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Near-infrared wavelength intersubband transitions in GaN/AlN short period superlattices

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Intersubband transitions in GaN/AlN short period superlattices prepared by molecular beam epitaxy were investigated using the optical absorption technique. The peak position wavelengths of these transitions are found to span the spectral range of 1.35–2.90 μm for samples cut into 45° waveguides with GaN quantum well thicknesses ranging between 1.70 and 2.41 nm. The Fermi energy levels are estimated from the carrier concentrations, which were measured using an electrochemical capacitance-voltage profiler. The well widths were inferred from comparing the measured peak position energy of the intersubband transitions and the bound state energy levels calculated using the transfer matrix method. © *2006 American Institute of Physics*.
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Intersubband transitions in GaN/AlN multiple quantum wells have been investigated for their application in the near infrared 1.3–1.5 μm spectral region.[1–4] Reaching this range is made possible due to the large conduction band energy offset, which is on the order of 1.70 eV, between these two binaries. In principle, this large energy offset allows one to design quantum structures with intersubband transitions for wavelengths longer than 0.70 μm. However, the technical difficulties associated with the epitaxial growth, doping, and the inherited large dislocation densities[5,6] in III-nitride materials hinder the production of good quality materials and impede the progress of the device performance. Despite these technical issues, a progress, though slow, has been made in fabricating detectors based on the intersubband transitions in GaN-based systems.[2,3,7,8]

In this letter, we report on the optical absorption of the intersubband transition in Si-doped GaN/AlN short period superlattices grown by the molecular beam epitaxy (MBE) on *c*-plane sapphire substrates. The Fermi energy levels in the GaN wells are calculated directly from the two dimensional electron gas densities, which are measured using an electrochemical capacitance-voltage (ECV) technique. Owing to a lack of sample rotation, a variation is observed across the wafer. The quantum well thickness was estimated from fitting the observed transition energy to that calculated from the transfer matrix method. This then allowed the calculation of the two dimensional electron gas density. A single intersubband transition is observed in superlattices with well widths smaller than 2.0 nm, while two intersubband transitions were observed in samples with well thicknesses (L_W) on the order of 2.4 nm, as expected. The oscillator strengths of the ground state (E_0) to the first excited state (E_1) were calculated assuming a symmetrical quantum well. The second intersubband transition observed in samples with $L_W \sim 2.4$ nm is attributed to the transition between E_0 and the second excited state (E_2). This transition is normally not allowed in symmetric quantum wells, but since the GaN quantum wells are too thin, the symmetry breaks down allowing the electrons to make the ($E_0 \rightarrow E_2$) transition. Additionally, the electric field which is present could also break the symmetry based selection rules.

The GaN/AlN samples were grown on *c*-plane sapphire substrates by rf MBE with rf plasma N_2 as an active nitrogen source. The substrates were not rotated during the growth, which resulted in nonuniform growth rate across the wafer. The typical buffer layer grown on the nitrided substrate is a combination of AlN, $Al_{0.5}Ga_{0.5}N$, and two sets of AlGaN/AlN superlattices introduced to reduce the defects. This buffer layer is followed by growth of 300 nm AlGaN:Si as a bottom contact layer. The GaN/AlN superlattices (active regions) were grown on top of the AlGaN:Si layer followed by 200 nm AlGaN:Si layer, which acts as the cap and the top contact layer. The details of a set of five samples investigated here are shown in Table I. The active regions of the samples consist of Si-doped GaN quantum wells with variable thicknesses depending on the sample, while the AlN barrier thickness was fixed at 2.0 nm for all samples except for sample 1293, where the barrier is 10 nm $Al_{0.5}Ga_{0.5}N$.

The optical absorption measurements were obtained at room temperature using a Bruker IFS 125HR spectrometer. The samples were mounted in a continuous flow cryostat. The samples were cut into waveguide geometry with the beveled facet having been polished at 45°. The carrier concentrations were measured using Accent ECVPro electrochemical capacitance-voltage profiler with a maximum etched depth resolution determined by the Debye length. The energy levels of the bound states were calculated using a transfer matrix method,[9] which is also known as propagation matrix method.[10]

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TABLE I. Characteristics of the five samples investigated. L_W is the well thickness, L_B is the barrier thickness, N_{3D} is the 3D carrier concentration, and E_F is the Fermi energy level.

Sample No.	L_W (nm)	L_B (nm)	Period	Peak position in μm (eV)	Oscillator strength (f_{01})	N_{3D} (10^{19} cm^{-3})	E_F 300 K (meV)
1293	2.3	10.0	50	2.897 (0.428)	2.180	4.37	109.6
2362	2.36	2.0	50	2.140 (0.580)	1.679	1.26	32.4
2353	2.41	2.0	50	2.230 (0.556)	1.460	2.68	59.9
2361	2.08	2.0	50	1.784 (0.695)	1.620	2.56	58.1
NA61	1.70	1.0	30	1.372 (0.904)	1.898	5.00	92.7

The absorbance spectra of the intersubband transition ($E_0 \rightarrow E_1$) in the five samples are plotted in Fig. 1. The peak position is blueshifted as the GaN well thickness decreases and the peaks have a Lorenzian line shape except sample NA61. For this sample, the spectrum appears to be composed of two peaks. Since the GaN well thickness in sample NA61 is on the order of 1.7 nm, a one bilayer fluctuation (liberally referred to as monolayer also) in the well thickness could produce a large shift in the peak position. Thus, it is possible that there are two dominant well thicknesses in the 30 periods of the superlattice stack giving rise to two different transitions with close energy peak positions. Furthermore, a low intensity second peak appears on the lower wavelength side of the spectrum of sample 2362. This peak is attributed to an electronic transition from the ground state to the second excited state ($E_0 \rightarrow E_2$) in agreement with the previously reported theoretical calculations.[1]

The presence of two intersubband transitions in GaN/AlN superlattices is further investigated in several waveguides cut from different locations on wafer 2362. The optical absorbance spectra of four waveguides labeled (A), (B), (C), and (D) are plotted in Fig. 2. It is clear from this figure that two transitions are present. It is also noted that the peak positions of the two transitions are shifted. For example, the shifts between waveguides (B) and (D) are ~100 and ~210 meV for the transitions ($E_0 \rightarrow E_1$) and ($E_0 \rightarrow E_2$), respectively. From the calculated energy levels, it is found that this energy shift is translated to a change of the well width of about 0.23 nm, which is approximately the thickness of one GaN bilayer in the c direction.

The calculated energy levels using the transfer matrix method are shown in Fig. 3 for four different superlattices of 50 periods. Since the AlN barrier thickness is 2.0 nm, bands (E_j, where $j=0,1,2,\ldots$) are formed instead of discrete energy levels. Each band is composed of 50 discrete levels. Fortunately, almost all the energy levels in the first band ($E_{j=0}$) are degenerate giving rise to a single value. As j increases the width of the band increases, as shown in Fig. 3. The inset in the figure illustrates the fine structure of E_2 band in 2.0×2.0 nm^2 superlattice. By varying the well width one can obtain the energy difference between E_0 and E_1. The results are then compared to the peak position of the intersubband transition observed experimentally. The oscillator strength (f_{01}) values of the ($E_0 \rightarrow E_1$) transition shown in Table I are calculated using the following expression:[11] $f_{01} = [2/(m^* \hbar \omega)](8\hbar/3L)^2$, where $\hbar$ is the Planck constant, $\hbar\omega$ is the peak position energy of the intersubband transition, m^* is the electron effective mass taken as $0.22m_0$, and m_0 is the free electron mass. The oscillator strength, f_{01}, is shown in Table I.

The GaN well width was used to estimate the density of the two dimensional electron gas (n_{2D}) using the following relation: $n_{2D} = L_w \times N_{3D}$, where N_{3D} is the three dimensional electron concentration measured using the ECV profiler. The N_{3D} values are tabulated in Table I. A typical example of the ECV profile is shown in Fig. 4 for sample 1293, where the carrier concentration is obtained as a function of the etched depth. The carrier concentration is almost constant in the active region then decreases as the material is etched toward the buffer layer. Sample 1293 was chosen because the active region was chemically etched. On the other hand, chemical etching of the other samples was difficult to obtain for the entire active regions. Consequently, the carrier concentrations in GaN/AlN samples were obtained from the values measured at the interface between the cap layer and the active region. Another important observation is that the carrier concentration profile shown in Fig. 4 does not exhibit

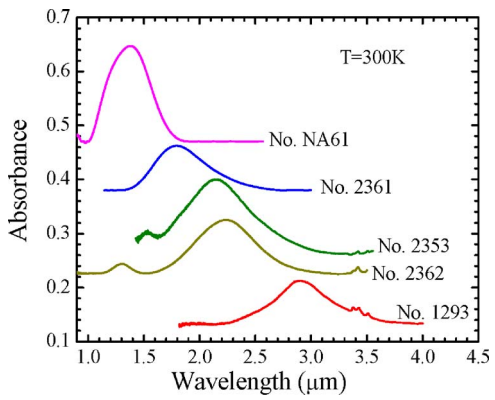

FIG. 1. (Color online) Absorbance spectra of the intersubband transitions measured at 300 K for five different samples from different wafers. The spectra were displaced vertically for clarity.

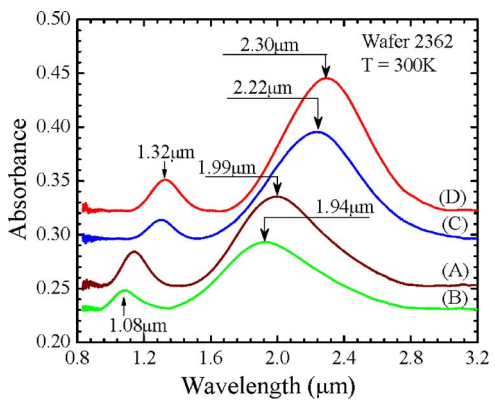

FIG. 2. (Color online) Absorbance spectra of intersubband transitions measured at 300 K for four different waveguides from the same wafer. The spectra were displaced vertically for clarity.

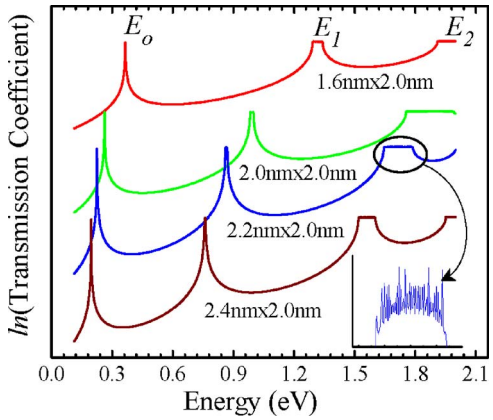

FIG. 3. (Color online) Transmission coefficient calculated as a function of energy for four different GaN/AlN superlattices. The inset illustrates the fine structure of the E_2 band calculated for the 2.0×2.0 nm^2 superlattice. The spectra were displaced vertically for clarity.

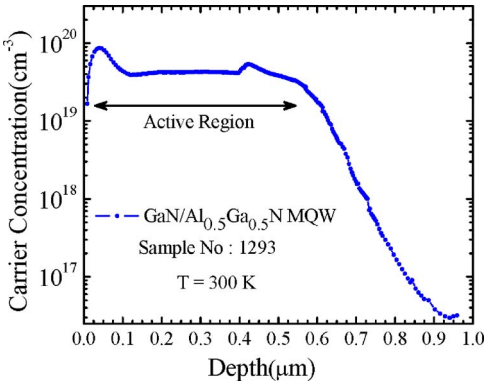

FIG. 4. (Color online) Carrier concentration in sample 1293 measured as a function of the etch depth using an ECV profiler.

the modulation (oscillation) behavior[12] usually seen in III-V semiconductor multiple quantum wells such as GaAs:Si/AlGaAs. This can be explained in terms of a possible significant dopant (Si) diffusion from the GaN well to the AlN barrier during the growth, which is performed at temperatures on the order of 800–850 °C. This growth temperature is high as compared to the growth temperature of 500–550 °C for GaAs/AlGaAs multiple quantum wells where the dopant diffusion is minimum.

Once the n_{2D} is determined, the Fermi energy (E_F) with respect to the ground state, E_0, can be calculated using $E_F = n_{2D}\pi\hbar^2/m^*$. The values of E_F are shown in Table I. Since E_F is above the ground state and well below the first excited state, the allowed transitions between the first and second excited states ($E_1 \rightarrow E_2$) cannot be observed in the present samples. The low values obtained for the Fermi energy levels support the assertion that the second intersubband transition observed at $\sim$1.30 μm in Fig. 2 is related to the $E_0 \rightarrow E_2$.

In conclusion, intersubband transitions in GaN/AlN superlattices were observed in the near infrared spectral region. Two transitions were observed: samples with thicker GaN wells are attributed to $E_0 \rightarrow E_1$ and $E_0 \rightarrow E_2$ transitions. This assignment is supported by the location of the Fermi energy level in the GaN wells as being above the ground state and below the first excited state. The observation of these two transitions is in agreement with the theoretical results reported by Suzuki *et al.*[1] in which the $E_0 \rightarrow E_2$ is expected to be observed in short period superlattices. The density of the two dimensional electron gas was determined from the electrochemical capacitance-voltage measurements. The GaN well widths were estimated from the transfer matrix method calculations. A 1 ML fluctuation (representing a bilayer along the c direction) in the GaN well is estimated from measuring the intersubband transitions in different samples cut from different locations in the same wafer in conjunction with the theoretical calculations.

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