Extended Abstracts of the 2004 International Conference on Solid State Devices and Materials, Tokyo, 2004, pp. 914-915

H-7-2

InAs Quantum Cascade Lasers Based on Coupled Quantum Well Structures

K. Ohtani*, K. Fujita and H. Ohno

Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University
Katahira 2-1-1, Aoba-ku, Sendai, Miyagi 980-8577, Japan
*PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama, Japan
E-mail: keita@riec.tohoku.ac.jp

1. Introduction

The properties of InAs/AlSb/GaSb quantum well (QW) structures are advantageous for the high performance intersubband quantum cascade lasers (QCLs) [1]. Its high conduction-band offset energy of 2.1eV offers widely tunable intersubband emission energies [2]. A large optical gain can be expected due to an increased optical dipole matrix element and a small nonradiative relaxation rate [3, 4]. The fast carrier depopulation from the ground state as well as the large oscillator strength is an essential ingredient to achieve efficient population inversion. We reported the first operation of InAs/AlSb QCLs employing carrier depopulation via intra-miniband scattering [5]. Here we present results on InAs/AlGaSb QCLs using the carrier depopulation from the ground state via resonant intersubband longitudinal optical (LO) phonon scattering. In order to make the subband energy spacing comparable to the InAs LO phonon energy to ensure ultrafast intersubband scattering time, InAs/AlGaSb coupled QW structures are employed as active layers.

2. Active Region Design

Fig. 1 shows a conduction band diagram of the injector/active/injector layers in the active region of the device under an electric field of 40kV/cm. In order to make the subband energy spacing between anti-symmetric (E_2) and symmetric (E_1) states comparable to the LO phonon energy, we use $Al_{0.2}Ga_{0.8}Sb$ as a middle barrier of coupled QWs. Since the conduction band offset energy between InAs and $Al_{0.2}Ga_{0.8}Sb$ is about two times smaller than that between InAs and AlSb, the energy difference between E_1 and E_2 can be increased up to the InAs LO phonon energy. The designed coupled QW active layer is composed of 11.1nm InAs well, 0.6nm AlGaSb barrier, and 10.5nm InAs well layers in which the subband energy spacing between E_1 and E_2 (33meV) is in close agreement with the InAs LO phonon energy (32meV). The injection layers are composed of modulation-doped InAs/AlSb superlattice. Two InAs wells in this superlattice are Si-doped to $n=2.5\times10^{17}cm^{-3}$. The active region consists of 50-repeated injection/active layers.

3. Molecular Beam Epitaxy Growth

InAs/AlGaSb QCLs are grown on n-InAs (100) substrates by a molecular beam epitaxy (MBE) system equipped with an As valved cracker cell and an Sb cracker cell. An InAs double plasmon waveguide structure is used for the optical confinement [6, 7]. After the surface oxide removal, a 1.0μm bottom high-doped n-InAs cladding region ($3\times10^{18}cm^{-3}$) is grown. The active region is sandwiched between two 3.5μm low-doped n-InAs core regions ($2\times10^{16}cm^{-3}$). Total thickness of the region is 2.6μm. After growth of the top low-doped n-InAs core region, a 1.0μm top high-doped n-InAs cladding region ($3\times10^{18}cm^{-3}$) is grown. During the MBE growth, the substrate temperature is kept at 410°C. The V/III beam equivalence pressure ratio for the active region is 5 for both InAs growth and AlGaSb growth. In order to decrease strain associated with lattice mismatch, AlAs interface bonds are adopted at each interface by controlling the shutter sequence. After growth, the sample is processed into 25μm-wide ridge laser structures using wet etching and photolithography. The laser structures are then cleaved into 1-2.5mm bars and the cleaved facets are left uncoated. The emission measurements are performed with a step-scan Fourier transform infrared (FT-IR) spectrometer.

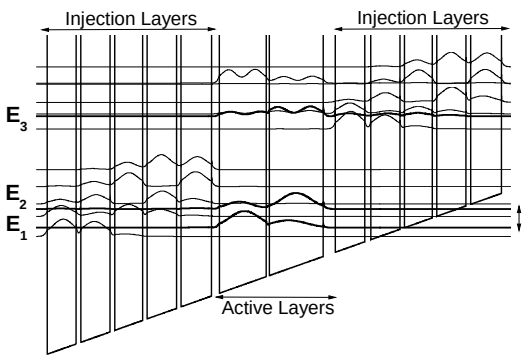

Fig. 1 Schematic conduction band diagram of injection/active/injection layers under the electric fields of 40kV/cm. The active layers consist of InAs/AlGaSb coupled QW.

4. Lasing Properties

Fig. 2 shows the emission spectra of the 1.0mm-long device at 80K. Electroluminescence spectra below threshold are included for comparison. Three intersubband emission peaks are observed at 126meV, 142meV, and 177meV. The two emission peaks (177meV and 142meV) at the higher energy side correspond to the intersubband

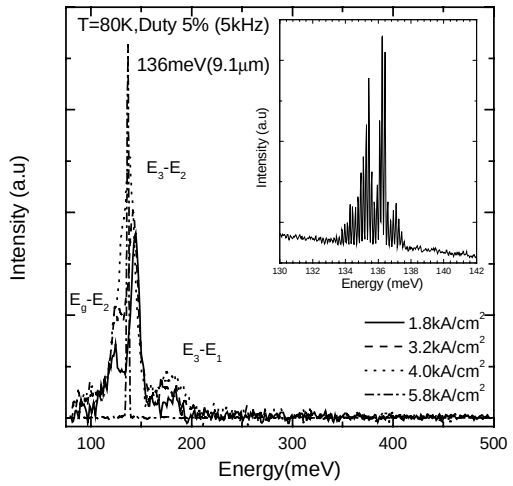

Fig. 2 Emission spectra of the 1.0mm-long device measured at 80K. The inset shows the high-resolution laser emission spectrum taken using the rapid-scan FT-IR.

emission from E_3 to E_1 and from E_3 to E_2, respectively. The observed subband energy spacing between E_1 and E_2 (35meV) is in close agreement with the InAs LO phonon energy. The emission at the lower energy side is attributed to the emission from the ground state in the injection layer and E_2. By increasing the current density, the emission intensity from E_3 to E_2 increases and above threshold, the line narrowing of the emission spectra is observed being a direct evidence of the laser action. The observed threshold current density is 5.4kA/cm^2. The laser emission is multi-mode with the peak energy around 136meV corresponding to the wavelength of 9.1μm. Both electroluminescence and laser emission are polarized normal to the layers, consistent with the intersubband

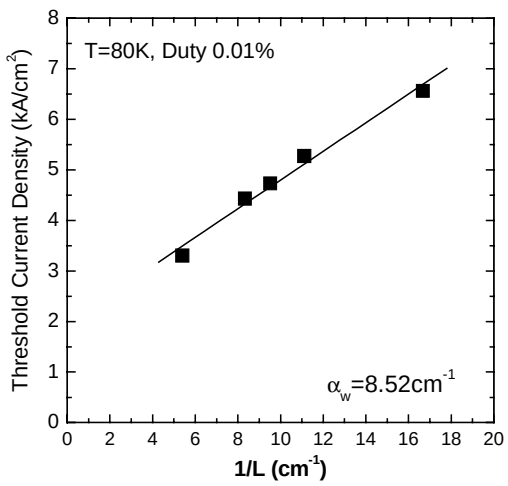

Fig. 3 Threshold current density versus reciprocal cavity length. The waveguide loss at 80K is measured at 8.52cm^{-1}.

selection rule. The maximum operation temperature of this device is 160K.

In order to investigate the waveguide loss of the InAs double plasmon waveguide, the reciprocal cavity length dependence on the threshold current density is measured. Fig. 3 shows the threshold current density versus the reciprocal cavity length at 80K. The mirror loss is derived from the measured effective refractive index. From the slope and the intercept of the straight line, the waveguide loss is measured at 8.52cm^{-1}. The observed waveguide loss is smaller than that of the GaAs-based double plasmon waveguide operating at the same wavelength region. This value is slightly smaller than that of the calculated value (12cm^{-1}), which is might due to the overestimation of the InAs free carrier scattering time.

5. Conclusions

We have reported the operation of InAs-based quantum cascade lasers based on InAs/AlGaSb coupled QW active layers. The intersubband scattering via resonant LO phonon emission is used for carrier depopulation from the ground state. The observed minimum threshold current density is 3.6kA/cm^2, which is smaller than that of the first InAs/AlSb quantum cascade laser. The maximum operation temperature is 160K. The measured waveguide loss is 8.52cm^{-1}, which is smaller than that of GaAs-based double plasmon waveguide operating at the same wavelength region.

Acknowledgements

This work is partly supported by Grant-in-Aids from MEXT and Creative Scientific Research and Telecommunications Advancement Organization (TAO) of Japan.

References

[1] H. Ohno, L. Esaki, and E. E. Mendez, Appl. Phys. Lett. **60**. 3153 (1992)

[2] K. Ohtani, N. Matsumoto, H. Sakuma, and H. Ohno, Appl. Phys. Lett. **82**, 37 (2003)

[3] J. L. Jimenez and E. E. Mendez, Solid. State. Commun. 110, 537 (1999)

[4] I. Vurgaftman, J. R. Meyer, F. H. Julien, L. R. Ram-Mohan, Appl. Phys. Lett. 73, 711 (1999)

[5] K. Ohtani and H. Ohno, Appl. Phys. Lett. **82**, 1003 (2003)

[6] K. Ohtani, H. Sakuma, and H. Ohno, J. Crystal. Growth, **251**, 718 (2003)

[7] C. Sirtori, P. Kruck, S. Barbieri, H. Page, J. Nagle, M. Beck, J. Faist, U. Oesterle, Appl. Phys. Lett. **75**, 3911 (1999)