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Evolution of the spin-split quantum Hall states with magnetic field tilt in the InAs-based double quantum wells

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Abstract. Development of quantum Hall peculiarities due to mobility gap between spin-split magnetic levels with addition of the parallel magnetic field component $B_{||}$ is analyzed in double quantum wells (DQW) created in InGaAs/GaAs and InAs/AlSb heterosystems chosen due to their relatively large bulk g-factors. In InGaAs/GaAs DQWs, the nonmonotonous behavior of these peculiarities is observed and explained within single-electron approach in terms of competition between enhanced spin splitting and localization of electrons in the layers of DQW with increased $B_{||}$. In InAs/AlSb DQW, the tunneling connection between the layers is very weak due to high barrier, nevertheless the collective odd-numbered peculiarities are revealed that exist due to spontaneous interlayer phase coherence. $B_{||}$ destroys these states that is manifested, in particular, in the suppression of the peculiarity for filling factor $\nu = 3$.

1. Introduction

Double quantum wells (DQWs) are attractive for physical researches due to the additional (pseudospin) degree of freedom and existence of collective interlayer modes [1]. Sufficient realization of *spin* degree of freedom (i.e. sufficient spin splitting of Landau levels) may still expand the circle of DQW peculiar features [2]. The main body of research in DQW physics is performed within GaAs/AlGaAs heterosystem as the most perfect with the highest mobilities. But the peculiar property of GaAs is its very small Lande g-factor: $|g| = 0.44$ (the bulk value, *i.e.* not exchange enhanced). This forms a stimulus for us to investigate quantum magnetotransport in DQWs with the well material having relatively high g-factor: InGaAs with $|g| = 1 \div 3$ and InAs with $|g| = 15$.

2. InGaAs/GaAs: nonmonotonous behavior with $B_{||}$ of $\nu = 3$ state

Specific DQW states are mostly manifested in the odd-numbered quantum Hall (QH) features since they can only exist when there is some interlayer interaction lifting the degeneracy of similar states within equal single wells. The most informative DQW state is the one for filling factor $\nu = 1$, but to trace its behavior under tilted magnetic fields may demand too high a value

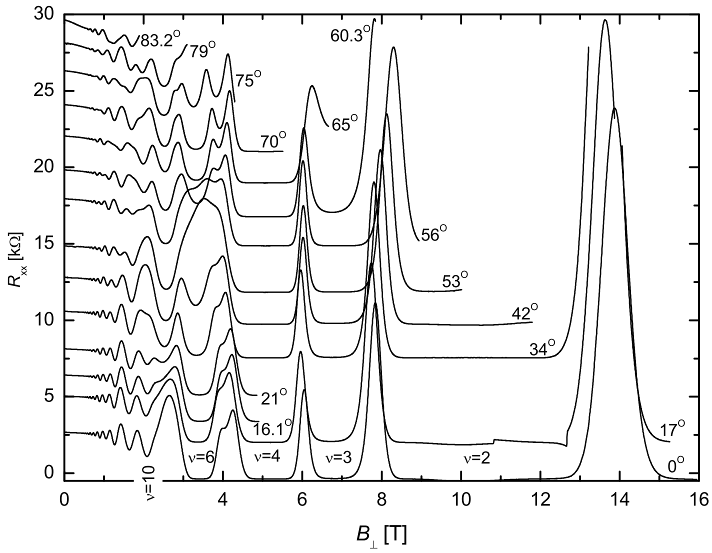

Figure 1. Magnetoresistance R_{xx} for different tilt angles vs. perpendicular field component. Traces are vertically shifted.

of the total field, so we concentrate on the behavior of the $\nu = 3$ features: see figure 1 around the perpendicular field component $B_\perp = 7$T.

The sample investigated is $In_{0.2}Ga_{0.8}As/GaAs$ DQW with InGaAs wells of 5 nm width, and 10 nm wide GaAs barrier, symmetrically doped on both sides with 19 nm spacers. Initial total density of 2D electron gas is $n_s = 2.3 \times 10^{15}\text{m}^{-2}$ that may be increased up to a factor of 3 with IR illumination that is accompanied by a considerable improvement of the sample quality. Measurements were performed at 50 mK by sweeping the magnetic field B at the fixed rotator angles θ between the field direction and sample normal, or by sweeping θ at fixed B at 1.8 K.

Unusual seems the behavior of the $\nu = 3$ minimum with tilt (fig.1 and fig2, inset): after its enhancement (widening), which is understandable in terms of increased spin splitting with

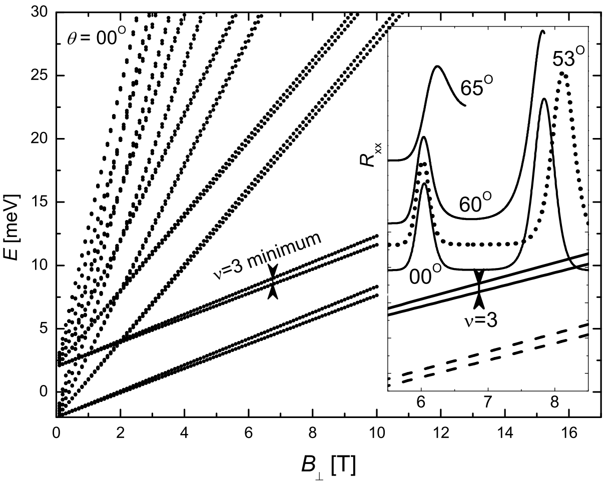

Figure 2. Calculated magnetic level picture for perpendicular magnetic field configuration, $|g| = 1.2$. Inset, bottom: enhanced part with indicated gap for $\nu = 3$ minimum; upper part: selected traces of $R_{xx}(B_\perp)$ for different tilts depicting nonmonotonous change of the minimum width.

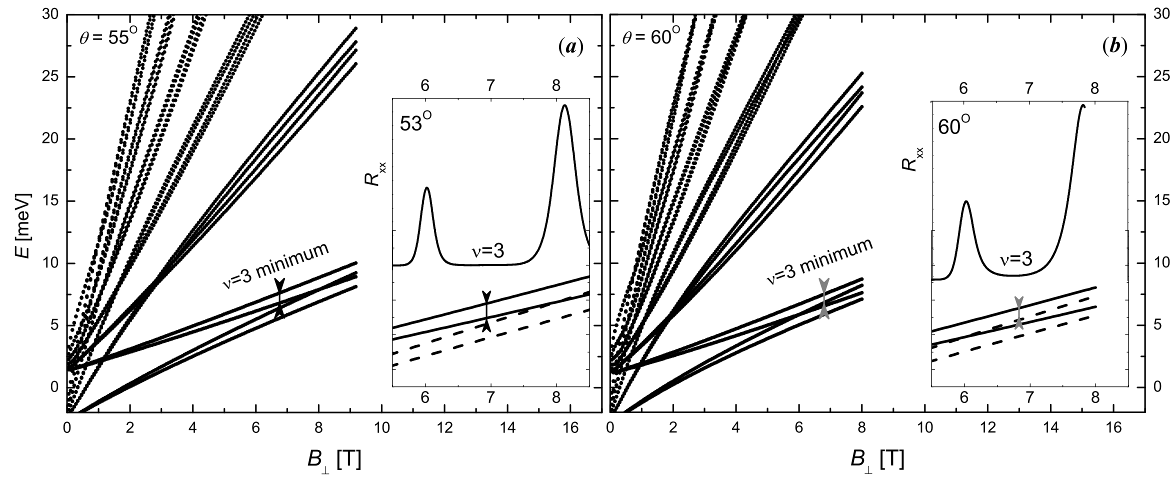

Figure 3. The same as figure 2, but in tilted fields: $\theta = 55^0$ (a) and $\theta = 60^0$ (b).

increasing total magnetic field, it is quickly suppressed at the largest tilts. The latter is explained within the magnetic level picture calculated according to the single-electron quantum treatment [3] (fig.2 and 3). The causes for the suppression are the tendency of DQW magnetic levels to gather in fours and the gradual merging of levels having the same Landau numbers and spin with growing parallel field component $B_{||}$, so that the gaps for the odd-numbered quantum Hall states change from the spin gaps into the gradually vanishing pseudospin gaps between similar symmetric and antisymmetric states. The change from enhancement to suppression should occur at the crossing of symmetric higher spin sublevel with the identical antisymmetric lower spin sublevel at the $B_\perp$ value corresponding to $\nu = 3$. According to calculations this should occur around $\theta = 60^0$, in agreement with our experiment (fig.1 and 3). The overall nature of this behavior is the suppression by $B_{||}$ of the connection between layers of DQW. This effect cannot be represented within quasiclassical description [4,5]. Similar behavior was also observed in GaAs/AlGaAs DQW [6], but without calculations.

3. InAs/AlSb DQW: novel conditions for the interlayer $\nu = 3$ state at $|g| = 15$

InAs/AlSb DQW is remarkable by its maximum, to the best of our knowledge, g-factor value $|g| = 15$ realized in a DQW so far. The sample structure is presented in fig.4a (see [7] for more details). The total 2D electron gas density in the DQW is 4.2×10^{15} m^{-2} with low temperature mobility of several tens m^2/V·s. Due to a high barrier (1.4 eV) the calculated tunnel gap is very small: $\Delta_{SAS} = 0.23$ meV, comparable to k_BT at the experiment temperature of 1.8 K. The smallness of the gap is confirmed by that we don't see any peculiarity in the magnetoresistivity under pure parallel magnetic field. Thus the conditions for existence of collective (odd-numbered) QH states should be tough here. Nevertheless several QH plateaus exactly match the odd-numbered $\rho_{xy} = h/ie^2$ values with $i = 3, 5, 7\ldots$: (figure 4b). The value of d/l_B [8] is estimated to be approximately 1.9 for our sample at $\nu = 3$, just on the border for existence of a QH state for a spin-unpolarized system defined as the critical value of this parameter equal to 1.9. Recently similar estimation was done for the spin-polarized case and the greater critical value of 2.33 was found [2]. In [2] the spin-splitting in GaAs/AlGaAs DQW was enhanced by tilting the magnetic field. In our InAs/GaSb DQW, substantially greater bulk g-factor yields the spin-polarized state without tilt thus allowing the many-body collective

(*a*)

6 nm GaSb cap layer
35 nm AlSb top barrier
15 nm InAs QW
5 nm AlSb intermediate barrier
15 nm InAs QW
15 nm AlSb bottom barrier
10 period (2.5 nm GaSb + 2.5 nm AlSb) superlattice
i-GaSb, 250 nm
i-AlSb, 2000 nm
i-AlAs buffer, 10 nm
i-GaAs buffer, 200 nm
SI GaAs substrate

(*b*)

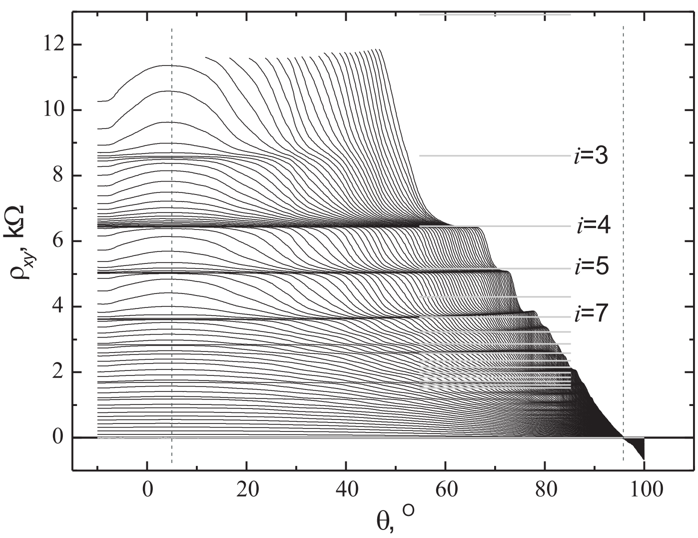

Figure 4. The structure of the InAs DQW (a) and the Hall magnetoresistance ρ_{xy} for rotations at different fixed total fields $B = 0 \div 9T$ (with the step of 0.1T) (b). Note the suppression of the $i = 3$ state with tilt. The dashed verticals denote that the real scale in θ should be shifted about 6^0 due to a misalignment of the sample in the rotator.

interlayer QH state to exist at $d/l_B = 1.9$.

The $\nu = 3$ plateau is suppressed by the parallel field component $B_{||}$ (fig.4b), thus excluding that nature of the odd-number states may by due to spin gaps (as it were in a single QW, in that case the odd-numbered QH states should be enhanced with tilt) or due to a strong asymmetry of the DQW potential (a strong dependence of the gap on $B_{||}$ is not expected then). So far only the suppression of the $\nu = 1$ DQW QH state has been observed [8] that was the main argument for its many-body spontaneous interlayer phase coherence nature. The cause for existence of strong many-body interlayer states at $\nu = 3$ in InAs-based DQWs is to be analyzed substantially with tentative emphasis on the combination of the pseudospin and strong spin degrees of freedom as well as strong spin-orbit coupling in this DQW.

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References

[1] Girvin S M and MacDonald A H 1997 *Perspectives in Quantum Hall Effects*, ed S Das Sarma and A Pinczuk (New York: John Wiley and Sons, Inc.) chapter 5 pp 161–224
[2] Giudici P, Muraki K, Hirayama Y and Fujisawa T 2008 *Phys. Rev. Lett.* **100** 106803
[3] Hu J and MacDonald A H 1992 *Phys. Rev.* B **46** 12554
[4] Harff N E, Simmons J A, Lyo S K, Klem J F, Boebinger G S, Pfeiffer L N and West K W 1997 *Phys. Rev.* B **55** 13405
[5] Yakunin M V, Galistu G and de Visser A 2008 *Physica* E **40** 1451
[6] Zeitler U, de Jonge J, van Tilburg J W W and Maan J C 2004 *International Journal of Modern Physics* B **18** 3693
[7] Sadofyev Yu G, Ramamoorthy A, Naser B, Bird J P, Johnson S R and Zhang Y-H 2008 *Appl. Phys. Lett.* **81** 1833
[8] Murphy S Q, Eisenstein J P, Boebinger G S, Pfeiffer L N and West K W 1994 *Phys. Rev. Lett.* **72** 728