Short wavelength intersubband emission from InAs/AlSb quantum cascade structures

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The InAs/AlSb material system is a promising candidate for the development of short wavelength quantum cascade lasers because of the large conduction band offset of 2.1 eV. In this letter, we present a study of room temperature electroluminescence of InAs/AlSb quantum cascade structures as a function of the emission wavelength. Intersubband emission with a transition energy of 500 meV (λ=2.5 µm) has been obtained. © 2005 American Institute of Physics.

In today’s research on high efficiency quantum cascade lasers (QCLs) two frontiers are attracting more and more attention. The first is the THz domain and the second is the short wavelength region of the mid-infrared. The latter is of great importance for such applications as high sensitivity selective gas detection and molecular spectroscopy in the wavelength range 2–5 µm. For short wavelength QCLs a key issue is the choice of a material system with sufficiently large conduction band discontinuity. The use of strained materials in the conventional InP-based system made it possible to realize the shortest wavelength QCL with emission at 3.5 µm. A similar approach based on strain compensated structures with AlAs barriers on InP has been used in QCLs emitting at 3.8 µm. The alternative solutions are based on antimonide systems, either employing AlSbAs barriers and InGaAs quantum wells in structures lattice matched to InP, or InAs/AlSb structures grown on InAs or GaSb.

The InAs/AlSb material system is a very promising candidate for the development of short wavelength QCLs due to the large conduction band discontinuity of 2.1 eV. InAs/AlSb-based QCLs operating at room temperature (RT) near 4.5 µm have been reported, as well as those emitting at longer wavelengths. In this letter we present a study of RT electroluminescence of InAs/AlSb quantum cascade structures as a function of the emission wavelength aiming to explore the short wavelength limit of their operation.

Small thicknesses of the quantum wells and the barriers and the high energy position of the upper state of intersubband transitions make the development of short wavelength QCLs more difficult compared with long wavelength devices in terms both of their modeling and realization. Typical values of the confinement energy of the upper state of the lasing transition in QCLs are twice the photon energy. For an active region designed to emit at 3 µm, electrons must be injected about 800 meV above the bottom of the conduction band of the active quantum well. The main difficulty in designing short wavelength InAs/AlSb QCLs is the lack of reliable band parameters for accurate modeling of the required high energy levels. An especially important issue is the precise alignment of the injector ground state eL with the upper state of the lasing transition e3 (see Fig. 1). In this respect, intersubband light emission is much more difficult to achieve than light absorption at the same wavelength. A small inaccuracy of the electron effective mass or band nonparabolicity used for modeling can provoke a dramatic shift of injector states by comparison with active quantum well states and prevent efficient electron injection in a real structure.

Our approach was to find, first, the best empirical set of parameters that describes the experimental intersubband emission energies for a large number of structures emitting at different wavelength. Then, for a given active region design, the best injection conditions were searched by slightly varying injector levels relative to active quantum well levels, and

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FIG. 1. Calculated conduction band profile and moduli squared of the relevant wave functions for sample D emitting at 2.55 µm under an applied field of 90 kV/cm. The photon emission occurs between the levels labeled e2 and e3. The layer sequence is in Å and starting from the injection barrier: 27, 32, 10, 30, 11, 28, 18, 25, 10, 21, 10, 20, 10, 18, 10, 18, 11, 17, 12, 16, 13, 17, 13, 16, 13, 15, 14, 14, 14, 14, 14, 13, 16, 13, 17, 13, 18, 13, where AlSb layers are in bold and Te-doped layers (n=1019 cm−3) are underlined.
TABLE I. Band parameters used for the modeling of InAs/AlSb structures.

<table>
<thead>
<tr>
<th>Material</th>
<th>$m^*$ ($m_0$)</th>
<th>$E_{c\text{eff}}$ (meV)</th>
<th>$E_c$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InAs on GaSb (0 K)</td>
<td>0.020</td>
<td>278</td>
<td>0</td>
</tr>
<tr>
<td>InAs on GaSb (300 K)</td>
<td>0.018</td>
<td>227</td>
<td>0</td>
</tr>
<tr>
<td>InAs on InAs (0 K)</td>
<td>0.024</td>
<td>333</td>
<td>0</td>
</tr>
<tr>
<td>InAs on InAs (300 K)</td>
<td>0.022</td>
<td>276</td>
<td>0</td>
</tr>
<tr>
<td>AISb</td>
<td>0.098</td>
<td>2380</td>
<td>2100</td>
</tr>
</tbody>
</table>

The studied samples were grown by molecular beam epitaxy on $n$-GaSb (100) or $n$-InAs (100) substrates in a RIBER Compact 21 machine equipped with valved cracker cells producing As$_2$ and Sb$_2$ molecules. Structures emitting beyond 4 $\mu$m were grown on InAs substrates, whereas GaSb substrates were used for shorter wavelengths. Formation of InSb-like interfaces between InAs and AISb layers was favored during the growth on GaSb substrates in order to improve lattice matching. For the same reason formation of AISb-like interfaces was forced in the wafers grown on InAs substrates. The structures consisted of ten periods of the active zone enclosed between digital grading regions providing band matching with the buffer and contact layers made of the same material as the substrate. In the case of GaSb substrates, an additional 50-nm-thick $n^+$-InAs contact layer was grown in order to improve ohmic contacts to the surface. For each sample presented in this letter, the period of the structure, extracted from x-ray diffraction rocking curves, corresponded to the desired value with accuracy better than 3%.

The wafers were processed into $160 \times 160 \mu$m$^2$-square deep etched mesas with nonalloyed Cr–Au contacts to the top $n^+$-InAs layer and alloyed In contacts to the $n$-GaSb or $n$-InAs substrate. Device bars with one edge polished at 45° were soldered with In onto copper heat sinks. The measurements were carried out in pulse regime, using typically 200-ns-long current pulses at a repetition rate of 20 kHz. Electroluminescence spectra of the samples were measured from the polished edge of the device bars in step scan regime using a Nicolet Nexus 810 Fourier spectrometer with a cooled InSb detector.

RT emission spectra are presented in Fig. 2. Clear emission peaks are observed down to the wavelength of 2.55 $\mu$m. For all samples, the measured peak energy corresponded to the intersubband transition energy, calculated with the above described band parameters, within 10 meV accuracy. The long wavelength results (samples A and B) are comparable to that reported in Ref. 5. On most devices a second peak is observed at higher energy (650–700 meV for GaSb substrates, 350–380 meV for InAs substrates) due to interband emission in the layers close to the active region, GaSb or InAs depending on the substrate type. The nature of the observed emission bands is clearly identified from their polarization (Fig. 3). The low energy peak is TM polarized (>90%), characteristic of intersubband emission, while the higher energy peak is not polarized, as expected for interband recombination. When temperature is varied from 300 to 80 K, the intersubband peaks shift by about 10 meV according to the band parameter change, while the interband peaks shift by about 60 meV according to the band gap change of InAs or GaSb. In these unipolar devices, the generation of minority carriers (holes) responsible for the interband emiss
mission is certainly due to hot electron related impact ionization. We already observed similar interband recombination in QCL structures, but it did not affect laser performances.

Electrical characteristics are shown in Fig. 4. The samples emitting at 4.5 and 3.1 μm exhibited low differential resistance and maximum current densities of 7 and 8 kA/cm², respectively. In the shorter wavelength devices, which have not yet been optimized, the series resistance is higher. The absolute optical power of the RT intersubband emission was measured after calibration of the Fourier transform infrared detector. For a given current density of 5 kA/cm², it increases from 1 μW for the structure emitting near 4.5 μm to 4 μW for the one emitting at 2.55 μm. We calculated the ratio of emitted power for samples B and D, using the relative change of oscillator strength (f) and excited state lifetime (τ):

\[
\frac{P(2.5 \text{ μm})}{P(4.5 \text{ μm})} = \frac{f \cdot \tau \cdot h\nu(2.5 \text{ μm})}{f \cdot \tau \cdot h\nu(4.5 \text{ μm})} = \frac{41 \times 1.35 \text{ ps} \times 495 \text{ meV}}{27 \times 1.05 \text{ ps} \times 275 \text{ meV}} = 3.5.
\]

While in general a higher energy intersubband transition exhibits a lower oscillator strength, the higher f in sample D is due to the specific design of the structure which involves a more vertical transition than in sample B. Nevertheless, the fair agreement of Eq. (2) with experimental data indicates that there is no extrinsic degradation of the emission efficiency for the high energy intersubband transition involved in sample D.

The emission peak widths have been measured for many samples (Fig. 5). Full widths at half maximum (FWHM) as small as 30 meV were observed for structures emitting at 3 μm. For λ=2.55 μm, the FWHM increased significantly to 57 meV. However, additional experimental data are needed to say whether this value is meaningful or accidental. The contribution of different broadening mechanisms to the linewidth of intersubband emission has been investigated (Fig. 5). The contribution of nonparabolicity to the FWHM has been calculated using the formalism given by Gelmont, Gorfinkel, and Luryi. Despite the large nonparabolicity due to the small band gap of InAs, it only causes a moderate broadening of 10–15 meV. The intrasubband phonon scattering is responsible for a few meV broadening at RT. The larger FWHM measured for short wavelength emission can be related to the increased influence of interfaces in the structures with narrow InAs wells, resulting in fluctuations of the energy level positions and enhanced interface scattering.

The calculated variation of the intersubband transition energy in InAs/AlSb quantum well due to the fluctuation of its width of one atomic monolayer (3 Å) is shown in Fig. 5. The inhomogeneous broadening appears to be a major contribution to the emission linewidth. This finding is not a specific characteristic of the InAs/AlSb system, it is rather due to the small layer thicknesses required to obtain short wavelength emission in general.

In conclusion, we have demonstrated InAs/AlSb quantum cascade structures operating at RT with peak emission wavelength down to 2.55 μm. The study of injection efficiency, emission efficiency, and emission linewidth did not show any degradation in structure performances with decreasing emission wavelength. The obtained results show that there is no fundamental limitation for the realization of InAs/AlSb QCLs down to the 3 μm wavelength range.

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