Low temperature electron magnetotransport in In$_x$Ga$_{1-x}$As/In$_{0.52}$Al$_{0.48}$As quantum wells with high electron density

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Abstract. We present the investigations of low temperature magnetotransport in the one- or two- side Si delta-doped quantum well structures In$_{0.52}$Al$_{0.48}$As/In$_x$Ga$_{1-x}$As/In$_{0.52}$Al$_{0.48}$As grown on InP with different InAs fraction in In$_x$Ga$_{1-x}$As and hence the different quantum well depth. Hall effect and Shubnikov- de Haas oscillations were measured in quantized magnetic field up to 7 T in the temperature interval 0.3<T<4.2 K. The oscillation analysis reveals the two pronounced frequencies with the different amplitudes from two filled subbands. The electron subband mobility is shown to be sensitive to composition and doping.

1. Introduction

Ternary heterosystem In$_{0.52}$Al$_{0.48}$As/In$_x$Ga$_{1-x}$As/In$_{0.52}$Al$_{0.48}$As on InP provides high electron mobility and drift velocity because of low electron effective mass. Furthermore, quantum well (QW) is deeper than in AlGaAs/InGaAs/GaAs pseudomorphic heterosystem, so more strong electron confinement in QW can be achieved, preventing a parallel conduction in the doped region. High electron mobility and density two-dimensional electron gas can be created in this system. These factors are determining for the choice of these structures for the ultimately faster and low-noise applications [1]. The highest reported cutoff frequency is about 550 GHz on this kind of structures combined with gate nanolithography [2]. Future trends to achieve THz frequencies are already outlined [3]. The idea of electron transport properties enhancement by either increase of InAs fraction in the In$_x$Ga$_{1-x}$As QW [4,5] or utilization of the stepped QWs [6] in various structures with pseudomorphic strained channel had been offered and tested.

However, the majority of the transistor heterostructure studies doesn't go beyond the measurements of Hall concentration and the mobility at 300 K and 77 K. In the Ref. [7] only the intersubband energy separation has been obtained from Shubnikov-de Haas (SdH) oscillations. Comprehensive study of double stepped QW including electron magnetotransport has been performed in Ref. [8]. Low temperature electron magnetotransport and quantum Hall effect have been studied in the low electron concentration range [9], where electron mobility have shown to be low. The detailed study of electron...
transport properties is very important for understanding the electron mobilities in case of high electron density and hence multisubband occupation. In this work we study electron magnetotransport in In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As/In_{0.52}Al_{0.48}As QW’s with high electron concentration $n_s \geq 3 \times 10^{12}$ cm$^{-2}$ and the different depth which is ruled by InAs content $x$ and QW thickness.

2. Experimental

2.1. Samples

The samples were grown at Institute of Ultra High Frequency Semiconductor Electronics by the molecular beam epitaxy on InP (100) substrates. Some structural and measured parameters are listed in Table 1. All samples have 380 nm thick In$_{0.52}$Al$_{0.48}$As buffer matched to InP. Samples #1-#3 have one-side delta-doping by Si. The spacer thickness was 4.3 nm. In the sample #4 the second Si delta-layer was introduced below the QW in order to achieve high electron concentration in the QW. Cap layer was thin undoped In$_{0.53}$Ga$_{0.47}$As. Growth temperature was 510 °C for all layers. The growth interruptions were performed before and after the QW layer growth in order to smooth the heterointerfaces. The QW width is reduced under the critical thickness in the sample #3 because of pseudomorphic compression of In$_x$Ga$_{1-x}$As layer in order to prevent the lattice relaxation and the deterioration of electron mobility by the dislocation scattering.

Table 1. Sample parameters. $L$ is QW thickness, $x$ - InAs content in QW, $n_H$ and $\mu_H$ - Hall concentration and mobility at 4.2 K, $n_0$ and $n_1$ - are electron subband concentrations determined by Shubnikov-de Haas effect.

| Samp. # | $L$, nm | $x$ (InAs) | $n_H$ | $n_0$ | $n_1$ | $\mu_H$ | $\mu_0/\mu_1$ |
|--------|--------|------------|-------|-------|-------|---------|-------------|
| 1      | 18     | 0.53       | 3.41  | 2.65  | 0.68  | 33 200  | 1.9         |
| 2      | 18     | 0.60       | 3.60  | 2.75  | 0.80  | 41 500  | 0.45        |
| 3      | 16     | 0.70       | 3.73  | 2.93  | 0.81  | 34 700  | 0.9         |
| 4      | 20     | 0.53       | 5.13  | 2.84  | 2.07  | 15 800  | -           |

2.2. Magnetotransport properties.

Temperature dependence of the resistance and Hall effect were measured in the temperature interval 0.3 K<T<300 K. At low temperatures magnetoresistance tensor components were measured in quantized magnetic field up to 7 T. For all samples SdH effect appears with two pronounced frequencies. We use traditional technique of Fourier transformation of the $\rho_{xx}(1/B)$ oscillations to obtain the electron subband concentrations by the frequencies of oscillations. In the figure 2 fast
Fourier transform spectra of the oscillations are shown. Quantum Hall effect was not observed in this range of magnetic fields. In the figure 3 magnetoresistance for the sample #4 is given, and the corresponding FFT spectra is presented in figure 4 for the temperature T=1.5 K.

3. Results and discussion

In all samples Hall mobility increased sufficiently from the room temperatures ($\mu_H \sim 9500 - 11000 \text{ cm}^2/\text{Vs}$) to liquid nitrogen temperature ($\mu_H \sim 28000 - 32000 \text{ cm}^2/\text{Vs}$) and weakly increased with the decrease of the temperature below 4.2 K. The overall tendency is Hall mobility increase when InAs content in QW is increased, as it clearly seen for the samples #1 and #2. In the sample #3 Hall mobility is only slightly increased in comparison to #1. This can be attributed to i) more narrow QW and ii) an additional scattering by some dislocations in QW partially relaxed layer. For the sample #4 Hall electron concentration is increased sufficiently, but electron mobility isn’t so high. This is because of rather small spacer layer thickness and possible, segregation of Si dopants from the lower delta-layer into following QW layer during the growth.

The Hall mobility in the case of several filled subbands gives averaged values of the subband mobility. But the analysis of the FFT spectra intensity for the different frequency peaks allow to find electron mobility ratio for the different electron subbands [10]. In the sample #1 the highest electron mobility is in the lowest subband. In the sample #2 the mobility of the second subband sufficiently increases and exceeds the mobility in the ground subband. Also the onset of the oscillations for the subband with high electron mobility occurs in the smaller magnetic field. The ratio of subband electron mobility is given in table 1. In the lattice-matched sample #1 the lower subband has the bigger electron mobility. With the increase of InAs content, and hence, in pseudomorphically strained QW #2 electron mobility in the second subband increases. Indeed, in the figure 1 one can see that the high frequency oscillations start in the lower field in the sample #1, but for the sample #2 it is the low frequency oscillations. For the sample #3 the subband mobilities are close to each other. So, the second electronic subband is rather sensitive to any changes of the QW structure.

3.1. Bandstructure calculation.

To analyse the experimental data, subband structure simulation is very helpful. The calculations show subband electron concentration, which is very close to the values observed by SdH effect. In the figures 5 and 6 conduction band structure of the QW and electron subband levels and wavefunctions are shown. The increase of both $n_0$ and $n_1$ in the sample #2 is due to more deep QW, while the difference $n_0-n_1$ coincides for the #1 and #2. The increased difference $n_0-n_1$ in the sample #3 and consequently, increased subbands energy separation, is due to smaller QW thickness in this sample. For the double-side doped sample #4 electron concentration in the upper subband is significantly increased, while for the lower subband it is compared to the values of $n_0$ in the samples #1-#3.
4. Conclusion

Electron magnetotransport properties of In$_{0.52}$Al$_{0.48}$As/In$_x$Ga$_{1-x}$As/In$_{0.52}$Al$_{0.48}$As/InP quantum wells with the different width and depth with two filled subbands are studied by Hall and Shubnikov-de Haas effects. It is found that the increase of the InAs fraction in quantum well leads to increase of the electron mobility, and especially for the second filled subband. While the quantum well thickness is close to critical for the further increased InAs content, the mobility decreases. The double-side doping allows to increase sufficiently electron density and to symmetrize quantum well profile.

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