Terahertz quantum cascade laser using AlGaAs wells for higher-temperature operation

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INTRODUCTION

Remarkable progress on terahertz quantum cascade lasers (THz-QCLs) has been made using GaAs/$Al_xGa_{1-x}As$ multi-quantum-well structures. However, the maximum operation temperature was limited to 200 K. Realization of room-temperature operation of THz-QCLs is remained as a challenging issue. The main degradation mechanism of population inversions at high temperatures is thought to be thermally activated longitudinal optical (LO) phonon scattering [1, 2], where electrons in the upper lasing level 3 acquire sufficient in-plane kinetic energy to emit LO phonons and relax to the lower lasing level 2 as depicted in Fig. 1. To reduce the thermally activated phonon scattering, use of AlGaAs instead of GaAs as the well material might be promising because the LO phonon energy of AlAs-like modes is higher than that of GaAs-like modes [3]. In this study, we calculated the performance of an $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ THz-QCL using the non-equilibrium Green's function (NEGF) method to find an appropriate Al composition of well layers for higher-temperature operations.

RESUTLTS AND DISCUSSIONS

Details of our NEGF calculation method were explained elsewhere [4, 5]. The Fröhlich interaction Hamiltonian was used for the self-energy of the LO phonon-electron coupling. The self-energy for the LO phonon scattering in $Al_xGa_{1-x}As$ layers was introduced as linear combinations of those in GaAs layers and AlAs layers as expressed in equation 1.

$$\Sigma_{\mathrm{LO(Al_xGa_{1-x}As)}} = x\Sigma_{\mathrm{LO(AlAs)}} + (1-x)\Sigma_{\mathrm{LO(GaAs)}} \qquad (1)$$

One period of the calculated THz-QCL sequence is **5.1**/9.6/**2.3**/7.3/**4.0**/15.8 nm as shown in Fig. 2. The bold and regular numbers represent quantum barrier and well layers, respectively. The 15.8-nm-thick quantum well is n-doped with $n = 1.9 \times 10^{16}$ cm^{-3}. Only the Γ-valley electron states are taken into consideration for simplicity. The conduction band discontinuity, the LO phonon energies of GaAs-like and AlAs-like modes are set to be constant as 120, 36, and 46 meV, respectively.

Figure 3 shows the optical gain averaged over one period of the THz-QCL at 200 K. The gain for the $Al_{0.85}Ga_{0.15}As$/AlAs QCL increased as much as 17 cm^{-1} at 12 meV (2.9 THz). Figure 4 shows the electron distributions in the active region as a function of energy. The distribution curve has a dip around 160 meV, which is caused by the thermally activated phonon scattering due to the GaAs-like LO phonon mode. For the $Al_{0.85}Ga_{0.15}As$/AlAs THz-QCL, the dip becomes small and the other dip appears around 170 meV, which corresponds to the thermally activated phonon scattering by the AlAs-like LO phonon mode. Further calculations and designs should be made including X-valley electron states.

CONCLUSION

We investigated the performance of an $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ THz-QCL by using the NEGF method to realize higher-temperature operations. We found that the optical gain improved by using $Al_{0.85}Ga_{0.15}As$ wells due to the reduction of the thermally activated phonon scattering by GaAs-like LO phonons.

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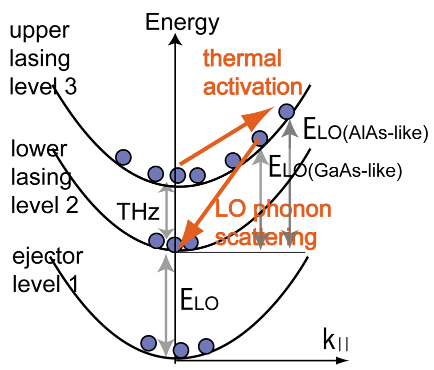

Fig. 1. Schematic of thermally activated LO phonon scattering.

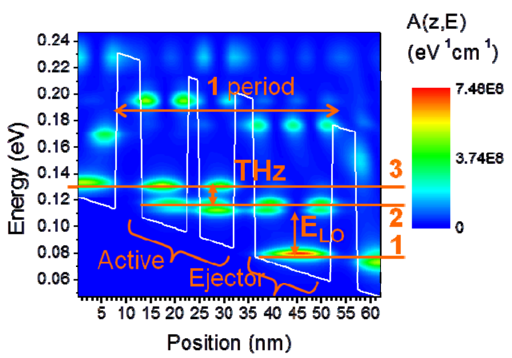

Fig. 2. Conduction band diagram and spectral functions *A*(*z*, *E*) of the calculated THz-QCL at 12 kV/cm.

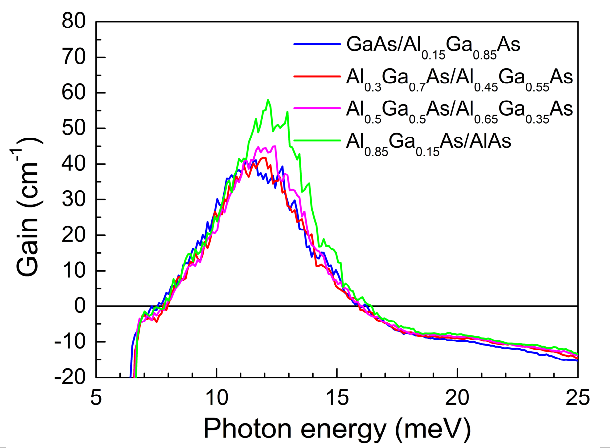

Fig. 3. Calculated gain averaged over one period of the THz-QCL structure at 200 K. The Al composition of wells was changed from 0 to 0.85.

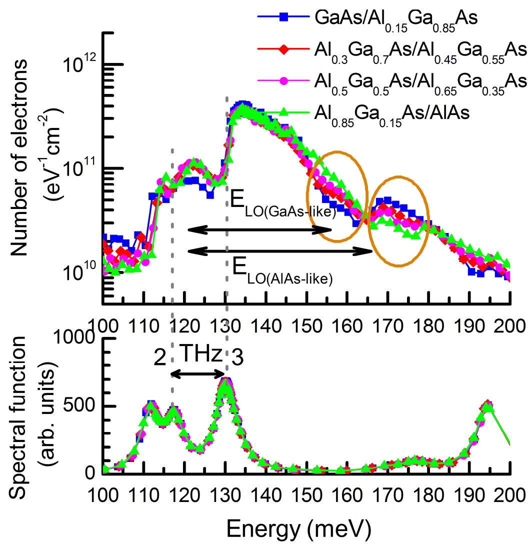

Fig. 4. Calculated electron distributions and spectral functions in the active region at 200 K.