International Journal of Modern Physics B
Vol. 23, Nos. 12 & 13 (2009) 2603–2606

TRANSPORT IN A BILAYER SYSTEM AT HIGH LANDAU FILLING FACTOR

G. M. GUSEV

Instituto de Fisica da Universidade de São Paulo, C.P. 66318, 05314-970–São Paulo-SP, Brazil.
gusev@romeo.if.usp.br

Received 15 October 2008

We have studied Shubnikov de Haas oscillations and the quantum Hall effect in GaAs-double well structures in tilted magnetic fields. We found strong magnetoresistance oscillations as a function of an in-plane magnetic field $B_{\|}$ at $\nu = 4N + 3$ and $\nu = 4N + 1$ filling factors. At low perpendicular magnetic field $B_{\perp}$, the amplitude of the conventional Shubnikov-de Haas (SdH) oscillations also exhibits $B_{\|}$-periodic dependence at fixed values of $B_{\perp}$. We interpret the observed oscillations as a manifestation of the interference between cyclotron orbits in different quantum wells.

1. Introduction

Double quantum wells or bilayer systems consist of two parallel quantum wells with high mobility separated by a tunneling barrier. The quantum tunneling induces hybridization of the subband energies and introduces subband splitting energy Δ_{SAS} with a typical value of 0.1-1 meV.[1] When a perpendicular magnetic field is applied, quantum Hall states are formed, and the minima in the resistance at total Landau filling factors $\nu = 2N + 1$ and $\nu = 2N + 3$, where N is the Landau level number, are ascribed to an Δ_{SAS} energy gap. Recently a novel oscillatory phenomena in quasi-one dimensional organic semiconductor[2] and semiconductor bilayers[3] has been analyzed and interpreted as the Aharonov-Bohm effect, in real and momentum space. For example, magnetic flux due to parallel component of the magnetic field $B_{\|}$ through the area $S = 2R_c d$, where $R_c = c\hbar k_F/eB_{\perp}$ is cyclotron radius and k_F is the Fermi wave vector, produces a phase shift between cyclotron orbits in different layers, which leads to oscillations of the effective interlayer tunneling amplitude.[3] In this paper we give an overview of recent results of magnetotransport measurements on bilayer electron systems in tilted magnetic field,[4,5] which is regarded as an interference phenomenon.

2. Experimental Results and Discussion

The samples are symmetrically doped GaAs double quantum wells with equal widths $d_W = 140$ Åseparated by $Al_xGa_{x-1}As$ barriers with different width d_b

varying from 14 to 31 Å.[6] The samples have a high total sheet electron density $n_s \approx 9 \times 10^{11}$ cm^{-2} (4.5×10^{11} cm^{-2} per one layer) and mobilities of $\mu \sim 10^6$ cm^{-2}/Vs. Both layers are shunted by ohmic contacts. We measure magnetoresistance at temperatures $T = 50$ mK for different tilt angles Θ between the normal to the quantum well plane and magnetic fields B up to 15 T using conventional ac-locking techniques with a bias current of 0.01-0.1 μA parallel to the layers.

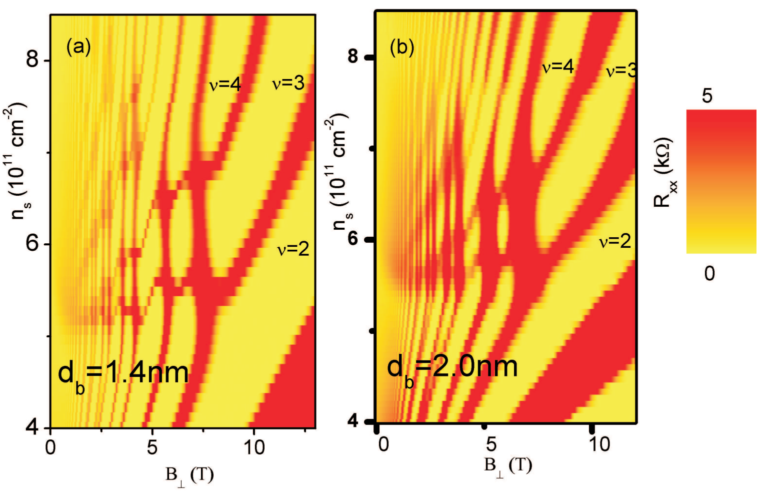

Fig. 1. (Color on line) The experimental plot of the resistance in the density-magnetic field plane for double well structure with barrier thickness $d_b = 14$ Å (a) and for $d_b = 20$ Å (b). Filling factors determined from Hall resistance are labeled. Filling factors $\nu = 4N+1$ and $\nu = 4N+3$ correspond to the tunneling gap.

The energy Landau level fan diagram for a double quantum well consists of two sets of spin split Landau level separated by symmetric antisymmetric energy gap. Fig. 1 shows an experimental plot of the longitudinal resistance in the density-perpendicular magnetic field plane for samples with a barrier thickness $d_b = 14$ Å (a) and $d_b = 20$ Å (b). Such $n_s - B_\perp$ topological diagram, in general, corresponds to the energy LL fan diagram.[7] We identify the minima at $\nu = 4N$ with the cyclotron gap, minima at $\nu = 4N + 2$ with the Zeeman gap and minima at $\nu = 4N + 1(3)$ with the symmetric-asymmetric gap.

We performed the magnetotransport measurements on the bilayer electron systems for different tilt angle Θ, and found repeated reentrance of the resistance minima at filling factors $\nu = 4N+1$ and $\nu = 4N+3$, where N is the Landau index number. Fig. 2 shows the phase diagram, or the plot of the longitudinal resistance R_{xx} in the $B_\perp - \theta$ plane for a Hall bar containing double well structures with d_b=1.4 nm (Fig. 2a) and d_b=2 nm (Fig. 2b). We may see that the minima in the resistance corresponding to the filling factors $\nu = 4N+1$ and $\nu = 4N+3$ vanish and

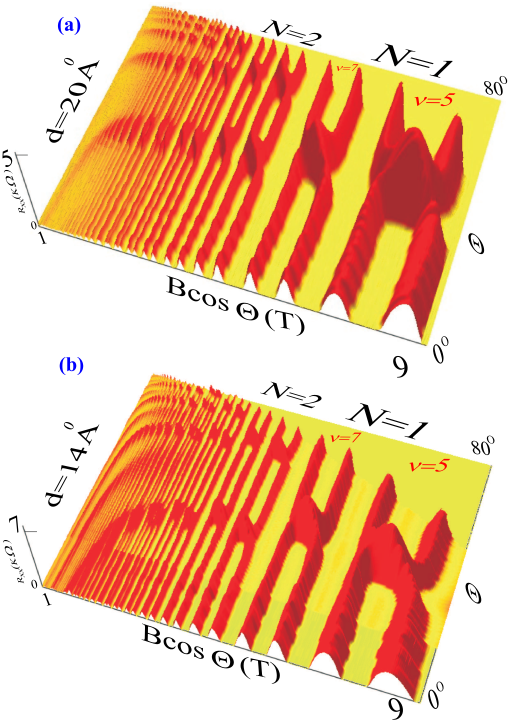

Fig. 2. (Color on line) The experimental plot of the resistance in $B_\perp - \theta$ plane for double well structure with barrier thickness $d_b = 20$ Å (a) and $d_b = 14$ Å (b). Filling factors $\nu = 4N + 1$ and $\nu = 4N + 3$ correspond to the tunneling gap.

re-establish several times for N=1,2,3,. . . , when the magnetic field is tilted. From this map we measure the resistance at fixed filling factor or the value of the perpendicular magnetic field as a function of the in-plane field. Reentrance of the quantum Hall state at filling factors $\nu = 4N + 1$ and $\nu = 4N + 3$ originates from the oscillations of the single-particle tunneling gap Δ_{SAS}. The resistance peak corresponds to the vanishing of the tunneling gap, and the resistance minimum corresponds to the maximum of the tunneling amplitude. At these integer filling factors R_{xx} exponentially depends on this energy gap $R_{xx} \sim R_0 \exp(-\Delta_{SAS}/2kT)$, therefore any decrease of the energy gap leads to an exponential grow of the resistance. Reentrant behaviour of the quantum Hall states agrees with oscillations of the tunneling amplitude

$$T_N = \Delta_{SAS} \exp\left(-Q^2 l_\perp^2/4\right) L_N^0 \left(Q^2 l_\perp^2/2\right), \qquad (1)$$

where L_N^0 is a generalized Laguerre's polynomial, the wave vector Q is defined as $Q = d/l_\parallel^2$, where $l_{\parallel,\perp} = \sqrt{\hbar c/eB_{\parallel,\perp}}$ magnetic lengths associated with the parallel and perpendicular magnetic field consequently.[8] We attribute such reentrant behaviour to oscillations of the tunneling gap due to Aharonov-Bohm interference effect between cyclotron orbits in different layers.[3]

At high filling factors the Shubnikov de Haas oscillations exhibit beating effects originating from interference of the symmetric assymetric states, which are also sensitive to the Aharonov-Bohm gauge phase within the quasiclassical approximation. In this regime the Laguerre polynomials in Eq. (1) reduce to Bessel functions for the high Landau levels:

$$\Delta_{SAS} = \Delta^0_{SAS} J_0 \left\{ k_F d \tan(\Theta) \right\}, \tag{2}$$

where J_0 is the Bessel function, $\tan(\Theta) = B_{\|}/B_{\perp}$. We use the asymptotic behaviour of the the Bessel function and finally obtain $\Delta_{SAS} \sim J_0(x) \sim \cos(x - \pi/4)/\sqrt{x}$. Therefore, it is expected that the resistance maxima occur at magic angles, when $\Delta_{SAS} = 0$, which corresponds $\Theta_n = \arctan \frac{\pi(n-1/4)}{k_F d}$. From comparison of the Shubnikov-de Haas oscillations beating and equation (2) we obtain the distance $d = 126 - 165$ Å, which corresponds to the distance between maxima of the wave functions. Finally we should note that there is a striking similarity of the magnetoresistance oscillations in our system and the angular magnetoresistance oscillations (AMRO) in many other layered materials such as organic conductors of the (BEDT-TTF)$_2$X group,[9] intercalated graphite,[10] $Tl_2B_2CuO_6$,[11] and quasi-one dimensional organic semiconductors.[2] It is very likely that all these phenomena can be explained by Aharonov-Bohm -like interlayer interference between orbits in different layers.

Acknowledgments

Support of this work by FAPESP, CNPq (Brazilian agencies) and USP-COFECUB (Uc Ph 109/08) is acknowledged.

References

1. *Perspectives in quantum Hall effects*, edited by S. Das Sarma, and A. Pinzuk (Jonh Wiley and Sons, New York, 1997).
2. B. K. Cooper, V. M. Yakovenko, *Phys.Rev.Lett.* **96**, 037001 (2006).
3. V. M. Yakovenko, B. K. Cooper, *Physica E* **34**, 128 (2006).
4. G. M. Gusev, T. E. Lamas, A. K. Bakarov, J.-C. Portal, *Phys. Rev. Lett.* **99**, 126804 (2007).
5. G. M. Gusev, C. A. Duarte, T. E. Lamas, A. K. Bakarov, J.-C. Portal, *Phys. Rev.B* **78**, 155320 (2008).
6. N. C. Mamani, G. M. Gusev, T. E. Lamas, A. K. Bakarov, O. E. Raichev, *Phys. Rev. B* **77**, 205327 (2008).
7. C. A. Duarte, G. M. Gusev, A. A. Quivy, T. E. Lamas, A. K. Bakarov, J.-C. Portal, *Phys. Rev. B* **76**, 075346 (2007).
8. J. Hu, A. H. MacDonald, *Phys. Rev. B* **46**, 12554 (1992).
9. K. Kajita, Y. Nishio, T. Takahashi, R. Kato, H. Kobayashi, W. Sasaki, A. Kobayashi, Y. Iye, *Solid State Commun.* **70**, 1189 (1989).
10. Y. Iye, M. Baxendale, V. Z. Mordkovich, *J. Phys. Soc.Jpn.* **63**, 1643 (1994).
11. N. E. Hussey, M. Abdel-Jawad, A. Carrington, A. P. Mackenzie, L. Ballcas, *Nature* **425**, 814 (2003).