Available online at www.sciencedirect.com
ScienceDirect
Physica E 40 (2008) 1451–1453
PHYSICA E
www.elsevier.com/locate/physe

Tilted magnetic field quantum magnetotransport in the double quantum well with a sizable bulk g-factor: $In_xGa_{1-x}As/GaAs$

Michael V. Yakunin[a,b,*], Gianni Galistu[b], Anne de Visser[b]

[a]Institute of Metal Physics RAS, Semiconductor Laboratory, GSP-170, S. Kovalevskaya Street, 18, Ekaterinburg 620041, Russia
[b]Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands

Available online 21 September 2007

Abstract

Rich patterns of transformations in the structure of quantum Hall (QH) effect and magnetoresistivity under tilted magnetic fields were obtained in the $In_xGa_{1-x}As/GaAs$ double quantum well at mK temperatures. Local features correspond to the calculated intersections of Landau levels from different subbands and are due to the sharp motion of their crossing points with parallel field component. An incipient quenching with parallel field of the filling factor $\nu = 3$ QH state is revealed, which should be due to suppression of the interlayer connection. The observed peculiar monotonous shift in perpendicular fields with increasing in-plain field of the peak between QH states $\nu = 1$ and 2 as well as an unusual minimum on some QH plateaus are probably beyond the single particle treatment.
© 2007 Elsevier B.V. All rights reserved.

PACS: 73.20.Dx; 73.40.Kp; 73.40.Lq

Keywords: Double quantum well; Quantum Hall effect; Tilted magnetic field; Parallel magnetic field; Interlayer correlations

1. Introduction

The double quantum well (DQW) is a unique object to study interparticle interactions, magnetotransport for the occupied upper subband and, in general, the effects of additional degree of freedom on the solid state physics [1]. Interest to a DQW made in the $In_xGa_{1-x}As/GaAs$ heterosystem is due to the $In_xGa_{1-x}As$ bulk g-factor, which is larger than that of GaAs, while almost all the researches in DQW physics have been performed on the GaAs/AlGaAs heterosystem so far. The spin effects observed in the latter DQW [2] are due to the spin splitting that is mainly caused by the exchange correlations. The initially greater g-factor value (i.e., the bulk value) in $In_xGa_{1-x}As$ leads to a more stable behavior of quantum magnetotransport and sheds a new light on the spin properties of the (quasi-)2D electron gas.

2. Experimental

Intricate transformations in the $In_xGa_{1-x}As/GaAs$ DQW magnetoresistivity ρ_{xx} as a function of two field components $(B_\perp, B_\parallel)$ have been revealed from thorough scans of the $(B_\perp, B_\parallel)$-plane at 1.8 K [3], and a strong interference with the magnetic breakdown effect was found. To improve resolution, we extended measurements of the quantum Hall effect (QHE) in DQW under tilted magnetic fields down to 50 mK in fields up to 16 T, with the results presented here as functions of the total field under its different fixed orientations φ relative to the sample normal. The sample is the same as in Ref. [3]: $In_{0.2}Ga_{0.8}As/GaAs$ DQW with 5 nm wide quantum wells and 10 nm barrier, symmetrically doped in both GaAs surroundings behind 19 nm spacers. The electron density n_s in the sample could be increased more than twice by infrared illumination at low temperatures, and the sample quality improved dramatically. The data presented here are for the illumination up to saturation that corresponds to $n_s = 5.1 \times 10^{15}\,m^{-2}$. To emphasize the features inherent to a DQW, a sample of similar heterostructure, but containing a single QW (SQW), was investigated as well.

*Corresponding author. Institute of Metal Physics RAS, Semiconductor Laboratory, GSP-170, S. Kovalevskaya Street, 18, Ekaterinburg 620041, Russia. Tel.: +7 343 3783644; fax: +7 343 3745244.
E-mail address: yakunin@imp.uran.ru (M.V. Yakunin).

1386-9477/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physe.2007.09.048

3. Effects of tilted magnetic field

Experimental results for some tilt angles are presented in Figs. 1–3. The addition of the parallel field leads to pronounced irregular local transformations in the structure of magnetoresistance peaks within restricted ranges of $B_\perp$ and $B_\parallel$ (or B and φ), in contrast to the results for a SQW, where the traces for all angles are reproduced if being built versus $B_\perp$, excluding some development of the odd-numbered QH features due to an enhance of spin splitting.

To analyze these data, we calculated magnetic level patterns for the DQW energy dispersions at fixed $B_\parallel = B_x$ values [4]:

$$E_{\mathrm{M}} = \frac{\hbar^2(k_x^2+k_y^2)}{2m} + \frac{E_{\mathrm{S}}+E_{\mathrm{A}}}{2} \pm \frac{1}{2}\sqrt{\Delta_{\mathrm{SAS}}^2 + \left(2\hbar \times \frac{eB_\parallel d}{m} \times k_y\right)^2},$$

where M = S, A denotes the symmetric and antisymmetric subbands with edges E_{S} and E_{A} and the tunneling gap Δ_{SAS} between them; k_x and k_y denote the wave vector projec-

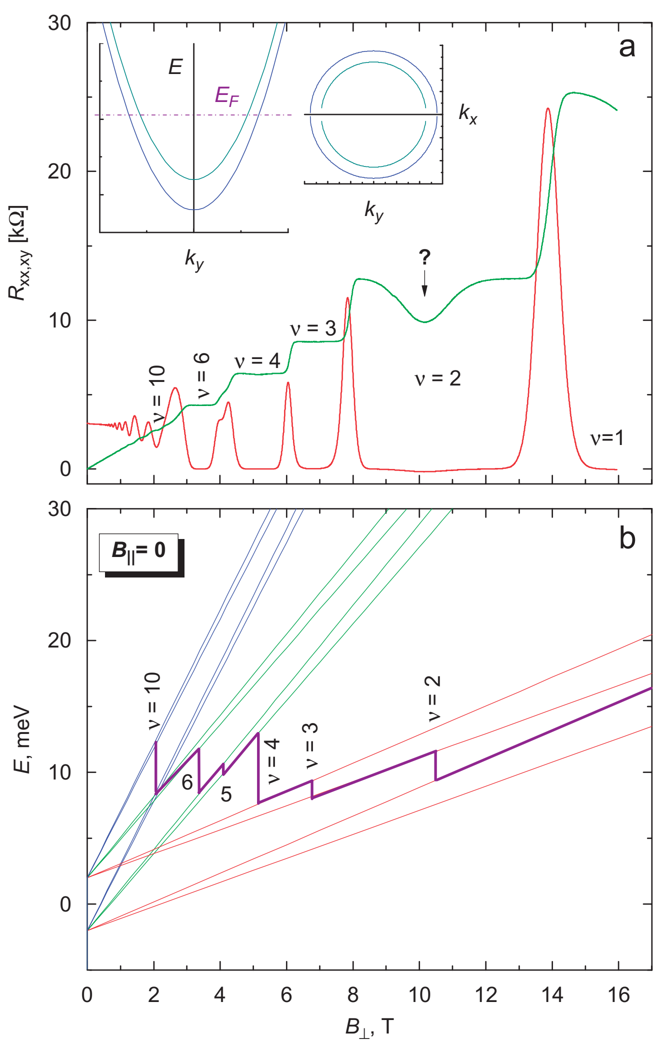

Fig. 1. (a) Quantum Hall effect under pure perpendicular field. The insets: energy dispersion and its Fermi energy cross-section. (b) The calculated magnetic level pattern with the Fermi level (bold) moving through it.

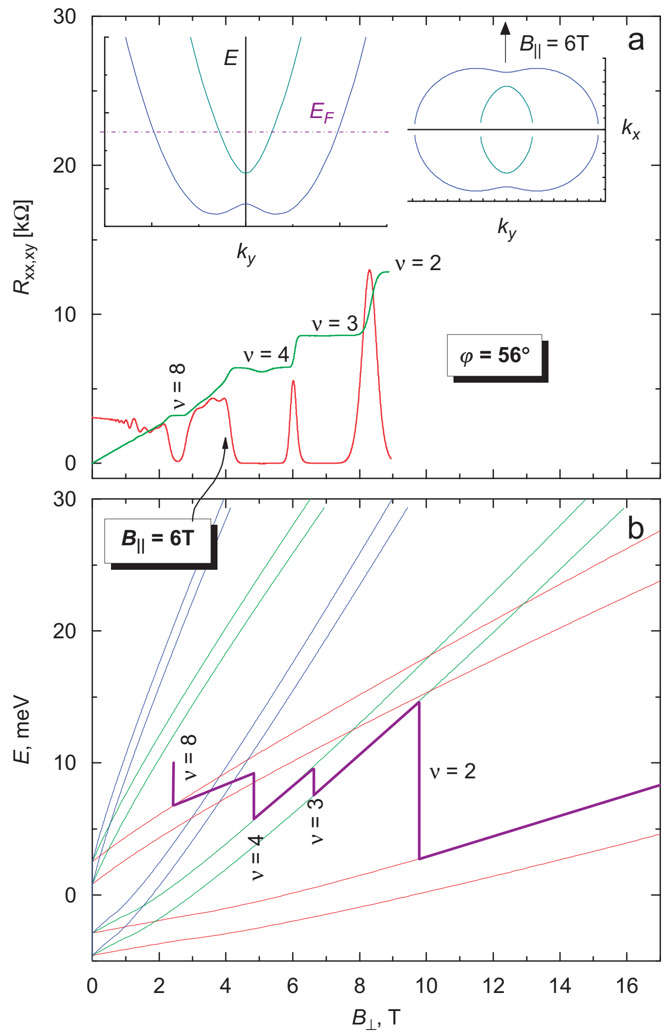

Fig. 2. (a) The same as Fig. 1, but for $\varphi = 56°$. (b) Calculated magnetic level pattern for the constant $B_\parallel = 6\,\mathrm{T}$ with the curved arrow indicating the $B_\perp$ position corresponding to this $(B_\parallel, \varphi)$ combination. Insets in part (a) are for $B_\parallel = 6\,\mathrm{T}$. Note the correspondence between the intricate-shaped peak around 4 T and the passing of Fermi level through the magnetic level crossings.

tions onto the DQW planes; $m = 0.058m_0$ denotes the effective mass and d denotes an effective interlayer distance.

First, for a given $B_\parallel$ value, the Landau levels in each of the subbands were calculated quasi-classically from the equation for the number of states $N_{\mathrm{M}}(E)$ in the area within the E_{M} projection onto the (k_x, k_y)-plane:

$$N_{\mathrm{M}}(E) \equiv \oint \frac{k_x(E_{\mathrm{M}})\,\mathrm{d}k_y}{4\pi^2} = \frac{eB_\perp}{h}\left(N + \frac{1}{2}\right), \quad N = 0, 1, \ldots$$

Then, the spin splitting $\pm 1/2g^*\mu_{\mathrm{B}}B$, where B, the total field, was added to each of the $E_{\mathrm{M,N}}\pm(B_\perp)$ Landau level. We used $g^* = 3$, as it was obtained for this sample in Ref. [3]. The results of calculations are in Figs. 1–3 together with calculated energy dispersions and their cross-sections at the Fermi energy E_{F}. The intricate-shaped peak in Fig. 2 coincides in its position in $B_\perp$ with the calculated

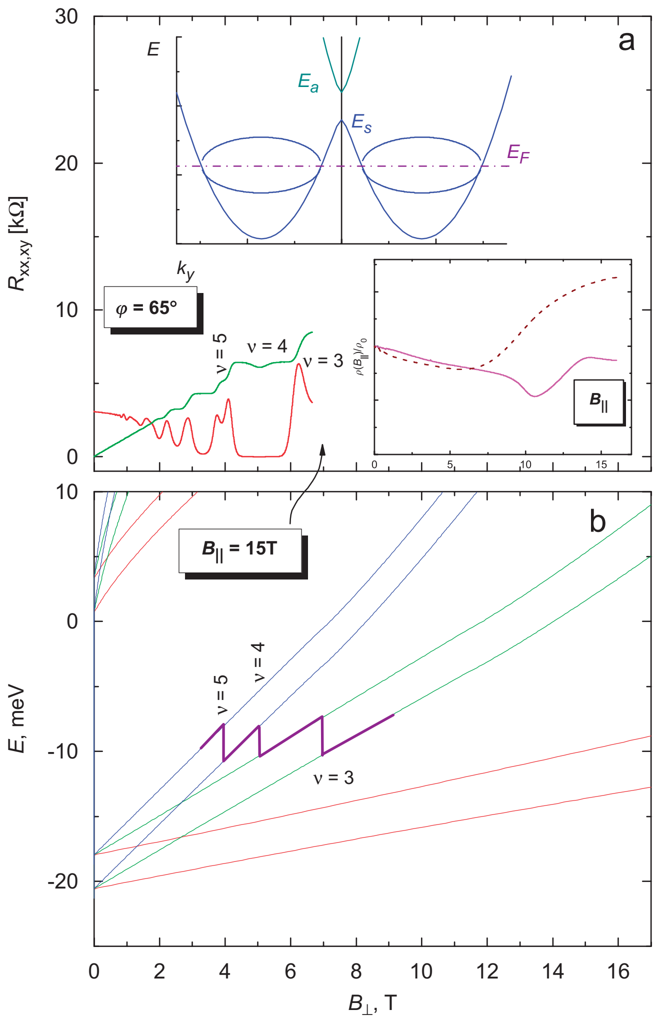

Fig. 3. The same as Fig. 1, but for $\varphi = 65°$. Calculations and upper inset in part (a) are for $B_{\parallel} = 15\,T$. Note that there are no crossings of different subband magnetic levels around $\nu = 3$. Lower inset in part (a)—magnetoresistivity for the pure parallel field before (dashed) and after illumination.

intersections between magnetic levels of S- and A-subbands, indicating that just this is the cause for the sharp transformations. In contrary, there are no intersections for the $\nu = 3$ minimum at the highest $B_{\parallel}$ available (Fig. 3) where its incipient suppression is observed. Thus, the latter feature should be due to some different cause. Notably, this suppression starts when $B_{\parallel}$ goes above the maximum on the structure observed in ρ ($B_{\parallel}$) under pure parallel field (Fig. 3, insets), when E_F goes below the tunneling gap and the Fermi cross-sections of *two* paraboloids part. Separation of the electron gas into two independent sheets should lead to a disappearance of the odd-numbered QH states [5]. Although the concomitant persistency of the $\nu = 5$ and 7 minima indicates that the physics is more complicated here.

Some unusual minima are observed on QH plateaus (Figs. 1–3); they exist only at even-numbered plateaus (except for the $\nu = 1$) in the DQW, contrary to the SQW, where only strict plain plateaus are observed. Also, a peculiar shift in perpendicular fields with increasing in-plain field of the peak between QH states $\nu = 1$ and 2 is observed, most pronounced in the unilluminated sample when the highest in-plain field is achievable for this peak. The effect is monotonous with almost no change in the peak amplitude and, considering that under the pure parallel field ρ ($B_{\parallel}$) is rather a smooth, compared to the sharp peak shape, and non-monotonous function (see Fig. 3, inset), the shift is not due to a mere superposition with ρ ($B_{\parallel}$). These features are probably beyond the single particle treatment used here.

Acknowledgments

The samples were grown by B.N. Zvonkov at Nizhniĭ Novgorod State University. The work was done within RAS Program (Project 01.2.006 13395), with partial support of RFBR (Projects 05-02-16206, 08-02-00222) and the Dutch NWO Foundation.

References

[1] S. Girvin, A.H. MacDonald, in: S. Das Sarma, A. Pinczuk (Eds.), Perspectives in Quantum Hall Effect, Wiley, NewYork, 1997, pp. 161–224.
[2] G.S. Boebinger, et al., Phys. Rev. Lett. 64 (1990) 1793.
[3] M.V. Yakunin, et al., J. Exp. Theor. Phys. 105 (2007) 241.
[4] G.S. Boebinger, et al., Phys. Rev. B 43 (1991) 12673.
[5] U. Zeitler, et al., Int. J. Mod. Phys. B 18 (2004) 3693.