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Transverse electric dominant intersubband absorption in Si-doped GaInAsN/GaAs quantum wells

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We report observation of transverse electric (TE) dominant intersubband absorption in Si-doped GaInAsN/GaAs multiple-quantum-well structures. The TE dominant absorption is believed to be caused by the incorporation of nitrogen and the associated nitrogen state. When the confinement is strong in narrow quantum wells, the ground state is pushed up, which enhances the interaction with nitrogen state and significantly changes the nature of the state. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2172719]

I. INTRODUCTION

GaInAsN alloys have been attracting great attention recently owing to the unique N-driven physical and optical properties and their possible applications for long wavelength optoelectronic devices based on GaAs.[1] Recent research revealed that the addition of a small amount of nitrogen to GaAs could significantly lower the band gap while the addition of indium to GaAsN compensates the strain induced by nitrogen.[2–4] In addition to the giant bowing in the band gap energy, other properties such as E^+ and E^- subbands in the conduction band and a significant increase of the electron effective mass with increasing nitrogen content have also been reported. They are attributed to the highly localized nature of perturbations induced by nitrogen although the exact physical mechanism behind remains a subject of ongoing debates.[1,5–8] With the new $Ga_xIn_{1-x}As_yN_{1-y}$ alloys, lasers emitting at 1.3 and 1.5 μm range have been demonstrated, which make the optical communication accessible to GaAs-based devices.[4,9–11] Solar cells with internal quantum efficiencies $>70\%$ have also been successfully fabricated.[12] As far as the intersubband transition is concerned, absorptions at wavelength around 10 μm from GaInAsN/GaAs quantum wells (QWs) have also been investigated by Duboz *et al.*[13] It was reported that the intersubband transition is TM polarized and the absorption is consistent with the increase of the electron effective mass as the N content increases.[13] In this article, we report the observation of TE dominant intersubband absorption in Si-doped GaInAsN/GaAs multiple-quantum-well (MQW) structures.

II. EXPERIMENT

Two Si-doped GaInAsN/GaAs samples were grown by a RIBER-32P solid source molecular beam epitaxy (SSMBE) on double-side polished (100) semi-insulating GaAs substrates. The nitrogen was provided by a radio-frequency plasma source, the As was provided by a valved cracker cell, and the rest were provided by thermal effusion cells. The first sample (S1) consists of eight periods of 2-nm-thick Si-doped $Ga_{0.68}In_{0.32}As_{0.986}N_{0.014}$ QWs and 35-nm-wide undoped GaAs barriers. An *n*-type GaAs buffer of 0.4 μm was first grown, followed by eight QWs and then a 0.2 μm GaAs cap layer. The Si doping concentration is 4×10^{17} cm^{-3} in the QWs and 5×10^{18} cm^{-3} in the buffer and cap layers. The growth temperatures are 440 °C for the QWs and 590 °C for the buffer and cap layers. Both the shutter of the ignited N plasma source and the N valve were closed during growth of the buffer, cap, and barrier layers to avoid N incorporation into the GaAs layers. The second sample (S2) consists of 20 periods of 2.3-nm-thick Si-doped $Ga_{0.7}In_{0.3}As_{0.99}N_{0.01}$ QWs with a Si concentration of 1.5×10^{18} cm^{-3} and 14.5-nm-wide undoped GaAs barriers. All layers in S2 were grown at the same temperature (460 °C). The shutter of the ignited N plasma source was closed but not the valve during growth of barrier layers, which causes a nitrogen composition of 0.002 into the barriers.[14] Clear streaky reflection high-energy electron diffraction (RHEED) patterns were observed for all samples.

High-resolution x-ray diffraction (HRXRD) and low temperature photoluminescence (PL) were employed to characterize the quality of the MQW structures. Fourier transform infrared (FTIR) systems were used to measure the absorption spectra at room temperature with the samples polished into multireflection waveguide geometry.

III. RESULTS AND DISCUSSION

From the measured HRXRD spectra, well-defined periodic satellite peaks were identified for both samples. Figure 1 shows the measured and simulated HRXRD spectra of S1. Compressive lattice mismatch between the well material and substrate was also observed. The simulated results show 32% In and 1.4% nitrogen in the GaInAsN wells of S1 and 30% In and 1% N in S2, which together with the period data are in very good agreement with the designed values. Both 5 K and room temperature photoluminescence spectra were observable and the low temperature luminescence has a line-

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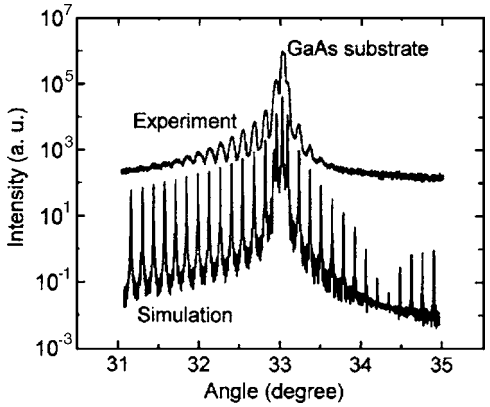

FIG. 1. Experimental (upper) and simulated (lower) x-ray rocking curves of the Si-doped GaInAsN/GaAs multiple-quantum-well sample which has eight GaInAsN 2-nm-thick wells and a Si concentration of 4×10^{17} cm^{-3} in the wells. A slight separation between the zero-order satellite peak and the substrate peak indicates a small lattice mismatch.

width of around 25 meV. The HEXRD and PL data clearly indicate the reasonable quality of MQW structures.

Figures 2(a) and 2(b) show the intersubband absorption spectra of S1 and S2, measured at 0°, 45°, and 90° polarizations. It is found that the absorption for the 90° polarized light is the highest and the absorption for the 0° polarized

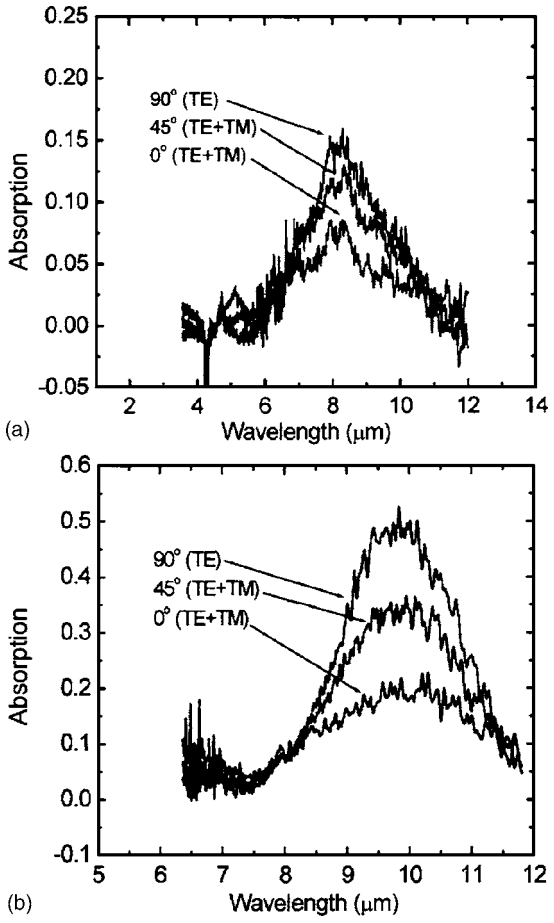

FIG. 2. (a) Absorption spectra of S1 measured by a Perkin-Elmer spectrometer at room temperature at 0°, 45°, and 90° polarizations. The sample has eight quantum wells and a Si concentration of 4×10^{17} cm^{-3} in the wells. (b) Absorption spectra of S2 which has 20 GaInAsN quantum wells with a Si concentration of 1.5×10^{18} cm^{-3}.

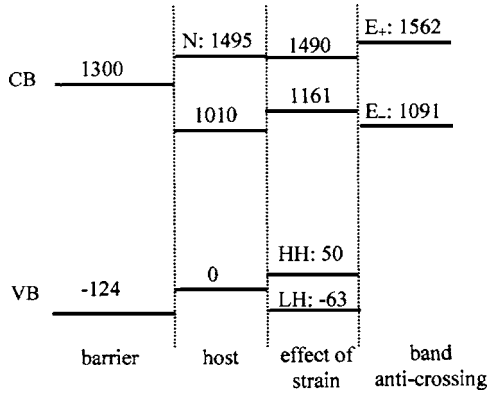

FIG. 3. Band edge lineup of the $Ga_{0.70}In_{0.30}As_{0.99}N_{0.01}$/GaAs system. The energy unit in the figure is meV.

light is the lowest. This observation indicates that the TE mode absorption dominates in both samples, which is contrary to the absorption observed in the conventional III-V MQWs.[15,16] As far as the absorption peak is concerned, it occurs at 8.1 μm in S1 and 9.7 μm in S2.

It was also observed that the TE mode absorption in S2 is stronger than that in S1. This is mainly due to the difference in the number of quantum wells and the Si concentration in the wells of the two samples. S1 has eight QWs with a Si concentration of 4×10^{17} cm^{-3} while S2 has 20 QWs with a Si concentration of 1.5×10^{18} cm^{-3}. From our estimation, the peak absorption intensity of the TE polarized light in S2 is 3.1 times that for S1. If each QW is assumed to contribute equally, the absorption of the TE polarized light in each well in S2 is about 22% higher than that in S1.

It should be pointed out that TE mode absorption in the *n*-type quantum well infrared photodetector (QWIPs) made of conventional III-V semiconductors has been reported by several groups.[17–21] Liu *et al.* also studied the possible overestimation of the TE mode absorption caused by scattering and imperfections.[22] However, the TE absorption is usually weaker than the TM absorption, which is different from what is observed here in the GaInAsN/GaAs MQWs. We believe that the incorporated nitrogen in the well material plays a key role for TE dominant absorption.

To calculate the energy band structure, wave function, and interband transition of the symmetric MQWs made of conventional III-V materials, an eight-band $k\cdot p$ model which includes the conduction band and light-hole, heavy-hole, and spin-orbit split-off valence bands is usually used.[23] For the GaInAsN/GaAs MQWs, a ten-band $k\cdot p$ model including the nitrogen band is needed in order to better reflect the effect of nitrogen. With such a ten-band $k\cdot p$ method, Tomic *et al.* have investigated the GaInAsN/GaAs laser devices.[24] In this work, we used the ten-band $k\cdot p$ model to calculate the intersubband absorption coefficient of the symmetric GaInAsN/GaAs MQWs.

Figure 3 shows the band edge lineup of the $Ga_{0.70}In_{0.30}As_{0.99}N_{0.01}$/GaAs system used in our $k\cdot p$ model. In our calculation, the valence band (VB) edge of the host material (GaInAsN) was chosen as the energy reference point. The N level is assumed to be 485 meV above the conduction band (CB) edge of the unstrained GaInAs, and

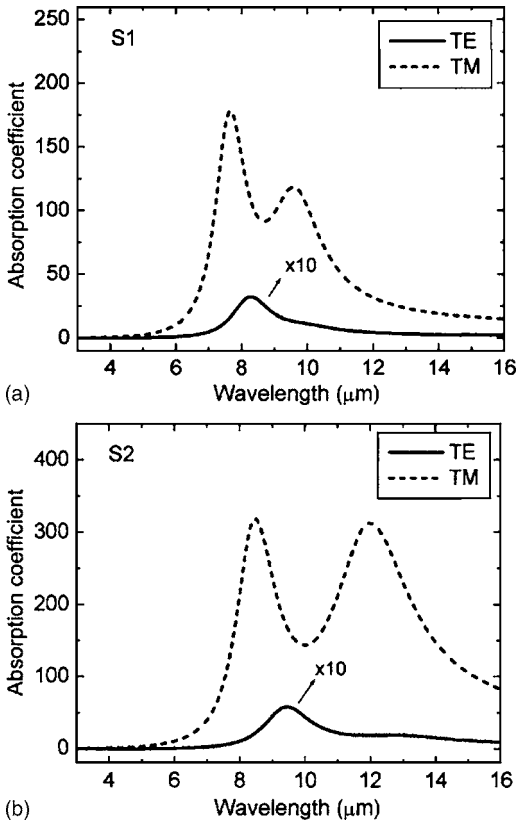

FIG. 4. Calculated TE (solid line) and TM (dash line) absorption spectra of (a) S1 and (b) S2 using the ten-band $k\cdot p$ model. The calculated main TE mode absorption peaks at 8.26 μm for S1 and 9.45 μm for S2 are close to the measured 8.1 and 9.7 μm, respectively. But the calculated magnitudes of the TE mode absorption for the two samples are smaller than those of TM mode absorption.

the coupling term between N level and GaInAs CB edge is assumed to be $1.68\sqrt{x}$ eV (where x is the N composition).[24,25] When compressive strain between GaInAsN and GaAs is included, the heavy-hole (HH) and light-hole (LH) bands split. E^+ and E^- appear due to the interaction between CB and N resonant states. The strong interaction pushes the well CB edge down from 1161 to 1091 meV (E^-), showing a reduction of 70 meV in our $Ga_{0.70}In_{0.30}As_{0.99}N_{0.01}$/GaAs sample. The reduction is smaller than the 108 meV in the $Ga_{0.70}In_{0.36}As_{0.99}N_{0.017}$/GaAs sample[24] of Tomic *et al.* and 100 meV in the $Ga_{0.95}In_{0.05}As_{0.988}N_{0.012}$ sample[6] of Shan *et al.* due mainly to the difference in compositions. The calculated E^+/E^- splitting in Fig. 3 is 471 meV which is comparable to the ~500 meV measured by Shan *et al.* in their $Ga_{0.95}In_{0.05}As_{0.988}N_{0.012}$ sample by taking the difference in compositions into account.[6] With this band edge lineup, the QW subbands and intersubband absorption can then be worked out.

Figure 4 shows the calculated TE and TM absorption coefficients of our two samples at 300 K. The absorption spectra are the sum of the calculated optical transitions between the ground state $e1$ and the excited states $e2$, $e3$, $e4$, and $e5$ in the conduction band well. It can be seen that the absorption for TM polarized light is mainly from $e1$-$e3$ and $e1$-$e5$ transitions, whereas the absorption for TE polarized

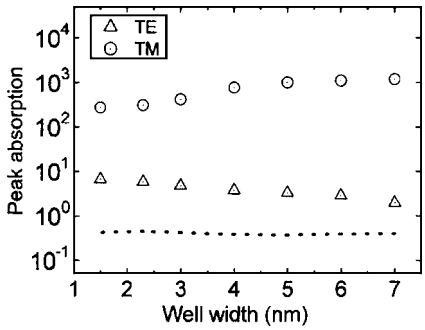

FIG. 5. Calculated TE (triangles) and TM (circles) absorption peaks of the $Ga_{0.7}In_{0.3}As_{0.99}N_{0.01}$/GaAs MQWs as a function of well width. The lower dot line is the TE absorption peak calculated using the eight-band $k\cdot p$ model for the same MQWs for comparison.

light is mainly from $e1$-$e2$ and $e1$-$e4$ transitions. The main TE absorption peak of sample S1 [Fig. 4(a)] occurs at 8.26 μm which is close to the measured 8.1 μm shown in Fig. 2(a). The TE absorption peak of sample S2 appears at about 9.45 μm which is also consistent with the measured 9.7 μm. However, the absorption coefficient for the TE polarized light (solid curve) for the two samples is much smaller than that for the TM polarized light (dashed curve), which is not consistent with the observations. For S1, there are two calculated absorption peaks for TM polarized light, which occur at 7.66 and 9.60 μm, respectively, and give a maximum ratio (TM over TE) of 54.4. For S2, there are also two main absorption peaks for TM polarized light, which occur at 8.48 and 12.0 μm, respectively, and give a maximum ratio of 54.8.

To view the effect of well width on intersubband transitions, we also calculated the absorption coefficient for TE and TM polarized lights as a function of well width using the ten-band $k\cdot p$ model. The results are shown in Fig. 5. For a comparison, the absorption coefficient for TE polarized light calculated using the eight-band $k\cdot p$ model (no N bands) is also included. It is found that (i) the absorption coefficient for TE polarized light calculated using the ten-band $k\cdot p$ model is much higher than that calculated using the eight-band $k\cdot p$ model, (2) TE mode absorption increases significantly with the decrease of well width, and (3) the absorption coefficient for TM polarized light decreases with the decrease of well width. These results indicate that the interaction between N state and band edges significantly enhances the TE mode absorption. When the well width is small, the confinement becomes strong in the narrow quantum wells, and the ground state is pushed up, which enhances the interaction with nitrogen state and therefore the TE mode absorption.

Our calculated results clearly indicate that the incorporated nitrogen in the wells plays a key role for the TE mode absorption, and the calculated absorption peaks are reasonably consistent with the observed values. However, the absorption coefficient for TE polarized light is still smaller than that for TM polarized light. It is well known that using the conventional eight-band $k\cdot p$ model which does not include nitrogen bands, the TE mode absorption coefficient is found to be about 10^3–10^5 times smaller than TM mode absorption

(Ref. 26 and this work). By adding two nitrogen bands to the eight-band $k \cdot p$ model, the TE mode absorption becomes about 55 times smaller than TM absorption. Obviously, the TE mode absorption is greatly enhanced in the GaInAsN systems due to the interaction between the N level and the original CB edges, especially for the samples with narrow wells. It is also known that using 14-band $k \cdot p$ formalism which includes the higher-lying antibonding p states perturbatively but excludes nitrogen bands, the magnitude of the TE mode absorption can be increased by about three orders but is limited to about 20% of the TM mode absorption.[26,27] It is likely that the TE mode absorption in the n-type narrow-well GaInAsN/GaAs MQWs becomes comparable to and even larger than the TM-mode absorption if the 14-band formalism is further extended to include nitrogen level.

IV. CONCLUSION

In conclusion, TE dominant intersubband absorption in Si-doped GaInAsN/GaAs MQWs is observed and it can be explained by the incorporation of nitrogen and associated nitrogen state. When well width is reduced, the ground state in the narrow MQWs is pushed up due to strong confinement and it interacts with nitrogen state, significantly enhancing the TE mode absorption.

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