Intersubband Raman laser from GaInAs/AlInAs double quantum wells

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We demonstrate optically pumped GaInAs/AlInAs based intersubband lasers operating at a wavelength of $\sim 5.5 \mu\text{m}$ applying a simple three-level design. Using a subnanosecond long pulsed excitation laser tunable over the linewidth of the transition from the first level to the third level E_{13} , Raman shift in the lasing spectra was observed. Lasing output power of $\sim 14 \text{ W}$ and an internal conversion efficiency between pump and intersubband laser of $\sim 1.3\%$ at 70 K is observed. © 2007 American Institute of Physics. [DOI: 10.1063/1.2790781]

Since the first quantum cascade laser (QCL) based on intersubband optical transitions was demonstrated in 1994,¹ its physics and device applications have attracted wide interest.^{2,3} Within the past decade, also optically pumped intersubband lasers have been demonstrated.⁴ Compared to the electrically pumped cascade laser, optically pumped lasers are based on the simpler active layer design and waveguides with reduced losses due to the lack of electrical contacts. In this kind of system, the Raman lasing which has been observed in many materials,⁵⁻⁷ can be strongly enhanced by bringing excitation and lasing energy in resonance with electronic transitions. For a three-level coupled well, the intersubband transition E_{13} from level E_1 to level E_3 is resonantly excited while the transition E_{32} from E_3 to the second level E_2 defines the lasing wavelength. The transition E_{21} from E_2 to E_1 defines the depopulation. Such an intersubband Raman laser was first demonstrated in a GaAs/AlGaAs material system at the lasing wavelength of $15 \mu\text{m}$.⁸

In this letter, we demonstrate InP-based optically pumped intersubband lasers based on a three-level design in a double quantum well (DQW) which was grown on undoped (100 oriented) InP substrates by molecular beam epitaxy. Two kinds of GaInAs/AlInAs samples were investigated: Sample A was grown lattice matched while for samples B and C about 0.5% strain is introduced in order to achieve better confinement of the upper laser and to shift E_{12} . In the following discussion we will focus on samples A and B for lack of space. The layer sequence of the waveguide structure for both samples starting from the substrate is $0.6 \mu\text{m}$ GaInAs cladding layer, 50 nm AlInAs core layer, the $1.1 \mu\text{m}$ active region, a 50 nm AlInAs core layer, and a $1.1 \mu\text{m}$ GaInAs cap layer. The active region consists of 60 periods of DQWs separated by a 9.5 nm thick AlInAs barrier. The center of this barrier is n doped over 3 nm at $3 \times 10^{17} \text{ cm}^{-3}$. For sample A (sample B), each DQW is composed of 4.7 nm (5 nm) GaInAs, 1.0 nm (1.2 nm) AlInAs, and 3.5 nm (3.8 nm) GaInAs. The corresponding band diagrams are shown in Fig. 1(a).

The design parameters were validated on the basis of absorption spectra taken at several temperatures T . Results of these measurements at 70 and 300 K are shown in Fig. 1(b)

and summarized in Table I. For sample B, the E_{12} transition could not be measured as it is below the cutoff of the mercury cadmium telluride (MCT) detector.

As pump laser, a 50 mm long periodically poled (PP) Li-niobate crystal is excited by $\sim 0.4 \text{ ns}$ long laser pulses obtained from a Q -switched neodymium-doped yttrium aluminum garnet (PowerChip, teemphotonics) laser operating at 1064 nm with a typical pulse energy of $70 \mu\text{J}$ at 1 kHz repetition rate. By parametric downconversion, infrared pulses at a wavelength around $3 \mu\text{m}$ having a pulse energy of $\sim 1.7 \mu\text{J}$ (measured after transport through the optic and the vacuum windows) are obtained. The wavelength is tuned by

FIG. 1. (a) Measured absorption spectra for temperatures of 70 and 300 K. The 70 K data are shifted for clarity. (b) Conduction band structure and square moduli of the wavefunctions for one period of each DQW structure.

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TABLE I. Transition energies, corresponding linewidth Γ , and peak absorption α_{peak} obtained in multipass 45° waveguide geometry. Energies marked by * and ** are calculated from $E_{12}-E_{13}$ and $E_{23}-E_{13}$, respectively.

Sample	E_{13}	Γ_{13}	α_{peak}	E_{12}	E_{23}
A (70 K)	313 meV	10 meV	0.55 cm ⁻¹	95 meV	217 meV*
(300 K)	305 meV	14 meV	0.3 cm ⁻¹	92 meV	212 meV
B (70 K)	302 meV	13 meV	2.1 cm ⁻¹	—	—
(300 K)	295 meV	17 meV	1.3 cm ⁻¹	76 meV**	219 meV

setting the temperature of the crystal between 50 and 200 °C and by using PP elements with different periods. The light is coupled into the $\sim 200 \mu\text{m}$ thick samples via a 45° polished substrate facet (see inset of Fig. 2). The broad area cavity is formed by cleaved facets, and the length of the cavity is equal to 5 mm. The samples were measured in a liquid helium optical cryostat equipped with ZnSe windows. For spectral analysis, the lasing light was detected by a midinfrared MCT detector located behind a grating spectrometer with a resolution of 0.2 meV for a slit width of 400 μm . The responsivity of the MCT detector has been calibrated using a pyroelectric detector (P3, Molelectron). To minimize the atmospheric absorption due to water and CO₂, the spectrometer was nitrogen purged and the outcoupled lasing light was guided from the cryostat to the detector through a nitrogen flow box.

For excitation at resonance energy-pumping energy $\hbar\omega_p$ coincides with E_{13} —strong lasing with a total output pulse energy from a single facet up to 2 nJ is obtained at 70 K for sample A. The lasing energies $\hbar\omega_l$ are found to be $\sim 217 \text{ meV}$ ($=5.71 \mu\text{m}$) and $\sim 222 \text{ meV}$ ($=5.59 \mu\text{m}$) for samples A and B, respectively, which is in good agreement with energy values given in Table I. The internal lasing efficiency is evaluated for sample A by considering the losses from the window of the cryostat and the lenses in front of the detector of 0.95 and 0.8, respectively. As we expect the same output on both facets, a total emitted pulse power of 5.3 nJ is achieved. On the incoupling side, the reflection losses of factor 0.3 and the absorption $1 - \exp(-2\alpha_{\text{peak}}L) = 0.36$ have to be considered, where L is the length of the cavity along

which the excitation pulse is traveling twice, in forward and backward directions. Hence, the internal energy conversion efficiency is 1.3% which corresponds to a quantum efficiency of about 7%.

Figure 2 shows the threshold characteristics for both samples for the pump photon energy $\hbar\omega_p$ equal to E_{13} at 70 K. The internal threshold pump pulse energy (absorbed power) of the lasing is equal to 86 nJ (208 W) for sample A and 113 nJ (283 W) for sample B. Based on the cavity length and a spot size of $\sim 100 \mu\text{m}$ of the excitation laser which was determined in a separate experiment using a pin-hole, the corresponding threshold intensities are equal to 52 and 57 kW/cm², respectively. The highest operation temperatures are found to be ~ 190 and ~ 120 K for samples A and B, respectively. To explain intersubband laser action in a coupled well, population inversion gain g_{PI} and Raman gain g_R have been invoked.⁹ From the threshold measurements, we find a higher threshold pump power than for common III-V QCLs which evidences a Raman process. To further identify the nature of gain, we measured the dependence of the lasing energy $\hbar\omega_l$ on the pumping energy $\hbar\omega_p$. This relation is plotted for three samples at 80 K in Fig. 3 and for sample A the spectra over the whole tuning range are shown in the inset of Fig. 3. In all cases, a linear dependence with a near unity slope is found. The deviation in the low energy tail is assigned to inhomogeneities within the sample structure. Besides this, the measured offset $(\hbar\omega_p - \hbar\omega_l)$ corre-

FIG. 2. Lasing threshold curves for both samples at $T=70 \text{ K}$ for resonant excitation with a fit of the experimental data points for clarity. The inset shows the coupling geometry.

FIG. 3. Peak position of the emission spectra vs pumping energy for samples A–C (points). The solid lines are the shifts expected from the absorption measurements. Sample C was designed to have a depopulation energy E_{12} higher than double phonon resonance ($\sim 100 \text{ meV}$) and is shown for completeness reasons but not discussed in further detail. For all samples, the shift of the peak emission with pumping wavelength follows the Raman shift. The inset shows the spectra of sample A over the whole tuning range.

FIG. 4. Comparison between absorption and lasing tuning range for sample A (a) and sample B (b) at $T=70$ K. The lines with symbols are the integrated spectra for the corresponding pump energy. The lines give the measured absorption spectra of the E_{13} transition.

sponds within 2 meV to the experimentally determined E_{12} transition. The fact that the value of E_{12} is changed between 79, 92, and 100 meV in samples B, A, and C, respectively, and do not correspond to phonon energies demonstrates that the Raman gain has a pure electronic origin.

From the above discussion we can state that the Raman process is the dominating gain mechanism in our samples although lifetimes calculated at an in-plane wavevector of $k=0$ predict a favorable ratio of $\tau_{32}/\tau_{21}=3.5$ for the population inversion. A more careful look at the electron dynamics show that this simple picture is invalid: Electrons that leave the third subband at $k=0$ will scatter to the subbands $n=1$ and $n=2$ with a large kinetic energy and thus will be distributed in k space. The intersubband lifetime τ_{21} from E_2 to E_1 at such large in-plane momentum is 1.6 ps instead of 0.7 ps at $k=0$. However, further simulations are necessary for a more detailed understanding of the k dependence as also hot carrier effects are expected to be relevant to electron distribution at these strong pumping intensities. However, also from this simple consideration, we already expect only a marginal population inversion between the third and second subbands. This picture is supported by the plot of the inte-

grated laser intensity versus measured absorption of the E_{13} transition, as shown in Fig. 4: The maximum gain is in resonance with the E_{13} absorption peak and the lasing can be tuned within the linewidth. Using Eq. (1) in Ref. 10, this behavior can only be modeled for a lower state lifetime only slightly smaller than the upper state lifetime, hence for a small population inversion gain and a clearly pronounced Raman gain.

In conclusion, we realized an optically pumped GaInAs/AlInAs lasers emitting at wavelengths of 5.5–5.7 μm . By detuning the excitation wavelength, we have shown Raman lasing and we argue that this observation implies a marginal population inversion. This is also indicated by the relatively high threshold obtained for this structure. Finally, we note that this behavior offers a chance to realize a Si/SiGe optically pumped laser as the lifetimes in that material system are short and heavily influenced by scattering mechanisms.

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