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Intersubband electroluminescence in InAs/GaSb/AlSb type-II cascade structures

K. Ohtani[a] and H. Ohno
Laboratory for Electronic Intelligent Systems, Research Institute of Electrical Communication, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan

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Intersubband electroluminescence in InAs quantum wells embedded in InAs/GaSb/AlSb type-II cascade structures is reported. The observed emission energy is in good agreement with calculation based on the multiband $k \cdot p$ theory. Dominant polarization of the emitted light is perpendicular to the quantum well layers. Difference in the spectrum shape between intersubband and interband cascade transitions is also presented. © *1999 American Institute of Physics.*
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Making use of carriers that undergo the same optical transitions a number of times (carrier recycling), quantum cascade lasers (QCL) realized coherent optical emission with a wide spectrum range from mid- to far-infrared using *intersubband* optical transitions in type-I heterostructure systems such as AlInAs/GaInAs.[1,2] The wavelength range covered by QCLs includes the atmospheric windows (3–5 and 8–13 μm) important for gas sensing and environment monitoring applications. High-power continuous-wave operation (~5 and 8 μm, ~200 mW/facet) has been achieved at 80 K.[3,4] Using type-II broken gap InAs/GaInSb quantum wells (QWs), *interband* cascade laser (ICL), proposed by Yang,[5] was demonstrated experimentally by Lin *et al.*[6] While keeping the advantage of carrier recycling, nonradiative relaxation due to polar optical phonon scattering, which is believed to be responsible for the high threshold current density in type-I QCLs, can be reduced in ICLs. ICLs with external efficiency of >200%[7] and near room temperature operation[8] have been reported.

The light source based on *intersubband* transition in type-II heterostructures proposed in Refs. 9–14 offers a number of advantages over QCL and ICL. The type-II structure shown in Fig. 1 blocks electrons injected into the excited state in the InAs QW by the adjacent GaSb band gap as in the InAs/GaSb ICLs, reducing the leakage current path present in type-I QCLs. The injected electrons can be extracted efficiently from the ground state after intersubband transition by interband tunneling through the InAs/GaSb broken gap. A recent theoretical appraisal of Sb-based intersubband lasers[13,14] showed that, since a small effective mass of InAs QW reduces the optical phonon relaxation rate of excited state and increases the oscillator strength of intersubband transition, the threshold current can be as low as 750 A/cm^2 at 300 K. This is almost a factor of 4 lower than the theoretical prediction for the 5 μm type-I InGaAs/AlInAs QCLs.[14] Moreover, compared to ICL, gain spectrum will be narrower and more symmetric due to the joint density of state which becomes delta-function like, and hence much less sensitive to the thermal broadening of electron distribution. In this letter, we report the first observation of mid-infrared *intersubband* electroluminescence in InAs/GaSb/AlSb type-II quantum cascade structures.

Figure 1 illustrates the band diagram of type-II intersubband quantum cascade structure (ISBQC) and its principle of operation. Under forward bias, electrons are injected from an injector into the excited state (E2) of the InAs QW. The direct tunneling path from E2 to the collector can be considerably reduced by the presence of adjacent GaSb band gap. The electrons at E2 undergo intersubband transition (radiative and nonradiative) and relax to the ground state (E1), which is designed to reside in the InAs/GaSb broken gap. The relaxed electrons tunnel to the collector through a GaSb QW and a thin AlSb barrier via interband tunneling. The collector acts as an injector for the next QW. Because of the presence of the InAs/GaSb broken gap at the interface, the lifetime of the E1 state can be made sufficiently small, which ensures fast extraction of carriers from QW to collector.

The ISBQC structures were grown on undoped InAs(100) substrates by a solid source molecular beam epitaxy system equipped with a compound As cell and a cracking Sb cell. After growth of 700 nm Si-doped ($3 \times 10^{17}\,\mathrm{cm}^{-3}$) n-type InAs as a bottom contact layer, 10 periods of injector structures and active layers were grown. The injector structure consisted of digitally graded InAs/AlSb superlattices in which the InAs layers were Si doped to $n = 2 \times 10^{17}\,\mathrm{cm}^{-3}$. The active layer consisted of an InAs/GaSb coupled QW which was made of 10 ML AlSb barrier, 30 ML

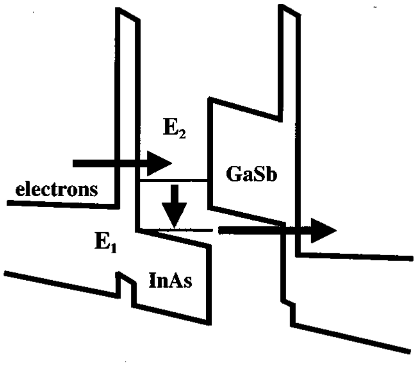

FIG. 1. Schematic band diagram of InAs/GaSb/AlSb type-II intersubband quantum cascade structure.

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[a] Electronic mail: keita@riec.tohoku.ac.jp

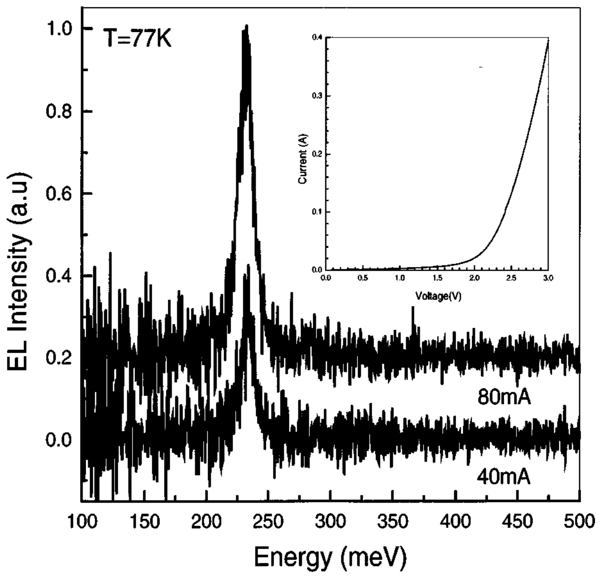

FIG. 2. Electroluminescence spectrum at ~77 K for injection current of 40 and 80 mA. Inset: Current–voltage characteristics at ~77 K of intersubband cascade structure. The mesa area is 300 μm×300 μm.

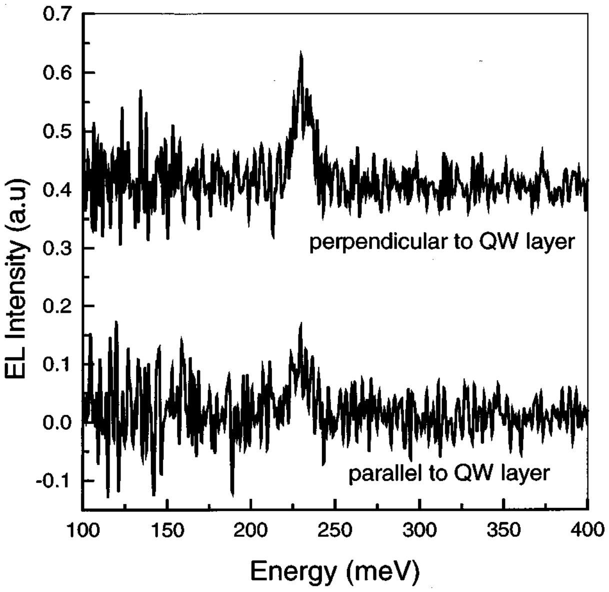

FIG. 3. Polarized electroluminescence spectrum at ~77 K for injection current of 80 mA.

InAs quantum well, 25 ML GaSb quantum well, and 5 ML AlSb barrier. Two alternate structures which had either a thicker InAs well (37 ML) or a thicker GaSb well (50 ML) were also grown. The ground state of light hole (LH1) in the GaSb QW is designed to lie lower than E1 in the InAs QW under a moderate bias using calculation based on the multiband $k\cdot p$ theory,[15] i.e., no anticrossing between E1 and LH1 is expected in the present bias conditions. After growth of the injector/active layer structures, 200 nm Si-doped ($3\times10^{17}\,\mathrm{cm}^{-3}$) InAs layer was grown as a top contact layer. All layers were grown at 420 °C. During growth of injector and active layers, the InAs growth rate was reduced to 0.2 ML/s and the As pressure was kept minimum to yield the group-V stable condition in order to prevent the As incorporation in Sb-based layers. The V/III beam equivalence pressure ratio was 5.5 for InAs growth and 2.5 for GaSb growth.

The grown sample was processed into 300 μm×300 μm mesa by wet etching and photolithography. Nonalloyed Cr/Au ohmic contacts were deposited on both top and bottom contact layers. The sample edge was then polished 45° wedge for light emission and mounted on to a copper cold finger of a cryostat which could cool the sample down to about 77 K. The electroluminescence measurement was performed with a rapid scan Fourier transform infrared (FTIR) spectrometer (Bio-Rad FTS-60A) using lock-in detection technique with the resolution of 4 cm^{-1}.[16] A liquid-nitrogen cooled HgCdTe detector was used for the detection. A polarizer was inserted in the optical path to verify the polarization of the emission. Current pulse at 15 kHz with duty cycle of 50% was used for electroluminescence measurements.

Typical current–voltage characteristics at ~77 K is shown in the inset of Fig. 2. The injector blocks the current up to a bias of ~2.2 V above which the alignment of injectors leads to current flow. Figure 2 shows the electroluminescence spectra at ~77 K under two different current biasing conditions. An emission peak was observed at 233 meV, corresponding to the wavelength of 5.6 μm with full-width at half-maximum (FWHM) being ~14 meV. The emission energy is in close agreement with the transition energy (218 meV) between E1 and E2 of InAs QW calculated using a multiband $k\cdot p$ theory. The emission of samples with 37 ML InAs was observed at 186 meV, which again agrees well with the calculation (170 meV). Changing the GaSb thickness to 50 ML did not alter the emission energy by more than 3 meV. Compared to the large blue shift reported previously for the interband quantum cascade (IBQC) structures,[17] the position of the peak shows a shift toward red with increasing injection current. This red shift may be interpreted as a Stark effect in InAs QW, where the ground state in a triangular potential well is pushed to higher energy while the energy increase of the excited state shows only a small second order shift.

Figure 3 shows polarization resolved electroluminescence spectra; light polarized perpendicular or parallel to the quantum well layer. The spectrum is polarized mostly perpendicular to the layer, which shows that the light emission is from the intersubband optical transition. The same measurements done for IBQC structures showed almost the same intensity for both polarization directions. The selection rule derived from the multiband $k\cdot p$ theory shows that the polarization characteristic to the intersubband transition is preserved in a low band-gap semiconductor such as InAs, where band mixing is appreciable, if the energy separation of E1 and E2 is small compared to the band gap.[15,18] This was verified by absorption measurements in the InAs/AlSb QWs.[18]

Figure 4 compares the emission spectra from an IBQC structure and that from the ISBQC structure (Fig. 2, 80 mA), both made of InAs/GaSb system. The IBQC structure was designed to give almost the same energy of light emission as that of the ISBQC structure. The light emission from the IBQC structure was collected from the sample surface. Emission from the IBQC structure results in wider FWHM of 37 meV with asymmetric shape compared to that from the IS-

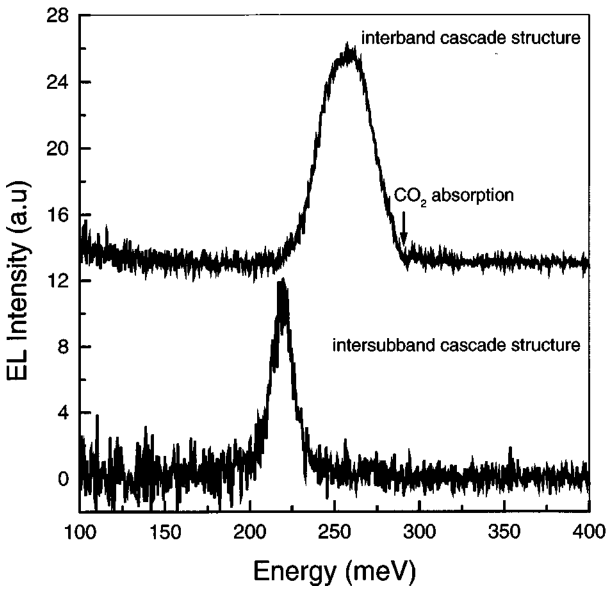

FIG. 4. Electroluminescence spectrum of the interband cascade structure and the intersubband cascade structure at ~77 K for the same injection current density. The mesa area is the same for both samples. Light was collected from the surface in the case of the interband cascade light emitting diode, whereas 45° waveguide structure was used for the intersubband cascade diode.

BQC structure. The origin of the difference could be due to a combined effect of the thermal distribution of carriers in the bands that have opposite dispersion and the layer thickness fluctuation. The narrower wells (IBQC structure, 13 ML) are more susceptible to the thickness fluctuation than the thicker wells (ISBQC structure, 30 ML). Because of the difference in the collection geometries, it is difficult to discuss about the intensity difference between the two structures at the present stage.

In conclusion, we have described the first observation of *intersubband* electroluminescence from InAs/GaSb/AlSb type-II cascade structures. The emission energies were in good agreement with the multiband $k \cdot p$ calculation. The spectrum was dominantly polarized perpendicular to QW layer and the emission spectrum was nearly symmetric. The FWHM was narrower than that of interband cascade light emitting diodes.

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