength of the PL emitted from the [100] direction would not benefit from such a grating effect, even if the QWRs were uniform. Consequently, there is no grating contribution to the PL and lasing wavelength behavior with respect to temperature seen in GaInAs QWR structures grown by the SILO process.

Band filling and higher-order subband effects have also been investigated as a source of anomalous emission behavior with respect to temperature by varying the incident laser intensity over three orders of magnitude (1.0–150 W/cm²) during PL experiments. No noticeable shift in peak wavelength was observed at 300 K in response to the increasing intensity. At 77 K, blueshifts in the peak PL wavelength equivalent to 10 meV or less were typical in various GaInAs QWR structures. These results imply that band filling may have a small effect on the QWR PL emission at low temperatures, but neither band filling nor band gap renormalization is significant near 300 K. Finally, no additional peaks were seen when varying the input intensity implying that higher order subbands do not contribute significantly to the observed luminescence. Thus, band gap renormalization and higher order subbands do not contribute to the observed temperature dependent PL. Because a 10 meV incident power dependent shift at 77 K does not account for temperature stable PL wavelengths, band filling does not contribute significantly to the unique temperature dependent PL emission characteristics seen in GaInAs QWRs. However, under lasing conditions, the carrier density is much higher than during PL spectroscopic measurements. Therefore, to conclusively determine the origin of temperature stabilized emission from SILO grown GaInAs QWRs, the gain spectra from the QWR laser has been derived.

A shift in wavelength of the gain peak in response to temperature changes is mainly due to the corresponding temperature induced change in the band gap energy. Therefore, a SILO grown QWR laser with temperature stabilized PL and lasing wavelengths will have a temperature stabilized gain peak if this phenomenon is due to a temperature stable band gap. To demonstrate that this temperature stabilized PL and lasing wavelength effect is due to the band gap, we have derived the gain spectra at 77 and 300 K from the corresponding amplified spontaneous emission spectra using the Hakki–Paoli method. Amplified spontaneous emission spectra were taken at 15% below the threshold current at 77 and 300 K from the GaInAs QWR laser. As seen in Fig. 3, the gain-peak wavelength is indeed stabilized against temperature with a wavelength-shift rate of only 1.4 Å°C, which is well below the usual range of 3–9 Å°C. This demonstrates that temperature stabilized emission in GaInAs QWRs grown by the SILO process is due to a temperature stabilized band gap. Furthermore, the wavelength-shift rate in gain peak of the QWR laser is similar to that observed in the reflectivity spectra of VCSELs, ~1.0 Å°C, which implies a GaInAs QWR active region could increase the output power of these devices. Finally, notice the full-width at half-maximum (FWHM) behavior of the gain spectra in Fig. 3. The gain spectrum at 77 K is clearly wider than at 300 K. This is due to the self-assembled nature of SILO grown QWRs. In fact, similar behavior has been observed in self-assembled quantum dots (QDs) and has been ascribed to the occupation distribution of quantum subbands at different temperatures in different size QDs.
As the temperature increases, the carriers have enough energy to scatter into potential minima of dots/wires that are, on average, larger. Consequently, a small subset of dots/wires contribute to the radiative recombination at higher temperatures which gives a smaller FWHM as seen in Fig. 3.

In summary, the temperature dependent lasing behavior of SILO grown GaInAs QWR laser diodes has been investigated. The lasing spectra and gain spectra from a simple broad-area Fabry–Perot QWR SCH laser were measured at 77 and 300 K. Both the lasing wavelength-shift rate and gain-peak wavelength-shift rate are stabilized to \( \sim 1 \text{ Å/°C} \).

As is the case with previously observed temperature stabilized PL wavelength emission, this behavior is due to a temperature stabilized band gap.

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1. Y. P. Varshni, Physica 34, 149 (1967).