Journal of Physics: Conference Series **568** (2014) 052031 doi:10.1088/1742-6596/568/5/052031

Surface Acoustic Waves Probe of the Spin Phase Transition at ν=2/3 in n-GaAs/AlGaAs structure

I L Drichko[1], I Yu Smirnov[1,4], A V Suslov[2], L N Pfeiffer[3] and K W West[3]
[1] A.F. Ioffe Physico-Technical Institute, St. Petersburg, 194021, Russia
[2] National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA
[3] Princeton University, Princeton, NJ 08544, USA

E-mail: ivan.smirnov@mail.ioffe.ru

Abstract. High frequency (ac) conductivity in the single quantum well AlGaAs/GaAs/AlGaAs with high mobility was investigated by contactless acoustic methods in the fractional quantum Hall effect regime in perpendicular and tilted magnetic fields. We studied the dependence of ac conductivity $\sigma^{ac}=\sigma_1-i\sigma_2$ on both the temperature and magnetic field tilt angle. Tilting the magnetic field relative to the sample surface enabled us to change the position of the conductivity oscillation minimum at ν= 2/3. We measured the temperature dependence of ac conductivity for each tilt angle and for the 2/3 state we calculated the activation energy ΔE which was derived by constructing the Arrhenius plot ln σ_1 against 1/T. Analyzing behavior of the activation energy in total magnetic field for the filling factor 2/3 we observed a distinct minimum which can be interpreted as the spin unpolarized-polarized phase transition.

1. Introduction

In high mobility GaAs/AlGaAs structures the fractional quantum Hall effect (FQHE) is observed in strong magnetic fields at low temperatures. In this regime at the filling factor ν=2/3 the spin unpolarized-polarized transition occurs with change of the magnetic field or electron density. In accordance with the composite fermions (CF) picture the ν=2/3 state becomes the CF state with the filling factor $\nu^{CF}=2$. The energy spacing between CFs Landau levels (LLs) is determined by a little portion of the Coulomb energy $\alpha_c E_c=\alpha_c e^2/\varepsilon l_B \sim\sqrt{B}$, where $l_B=\sqrt{\hbar/eB}$ is the magnetic length, $\alpha_c<<1$ is the critical parameter [1]. Each CF LL could in turn be spin-split into two levels separated by the Zeeman energy $E_Z= g^{CF}\mu_B B\propto B$, where μ_B is the Bohr magneton, and $g^{CF}=g=-0.44$. The energy gap between nearest CF LLs with different spin orientation at $\nu^{CF}=2$ can be expressed as $\Delta E=\alpha_c E_c-g\mu_B B$. Because of different scaling of the energies E_Z and E_C with B, CF LLs could cross at some critical magnetic field B_c, resulting in $\Delta E\to 0$. Thus, the two CF LLs with the same spin orientation could turn to be under the Fermi level, i.e. the system becomes spin-polarized.

This spin phenomenon has been investigated in numerous papers by different methods [1-16]. In Fig.1 we have summarized the available data on the spin transition critical magnetic field B_c. It is seen from the figure that B_c increases with the electron density in the sample [2-5,13,14].

[4] To whom any correspondence should be addressed.

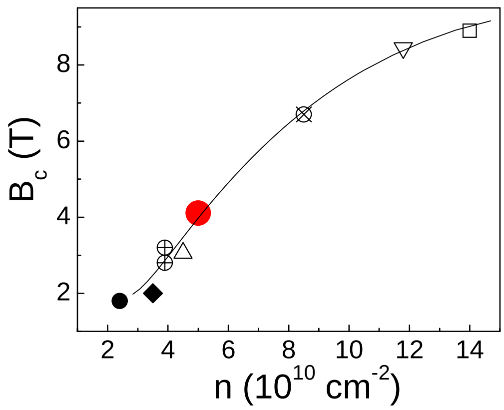

Figure 1. The transition critical field vs the electron density following the results of Ref.2 (⊕), Ref.3 (●), Ref.4 (∇), Ref.5 (Δ), Ref.13 (⊗, □), Ref.14 (♦), and the current paper (●).The line is a guide for the eye.

A study of the FQHE using acoustic methods at ν=2/3 was implemented in Ref. [4], where the acoustic velocity shift was measured, but no transition effects were observed. Earlier we also used the acoustic methods [12] for study the ac conductivity of the fully spin-polarized state of composite fermions at ν=2/3 in the GaAs/AlGaAs with electron density $n \cong 2\times10^{11}$ cm^{-2} and mobility $\mu \cong 1.5\times10^{6}$ cm^2/Vs. Rather high concentration of our sample did not allowed us to explore this transition directly, since the ν=2/3 state in our experiment was at B=12 T, while the spin transition occurs at lower magnetic fields. That is why we have determined just the dependence of the energy gap ΔE on magnetic field in the fully spin polarized state, where it turns out that $\Delta E \propto B$.

In this paper, we report the activation energy study of the 2/3 state using the Surface Acoustic Wave (SAW) contactless technique in a high mobility heterostructure GaAlAs/GaAs in tilted magnetic fields. The concentration of electrons $n=5.5\times10^{10}$ cm^{-2} provides position of the oscillation corresponding to ν=2/3 at $B_{\perp}$~3.2 T, which is rather low. Accordingly with Fig. 1, we shall be possibly able to determine the energy gap in the transition region by tilting the magnetic field. Thus, for the first time we would apply the acoustic methods to observe the spin unpolarized-polarized phase transition at ν=2/3.

2. Experiment

In the experiments we used the “hybrid” configuration of the contactless acoustic method: the surface acoustic wave, excited by interdigital transducers, propagates along the surface of the piezodielectric lithium niobate, and the studied structure is pressed onto the surface of the $LiNbO_3$ (see Fig. 2a). The electric field produced by the SAW interacts with the carriers in 2D channel. Thus, the attenuation Γ and velocity $\Delta v/v_0$ of the acoustic wave are affected by the conductivity of the 2DEG. In this “hybrid” setup no deformation is transmitted into the sample. The technique was first employed for GaAs/AlGaAs structures in [17]. A detailed acoustic study of the FQHE has been performed in [18].

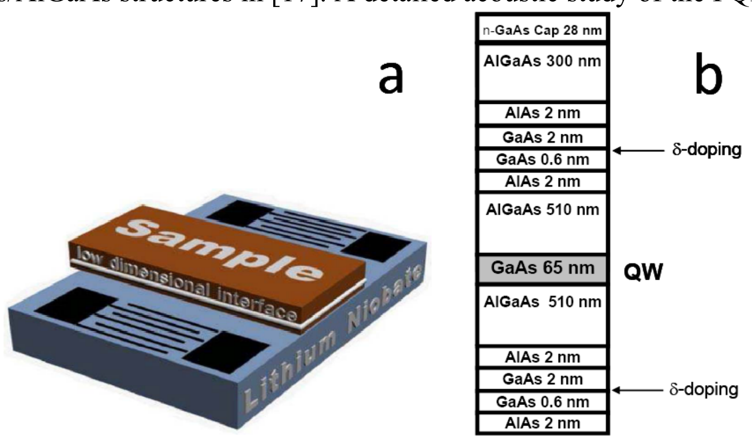

Figure 2. A sketch of the acoustic experimental setup (a) and a cross-section of the studied sample (b).

The samples grown by molecular beam epitaxy has a 65 nm wide symmetrically doped GaAs/AlGaAs quantum well (QW) with the density of n=5.5×10^{10} cm^{-2} and mobility of μ=8.5×10^{6} cm^2/Vs and contained undoped $Al_{0.24}Ga_{0.76}As$ spacer layers and Si δ-doped layers (see Fig. 2b). The low temperature measurements in the perpendicular field were done at a dilution refrigerator while tilting the sample was carried out in a ^{3}He system equipped with a one-axis rotator.

3. Experimental results and discussion

The measurements of the SAW attenuation Γ and velocity change $\Delta v/v_0$ in this system were done at the frequency of 86 MHz in magnetic fields B up to 18 T and in the temperature range of 0.1 – 1.6 K. Figure 3 shows the dependences of the SAW attenuation change Γ (top panel) and the change of the SAW velocity $\Delta v/v_0$ (middle panel) on the magnetic field B applied along the QW normal z for different temperatures in the QHE regime. One can see that both the absorption coefficient and the velocity change exhibit IQHE and FQHE type oscillations in the magnetic field.

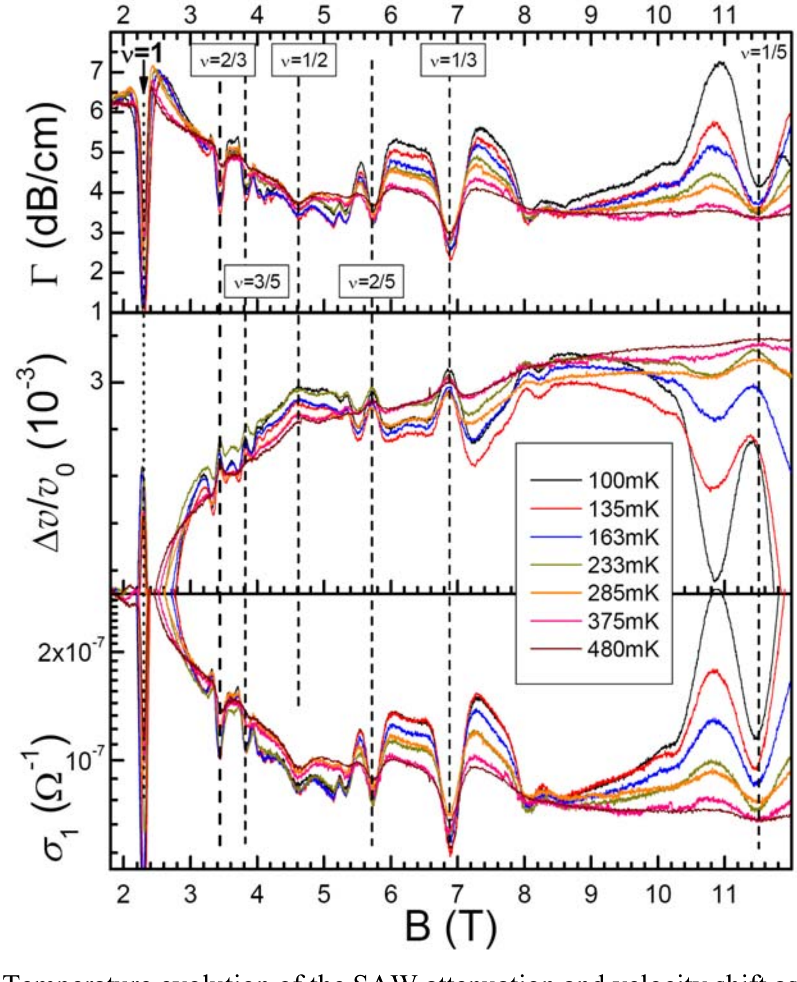

Figure 3. Temperature evolution of the SAW attenuation and velocity shift as well as the real part of the ac conductivity σ_1 in the QHE regime in the perpendicular magnetic field, f=86 MHz. The values of the filling factors ν are shown by vertical dash lines.

From the experimentally measured values of the SAW absorption Γ and the relative change of the SAW velocity $\Delta v/v_0$, one can calculate the real σ_1 and imaginary σ_2 components of the high-frequency conductivity $\sigma^{ac}=\sigma_1-i\sigma_2$ in the electron channel using the Eqs. (1) and (2) of Ref. 12. Below, we focus only on the real part of the ac conductivity since analysis of this conductivity enables us to determine the parameters of the energy spectrum. The corresponding dependence of σ_1 on the magnetic field for different temperatures at *f*=86 MHz is presented in the bottom panel of Fig. 3. The magnetic field dependence of the ac conductivity also contains a rich oscillations pattern. At the fields higher than 3 T σ_1(B) manifests pronounced FQHE oscillations, which are caused by the formation of CF Landau levels in the two-dimensional electron gas and are similar to the oscillations of the magnetoconductivity in the quantum Hall effect observed in dc transport measurements.

In this paper we aimed at the activation gap studies. To conduct such measurements properly one indeed needs to find at first the temperature domain where the conductivity is activated. Compassed in this way we studied the behavior of ac magnetoconductivity as a function of temperature down to 100 mK. We found that the ac conductivity at ν=2/3 is reliably activated at T>0.3 K.

We also carried out measurements of the acoustoelectric effects and calculated σ_1 in a tilted magnetic field, being focused mainly on the 2/3 state which corresponds to the normal component of total magnetic field $B_{\perp}=B_{TOTAL}\cos(\Theta)\approx 3.2$ T. We measured the angle Θ by tracing position of the most pronounced oscillations, namely the one of ν=1. Tilting the magnetic field relative to the sample surface enabled us to change the position of the conductivity oscillation minimum at ν=2/3.

We measured the temperature dependence of Γ and $\Delta v/v_0$ in the range of 0.3 to 1 K for each tilt angle and derived σ_1. The activation energy $\Delta E_{2/3}$ was derived by constructing the Arrhenius plot ln σ_1 against 1/T assuming that the conductivity $\sigma_1 \propto \exp(-\Delta E_{2/3}/2k_BT)$. Dependence of the activation energy for ν=2/3 $\Delta E_{2/3}$ on total magnetic field is illustrated in Fig. 4. As one can see, the energy gap in the magnetic field for filling factor 2/3 passes through a distinct minimum, which can be interpreted as the unpolarized-polarized phase transition when a crossing of the composite fermion's Landau levels with different spin directions at ν^{CF}=2 occurs. At the crossing between two CF LLs the energy gap should disappear at the transition point. However, as seen in Fig. 4 $\Delta E_{2/3}$ does not approach the zero. This anticrossing could evolve as a result of the electron exchange interaction as discussed in Ref.[4].

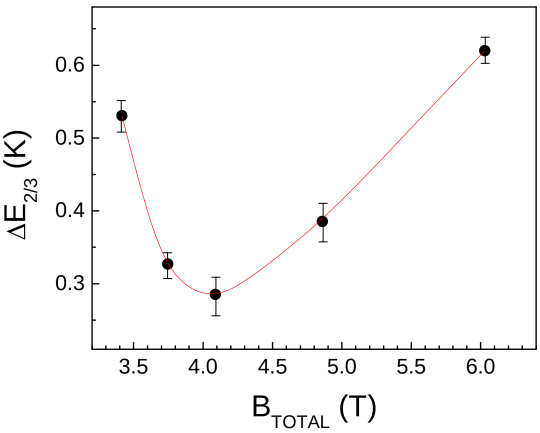

Figure 4. Dependence of the activation gap for ν=2/3 on total magnetic field. The line is a guide to the eye.

It is known that if a quantum well is wide the Coulomb interaction could be weakened. As a result, at the layer thickness exceeding $3l_b$ the FQHE quickly collapses (see [19] and refs therein). In our sample the QW width is 65 nm, which several times exceeds the magnetic length at B≈4T. However, using the acoustic technique we were able not only to observe a rich FQHE pattern, but also to measure the temperature dependence of conductivity at ν=2/3, as well as to determine the dependence of the energy gap for ν^{CF}=2 on the magnetic field. These measurements allowed us to observe the transition from unpolarized to polarized FQHE states at the CF filling factor ν^{CF}=2.

Critical field of this transition B=4.2 T is indicated in Figure 1 by the red dot. If we assume that CF g-factor $|g^{CF}|= |g|=0.44$, then in the spin transition point at B_c we can estimate the value of the critical parameter $\alpha_c=E_z/E_c=0.012$, which is close to the value of $\alpha_c\approx0.008$, determined in the Ref. [1] for the 65 nm wide quantum well for $\nu= 2/3$.

In conclusion, we performed Surface Acoustic Waves contactless measurements of the activation energy of the 2/3 state in tilted magnetic fields, thus, having found the critical field of the spin transition in dilute GaAs/AlGaAs structure with wide quantum well.

Acknowledgments
The authors would like to thank E. Palm, T. Murphy, J.-H. Park, and G. Jones for technical assistance. NHMFL is supported by NSF Cooperative Agreement No. DMR-1157490, the State of Florida, and the U.S. Department of Energy. The work at Princeton was partially funded by the Gordon and Betty Moore Foundation through Grant GBMF2719, and by the National Science Foundation MRSEC-DMR-0819860 at the Princeton Center for Complex Materials.

4. References

[1] Liu Y Hasdemir S Wojs A Jain J K Pfeiffer L N West K W Baldwin K W and Shayegan M 2014 *Arxiv.org* 1406.2387
[2] Eisenstein J P, Stormer H L, Pfeiffer L N and West K W 1990 *Phys. Rev.* B **41** 7910
[3] Engel L W, Hwang S W, Sajoto T, Tsui D C and Shayegan M 1992 *Phys. Rev.* B **45** 3418
[4] Stern O 2004 *Ph.D. thesis* (Stuttgart: Max Planck Institute)
[5] Clark R G Haynes S R Branch J V Suckling A M Wright P A Oswald P M W Harris J J and Foxon C T 1990 *Surf. Sci.* **229** 25
[6] Nicholas R J Leadley D R Daly M S van der Burgt M van der Gee P Singleton J Maude D K Portal J C Harris J J and Foxon C T 1996 *Semicond. Sci. and Technol.* **11** 1477
[7] Leadley D R Nicholas R J Maude D K Utjuzh A N Portal J C Harris J J and Foxon C T 1997 *Phys. Rev. Lett.* **79** 4246
[8] Schulze-Wischeler F Mariani E Hohls F and Haug R J 2004 Phys. Rev. Lett. **92** 156401
[9] Haug R J von Klitzing K Nicholas R J Maan J C and Weimann G 1987 *Phys. Rev.* B **36**, 4528
[10] Boebinger G S Stormer H L Tsui D C Chang A M Hwang J C M Cho A Y Tu C W and Weimann G 1987 *Phys. Rev.* B **36** 7919
[11] Khrapai V S Shashkin A A Trokina M G Dolgopolov V T Pellegrini V Beltram F Biasiol G and Sorba L 2007 *Phys. Rev. Lett.* **99** 086802
[12] Drichko I L Smirnov I Yu Suslov A V and Leadley D R 2011 *Phys. Rev.* B **83** 235318
[13] Freytag N Tokunaga Y Horvatic M Berthier C Shayegan M and Lévy L P 2001 *Phys. Rev. Lett.* **87** 136801
[14] Kukushkin I V von Klitzing K and Eberl K 1999 *Phys. Rev. Lett.* **82** 3665
[15] Vanovsky V V Khrapai V S Shashkin A A Pellegrini V Sorba L and Biasiol G 2013 *Phys. Rev.* B **87** 081306(R)
[16] Verdene B Martin J Gamez G Smet J von Klitzing K Mahalu D Schuh D Abstreiter G and Yacoby A 2007 *Nature Physics* **3** 392
[17] Wixforth A Scriba J Wassermeier M Kotthaus J P Weimann G and Schlapp W 1989 *Phys. Rev.* B **40** 7874; Wixforth A Kotthaus J P and Weimann G 1986 *Phys. Rev. Lett.* **56** 2104
[18] Willett R L 1997 *Adv. Phys.* **46** 447
[19] Shayegan M 2006 Flatland Electrons in High Magnetic Fields *High Magnetic Fields: Science and Technology, Theory and Experiment* vol 3 ed F Herlach and N Miura (Singapore: World Scientific) pp 31-60