Design and Fabrication of Quantum Cascade Laser Structure based on III-Nitride Semiconductors in the THz Frequency Range

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***Abstract*—We performed the design and fabrication of a resonant phonon-type quantum cascade structure using III-Nitride semiconductors for emission in the 5 to 12 terahertz frequency range. We could design a quantum cascade structure in which population inversion could be obtained by making calculations based on a self-consistent rate equation model. We also successfully fabricated the designed quantum cascade structure by radio-frequency molecular beam epitaxy.**

I. Introduction And Background

Since the first demonstration of the terahertz (THz) quantum cascade laser (QCL) [1], THz-QCL device have received much attention in view of their potential for compact, high power, narrow line-width and continuous wave operable THz light sources. Up to now, the operating range of THz-QCL based structures on III-V compound semiconductors such as GaAs, InSb and InP (which are the main materials that are utilized for QCL devices at present) has been limited to the 4.8 to 1.2 THz range [2, 3] and further expansion of the operating frequency range, that is, operation at frequencies below 1 THz and from 5 to 12 THz [4], is now being demanded. However, we consider that it is difficult in principle for III-V compounds to operate in the 5-12 THz range, because this frequency region is just in the phonon domain for these materials, which means that non-radiative recombination is centered by electron-longitudinal (e-LO) phonon resonant scattering. On the other hand, if we could make use of III-Nitride semiconductors as QCL materials, it would be possible to operate at frequencies which include the 5-12 THz regime, because these compounds have much larger LO phonon energies (> 18 THz) than 'conventional' III-V compounds.

In this paper, to investigate the possibility of using III-Nitride semiconductors as THz-QCL materials, we designed a nitride-based QC structure and its subband populations were calculated using a self-consistent rate equation model. Further, we then fabricated such a QC structure experimentally.

II. Results

The target design for the QC structure is a resonant phonon (R.P.)-type one, which directly uses LO-phonons for the fast depopulation of electrons into the lower state level. The materials that we used were GaN for the quantum wells and quaternary $In_{0.05}Al_{0.23}Ga_{0.72}N$ alloys for the barriers; this alloy is well lattice-matched to GaN, and so minimizes the introduction of new defects into the growth. Starting from these considerations, we performed the design of a QC structure that was tuned for emission at 7.6 THz by adjusting the thicknesses and the voltage bias. The electron energies and wave functions

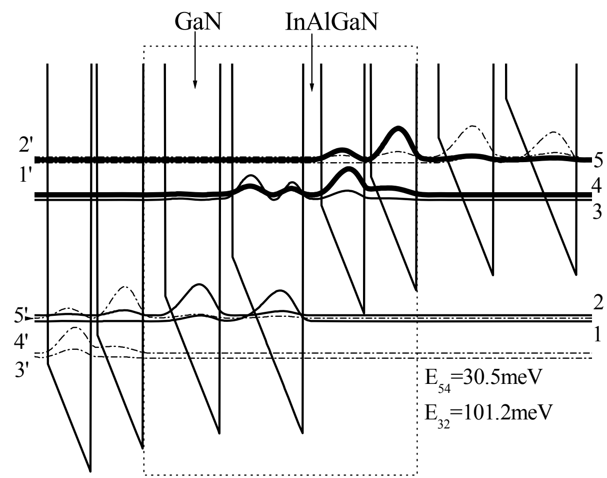

Fig. 1. Conduction band profile and associated square-wave functions for an R.P. type 7.6 THz emission QC structure biased at 60 kV/cm. The layer sequence for one period of the structure (in Angstroms) is **18**/47/**10**/60/**15**/37/**5**/39, beginning from the left in the LO phonon scattering region. The normal and bold scripts denote the wells and the barriers, respectively.

were obtained by solving the Schrödinger equation within the envelope function and the effective mass approximation. Figure 1 shows the designed conduction band profile and associated square wave functions for the two periods. One period consists of a four-quantum-well module structure. The index indicates individual subband levels which contribute to electron scattering. Electrons, which are injected from n = 1' and 2' into n = 5, make a vertical optical transition into n = 4 (highlighted with thicker lines). Resonant depopulation of electrons by LO phonons is performed at the subband levels between n = 4 and 3, and n = 2 and 1, because these inter-subband energies are only slightly above the LO phonon energy of the materials (~90 meV). Next, we calculated every sub-band population by solving the self-consistent rate equation model. In the calculation of the electron scattering rates, we considered electron-electron (e-e) and/or e-LO scattering interactions for the inter-subband emission processes. In the calculation of the e-LO scattering processes, an approximation to bulk LO-phonon mode was used, because the properties of the well and barrier were almost the same [5]. The values of temperature T and sheet carrier density N_s were set to 10 K and 3.0×10^{10} cm^{-2}, respectively. The required condition for population inversion in this case is $n_5 > n_4$ under equilibrium conditions. Table I shows the populations of the individual levels in the QC structure shown in Fig. 1. It clearly indicates

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Table I. Population of the individual levels in the designed QC structure, calculated at T = 10 K and $N_s = 3.0 \times 10^{10}$ cm^{-2} with e-e and e-LO scatterings.

Subband Index	Energy (meV)	Population (10^9 cm^{-2})
1	0.00	6.688
2	5.12	7.748
3	106.24	0.133
4	110.80	0.993
5	141.32	14.437

that population inversion of $\Delta n = 1.3 \times 10^{10}$ cm^{-2} would be obtained. The calculated lifetimes of τ_{54} and τ_4 were 1.0 ps and 70.2 fs, respectively.

Before fabricating the QC structure, we studied radio-frequency molecular beam epitaxy (RF-MBE)-grown quaternary InAlGaN alloys in terms of compositional control. The same approach as that used for metal organic chemical vapor deposition (MOCVD)-grown quaternary InAlGaN alloys [6] was adopted for the growth of the InAlGaN, that is, a self-composition control method for InN by controlling growth temperature, which utilizes the high equilibrium vapor pressure properties of InN. The growth conditions for the InAlGaN were kept unchanged, except for the growth temperature. Figure 2 shows a series of x-ray diffraction (XRD) (0002)-plane 2θ–ω scans for InAlGaN grown at different growth temperatures and that of AlGaN in the case where there was no In irradiation, as a reference. Every composition for these samples was estimated by XRD fitting. It is shown in Fig. 2 that the InAlGaN diffraction peaks shift toward lower angles with decreasing the growth temperature, which means that the InN composition in

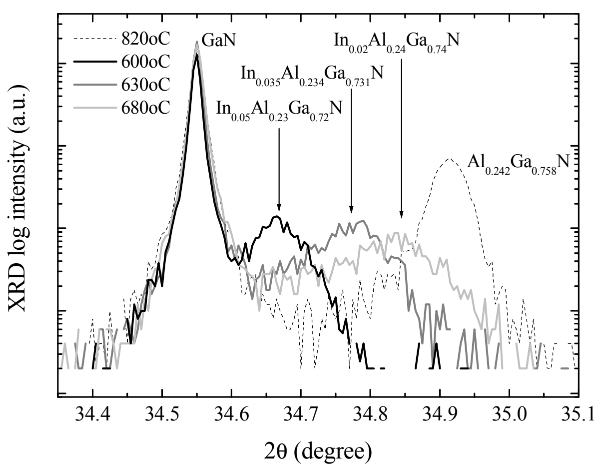

Fig. 2. XRD (0002)-plane 2θ–ω scans for quaternary InAlGaN grown at temperatures ranging from 680 to 600 °C. As a reference, the spectrum of a ternary AlGaN alloy (i.e. the case of no In irradiation) grown at a temperature of 820 °C is also included.

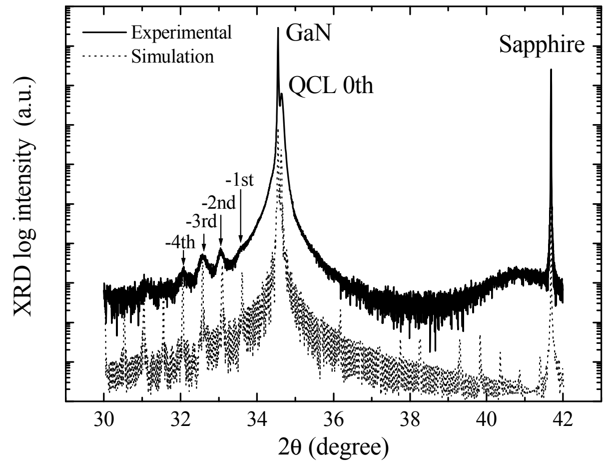

Fig. 3. XRD (0002)-plane 2θ–ω scan and simulation spectra for the $GaN/In_{0.05}Al_{0.23}Ga_{0.72}N$ QC structure. The solid and broken lines denote experimental and simulated results, respectively.

the InAlGaN is increasing. In this study, the desired composition for InAlGaN, i.e., $In_{0.05}Al_{0.23}Ga_{0.72}N$ was obtained at a growth temperature of 600 °C.

Finally, we tried fabricating a QC structure based on our design rules. A "50-pairs" QC structure was grown on an MOCVD-grown GaN template by RF-MBE. The growth temperature in the QC structure was set to the same conditions as those used for the quaternary InAlGaN alloy growth.

Figure 3 shows the XRD (0002)-plane 2θ-ω scan and the simulation spectra for the QC structure. Clear satellite peaks up to 4th order can be observed, which were in agreement with the simulation spectrum. We successfully fabricated the designed QC structure.

III. Conclusion

In summary, we have performed the design and fabrication of a QC structure based on nitride semiconductors for the realization of THz-QCL, including the unexplored frequency range from 5 to 12 THz. We successfully designed and fabricated an R.P.-type QC structure emitting at 7.6 THz, in which population inversion could be obtained. These results indicate that III-Nitride semiconductors would be promising materials for THz-QCL.

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