電気材料技術雑誌 第14巻第2号
J.Soc.Elect.Mat.Eng. Vol.14, No.2, 2005

Linewidth broadening of intersubband transitions in narrow InAs/AlSb multi-quantum wells

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1. Introduction

The 6.1-Å group of semiconductors (GaSb, InAs, and AlSb) is a promising system for applications in both infrared optoelectronics [1] and high-speed and low power-consumption electronics.[2] For example, high-speed all-optical switches and modulators are possible applications relying on the extremely short intersubband relaxation times. Because of the large conduction band discontinuity between InAs and AlSb (~ 2.1 eV), the 6.1-Å group offers greater flexibility in designing intersubband optical devices operating at a shorter wavelength range compared to the well-developed GaAs/AlGaAs system. For applications to optical communications, operations in the near infrared (NIR) region such as 1.55 ≤m (0.80 eV) are desirable. Operations at this wavelength are also advantageous for the realization of all optical THz sources pumped by a compact NIR diode laser.[3]

We have recently reported the well width dependence of the intersubband transitions (ISBTs) in heavily-doped InAs/AlSb multiple quantum wells (MQWs) with 10, 20 or 60 periods.[4] Near infrared (NIR) absorption was observed in very narrow quantum wells down to 2.1 nm whose peak energy was as high as 680 meV at 77K demonstrating the advantageous feature of this material system. However, a large linewidth increase was also observed as the well width decreased below 3 nm. A broader linewidth might be useful for detector applications, however, a sharper spectrum is desirable for high efficiency light emitting device developments such as quantum cascade lasers.

The mechanism of the linewidth broadening for intersubband transitions are extensively studied for GaAs/AlGaAs systems. However, most of work focus on relatively wide quantum wells.[5-7] Only a few reports were made for InAs based systems.[8] Here we report that the linewidth of the intersubband transition for narrow quantum wells are governed primarily by interface roughness scattering and impurity scattering also plays an important role.

2. Sample preparation

The InAs/AlSb MQWs were prepared by molecular beam epitaxy. The structure is grown on a (100) semi-insulating GaAs substrate. In order to accommodate the lattice mismatch between the MQW layer and GaAs substrate, a 300-nm-thick GaSb layer, a 1-≤m-thick AlSb layer, 15 periods of GaSb (6 nm)/AlSb (6 nm) superlattice layers, and a 200-nm-thick AlGaSb layer were grown as the buffer layer. On top of the buffer layer, 20 periods of Si-doped InAs/AlSb MQWs were grown at a substrate temperature of 420°C. The MQW is composed of InAs quantum wells with various thicknesses and AlSb barrier layers. The InAs well width, d, was varied from 5 nm down to 2.1 nm, while the AlSb barrier layers were kept constant at 10 nm (Fig. 1). The heterointerface between InAs and AlSb was controlled by the shutter sequence to be InSb bonds. Finally, a 5-nm-thick InAs cap layer was grown to pin the surface Fermi energy at about the same energy above the InAs conduction band as the Fermi energy deep in the MQWs. This ensures a uniform distribution of

electrons through the MQW structure.[9] Since the ISBT intensity is proportional to the total electron density in the structure, a heavy doping with Si was made in each InAs QW layer. For $d \leq 2.7$ nm, a 1-nm-thick InAs set back layer was formed at each side of the doped region in order to eliminate dopant incorporation into the AlSb barrier, in which a Si atom becomes an acceptor. The central part of the InAs was uniformly doped. In order to keep the sheet doping density constant, the Si-cell temperature was adjusted depending on the well thickness. The sheet electron density in each QW is about 2 to 3 x 10^{12} cm^{-2}. Therefore, the total concentration was a few x 10^{13} cm^{-2} regardless of the well width except for sample E. For sample E, the total density was increased by using Si-delta-doping at the center of each InAs well and by increasing the MQW period to 60. The structural integrity was confirmed by X-ray diffraction (XRD) measurement. The simulated XRD spectra reproduce the observed ones only when the strain in the InAs and one monolayer of InSb interface layer at both heterointerfaces are taken into account. The samples were characterized by intersubband absorption and Hall measurements.

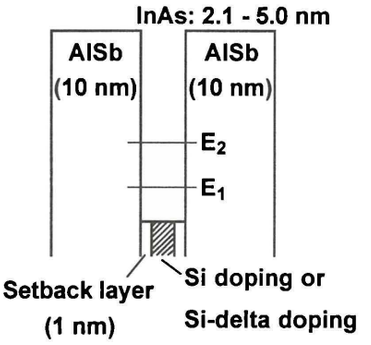

Fig. 1 InAs/AlSb MQW structure.

Table 1 summarizes the sample structure and corresponding transport properties measured at 77 K used in this experiment.

Table 1.

Sample	Well width, d (nm)	Setback layer (nm)	Period	Total density (cm^{-2})	Mobility (cm^2/Vs)
A	5.0	1	20	4.2 x 10^{13}	4150
B	4.0	1	20	5.8 x 10^{13}	2490
C	3.0	1	20	5.6 x 10^{13}	1190
D	2.7	1	10	6.0 x 10^{13}	1720
E	2.1	1.05	60	5.5 x 10^{14}	209

Sample structure, electron density, and mobility in MQWs measured by van der Pauw method at 77K.

3. Experimental

The ISBT was measured with a Fourier transform infrared spectrometer as described in Ref. 10. The sample was processed in a multibounce geometry and the ratio of the transmission of p- and s¬- polarized light (ISBT active and inactive) was measured. The background was the p/s ratio with no sample. The absorption coefficient is –ln(transmission ratio), normalized by the size of the sample and the number of QWs. Figure 2 shows the absorption signals measured at 79 K for all the MQW structures. As is summarized in Table 1., the period of MQW is 20 except for samples D (10 periods) and E (60 periods). In order to keep the total density constant, the sheet doping density per well was doubled for sample D. A strong absorption due to ISBT is observed for all the structures, although the number of InAs QW layers is relatively small. This is an advantageous feature of InAs-based MQWs for applications to all-optical devices. The highest peak energy obtained for sample E was as high as 670 meV, which is to our knowledge the highest energy value reported for InAs based systems. A large linewidth broadening is also observed for sample D and E while a gradual increase in the linewidth is observed for samples between A and C. Various mechanisms such as phonon scattering, electron-electron scattering, impurity, or interface roughness scattering, for the large linewidth broadening for sample D and E could be possible. For samples D and E, the large linewidth increase is accompanied by a drastic reduction in the integrated absorption intensity (normalized by the number of wells and doping density). Both linewidth increase and intensity reduction are prominent for $d < 3$ nm. The oscillator strength of the transition is in proportion to the inverse of the effective mass. Therefore, the absorption intensity reduces as the well width decreases due to the large conduction band nonparabolicity in InAs. The drastic decrease in the absorption intensity, however, cannot be quantitatively explained.

In order to clarify the mechanism of the linewidth broadening, we measured Hall effect by van der Pauw configuration at 77 K. In GaAs/Al(Ga)As systems, the importance of interface roughness scattering is reported. [5, 6] It is also pointed out that the contribution of the interface roughness to the linewidth and to the transport properties or mobility is different and the linewidth is much more sensitive to the interface roughness compared to the mobility values.[6] The sensitivity of the linewidth, thus for ISBT, comes from the involvement of higher subbands which lies higher in energy. The variation of the subband energy due to a monolayer fluctuation of the well width is much more sensitive in higher subbands compared to the lowest subbands in which the electrical conduction takes place. The well width studied in GaAs/Al(Ga)As MQWs is about 8 nm where the interface roughness scattering becomes prominent in the transport properties.[11] As is summarized in Table 1, for InAs/AlSb MQWs, the mobility value monotonically decreases as the well width decreases. Figure 3 shows the mobility values as a function of well width, d. In the figure, additional data points which are not listed in the Table. 1 are also plotted. In order to eliminate the contribution of the electrical conduction through the 5-nm-thick InAs cap layer, all the measurements were carried out after the removal of the InAs cap layer. The figure clearly shows that the mobility in heavily doped InAs/AlSb MQWs shows a d^6 dependence for d below 3 nm.

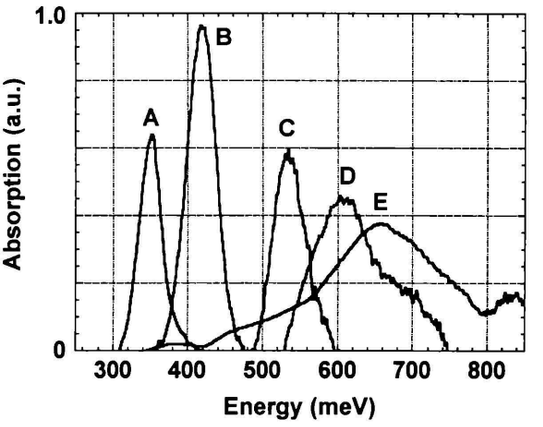

Fig. 2 Intersubband absorption spectra of narrow InAs/AlSb MQWs at 79 K.

Next we estimate the transport energy broadening $2G_{tr} = 2h/t_{tr}$ from the mobility values $m = et_{tr}/m^*$. Although the higher sensitivity of the linewidth to the interface roughness compared to the mobility was reported in remote doping case, [6] the doping in the well region is reported to enhance the influence to the mobility.[12] In our case, the sheet doping density in the well is kept constant. Therefore, the mobility reduction is caused by the doping for the whole range of d. However, the change in the mobility when varying the well width, d, is considered to be primarily determined by the interface roughness. The transport energy broadening, $2G_{tr}$ and the full width at half maximum (FWHM) of the ISBT spectra are plotted with respect to d in Fig. 4. In the figure, the solid circles indicate the FWHMs of the ISBT spectra and the diamonds show the energy broadening, $2G_{tr}$s, estimated from the mobility values. For wider wells, the FWHM is larger than $2G_{tr}$. It is because that we neglect the other possible scattering mechanisms, such as phonon scattering. Since the well width studied here is so narrow that the energy separation between E_1 and E_2 states is much larger than the optical phonon energy of InAs. Therefore, the optical phonon emission process is for $d > 3$ nm where G_{tr} is much smaller than the ISBT linewidth. We can estimate the residual scattering lifetime to be 1.8×10^{-14} s from the difference between the FWHM and G_{tr} values for large d. For $d < 3$ nm, the transport energy broadening rapidly increases as d decreases because of the d^6 dependence of the mobility, thus d^{-6} dependence for G_{tr}, in this range of d. The good agreement between FWHMs and G_{tr}s, for $d < 3$ nm, indicates that the linewidth is dominated by the interface roughness and the sensitivity of the linewidth to the interface roughness and the one to the mobility are about the same

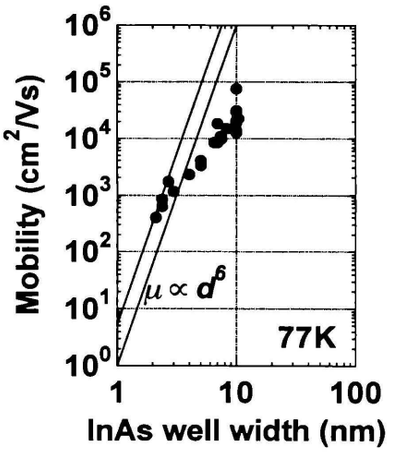

Fig. 3 Electron mobility vs InAs well width, d. d^6 dependence is observed for $d < 3$ nm.

magnitude. The discrepancy of the sensitivity between our case and ref. 6 can be explained by the different doping scheme: in the well in this work, modulation doping in ref. 6, as is mentioned in ref. 12 and/or the weaker contribution to the ISBT linewidth from the interface roughness in InAs/AlSb compared to that in GaAs/Al(Ga)As. In GaAs/Al(Ga)As, energy variations in E_2 states due to the well width fluctuation is much larger (4 times for infinite barrier) than those in E_1 states. For InAs/AlSb, the energy variations in E_2 states become less sensitive (roughly 2 times) to the well width for very narrow wells because of the large nonparabolicity in InAs. One should also note that the subband energy fluctuation due to 1 ML fluctuation of the well thickness is much smaller to explain the ISBT linewidth.

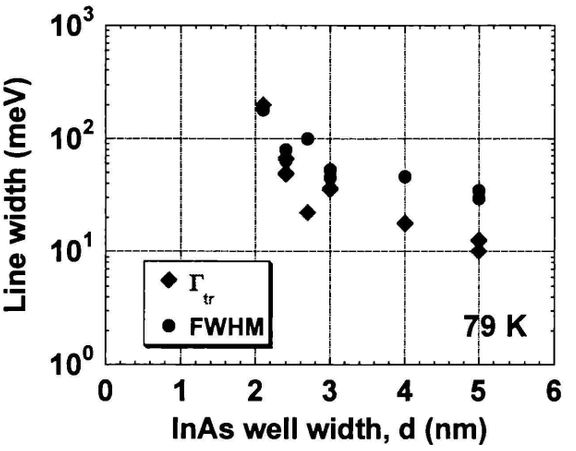

Fig. 4 ISBT linewidth and transport energy broadening as a function of InAs well width, *d*.

4. Conclusion

We studied the well width dependence of the ISBTs in heavily-doped narrow InAs/AlSb MQWs (2.1 nm $\leq d \leq$ 5 nm) with 10, 20 or 60 periods and considered the mechanism of the linewidth broadening. The ISBTs were observed for d down to 2.1 nm with the peak energy of 0.67 eV at 79 K. As the well width decreased, the ISBT linewidth gradually increased for $d > 3$ nm but rapidly increased for $d < 3$ nm. For $d > 3$ nm, the optical phonon scattering process is dominating the linewidth. However, for $d < 3$ nm, the ISBT linewidth is well described by the transport energy broadening indicating that, for this range of d, the interface roughness scattering becomes dominant for determining the linewidth. In addition, the sensitivity of the ISBT linewidth to the interface roughness is comparable to the mobility values.

Acknowledgements

The authors are grateful to G. G. Walden for sample preparation and A. J. Rimberg for the use of his evaporator. This work is partly supported by DARPA/AFOSR F49620-01-10543, NASA-NCIBSRP, and the Robert A. Welch Foundation.

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