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PECULIARITIES OF QUANTUM MAGNETOTRANSPORT IN $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HETEROSTRUCTURES GROWN ON (100)InP

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ABSTRACT

Magnetotransport properties of the Si δ-doped $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructures grown on (100)InP substrates were investigated by performing classical Van der Pauw Hall effect as well as high field quantum magnetotransport measurements. The results of the conventional Hall measurements are ambiguous because the mobility obtained at liquid helium occurred to be smaller than at room temperature. The qualitative analysis of the conductivity tensor revealed at least two conducting channels. Thus, the properties of whole structure are limited by the low mobility of the parasitic parallel conduction layer. On the other hand, the fast Fourier transform of the quantum magnetooscillations consists of a lot of frequencies. None of them can not be attributed to the presence of the two-dimensional electron gas (2DEG) in a single quantum well. We interpret our rich Fourier spectrum as due to quantum interference (QI) between open electron path commonly found in superlattices structures.

1. Introduction

The InGaAs/InAlAs lattice-matched to InP system is of great interest for both electronic and optical devices and circuits. It offers the potential for higher speed electronic devices by virtue of the smaller effective mass (0.041 m_0 for InGaAs vs 0.067 m_0 for GaAs), a larger conduction band discontinuity (0.52 eV vs 0.3 eV for $Al_{0.40}Ga_{0.60}As$) and a larger Γ to L valley separation (0.55 eV for InGaAs vs 0.3 eV for GaAs). These characteristics have permitted the fabrication of very high speed modulation doped field – effect transistors and 2DEG structures with large sheet densities [1]. Recent progress of the growth technique has enabled us to obtain modulation-doped heterojunctions by the invention of the superlattice (SL) concept in order to reduce the threading dislocation density [2], [3]. In this article we report magnetotransport data of the n-type $In_{0.53}Ga_{0.47}As/$ $/In_{0.52}Al_{0.48}As$ heterostructures grown according to above mentioned state-of-the-art. The main goal was to obtain the high mobility 2DEG located at hetero-interface. It occured that the low temperature magnetooscillations are much more complicated than ordinary Shubnikov-de Haas effect for single quantum well. We have tentatively attributed them as originate either from self-interference along closed electron orbits or from quantum interference between open electron paths [4–8].

2. Experiment

The samples investigated in this paper were grown at MOCVD reactor. Further details regarding the fabrication are given in Ref. [9–11]. The samples used in this work were grown on Fe-doped semi-insulating (100)-oriented InP substrates and consisted of the following structures: a 15 nm Si-doped ($n =$ $= 3.0\cdot10^{18}$ cm^{-3}) $In_{0.53}Ga_{0.47}As$ capping layer for ohmic contacts, a 20 nm undoped $In_{0.52}Al_{0.48}As$ layers, an Si δ-doping concentration of $2.0\cdot10^{12}$ cm^{-2}, a 4 nm undoped $In_{0.52}Al_{0.48}As$ spacer layer, a 20 nm undoped $In_{0.53}Ga_{0.47}As$ quantum well, a 10 nm undoped $In_{0.52}Al_{0.48}As$ buffer layer and 11 periods of an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ superlattice buffer layer. A lattice matched superlattice buffer layer was grown in order to reduce the threading dislocation density [3]. Ohmic contacts for the Hall and magnetoresistance measurements were made by annealing in nitrogen atmosphere In-Sn dots at 420°C for 1.5 min. The high field magnetoresistance measurements were carried out in the magnetic field up to 13 T at temperatures from 1.5 to 77 K with a Van der Pauw square shape sample. Low field classical Hall effect measurements were performed in the magnetic field up to 1T in temperature range 4.2 K to 300 K.

3. Results and discussion

Classical Hall effect measurements at 293 K, 77 K and 4.5 K in magnetic field of 0.6 T yielded a mobility and sheet carrier density of $1.6\cdot10^3$ cm^2 (V·s)$^{-1}$ and $1.0\cdot10^{12}$ cm^{-2}, $1.8\cdot10^3$ cm^2 (V·s)$^{-1}$ and $0.5\cdot10^{12}$ cm^{-2}, $1.0\cdot10^3$ cm^2 (V·s)$^{-1}$ and $1.8\cdot10^{12}$ cm^{-2}, respectively. The low field Hall effect measurements $\mu(T)$ and $n_s(T)$ are non-monotonically dependent of temperature in a manner quite different to that of other modulation-doped heterostructures.

Moreover, at liquid helium temperature mobility is reduced to most lower value. It is probably due to the presence of parasitic parallel conduction channel of low mobility.

To check this hypothesis we have performed low temperature high field resistivity tensor measurement which are related to the elements of the conductivity tensor in the standard way [12], [13]:

$$\sigma_{xx}(B) = \sum_{i=1}^{m} \frac{en_i\mu_i}{1+(\mu_i B)^2}, \qquad (1)$$

$$\sigma_{xy}(B) = \sum_{i=1}^{m} S_i \frac{en_i\mu_i^2 B}{1+(\mu_i B)^2} \qquad (2)$$

where n_i and μ_i are the concentration and mobility of the i-th carrier species, respectively, and S_i equals to +1 for holes and –1 for electrons. The physical meaning of these two equations has been discussed in Ref. [13]. It is primarily the $1 + \mu^2 B$ terms in the denominators of Eq. (2) which differentiate the contributions from the various carrier species. The Hall conductivity (σ_{xy} (B) increases linearly with B until μB approaches unity, at which point it passes through a maximum and then decreases as B^{-1} at large B. On the other hand, the diagonal conductivity (σ_{xx} (B) is constant at low fields and then begins to decrease when $\mu B \approx 1$. The simplest case was assumed, that only two conductive channels are present in the sample (characterized by n_1, μ_1 and n_2, μ_2, respectively). The results of such decomposition are shown in Fig. 1. The agreement between theory and experiment is not perfect, but one can see qualitatively that at least two conducting channels are present in the sample. One of low mobility $\mu_2 = 3.3\cdot10^3$ cm^2 (V·s)$^{-1}$ and another one with considerably higher mobility $\mu_1 = 2.0\cdot10^4$ cm^2 (V·s)$^{-1}$. This high mobility channel could be attributed to the presence of 2DEG in the sample. The accompanying sheet carrier density equals to $n_1 = 5\cdot10^{12}$ cm^{-2}. For such high electron density the second subband in InGaAs/InAlAs heterostructure should be occupied. It was already observed even for smaller electron densities of the order $2\cdot10^{12}$ cm^{-2} [14], [15]. In such

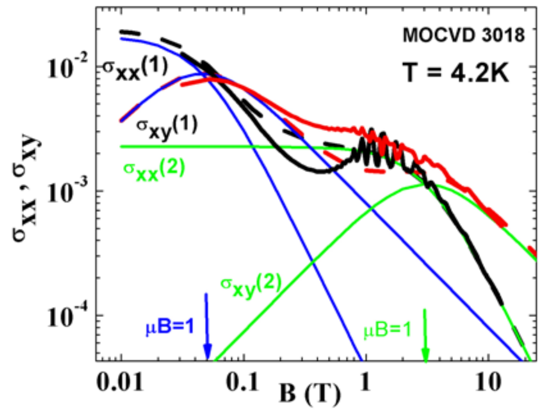

Fig. 1. Decomposition of diagonal $\sigma_{xx}(B)$ and Hall conductivities $\sigma_{xy}(B)$ into two major components (*1*, *2*); solid lines (red and black) – experiment; blue lines – 1st components, green lines – 2nd components; dashed lines (red and black) – resulting sum of 1st and 2nd components for an n-type $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure at $T = 4.2$ K.

a situation when two electrical subbands are occupied one can expect the magnetointersubband scattering phenomena in the quantum transport. It can be easily verified by the careful analysis of the oscillating magnetoresistance data collected at low temperatures. Therefore, we have performed S-dH measurements at 1.5 K and 4.2 K in magnetic field swept up to 13 T. From the measured total magnetoresistance the monotonous raising background was subtracted as presented in Fig. 2.

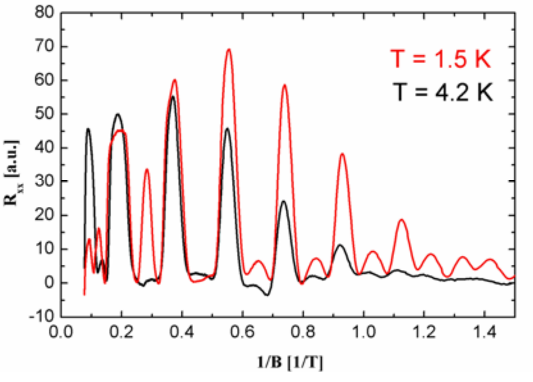

Fig. 2. S-dH oscillations in longitudinal (R_{xx}) resistance after background removed at 1.5 and 4.2 K.

One can see that observed quantum oscillations behave in a non-standard way. Several peaks are enhanced and several are damped depending on small temperature change from 1.5 to 4.2K.

In order to shed light on this unusual behavior we have performed Fast Fourier Transform (FFT) of the measured oscillations. The power spectrum of FFT presented in Fig. 3 consists of many well resolved peaks at different frequencies. Let's assume that peak frequency corresponding to peak denoted by letter α is our fundamental frequency related to the presence of 2DEG. The 2DEG density n_α can be obtained from the frequency of the S-dH oscillation using the following expression $n_\alpha = 2ef_\alpha/h = 4.82\ 10^{10}\ f_\alpha$ (cm^{-2}). An oscillation frequency of 5.3 T corresponds to an

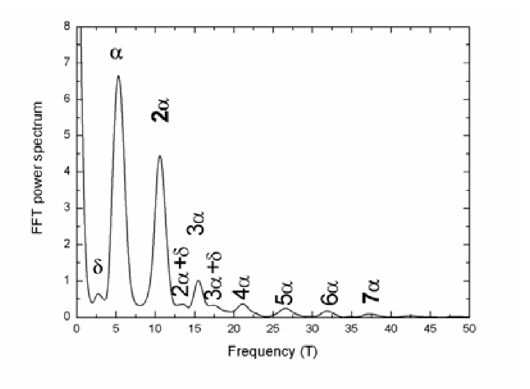

Fig. 3. FFT result corresponding to 1.5K traces.

electron density of $2.5\cdot10^{11}$ cm^{-2}. It is one order of magnitude less than the density estimated from high field conductivity tensor analysis. Thus, magneto-intersubband scattering can be excluded as an origin of observed magnetooscillations pattern. Although, such a strong discrepancy between electron concentrations obtained by two mentioned methods is striking and remains unexplained. On the other hand, such a rich Fourier power spectrum closely resembles that one observed in magnetoresistance studies of SL GaAs/$Al_{0.32}Ga_{0.68}As$ [4], and even 2DEG organic conductors [5], [8]. In these papers authors have interpreted their spectra as caused by quantum interference phenomenon. They found simple relation between observed frequencies in the form $\delta + n\alpha$, where n is integer number [8]. Several of them are clearly present in our case (Fig. 3). We suppose that oscillations with such frequencies originate from the $1/B$– periodic modulation of the backscattering probability due to quantum-mechanical interference between open electron paths. These features suggest that additional contributions, such as frequency mixing due to oscillation of the chemical potential or interplay of electronic states from the different bands crossing the Fermi level, strongly influence the oscillatory behavior. In our case this interpretation is valid, when assumed that our intentionally undoped SL may take part in the electronic transport. With this assumption our sample is identical to the device prepared by Deutschmann et al. [4]. In our case the possibility of the redistribution of the δ-doped Si and degradation of spacer/channel interface could lead to nonzero population of the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ superlattice [16], [17].

4. Conclusion

The results of classical Van der Pauw Hall effect measurements and high field quantum magneto-transport are inconsistent at the first sight. The closer analysis of the conductivity tensor components reveals at least two competing conducting channels in the sample. One of them could originate from 2DEG. On the other hand, it cannot be confirmed in quantum magnetooscillations. Their rich Fourier power spectrum suggest instead, that superlattice introduced formerly in order to reduce threading dislocations density, now dominates in quantum magneto transport.

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