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Nearinfrared Intersubband Transitions in InGaAs/AlAs Quantum Wells on GaAs Substrate

Takashi ASANO, Susumu NODA, Tomoki ABE, and Akio SASAKI

Department of Electronic Science and Engineering, Kyoto University
Kyoto 606-01, Japan

We report the intersubband-transition (ISB-T) in InGaAs /AlAs quantum wells (QWs) on GaAs substrate. The ISB-T wavelength and the integrated absorption coefficient (IAC) are investigated as functions of sample structures and growth conditions. The decrease of the well width leads to the shorter ISB-T wavelength but the reduction of IAC. The reduction of IAC can be recovered by increasing the In composition of the well and by suppressing sufficiently the segregation of In during the growth. With the optimization, a very short ISB-T wavelength of 1.9μm is achieved.

1. Introduction

Intersubband-transition (ISB-T) in quantum well (QW) is drawing much attention because of its unique characteristics such as large transition probability and very fast energy relaxation time. All optical modulators [1)-3)], detectors [4)], and laser diodes [5)] are being developed by utilizing the ISB-T. The important issue for the ISB-T is how short the wavelength becomes since the typical ISB-T wavelength is longer than 4μm. A material system with a large conduction band offset is strongly required.

Recently, the $In_{0.53}Ga_{0.47}As$/AlAs QW on an InP substrate has been reported [6)], where the conduction band offset is as large as 1.3eV. In this material system, however, since the lattice- mismatching degree between AlAs and InP is as large as 3.7%, the AlAs barrier layer cannot be made so thick ($\leq$10 monolayer, ML). Thus, (a) an effective barrier height becomes small and (b) a repetition of the QW is very difficult ($\leq$ 2periods).

To solve these problems, we have recently proposed to utilize the GaAs substrate in place of the InP [8)], where AlAs is almost lattice-matched to GaAs. In this material system, the AlAs barrier layer can be so thick that the reduction of the effective barrier height dose not occur [8)]. Moreover, since the strain is contained in the thin InGaAs well layer, the repetition of QW is considered much easier than the InP based system. This feature is very important for the device application since the multiple QW (MQW) structure is often required.

Up to this time, we have reported the ISB-T of about $\sim$ 2.5μm with one of structures in this system ($In_{0.2}Ga_{0.8}As$/AlAs MQW on GaAs) by an indirect method utilizing an electro-reflectance measurement [8)]. In this paper, we report a direct measurement result of the ISB-T in $In_xGa_{1-x}As$/AlAs MQW on GaAs substrate with various In compositions x by infrared absorption spectroscopy and show that the transition wavelength shorter than 2.0μm has been successfully achieved.

2. Experimental Condition

Samples used for the measurements were n-doped $In_xGa_{1-x}As$/AlAs MQW on semi-insulating GaAs substrate grown by molecular beam epitaxy (MBE). The structure of the sample is shown in Fig.1: the well layer was doped with Si ($\sim 1\times10^{19}cm^{-3}$), the In composition x and the width W of the well layer were variously changed as 0.2 to 0.4 and 7 to 13 ML, respectively, and the thickness of the barrier layer was fixed as 36ML. The repetition numbers of MQW are designed as 30 periods for x=0.2 samples, and 10 for x=0.3 and 0.4 in order not to exceed the critical thickness. The V/III ratio of $\sim$ 12 and growth temperature (T_g) $\leq$ 520°C were used to suppress the In segregation during the growth. Here, to investigate the influence of the In segregation due to the gorwth temperature difference, each sample was grown at two different temperature T_g $\sim$520°Cand $\sim$420°C.

GaAs (CAP) 100 Å
AlAs 36ML
$In_xGa_{1-x}As$(:Si) W ML
AlAs 36ML
⋮
AlAs 36ML
$In_xGa_{1-x}As$(:Si) W ML
AlAs 36ML
GaAs (BUFFER) 1000 Å
GaAs SUBSTRATE (SEMI INSULATING)

Fig.1. Sample structure used for ISB absorption measurements. x=0.2 $\sim$ 0.4, and W=7 $\sim$ 13 ML. Each well layer was doped with Si $\sim 1\times10^{19}cm^{-3}$. This structure is much more useful for MQW since the strain is contained in the thin InGaAs well layer in comparison with InP based structure.

After confirmation of coherent growth of the MQW on the substrate with very low dislocation density, polarization-resolved infrared absorption spectroscopy was carried out using an experimental set-up shown in Fig.2. The absorption spectra were measured with 45° multi-pass waveguide geometry since the ISB-T is considered to be allowed only for electric field component parallel to the MQW growth direction.

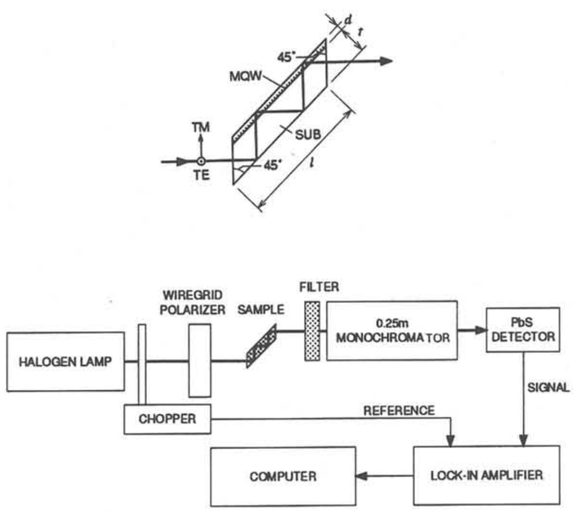

Fig.2. The experimental set-up for the ISB absorption measurement. The 45° multi-pass waveguide geometry was used since the ISB-T is considered to be allowed only for electric field component parallel to the MQW growth direction from the selection rule.

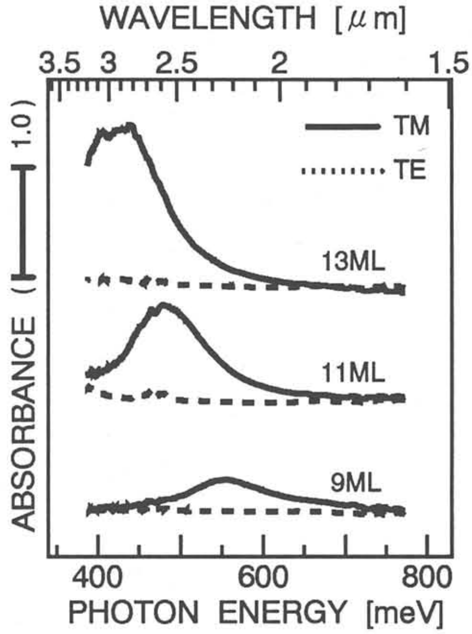

Fig.3. Polarization resolved infrared absorption spectra of $In_{0.2}Ga_{0.8}As$ MQW. Distinct absorption peaks are observed only with TM polarization. A very short ISB-T of 2.2 μm(560meV) has been achieved even in the case of such a small In composition of 0.2.

3. Result and Discussion

Figure 3 shows typical ISB absorption spectra observed with the samples (x=0.2, $T_g\sim$520°C, W=9, 11,and 13). Distinct absorption peaks are observed only with TM polarization, which agrees with the selection rule of ISB-T, and the energy of the peak is shifted to higher energy side with decreasing the well width. From the above two facts, the observed absorption peaks can be assigned as ISB-T, and we can see that a very short ISB-T of 2.2 μm(560meV) was achieved even in the case of such a small In composition of 0.2.

The absorption measurements were carried out on all other prepared samples. A distinct absorption peak was observed with samples which showed the Type–I photoluminescence (PL) properties. Here, we note that the PL type (I or II) is strongly affected by the sample structures. Figure 4 shows the measured ISB-T energy as a function of the well width. As can be seen in the figure, ISB-T energy becomes larger with decreasing W, and as short as 1.90μm(650meV) was achieved with 7ML-wide well (x=0.4, T_g=400°C). This is the shortest ISB-T wavelength ever reported in this GaAs-based material system.

It may be worth to point out that the absorption peaks were observed only with TM polarization in all cases, which is quite different from the results reported with the InGaAs/AlAs QW on InP substrate, where an absorption peak was observed also with TE polarization at lower energy side of the TM absorption peak [6]. Here, we note that only TM absorption peak would be observed due to the selection rule of ISB-T in usual one band model.

The calculated ISB energy for x=0.3 was also shown in Fig.4 with a broken line (the calculated ISB energies for x=0.2 or 0.4 were nearly equal to the result for x=0.3). The envelope function approach was used to calculate the ISB energy, and the effect of strain and band- nonparabolisity were taken into account using a k-p purtubation theory [7]. The good agreement btween the calculated and the experimental results can be seen in the figure.

Not only the peak wavelength, but also the magnitude of ISB-T are important for device applications. The measured absorption spectra were normalized by the sample size and the structure, and integrated over all photon energy to obtain integrated absorption coefficient (IAC). Figure 5 shows the IAC as functions of W, x, and T_g. It is seen in the figure that IAC rapidly decreases with decreasing W. It is also seen that the samples with larger x and lower T_g show the larger IAC.

From a theoretical point of view, the IAC is determined mainly by the square of ISB dipole moment (M^2) and the electron density of the first subband (n_1). Here, it should be noted that ISB absorption was observed only for the samples with Type I photoluminescence. In the Type–I /II transition region, n_1 is very sensitive to the structure of the QW since electrons can be easily transfered from Γ minimum of the well layer (first subband in the well) to X minimum of the barrier layer. On the other hand, M^2 decreases only from 54 to 31 $(e\text{Å})^2$ when W is reduced from 11 to 7ML, by which the rapid decrease of IAC cannot be explained.

From the above considerations, the well width dependence of IAC can be explained mainly by the reduction of n_1: when W is decreased, the QW becomes more Type–II like and n_1 becomes smaller to reduce IAC. The

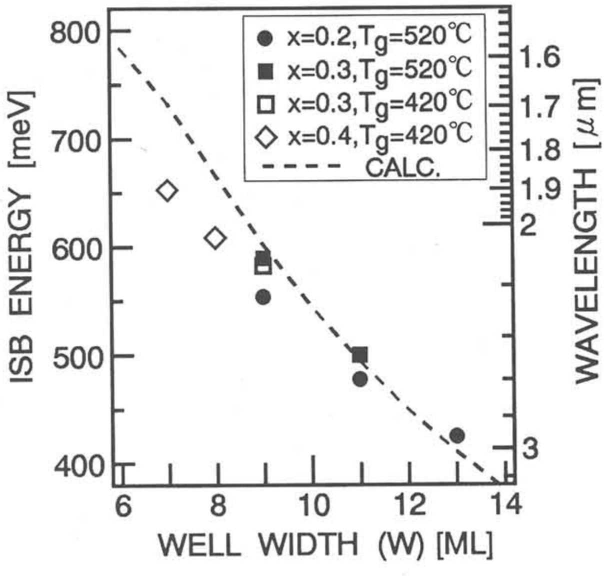

Fig.4. Relation between the well width of the sample and measured ISB-T wavelength. A very short ISB-T of 1.9 μm has been successfully achieved 7ML sample. The calculated ISB energy (broken line) shows good agreement with experimental results.

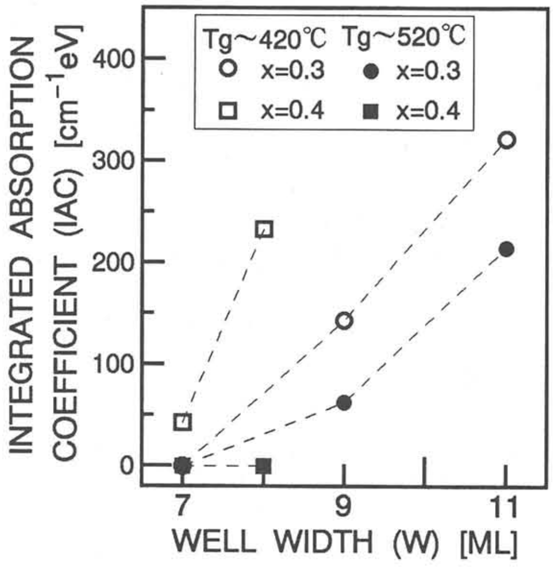

Fig.5. Measured IAC as functions of W, x, and T_g. IAC rapidly decreases with decreasing W and increases with increasing x and decreasing T_g.

IAC dependence on T_g can be also explained by Type–I/II transition as follows: when the sample is grown at lower T_g the average x becomes larger compared with the sample grown at higher T_g since the segregation of In is sufficiently supressed at lower T_g, and the increase of average x leads to the reduction of the band-gap of the well layer and thus the QW becomes more Type–I like to increase n_1 and IAC. Similarly, the IAC dependence on x can be explained by the Type–I/II transition.

From these results, it is indicated that the sample with smaller W for shorter wavelength ISB-T requires larger x and lower T_g to maintain the magnitude of IAC. Indeed, the aforementioned very short ISB-T wavelength of 1.9μm was archieved only by the optimization.

4. Conclusion

We have investigated InGaAs /AlAs QWs on GaAs substrate for nearinfrared ISB-T. It has been shown that this material system is very useful for device application since the MQW structures can be easily formed due to small lattice-mismatching degree. 10~30 periods of MQW samples have been grown and investigated on the ISB-T wavelength and the integrated absorption coefficient (IAC). It has been shown that the decrease of the well width leads to the shorter ISB-T wavelength but the rapid reduction of IAC. It has been also shown that the reduction of IAC can be recovered by increasing the In composition of the well and by suppressing sufficiently the segregation of In during the growth. With the optimization a very short ISB-T wavelength of 1.9μm has been successfully achieved.

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