Large effective mass enhancement of the $\text{InAs}_{1-x}\text{N}_x$ alloys in the dilute limit probed by Shubnikov-de Haas oscillations

D.R. Hang^{a,b}, D.K. Shih^c, C.F. Huang^d, W.K. Hung^e, Y.H. Chang^a,
Y.F. Chen^{a,*}, H.H. Lin^c

^aDepartment of Physics, National Taiwan University, Taipei 106, Taiwan, ROC

^bDepartment of Materials Science and Optical Engineering, National Sun Yat-Sun University, Kaohsiung, Taiwan 804, ROC

^cDepartment of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan, ROC

^dNational Measurement Laboratory, Center for Measurement Standards, Industrial Technology Research Institute, Hsinchu 300, Taiwan, ROC

^eDepartment of Electro-optical Engineering, National Taipei University of Technology, Taipei, Taiwan, ROC

Abstract

Transport properties of two-dimensional electron gases formed in low-nitrogen-content $\text{InAs}_{1-x}\text{N}_x/\text{InGaAs}$ single quantum wells have been investigated using Shubnikov-de Haas (SdH) oscillations. We determine the nitrogen-content-dependent two-dimensional carrier concentration and electron effective mass by analyzing the SdH oscillation function. The carrier mobility decreases with the increase of nitrogen composition, suggesting some deterioration of crystal quality. Our result shows that even in the dilute alloy limit, the electron effective mass increases considerably, and such an enhancement cannot be explained by the present simple band anticrossing model.

© 2003 Elsevier B.V. All rights reserved.

PACS: 73.40.Kp; 73.63.Hs; 72.20.My

Keywords: Two-dimensional electron system; Shubnikov-de Haas; Nitride; InAsN

1. Introduction

There is currently considerable interest in III–V alloys containing nitrogen because of their potential application for use in infrared devices and their interesting physical properties. In contrast to conventional alloys in which electronic properties vary smoothly with composition, the incorporation of even a small fraction of nitrogen into the host III–V crystal brings

about drastic modifications of the electronic properties of the alloys.

The $\text{GaAs}_{1-x}\text{N}_x$ alloys have been intensively studied to expand the infrared capability of existing GaAs-based devices. For optoelectronic applications in the mid-infrared wavelengths, the $\text{InAs}_{1-x}\text{N}_x$ -based heterostructures have been proposed to be very promising candidates [1–6]. They are ideally suited to extend the long-wavelength limit of InAs-based laser diodes. Recently, it has been shown that a better heterointerface and a better carrier confinement can be achieved by replacing InAs with InAsN alloys [2]. Hence the study on InAsN alloys improves

* Corresponding author. Tel.: 886-2-3366-5125;

fax: 886-2-2363-9984.

E-mail address: yfchen@phys.ntu.edu.tw (Y.F. Chen).

relevant optoelectronic device qualities and broadens our knowledge of III–N–V alloys.

Before a full realization of long-wavelength InAs_{1-x}N_x-based devices can be achieved, many physical parameters such as the electron effective mass must be clarified. In this paper, we present the investigation of Shubnikov-de Haas (SdH) oscillations of two-dimensional electron gas (2DEG) formed in low-nitrogen-content InAs_{1-x}N_x/InGaAs single quantum wells (SQW) grown on InP substrates. We find that the electron effective mass increases noticeably even if a small amount of nitrogen is incorporated. The effective mass enhancement is mainly due to the band structure modification induced by nitrogen. Moreover, it cannot be explained within the framework of the simple band anticrossing (BAC) model. Our result agrees with a recent study on InAsN bulk alloys [6].

2. Experimental

The samples used in this study were grown on semi-insulating InP (1 0 0) substrates by a VG V-80H gas source molecular beam epitaxy system. The elemental In and Ga sources and thermally cracked AsH₃ source were used to produce molecular beams. The active N species were generated from an EPI UNI-bulb RF plasma source. The RF power for the growths was kept at 180 W. The SQW structures were grown on InP substrates and consist of a 0.3-μm-thick In_{0.53}Ga_{0.47}As layer which is lattice matched to InP, a 3-nm-thick InAs(N) well, and a 40-nm-thick In_{0.53}Ga_{0.47}As barrier. The growth temperature was 400°C. More details of growth conditions can be found elsewhere [2]. The InAs(N) SQWs were first examined by photoluminescence (PL) measurements. The PL measurements were carried out in a closed cycle helium cryostat. The 488 nm line of an argon laser was used for the excitation source. The signal was detected by a liquid nitrogen cooled InSb photodiode with a Hamamatsu P3357-02 preamplifier. Fig. 1 shows the 10 K PL spectra of InAs(N) SQW structures. As can be seen, the PL peak energy of the InAsN SQW decreases because of the incorporation of nitrogen. This result confirms the giant bowing effect. From the amount of the PL peak position shift and X-ray diffraction, the nitrogen composition can

Fig. 1. The PL spectra of InAs(N)/InGaAs SQWs taken at temperature 10 K.

be estimated [4]. The highest nitrogen concentration in our samples is 0.4%.

For the transport measurements, ohmic contacts were formed by depositing indium drops to the corners of the samples, and annealing the contacts at 400°C for 10 s. The samples were immersing in liquid helium. The properties of the 2DEG formed in the InAs_{1-x}N_x/InGaAs SQW were investigated by magnetotransport measurements at low temperatures and magnetic fields up to 6 T in a ³He refrigerator. The data were taken by conventional lock-in techniques. During measurements, the current was monitored and kept small to avoid electron-heating effect.

3. Results and discussion

The SdH measurement has been a well-received tool to study the properties of 2D carriers, such as the effective mass, the carrier concentration, and the scattering time. The SdH oscillations of the InAs_{1-x}N_x/InGaAs SQWs with proper background subtraction are shown in Fig. 2 for (a) $x=0\%$, (b) $x=0.25\%$ and (c) $x=0.4\%$. The data were taken at 0.33 K and the 2D character has been further confirmed by rotating the sample orientation against the magnetic field.

As can be seen in Fig. 2(a), the magnetoresistance of the unperturbed InAs/InGaAs SQW starts to oscillate with inverse magnetic field at magnetic fields as low as 0.54 T. From the onset of the SdH

Fig. 2. The SdH oscillations of the $\text{InAs}_{1-x}\text{N}_x/\text{InGaAs}$ SQWs for (a) $x = 0\%$, (b) $x = 0.25\%$ and (c) $x = 0.4\%$ at 0.33 K.

oscillations ($\mu_B \sim 1$), the mobility near the liquid-helium temperature is roughly estimated to be as high as $1.85 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, suggesting a rather good crystalline quality. Since there is only one series of oscillations, the carrier concentration n can be determined from the frequency of the oscillation $f_{\text{SdH}} = nh/2e$, where h is the Planck constant and e is the electron charge [7]. The obtained carrier concentration is $1.3 \times 10^{11} \text{ cm}^{-2}$. In addition to the carrier concentration, the electron effective mass value can be determined from the temperature-dependent amplitudes of the SdH oscillations according to the relation [8], $A(T) \sim Z/\sinh Z$, where $Z = 2\pi^2 k_B T / \hbar \omega_C$, $\hbar$ is the reduced Planck constant, k_B is the Boltzmann's constant, cyclotron frequency $\omega_C = eB/m^*$, B is the magnetic field, and m^* is the electron effective mass. In our experiments, the temperature is varied from

Fig. 3. The electron effective mass and the estimated carrier mobility as functions of nitrogen composition.

0.3 to 4.3 K. The effective mass is determined to be $0.029 \pm 0.001 m_0$, which is in reasonable agreement with a previous report with $m^*(\text{InAs}) \sim 0.026 m_0$ [9].

For $\text{InAs}_{1-x}\text{N}_x/\text{InGaAs}$ SQW samples, the SdH onset field increases as the nitrogen composition increases, as shown in Fig. 2(b) and (c). Fig. 3 shows the carrier mobility near the liquid-helium temperature as a function of nitrogen concentration, which is estimated from the onset magnetic field. It can be seen that the carrier mobility decreases with the increase of nitrogen composition, suggesting some deterioration of crystal quality once nitrogen atoms are incorporated into the host lattice. Yet the crystal quality remains good enough so that the properties of 2DEG can still be probed by the SdH oscillations. The carrier densities for the samples with $x = 0.25\%$ and 0.4% are 2.64×10^{11} and $2.85 \times 10^{11} \text{ cm}^{-2}$, respectively.

The electron effective mass as a function of nitrogen content is also shown in Fig. 3. It is found that with increasing nitrogen composition, the effective mass value increases. For the sample with the largest nitrogen content, an effective mass of $0.1 \pm 0.01 m_0$ is found. It is very surprising that even the nitrogen content is far less than one percent, the effective mass increases to almost four times larger than the nitrogen-free one. The effective mass enhancement can be attributed to size quantization, band non-parabolicity and the nitrogen-induced band structure modification. In a previous report [5], we have shown by a self-consistent calculation that for such a 3 nm wide SQW, the effective mass enhancement due to

size quantization is about 77%. Moreover, the enhancement due to the nonparabolicity effect is about 3%. It is clear that the size quantization and the nonparabolicity effect cannot explain such a drastic effective mass enhancement. Therefore, the mass enhancement is mainly due to the incorporation of nitrogen into the host lattice. This result is in agreement with previous theoretical studies proposing that the strong interaction or admixture of the conduction band minimum with upper states results in an increase of the electron effective mass [10,11]. In the BAC model, the resonant N level repulses the extended conduction band states and splits the conduction band into two nonparabolic subbands. The lower flattened subband brings about the increase of the electron effective mass. Besides, one further notes that under this theoretical framework, the electron effective mass cannot be two times larger than the nitrogen-free one in the host lattice. However, our measured value of the effective mass clearly exceeds this limit. This result is consistent with a recent study on bulk $\text{InAs}_{1-x}\text{N}_x$ by means of infrared reflectivity that the measured effective masses either approach or are extremely larger than this limit [6]. Consequently, the simple BAC model seems to be inadequate for InAsN though it works well for InGaAs . Another refined form of the BAC model suggests that the conduction band edge is a mixing state caused by the strong perturbation introduced by smaller nitrogen atoms on arsenic sites [12]. The mixing state consists of components of the Γ , L and X states and the Γ character decreases as nitrogen composition increases. Since the L electrons have much heavier mass than the Γ , the electron effective mass can possibly exceed this limit. The mixing state model therefore supplies a plausible explanation. Nevertheless, the exact mechanism of band structure modification still calls for further investigation.

4. Conclusions

In summary, we present the investigation of transport properties of 2DEG formed in low-nitrogen-content $\text{InAs}_{1-x}\text{N}_x/\text{InGaAs}$ SQWs by SdH oscillations. The PL peak energy originated from the SQW decreases with increasing nitrogen concentration,

which is in accord with the bowing effect associated with the introduction of nitrogen. We determine the 2DEG density and electron effective mass by analyzing the SdH oscillation function. It is found that the carrier mobility decreases with the increase of nitrogen composition, suggesting some deterioration of crystal quality. Our result shows that even in the dilute alloy limit, the electron effective mass increases considerably, and such an enhancement cannot be explained by the present simple BAC model.

Acknowledgements

This work was partly supported by the National Science Council and the Ministry of Education of the Republic of China.

References

- [1] J.S. Wang, H.H. Lin, *J. Vac. Sci. Technol. B* 17 (1999) 1997.
- [2] J.S. Wang, H.H. Lin, L.W. Song, G.R. Chen, *J. Vac. Sci. Technol. B* 19 (2001) 202.
- [3] J.C. Fan, W.K. Hung, Y.F. Chen, J.S. Wang, H.H. Lin, *Phys. Rev. B* 62 (2000) 10990.
- [4] T.Y. Chu, H.H. Lin, D.K. Shih, *Electron Devices and Material Symposia*, Kaohsiung, Taiwan, R.O.C., 2001, pp. 126–129.
- [5] D.R. Hang, C.F. Huang, W.K. Hung, Y.H. Chang, J.C. Chen, H.C. Yang, Y.F. Chen, D.K. Shih, T.Y. Chu, H.H. Lin, *Semicond. Sci. Technol.* 17 (2002) 999.
- [6] W.K. Hung, K.S. Cho, M.Y. Chern, Y.F. Chen, D.K. Shih, H.H. Lin, C.C. Lu, T.R. Yang, *Appl. Phys. Lett.* 80 (2002) 796.
- [7] P.T. Coleridge, R. Stoner, R. Fletcher, *Phys. Rev. B* 39 (1989) 1120.
- [8] D.R. Hang, C.-T. Liang, J.-R. Juang, Tsai-Yu Huang, W.K. Hung, Y.F. Chen, G.-H. Kim, J.-H. Lee, J.-H. Lee, *J. Appl. Phys.* 93 (2003) 2055.
- [9] I. Vurgaftman, J.R. Meyer, L.R. Ram-Mohan, *J. Appl. Phys.* 89 (2001) 5815.
- [10] W. Shan, W. Walukiewicz, J.W. Ager III, E.E. Haller, J.F. Geisz, D.J. Friedman, J.M. Olson, S.R. Kurtz, *Phys. Rev. Lett.* 82 (1999) 1221.
- [11] C. Skierbiszewski, P. Perlin, P. Wisniewski, W. Knap, T. Suski, W. Walukiewicz, W. Shan, K.M. Yu, J. W. Ager, E.E. Haller, J.F. Geisz, J.M. Olson, *Appl. Phys. Lett.* 76 (2000) 2409.
- [12] T. Mattila, S.H. Wei, A. Zunger, *Phys. Rev. B* 60 (1999) R11245.