Far-infrared quantum cascade lasers operating in AlAs phonon reststrahlen band

Keita Ohtani, Mattias Beck, Martin Josef Süess, and Jérôme Faist

Institute for Quantum Electronics, ETH Zurich, Auguste-Piccard-Hof 1, 8093 Zurich, Switzerland

Aaron Maxwell Andrews, Tobias Zederbauer, Hermann Detz, Werner Schrenk, and Gottfried Strasser

Institute of Solid State Electronics and Center for Micro- and Nanostructures, Vienna University of Technology, Floragasse 7, 1040 Vienna, Austria

Supporting Information

Characterization of wavefunction coupling between InGaAs/GaAsSb quantum wells

The wavefunction coupling between quantum wells (QWs) determines carrier transport, lasing energy, and optical gain of QCLs. First we evaluate the wavefunction coupling on InGaAs/GaAsSb QWs since it is a crucial parameter to design the active region structure. Coupled QWs (CQWs) having two different intersubband transitions as depicted in Fig. S1 (a) are suited for this purpose because energies and oscillator strengths of those transitions are dependent on how far wavefunctions penetrate into the adjacent wells. Here three CQWs samples (the left well thickness is 6 nm and the right well thickness is 2.3 nm) having different middle GaAsSb barrier thicknesses (d = 1.4, 1.8, and 2.2 nm thick, respectively) are prepared. Fig. S1 (b) shows intersubband absorption spectrum of one of the three samples. Two absorption peaks are observed, where the lower energy absorption peak is attributed to the intersubband transition from E1 to E2 and the higher energy one is associated with the transition between E1 and E3. The numbers in the parentheses are the computed energies by the Schrödinger and Poisson solver taking into account the depolarization shift. Fig. S1 (d) depicts integrated absorption intensity ratios (I_{12}/I_{13}) of those two peaks. I_{12}/I_{13} is here given by $I_{12}/I_{13} = (E_{12}/E_{13}) \times (z_{12}/z_{13})^2$. The dotted line represents the computed I_{12}/I_{13}. Since the energy ratio of E_{12}/E_{13} from the experiments is in close agreement with the computed ones, within 5% (Fig. S1 (c)), the large discrepancy as seen in Fig. S1 (d) is attributed to the term of $(z_{12}/z_{13})^2$. In those CQWs, a thicker middle barrier makes the states (E_1, E_2, and E_3) localized, leading to an increase of z_{13} and a reduction of z_{12}. Hence, the larger $(z_{12}/z_{13})^2$ experimentally observed reveals that the actual wavefunctions must penetrate into the adjacent wells. In order to compensate the difference, we increase the barrier thicknesses, in particular, for thicker barriers, compared to the nominal value by a factor of 10-20% as follows:

(Designed structure) **4.0**/5.4/**0.55**/8.6/**0.75**/8.2/**0.75**/8.1/**0.8**/7.1/**0.9**/6.1/**1.4**/6.4/**2.6**/7.2

(Grown structure) **4.8**/5.4/**0.55**/8.6/**0.75**/8.2/**0.75**/8.1/**0.85**/7.1/**1.05**/6.1/**1.6**/6.4/**3.0**/7.2

Here the layer sequence is started from the injection barrier and the GaAsSb barriers are in bold.

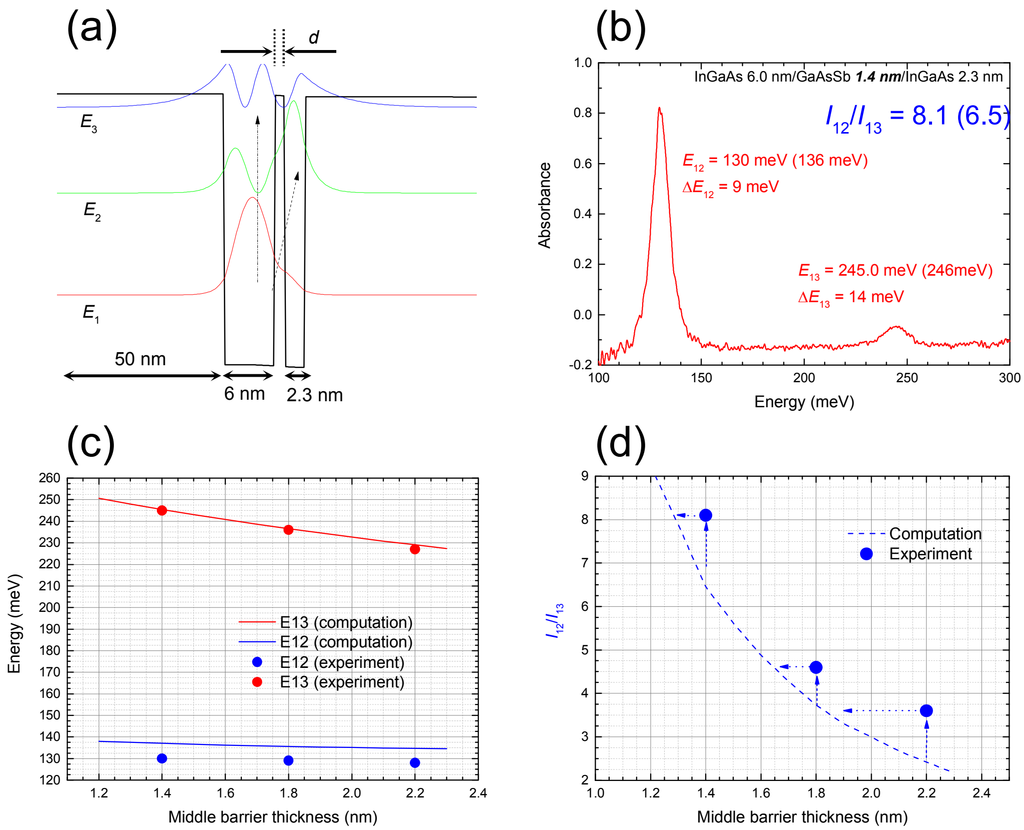
(a)
d
E_3
E_2
E_1
50 nm
6 nm
2.3 nm
(b)
InGaAs 6.0 nm/GaAsSb 1.4 nm/InGaAs 2.3 nm
I_{12}/I_{13} = 8.1 (6.5)
E_{12} = 130 meV (136 meV)
ΔE_{12} = 9 meV
E_{13} = 245.0 meV (246meV)
ΔE_{13} = 14 meV
Absorbance
Energy (meV)
(c)
Energy (meV)
E13 (computation)
E12 (computation)
E12 (experiment)
E13 (experiment)
Middle barrier thickness (nm)
(d)
I_{12}/I_{13}
Computation
Experiment
Middle barrier thickness (nm)

Fig. S1