論文内容の要旨

論文題目　Fabrication and Characterization of GaAs-based Mid-Infrared Quantum Cascade Lasers with Coupled Microcavity Structures
(結合微小共振器構造を有する GaAs 系中赤外量子カスケードレーザの作製と評価)

氏名　若山 雄貴

Quantum cascade lasers (QCLs) are unipolar lasers based on intersubband transition (ISBT) in a multi-quantum-well heterostructure, which enable one to obtain lasing action at wide spectral range from mid-infrared to THz region. QCLs have been much developed during the past fifteen years after their first demonstration. This rapid progress is mostly due to the quickly advancing understanding of how 'band-structure engineering', which means designing quantum well and barrier thicknesses and band-offset, can be most successfully used to control the electron flow and thus increase population inversion.

At present, QCLs seem to have reached their mature state, at least in the mid-infrared region. Therefore, the band-structure engineering as a driving force for major performance improvements will have diminishing returns. However, there are still a room to make improvements in areas such as high power single mode lasers, wide-tunable single mode lasers, and QCL-based functional devices, such as optical modulators, amplifiers, and switching devices. In order to develop these devices, not only traditional approaches based on band-structure engineering, but also new approaches to efficiently manipulate photons are required.

One of the promising ways to develop high-functional intersubband devices is to utilize novel cavity structures, such as microcavities and coupled cavities. The microcavities enable single-mode operation, allow easy monolithic integration of the lasers with other components, and have very low energy consumption owing to their small sizes. Moreover, it is possible to achieve switching operation of lasing wavelength in the coupled cavity structures.

When these cavity structures are to be applied to QCLs, it is necessary to deeply understand the unique electrical and optical characteristics of QCLs caused by intersubband carrier relaxations and optical transitions. Objectives of this thesis are to investigate the effects of the exploitation of the microcavity structures and the couple cavity structures on the characteristics of the intersubband lasers, and to develop the performance of mid-infrared QCLs with these cavity structures.

This thesis presents original research work on design, fabrication, and characterization of mid-infrared QCLs with these cavity structures. It is organized into eight chapters. Chapters 1-3 give fundamentals of this thesis. Chapter 1 presents the research background and thesis objectives. In Chapter 2, basics of ISBT in quantum wells and its applications, especially to intersubband lasers are introduced. Chapter 3 describes calculation methods for electronic properties in quantum cascade structures, such as energy levels, carrier scattering times, and optical dipole matrix elements. Calculation methods for optical properties of the cavity structures, such as resonant frequencies, Q-factors, and field distributions are also introduced in this chapter.

In Chapter 4, crystal growth, fabrication, and characterization methods and experimental results on fundamental characteristics of the ridge waveduide lasers are described. Details on the crystal growth by molecular beam epitaxy (MBE) and analysis of the grown wafers by X-ray diffractometer (XRD) and scanning electrical microscope (SEM) are given. Methods to precisely control layer thickness, composition, interface roughness, and doping density are also presented. Then the fabrication processes of ridge-waveguide cavity structures by photolithography, wet-etching, sputtering deposition of dielectric material, metal deposition, thinning of wafer, and wire-bonding are described in details. Finally, electrical properties, output power characteristics, and emission spectrum of the pulsed operated ridge waveguide QCLs are given. The emission from the devices is detected by mercury cadmium telluride (MCT) detector and lock-in amplifier technique. Lasing spectra are measured by Fourier transformed infrared spectroscopy. Demonstration of room temperature lasing operation around $\lambda \sim 11.5\ \mu m$ is shown.

Chapter 5 concerns two-segment ridge waveguide QCLs. The objective of this chapter is to investigate the possibility of realization of intra-cavity optical power modulation and bistable operation utilizing intersubband absorption property in two-segment QCLs. When the reverse bias voltages are applied to one of the two cavities with smaller size while keeping the longer cavity lased, output power is clearly attenuated. Dependence of absorption coefficient in the quantum cascade structure on applied reverse bias voltage is calculated and showed that the absorption coefficient strongly depends on the bias voltage. The reason is related to quantum-confined Stark effect. This calculation result reveals that the optical power attenuation is caused by the intersubband absorption. Feasibility of QCL-based bistable devices utilizing the saturable intersubband absorption properties is discussed. It is also numerically shown that it is possible to realize QCL-based bistable devices by using two-segment cavity structures, although the condition is strict due to intraband ultra-fast carrier relaxation processes.

Chapter 6 presents experimental results on ridge-waveguide QCLs coupled with microcylindrical cavity. Compared with the coupled cavity structure presented in the previous chapter, one cavity is replaced by the microcylindrical-shaped two-dimensional cavity and is located close to the one-dimensional ridge-waveguide cavity. First half of this chapter gives the evidence of mode-coupling between two cavities and the latter half presents a demonstration of mode-switching over wide-spectral range. Several samples with different spacing between the two cavities are investigated to optimize the cavity spacing. When current is injected only into the microcylindrical cavity, threshold currents of those devices clearly depend on the spacing. The increment of threshold current is observed in the devices with the spacing shorter than 4μm. It is considered that increase of threshold current in the short spacing devices is an indirect evidence of the mode-coupling between the two cavities. Dependence of Q-factor of the integrated microcylindrical cavity on the spacing is calculated by three-dimensional finite-difference time-domain (3D-FDTD) method. As the spacing is decreased, the abrupt decrease of Q-factor after 4 μm is obtained because of the optical coupling with the ridge-waveguide modes. This calculated result explains the experimental result well. Regarding the 1-μm-spacing device, switching of the lasing wavelength is observed when the currents injected into both cavities are controlled. This switching behavior is a unique property of coupled cavity lasers. The switchable range of wavelength is over 120 nm, which is very wide compared with the value reported so far. These wide-range mode-switching is resulted from the large free spectral range of the integrated cavity with small size.

Chapter 7 serves for work on further reduction of the cavity size of the QCLs by exploiting two-dimensional photonic crystals (PCs). By carefully designing photonic crystal-based microcavities, the cavity size can be significantly decreased, and consequently, the consumption energy of QCLs can be reduced. Futhermore, emission direction can be tailored by controlling Q-factors for each direction. By intentionally introducing a defect into the perfect crystal, defect modes with high-Q factors can be formed in the photonic crystal. However, because the emission caused by ISBT in quantum wells is polarized in transverse magnetic- (TM-) modes, in which conventional two-dimensional photonic crystal structures do not possess a photonic bandgap, it is difficult to develop intersubband lasers with photonic crystal defect-mode microcavities. Therefore, several photonic crystal structures are investigated and optimized for the TM-like polarized light. One of the structures is a triangular-lattice PC cavity with triangular-shaped air holes. It is shown that it is difficult to apply these structures to

QCLs because higher guided modes close the photonic band gaps. Then a triangular lattice PC cavity with circular-shaped dielectric pillars is optimized. In the pillar based structures, since there are wide photonic band gaps for the TM- like polarized light, main effort is dedicated to suppressing radiation losses in the vertical direction. Delocalization of cavity mode distributions in the real space by modifying line-defect cavities enhances the vertical Q-factor, which is due to the suppression of the momentum components of the cavity mode within the light cone. The last structure is a graded square-lattice PC cavity with circular-shaped air holes. The highest Q-factor (~2200) among three structures mentioned above is achieved even there is no photonic band gap for lateral direction in this structure. This value of Q is shown to be sufficiently high for lasing action. The origin of high-Q is attributed to the decoupling between the cavity modes and the guided modes, and also radiation-modes in the momentum space. Finally, design and characterization of coupled cavity lasers with these photonic crystal defect-mode microcavities are also discussed.

In Chapter 8, conclusions to this thesis are presented. Implications of the results presented in this thesis are discussed. The outlook for future research and development is also given.