Intersubband transition in p-type wurtzite GaN/AlGaN quantum well

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***Abstract*—The intersubband (ISB) transition of wurtzite (WZ) p-type GaN/AlGaN quantum well (QW) structures was investigated as a function of Al content in barrier using the multiband effective-mass theory. The peak wavelength of the TE-polarization absorption spectrum is rapidly redshifted with decreasing Al content in the barrier. The peak intensity of the TE-polarization absorption spectrum is shown to be similar to that of the TM-polarization absorption spectrum. We find that the peak wavelength of the TE-polarized absorption spectrum of 1.55 μm is possible even for the QW structure with a small Al content of x=0.7. We expect that a p-type WZ GaN/AlGaN heterostructure is attractive for a photodetector application for fiber-optic communications.**

***Index Terms*—Photodetector, GaN, AlGaN, Quantum well, Intersubband**

I. Introduction

Intersubband (ISB) devices have several potential advantages in comparison with interband devices for speed up and reproducibility. In particular, wide band gap III-nitride-based heterostructures are very interesting because ISB devices operating in the 1.3−1.55 μm wavelength range for fiber-optic communications are possible [1]–[3]. On the experimental side, room-temperature ISB absorption has been reported for n-type GaN/AlGaN or GaN/AlN quantum well (QW) structures [4]–[7]. On the other hand, the absorption by the TE-polarized light in these devices becomers zero when the optical wave is normally incidented on the QW because of the optical selection rule for the dipole moment [8]. Thus, gratings are needed to bend the incident radiation so that it enters the quantum well stack with a nonzero polarization component in the epitaxial growth direction (TM polarization) [9].

Recently, a p-type wurtzite (WZ) GaN/AlN QW structures grown on GaN substrate was proposed as a promising candidate for a photodetector application for fiber-optic communications. It was theoretically shown that ISB transitions giving the intersubband transition wavelength near 1.55 μm is possible with GaN/AlN QW structures [10]. However, it has been well known that the p-type doping in AlGaN layer with a high Al content is very difficult [11]. Thus, it will be desirable to reduce Al content in AlGaN barrier to obtain high hole concentration in well, if possible.

In this research, we theoretically investigate the ISB transition of WZ p-type GaN/AlGaN QW structures as a function of Al content in barrier using the multiband effective-mass theory. We assume that a GaN/AlGaN QW structure is grown on a thick GaN buffer layer. The self-consistent solutions such as valence band structures and wavefunctions are obtained by solving the Schrödinger equation for electrons, the block-diagonalized 3×3 Hamiltonian for holes, and Poisson's equation iteratively [8], [12].

II. Theory

The intersubband absorption coefficient for the intersubband transition is given by [8]

$$\alpha(\hbar\omega) = \omega\sqrt{\frac{\mu_0}{\epsilon}}\frac{1}{4\pi L_s}\int k_\rho dk_\rho \sum_{m_1,m_2}\left|\frac{e}{\hbar\omega}\frac{\hbar}{m_o}\hat{\epsilon}\cdot\mathbf{P}^{av}_{m_1m_2}\right|^2 \times\frac{(\Gamma/2)}{(E^h_{m_2}(k_\rho)-E^h_{m_1}(k_\rho)-\hbar\omega)^2+(\Gamma/2)^2} \times(f^h_{m_2}(k_\rho)-f^h_{m_1}(k_\rho)) \quad (1)$$

where ω is the angular frequency, μ_o is the vacuum permeability, ϵ is the dielectric constant, L_s is the length of the superlattice, k_ρ is the in-plane wave vector, m_i is the quantized subband index, e is the charge on an electron, f^h is the fermi-function for holes, and Γ is the linewidth. $\left|\frac{\hbar}{m_o}\hat{\epsilon}\cdot\mathbf{P}^{av}_{m_1m_2}\right|^2$ is the momentum matrix element averaged over the angle ϕ, which is given in Ref. [10]. The material parameters used in the computations are taken from Refs. [13]

III. Results and discussion

Figure 1 shows (a) intersubband transition wavelength as a function of Al content in the barrier for the absorption from the first subband (m_1=1) to the 15th higher subbands ($m_2 = 15$) of (0001)-oriented wurtzite GaN/$Al_xGa_{1-x}N$ QW structure with $L_w = 18$ Å and $L_b = 20$ Å and (b) potential profile and the wave functions for 1st and 15th subbands at

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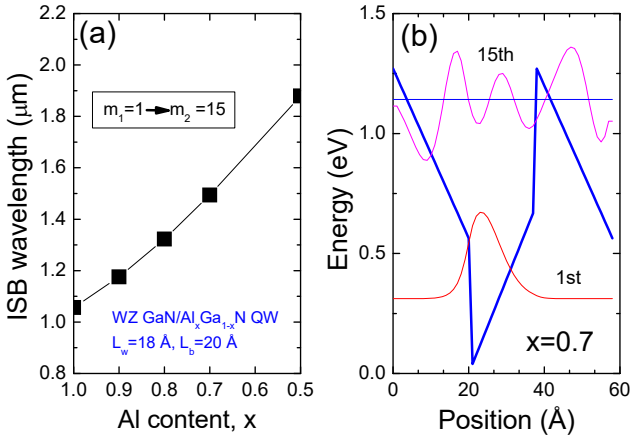

Fig. 1. (a) Intersubband transition wavelength as a function of Al content in the barrier for the absorption from the first subband (m_1=1) to the 15th higher subbands (m_2 = 15) of (0001)-oriented wurtzite GaN/Al_xGa_{1-x}N QW structure with L_w = 18 Å and L_b = 20 Å and (b) potential profile and the wave functions for 1st and 15th subbands at zone center for the QW structure with x=0.7.

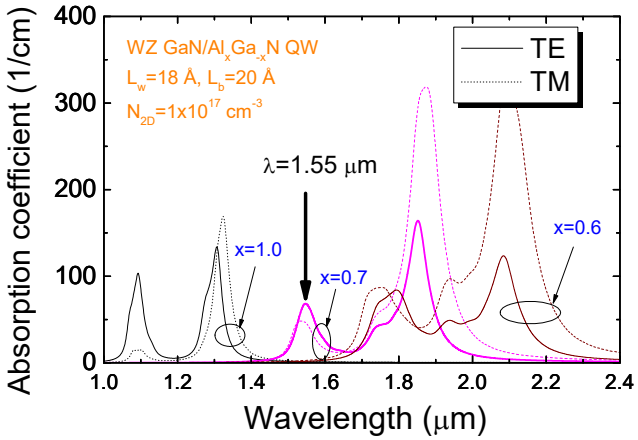

Fig. 2. TE(solid line)- and TM(dashed line)-polarized absorption spectra of (0001)-oriented wurtzite GaN/Al_xGa_{1-x}N QW structure (L_w = 18 Å, L_b = 20 Å) with several Al contents in the barrier.

zone center for the QW structure with x=0.7. The intersubband transition wavelength and potential profile are calculated at a carrier density of $1 \times 10^{17} cm^{-3}$. For a p-type semiconductor superlattice consisting of N quantum wells with each period L_p and the total length of L_s, we impose the periodic boundary condition at the two end points of the superlattice [14]. Then, the valence band structures can be obtained by solving the Hamiltonian equation for a single period $-L_p/2 \leq z \leq L_p/2$. For a given well width, the GaN/AlN QW structure shows that the transition wavelength is short and its value is about 1.07 μm. However, it rapidly increases with increasing Al content in he barrier because the valence band offset is reduced. We observe that the wavelength near 1.55 μm can be obtained for the GaN/AlGaN QW structure with x=0.7.

Figure 2 shows TE- and TM-polarized absorption spectra of (0001)-oriented wurtzite GaN/Al_xGa_{1-x}N QW structure (L_w = 18 Å, L_b = 20 Å) with several Al contents in the barrier. The absorption spectra are calculated at a carrier density of $1 \times 10^{17} cm^{-3}$. The absorption spectra are obtained from a summation of absorption transitions from $m_1 = 1, 2, 3$ to m_2=11,12,13,14,15. The peak wavelength of the TE-polarization absorption spectrum is rapidly redshifted with decreasing Al content in the barrier. Also, the peak intensity of the TE-polarization absorption spectrum is similar to that of the TM-polarization absorption spectrum. The GaN/AlGaN QW structure with x=0.7 shows that the peak wavelength of the TE-polarized absorption spectrum is near 1.55 μm. On the experimental side, Kinoshita *et al.* demonstrated that the free hole concentration of about $1 \times 10^{17} cm^{-3}$ can be obtained in the AlGaN layer with x=0.7. Thus, we expect that a p-type WZ GaN/AlGaN heterostructure is attractive for a photodetector application for fiber-optic communications.

IV. Summary

In summary, the ISB transition of WZ p-type GaN/AlGaN QW structures was studied as a function of Al content in barrier using the multiband effective-mass theory. We observe that the peak intensity of the TE-polarization absorption spectrum is similar to that of the TM-polarization absorption spectrum. The GaN/AlGaN QW structure with x=0.7 shows that the peak wavelength of the TE-polarized absorption spectrum is near 1.55 μm. We expect that a p-type WZ GaN/AlGaN heterostructure is attractive for a photodetector application for fiber-optic communications.

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