Continuous transformation from spin- to pseudospin-type excitation

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Abstract

We measured the activation energy of bilayer $\nu = 1$ quantum Hall states. By changing the density difference between layers, the tilting behavior of the pseudospin(P)-type activation energy at the equal density point gradually transforms into the spin(S)-type one at the monolayer density point. At the intermediate density difference, by increasing the tilting angle the activation energy starts to decrease as the P-type excitation gap and then increases as the S-type excitation gap. It is impossible to explain this behavior by the level crossing of the P-type and S-type excitations. The result of the overall behavior indicates the excitation in a bilayer system is the simultaneous flip of spin and pseudospin.

Key words: Quantum Hall effect; bilayer system; Skyrmion; magnetotransport

In the bilayer $\nu = 1$ quantum Hall(QH) state, an anomalous energy gap behavior was observed by tilting a sample in the magnetic field, which is originated in a phase transition of the QH ground state [1]. The phase transition is explained by a competition between the pseudospin Coulomb exchange and tunneling energies, called commensurate-incommensurate(CIC) phase transition [2]. Pseudospin refers to an electron state in the layer degree of freedom. The bilayer $\nu = 1$ QH state is characterized by *the decrease of the activation energy against the increase of the tilting angle*. We call this the pseudospin(P)-type behavior.

On the other hand, the monolayer $\nu = 1$ QH state is a spin ferromagnet by the Coulomb exchange interaction, where the lowest-energy charged excitation is a spin texture called Skyrmion [3–5]. The monolayer $\nu = 1$ state is characterized by *the increase of the activation energy with the increase of the tilting angle*. We call this the spin(S)-type behavior.

Note that the bilayer $\nu = 1$ QH state is stable against the density difference from the balanced point up to the limit of the monolayer point [6]. It is interesting how the activation energy changes from the P-type to S-type behavior by increasing the density difference [7]. Specially, we question whether a clear transition point from the P-type to the S-type behavior exists.

The sample used in the experiment is double quantum well GaAs/$Al_{0.33}Ga_{0.67}$As heterostructures grown by molecular beam epitaxy. The quantum wells of 20 nm GaAs are separated by a 3.1 nm $Al_{0.33}Ga_{0.67}As$ barrier, and the tunneling energy gap Δ_{SAS} is 10.9 K. The front- and back-layer electron densities can be independently controlled by adjusting the front and back gate voltages. The low temperature mobility of the sample is 2×10^6 cm^2/Vs [8].

In Fig.1, we show the tilting angular dependence of the activation energy at various density differences $\sigma = (n_f - n_b)/(n_f + n_b)$, where n_f (n_b) is the electron density in the front (back) layer. The activation energy at $\sigma = 0$ shows the P-type behavior in consistency with the result due to Murphy *et al.* [1]. It decreases and then turns to constant for $\theta > \theta_c$. At the monolayer point ($\sigma = 1$), the activation energy shows the S-type behavior, indicating Skyrmion excitations

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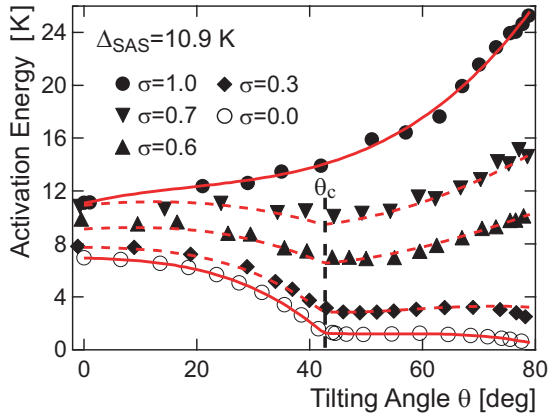

Fig. 1. The angular dependence of the activation energy. The P-type behavior at $\sigma = 0$ evolves continuously into that at $\sigma = 1$. The solid lines were obtained by the polynominal fitting of the data at $\sigma = 0$ and $\sigma = 1$. The broken lines are obtained from the formula (1).

[5]. The number of flipped spins N_s, which is obtained from the total field gradient of the activation energy, is $N_s \simeq 7$ for $\theta \leq 70^\circ$ and decrease for $\theta \geq 70^\circ$.

The CIC transition in the intermediate density difference occurs at the same critical angle $\theta_c \simeq 43^\circ$ as that of $\sigma = 0$, while the reduction of the activation energy for $\theta \leq \theta_c$ becomes smaller as σ increases. We recognize that the feature of the P-type behavior survives in the intermediate density difference. Moreover, the activation energy exhibits the S-type behavior after the CIC transition, and the tilting angles $\theta \simeq 70^\circ$ at which N_s changes are almost the same as that of $\sigma = 1$. In short, the P-type behavior evolves continuously into the S-type behavior as σ increases from 0 to 1.

As the density imbalance is made in bilayer systems, excitations with smaller energy gap between the P-type or the S-type would be naively expected to realize. On the contrary, it looks like the experimental results rather trace the larger gap, that is, the P-type excitation costing higher energy for lower θ, while the S-type excitation for higher θ. It is impossible to explain these behavior by the crossing of the two different excitation levels.

Therefore, we figure out that the excitation possesses both features of S-type and P-type with each characteristic tilting behavior at intermediate density differences. Thus we fit our experimental results by the following formula

$$\Delta(\sigma,\theta) = (1-\sigma^2)\Delta(0,\theta) + \sigma^2\Delta(1,\theta) + b(\sigma), \qquad (1)$$

where $\Delta(\sigma,\theta)$ is the tilting behavior of the activation energy at the density difference σ. We choose the ratio $1-\sigma^2 : \sigma^2$ from a fact that the activation energy in the perpendicular magnetic field almost changes as $\propto \sigma^2$ [6]. Here $\Delta(0,\theta)$ and $\Delta(1,\theta)$ curves are obtained from the polynomial fitting to the tilting angular dependence of the activation energies at $\sigma = 0$ and $\sigma = 1$. The bias term $b(\sigma)$ is the only fitting parameter independent on θ. The $b(\sigma)$ values are 0.43 K ($\sigma = 0.3$), 0.69 K ($\sigma = 0.6$) and 1.95 K ($\sigma = 0.7$). It is clear in Fig.1 that the tilting behavior of the activation energy is reproduced by formula (1) quite well for all σ.

We discuss possible explanations of these behavior of the activation energy. The collective lowest-energy charged excitation in the monolayer $\nu = 1$ QH state is the spin texture or Skyrmion, which possesses vortex structure of spins and a real charge $\pm e$ [3]. On the other hand, the pseudospin texture is called a meron. The lowest-energy charged excitation in the bilayer $\nu = 1$ QH state is a bound meron-antimeron pair which possesses a charge $\pm e$ [9]. These excitations in bilayer and monolayer systems are very similar to each other. The spin stiffness ρ_s increases as σ^2 because the exchange energy is proportional to the probability of the adjacent electron existence. The pseudospin stiffness ρ_p has the form $\rho_p = (1-\sigma^2)\rho_{p0}$, where ρ_{p0} is the pseudospin stiffness at the balanced density state [10]. In conclusion, there exists a charged excitation with simultaneous spin and pseudospin flips at intermediate densitiy differences [11].

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