博士論文（要約）

Study on Characterization of Intersubband Transition in Non-polar m-plane AlGaN/GaN Quantum Wells

（非極性 m 面 AlGaN/GaN 量子井戸における

サブバンド間遷移の評価に関する研究）

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Intersubband (ISB) devices have been attracting much interest, especially in the infrared (IR) and terahertz (THz) spectral range. Because III-Nitrides (III-N) have a much larger longitudinal optical (LO) phonon energy and band offset than conventional gallium arsenide (GaAs)-based materials, III-N are considered promising for high-speed switching devices operating at telecommunications wavelength, and quantum cascade lasers (QCLs) in THz range.

Studies on ISB transitions in III-N have mainly been done on c-plane multiple-quantum wells (MQWs). However, in c-plane MQWs, the spontaneous and piezoelectric polarization make the subband design and transition energy tuning much more complex, especially in the mid-IR/THz ranges.

A non-polar nitride QW is one solution for ISB devices in the long wavelength range. Recently, high-quality m-plane gallium nitride(GaN) bulk substrates have become commercially available, and high-quality interband devices have been developed. Because non-polar QWs do not have a built-in electric field, the design of ISB devices using non-polar structures should be more flexible. However, there have been no studies on ISB transition of m-plane AlGaN/GaN QWs prior to this research.

For ISB device applications, it is important to understand the fundamental physics of ISB transition such as absorption properties, many-body effects, and temperature dependences. Also important are the development of the crystal growth technique for high-quality QWs and the numerical design based on relevant modeling and simulation technique.

This thesis focuses on those research issues, and original research conclusions for the ISB transition in non-polar m-plane AlGaN/GaN QWs are presented in the following.

First, we have succeeded in growing high-quality m-plane AlGaN/GaN QWs by metal-organic chemical vapor deposition (MOCVD), and we have observed the ISB absorption from MOCVD-grown m-plane AlGaN/GaN for the first time.

Second, we have quantitatively explained the many-body and scattering effects in ISB transition in m-plane AlGaN/GaN QWs both experimentally and theoretically. In addition, we have extracted the material parameter sets nicely to reproduce the ISB absorption.

Third, we have, both experimentally and theoretically, shown that the subband structures of m-plane AlGaN/GaN QWs are much more stable in temperature change (a few meV shift between below 10 K to 300 K) than that of the other III-V materials.

Finally, using the extracted material parameter sets, we have theoretically demonstrated that the non-polar m-plane AlGaN/GaN QCLs can be operated at much higher temperatures in THz than the conventional AlGaAs/GaAs QCLs. The automated optimization of m-plane AlGaN/GaN QCLs based on genetic algorithm were carried out. We found the optimized m-plane AlGaN/GaN QCL has the large material gain even at room temperature (300 K) with the comparable power consumption to the conventional AlGaAs/GaAs QCLs. The simulation results suggest that non-polar m-plane AlGaN/GaN QWs are promising materials for THz emission devices.

Chapter 1 provides an introduction and present the motivation, background, and overview of this research.

In Chapter 2, the general material properties of the iii-n semiconductors and their isb transition properties are presented.

In Chapter 3, the optimization of the growth condition for m-plane AlGaN/GaN qws by mocvd is presented. Several growth conditions, such as growth temperature and carrier gases, are optimized. The optimized m-plane AlGaN/GaN QWs have atomically flat surfaces with periodic step-terrace structures. The surface roughness was in the 0.1 nm range, and the abrupt interface was confirmed by xrd. The crack-free thick AlGaN was also grown by inserting a thin AlN interlayer between the GaN and AlGaN.

In Chapter 4, the interband and isb optical properties of non-polar m-plane AlGaN/GaN qws are presented. The narrow pl spectra at room temperature were observed, and their peak position were in good agreement with the simulation based on the 6-band $\boldsymbol{k} \cdot \boldsymbol{p}$ method. The isb absorption in mocvd-grown m-plane AlGaN/GaN qws was also clearly observed for the first time.

In Chapter 5, the doping-density dependent isb absorption properties are presented. As doping density increased, the peak energy of isb absorption shifts to a higher energy, and the linewidth gets broader. The theoretical analysis on isb absorption spectra based on many-body and scattering theory was carried out. The screening in many-body effects plays an important role,, and our simulation nicely reproduces the experimentally observed spectra.

In Chapter 6, the temperature dependence of isb absorption properties is presented. We found that the isb absorption in m-plane AlGaN/GaN did not show a significant shift when the temperature was decreased to below 10 K. The amount of shift of isb absorption in m-plane AlGaN/GaN QWs was much smaller than that in other III-V materials, which suggests that the isb device by m-plane AlGaN/GaN may be robust in temperature changes.

In Chapter 7, m-plane AlGaN/GaN qcl structures were designed by the negf-msb method. It is demonstrated that m-plane AlGaN/GaN QCLs shows superior temperature performance to the conventional AlGaAs/GaAs qcls. In addition, the novel m-plane AlGaN/GaN qcl structures showing a large gain even at room temperature were designed by ga-based optimization scheme.

In Chapter 8, the conclusion and the future perspective of this research are presented.