Abstract of Dissertation

Title of Dissertation:
Low Temperature MOVPE Growth of AlN/GaN MQWs by Pulse Injection Method for Realization of Intersubband Transition at 1.55 μm

(1.55 μm でのサブバンド間遷移の実現を目指したパルスインジェクション方式による **AlN/GaN** 多重量子井戸の低温 **MOVPE** 成長**)**

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Intersubband transition (ISBT) in AlN/GaN multi quantum wells (MQWs) has attracted much attention recently for optoelectronic devices because of its easy wavelength-tunability and extremely fast carrier relaxation process. The extension of ISBT wavelength to near-infrared wavelength, especially at optical communication wavelength such as 1.55 and 1.3 μm, is of particular interest since it is vital for the development of ultrafast photonic devices for silica-fiber-based optical communication networks. The material system of AlN/GaN MQWs structure has several promising properties such as large conduction band offset of approcimately 2 eV and large LO phonon energy. Therefore, the relaxation time in AlN/GaN material system is expected to be in the order of sub-picoseconds. This can contribute to the development of ultrafast all-optical switch operating at a bit rate higher than 1 Tb/s.

The observation of ISBT in AlN/GaN MQWs at 1.55 μm and shorter wavelength has been achieved by molecular beam epitaxy (MBE) system. The shortest ISBT wavelength reported in MBE system is 1.08 μm. On the other hand, the observation of ISBT by metal organic vapor phase epitaxy (MOVPE) system has not provided satisfactory results. ISBT at around 1.55 μm, which is achieved at very recently, showed very weak absorption magnitude and broad peak width. Furthermore, relatively strong ISBT absorption at around 1.55 μm was realized by using photo-induced absorption technique meaning that the carrier density in well is not sufficient. The demonstration of ISBT at 1.55 μm by MOVPE system is very important since MOVPE has a merit for mass production and better crystal quality for device fabrication. In this study, the

observation of the ISBT at communication wavelength such as 1.55 and 1.3 μm was considered as a main target of research. For the realization of this aimed-goal, I suggest two issues of interface abruptness and sufficient carriers in well for observing strong ISBT at communication wavelength region. According to the numerical calculation results, the main factor for shifting the ISBT wavelength to shorter region covering 1.55 and 1.3 μm was found to be the thickness of interfacial layer between well and barrier. For the improvement of interface abruptness and uniformity of MQWs, low temperature growth can be a key since it can suppress inter-diffusion between well and barrier and reduce the incorporation of adducts by gas phase reaction in AlN growth and agglomeration of grains. Fabrication of *n*-type GaN layer at low temperature region, however, is still challenging in conventional growth process since impurities originating from low thermal dissociation of group-III precursors, especially carbon, are heavily incorporated into GaN layer trapping the intentionally doped carriers. As a breakthrough, I suggest pulse injection (PI) method in which group-III precursors are alternately supplied, while NH_3 is continuously supplied. PI method is considered to be effective in decreasing the incorporation of carbon in GaN layer due to the reduction at only NH_3 supply time. By resolving these two issues, I succeeded in the observation of strong ISBT at 1.55 μm.

Interface abruptness has been considered as a main problem in typical MOVPE system for achieving short ISBT. It was found that the shortest ISBT wavelength in AlN/GaN MQWs grown by conventional MOVPE system using high growth temperature of 1130 ˚C was 2.2 μm. It is attributable to the formation of interfacial layer due to inter-diffusion between well and barrier by high growth temperature. Low temperature growth was proved to be very effective in improving interface abruptness as well as surface morphology. Rapid thermal annealing of abrupt MQWs induced the disappearance of MQWs-related satellite peaks, which supports that high growth temperature, indeed lead to the degradation of interface abruptness. According to secondary ion mass spectroscopy (SIMS) measurement to observe impurities, the incorporation level of carbon in low temperature-grown GaN layer was drastically increased. It was well reported that carbon in GaN plays a role of an acceptor trapping the intentionally doped carriers.

PI method was introduced in the fabrication of *n*-type GaN layer at low temperature region. As the main process parameters influencing the carbon incorporation as well as surface flattening, NH_3 supply time without the supply of group-III precursors (τ_2) and partial pressure of trimethylgallium (TMGa) are examined. It was clearly observed that the carbon incorporation was decreased with increasing τ_2 and 7 s was considered as best time since longer time than 7 s resulted in the surface roughening. The partial pressure of TMGa has affects both further decreasing carbon incorporation and flattening the surface to have monolayer level surface roughness. By precisely controlling these two parameters, carrier concentration as high as 1.6 x 10^{19} cm^{-3} could be realized at low temperature of 950 ˚C.

Since two issues of interface abruptness and sufficient carriers are resolved by low temperature growth by PI method, the fabrication of MQWs based on the optimized PI sequence was followed to observe ISBT absorption. ISBT absorption was firstly observed in MQWs grown at relatively low temperature of 950 ˚C and its absorption properties was better than those realized by conventional method at 1130˚C showing stronger absorption magnitude and narrower peak width. One of the important finding in this study, the ISBT wavelength was clearly blue-shifted with decreasing the growth temperature from 950 to 770˚C. It is strongly suggested that the interface abruptness was further improved by lowering the growth temperature, which is well consistent with simulation results. ISBT at 1.55 μm was firstly achieved at room temperature in MQWs grown at 770˚C by using PI method in GaN well growth. This result is for the first time reported in MOVPE system using GaN buffer layer.

For further blue-shift of ISBT wavelength, covering 1.3 μm, AlN buffer layer was introduced since it can give stronger built-in electric field in well and grow smooth MQWs without the lattice relaxation. ISBT at 1.3 μm was found to be very hard to realize since it is possible when the well thickness is decreased to 1.2 nm which is close to the minimum well thickness (~ 1.0 nm). Precise control of well and barrier thickness is therefore very important and eventually, shortest ISBT wavelength of 1.49 μm was observed in this study. It was suggested that the surface roughness is required to be improved to shift the ISBT wavelength to shorter region and improve absorption properties.

The observation of strong ISBT at 1.55 μm is considered as the most important achievement in this study. With this absorption properties at 1.55 μm, it is considerably possible to fabricate all-optical switch. Clarifying the reason of difficulties in MOVPE system for realizing short ISBT is thought to be meaningful. The development of PI method which is considered as my originality can be another achievement. This method can be applicable to other research areas which need low temperature fabrication of *n*-type GaN layer and flattening the surface of GaN at low temperature region.