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Infrared optical absorbance of intersubband transitions in GaN/AlGaN multiple quantum well structures

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Intersubband transitions in Si-doped molecular beam epitaxy grown GaN/AlGaN multiple quantum wells on c-plane sapphire were investigated using the Fourier-transform infrared optical absorption technique. Several GaN quantum well samples were grown with either AlGaN bulk or GaN/AlGaN short period superlattice barriers. The measurements were made in a waveguide configuration utilizing a facet polished at 45° to the c plane. The integrated area of the intersubband transitions in several waveguides cut from different location of the wafer was measured, from which we estimated the two-dimensional electron gas density (σ). The measured values of σ are about two orders of magnitude larger than the Si doping level of \( \sim 8 \times 10^{17} \text{ cm}^{-3} \), which is consistent with the polarization effects, particularly considering the large number of GaN/AlGaN interfaces. The internal quantum efficiency of the intersubband transitions was estimated to be on the order of 40% for samples with superlattice barriers. © 2003 American Institute of Physics.

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III-nitride materials have attracted tremendous interest for their applications to ultraviolet, blue/green diode lasers and light-emitting diodes, high-temperature electronics, high-density optical data storage, and electronics for aerospace and automobiles.1–3 While most of the applications of high-density optical data storage, and electronics for aerospace and light-emitting diodes, high-temperature electronics, for their applications to ultraviolet, blue/green diode lasers short period superlattice barriers. The measurements were made in a waveguide configuration utilizing a facet polished at 45° to the c plane. The integrated area of the intersubband transitions in several waveguides cut from different location of the wafer was measured, from which we estimated the two-dimensional electron gas density (σ). The measured values of σ are about two orders of magnitude larger than the Si doping level of \( \sim 8 \times 10^{17} \text{ cm}^{-3} \), which is consistent with the polarization effects, particularly considering the large number of GaN/AlGaN interfaces. The internal quantum efficiency of the intersubband transitions was estimated to be on the order of 40% for samples with superlattice barriers. © 2003 American Institute of Physics.

The GaN/AlGaN multiple quantum well structures were grown on c-plane sapphire (Al₂O₃) substrates using a MBE system with rf plasma N₂ as active nitrogen source. The 2 in. substrate was not rotated during the growth, which resulted in nonuniform growth. An initial AlN buffer layer of \( \sim 50 \text{ nm} \) was grown on nitrated Al₂O₃ substrate as a template for the subsequent epilayers. The growth parameters thus chosen consistently lead to a Ga polarity film. Three wafers denoted A, B, and C were chosen for the present study. The GaN quantum wells in the three samples were doped with [Si] \( \sim 8 \times 10^{17} \text{ cm}^{-3} \). Wafer A consists of a buffer, which is made of 500 Å AlN followed by 0.5 μm GaN, and 50 periods of 35 Å GaN/100 Å Al₀.₃₅Ga₀.₆₅N multiple quantum wells (MQWs) were grown. A cap layer of 300 Å GaN was then grown at the top of the quantum well structure. Wafer B consists of a buffer layer similar that of sample A and 50 periods of the well/barrier structure. The well is 27.7 Å doped GaN and the barrier is made of four periods of 10 Å Si-doped GaN/15Å Al₀.₆₅Ga₀.₃₅N. Wafer C consists of a 540 Å AlN and 1.33 μm Si-doped Al₀.₅₀Ga₀.₅₀N buffer layer followed by 50 periods of well/barrier structure. The well is 13 Å GaN and the barrier consists of four periods of 5 Å Si-doped GaN/10 Å Al₀.₆₅Ga₀.₃₅N. The cap layer of this wafer was 10 Å Al₀.₆₅Ga₀.₃₅N. The optical absorbance measurements were recorded using a BOMEM DA8 spectrometer in conjunction with a continuous flow cryostat. The samples were cut into waveguide geometry with the beveled facet having been polished at 45°. The light beam was zigzagged across the width (w) of the sample, which was typically 2.5 mm. The sample thickness (d) including the substrate and the
quantum well structure is on the order of 0.43 mm. Thus, the number of passes \((P)\) for the present waveguides is \(P = \frac{w}{d \times \tan(69.6^\circ)} \approx 2\), assuming that the refractive index of the sapphire substrate is 1.7.

In Fig. 1, we show the absorbance of the intersubband transitions as a function of wavelength for the three waveguide samples, which were cut from the center of each of the three wafers. The fine structure observed around 3.4 μm is due to C-H local vibrational modes. The intersubband transition spectra in this figure indicates that the peak position energy of the intersubband transition is almost the same for the waveguides cut from the center of the wafer and the edge of the wafer. Another observation in Fig. 2 is that the peak position energy measured at the Brewster angle for a sample cut from the center of the wafer is blueshifted as compared to the peak position energy measured at the Brewster angle. This, however, is opposite to the trend reported for GaAs MQWs, but in agreement with the multiple quantum dot measurements.

The uniformity of the wafers was investigated by cutting several waveguides from each wafer and then running the absorbance measurements for each waveguide. Some of the results are shown in Fig. 2. The intersubband transition spectra in Fig. 2 were recorded for a sample (cut from the center of wafer B) measured at the Brewster angle configuration [spectrum (a)], and for four waveguides cut from the center [spectra (b) and (c)], middle [spectrum (d)], and edge [spectrum (e)], of wafer B. It is clear from Fig. 2 that the peak position energy of the intersubband transition is almost the same for the waveguides cut from the center of the wafer [see spectra (b) and (c)] but it is blueshifted (shorter wavelength) for the waveguide that was cut halfway between the center and the edge (we refer to this piece as the middle waveguide) of the wafer [see spectrum (d)]. The shift can be explained in terms of the reduction of the well thickness.

However, spectrum (e), which was measured for a waveguide that was cut from the edge of the wafer, shows two peaks. This indicates that there are two dominant well thicknesses of the 50 quantum wells. Moreover, the intensity of the peak is reduced for waveguides cut from the middle and the edge of the wafer. Another observation in Fig. 2 is that the peak position energy of the intersubband transition measured for the waveguides is blueshifted as compared to the peak position energy measured at the Brewster angle. This, however, is opposite to the trend reported for GaAs MQWs, but in agreement with the multiple quantum dot measurements.

The total integrated area \((I)\) of the intersubband transition can be related to the 2DEG density \((\sigma)\) according to the following relationship:

\[
I \sim \frac{PNb\sigma L e^2 h}{4 \varepsilon_0 m^* c} \frac{f}{n^2 (n^2 + 1)^{1/2}},
\]

where \(P\) is the number of passes in the waveguide, \(N\) is the period of the quantum wells, in this case 50, \(b\) is the number of interfaces per period that contribute polarization-induced sheet charges (\(b = 1\) for wafer A and 5 for wavers B and C), \(\sigma\) is the 2DEG density, \(L\) is the well thickness, \(e\) is the charge of the electron, \(h\) is Planck’s constant, \(\varepsilon_0\) is the permittivity of space, \(m^*\) is the electron effective mass, \(c\) is the speed of light, \(n\) is the refractive index of the quantum well material, and \(f\) is the oscillator strength which is taken as 0.96 \(m_0/m^*\) for the ground state to the first excited state transition. From Eq. (1) one can estimate \(\sigma\) and the results are shown in Table I for the three spectra shown in Fig. 1.

Based on the results obtained for the integrated area of the spectra in Fig. 1, we estimated that the integrated area of samples B and C is larger than that of sample A by a factor \(\sim 4.6\). Hence the value of \(b=5\) in Eq. (1) is a good assumption.

The Fermi energy level \((E_F)\) is also estimated using the expression \(\sigma_{3D} = \frac{2(2\pi m^* k T)^{3/2}}{\hbar^2} e^{(E_F - E_c)/k T}\), where \(k\) is the Boltzmann constant, \(T\) is the temperature, \(\sigma_{3D}\) is the three-dimensional electron density, and \(E_c\) is the bottom of the bandgap.
the conduction band. The results are shown in Table I, where \( (E_F - E_c) \) is calculated for both 77 and 300 K. From the calculated \( E_F \) and the measured intersubband transition energies, it is determined that the Fermi energy level lies between the ground and the first excited states for both 77 and 300 K.

From Table I, it is clear that the Si-doping level cannot alone account for the high 2DEG density estimated from the integrated area of the intersubband transitions. One plausible explanation for the high \( \sigma \) values is that the polarization-induced electrostatic sheet charges at the GaN/AlGaN interfaces contribute most of the electrons in the well. This premise is supported by the fact that a single interface exists in wafer A (bulk barrier), while there are five interfaces per period (one comes from the quantum well and four come from the superlattice barrier) in wafers B and C. Figure 1 shows clear evidence that the intensity of the intersubband transition for wafer A is much smaller than that of the intersubband transitions in wafers B and C. Hence Eq. (1) was modified by adding the interface factor \( b \).

The internal quantum efficiency \( \eta_i \) for the three samples was calculated from the absorbance spectra in Fig. 1 according to the following relationship:

\[
\eta_i = \frac{(I_I - I_{ta})/I_{ta}}{1 - (1 - \xi)^{Npb}},
\]

(2)

where \( I_I \) is the incident light intensity, \( I_{ta} = I_I(1 - \xi)^{Npb} \), \( N=50 \), \( P=2 \), \( b=1 \) for wafer A and \( 5 \) for wafers B and C, and \( \xi \) is the fractional absorption per quantum well. \( \zeta \) is related to the maximum absorbance \( A_{max} \) according to the relationship \( A_{max} = -\log_{10}((1 - \xi)^{Npb}) \). With the measured values of \( A_{max} = 0.0795, 0.218, \) and 0.222 for the three spectra in Fig. 1, one finds \( \zeta = 1.823 \times 10^{-3}, 1.003 \times 10^{-3}, \) and \( 1.021 \times 10^{-3} \), for spectra (a), (b), and (c), respectively. For these values, the quantum efficiency is calculated to be 16.70%, 39.50%, and 45.40% for the three spectra (a), (b), and (c) in Fig. 1, respectively.

In conclusion, the infrared absorbance measurements of the intersubband transitions in GaN/AlGaN multiple quantum wells are reported for samples with either bulk or short period superlattice barriers. The two-dimensional electron gas density formed in the quantum wells was estimated from the total integrated area of the intersubband transitions and found to be at least two orders of magnitude larger than the intentional Si-doping level. The large electron density is attributed to the polarization-induced sheet charges formed at the GaN/AlGaN interfaces. This assertion was confirmed by the observation of the low (high) value of the integrated area of intersubband transition in samples with AlGaN bulk (GaN/AlGaN superlattice) barriers. The internal quantum efficiency was estimated for the intersubband transition, and it was found that samples with superlattice barriers possess higher quantum efficiency as compared to samples with bulk AlGaN barriers.

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