Activated transport in the $\nu = 1$ bilayer quantum Hall states with small tunneling energy $\Delta_{\text{SAS}} = 1K$

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Abstract. We carried out magnetotransport experiments in the $\nu = 1$ bilayer quantum Hall state (BQHS) using a GaAs/AlAs double-quantum-well structure with tunneling energy as small as 1 K. We focus on measurements of not only activation energies but also onset temperatures of the BQHS for a wide range of the total density and the layer density imbalance. We have found that the dependency of onset temperature on the total density is different from that of the activation energy. We discuss physical interpretations of the onset temperature with relationship to finite-temperature phase transitions in the $\nu = 1$ BQHS.

1. Introduction
The bilayer quantum Hall state (BQHS) has served as a good example of strongly correlated two-dimensional electron systems having the layer degree of freedom called pseudospin[1]. These correlations manifest themselves in a variety of topological objects involving spins and/or pseudospins, in contrast to monolayer quantum Hall states (QHSs) where only spins play an important role. In particular, the Landau level filling factor $\nu = 1$ BQHS can be interpreted as an ideal XY-ferromagnet in the pseudospin language[2]. In the XY-ferromagnet, twin half-quantized vortices of pseudospins called “meron-pair” play an important role in the activated transport. A key property of the elementary excitations in the XY-ferromagnet is to detect the Kosterlitz-Thouless (KT) phase transition. In the standard two-dimensional KT model, the super-to-normal phase transition occurs by the thermal dissociation of vortex pairs, which is characterized by the KT transition temperature $T_{\text{KT}}$, related to the stability of BQHS. In earlier experiments, the stability in the $\nu = 1$ BQHS was evaluated qualitatively by the plateau width appearing just around the filling of $\nu = 1$ [3]. A current standard method to evaluate the stability of QHS is an activation energy employed in many succeeding experiments. For instance, we recently found the new class of topological defects - pseudospin soliton lattice[4], and it was quantitatively characterized by a shallow dip of the activation energy as a function of in-plane fields[5].

In this article, we elaborately measured the temperature dependence of the longitudinal resistance in the wide range of total density $n_T$ and layer density imbalance $\sigma$ in the $\nu = 1$ BQHS with tunneling energy of 1 K, from which we deduce not only the activation energy but
Figure 1. Image plot of $R_{xx}$ at $T = 200\, \text{mK}$ in the $\nu = 1$ BQHS as a function of $n_T$ and $\sigma$. See text about lines and region numbers.

also onset temperature $T^*$ for BQHS. We discuss the physical interpretation of $T^*$ in contrast to $T_{KT}$. We also suggest that $T^*$ is a possible index to describe the stability of BQHS even in the low-mobility region.

2. Experiments
Magnetotransport experiments were carried out under high magnetic fields in a dilution refrigerator with a base temperature of 40 mK. To measure Hall resistance $R_{xy}$ and magnetoresistance $R_{xx}$, we used standard low-frequency lock-in techniques with a current of $I = 10\, \text{nA}$ to avoid heating and a frequency of $f = 17.7\, \text{Hz}$. The sample used in this experiment consists of two GaAs quantum wells of 20 nm in width separated by a 3.1-nm-thick AlAs barrier. The tunneling gap is estimated at $\Delta_{SAS} = 1\, \text{K}$. The electron densities in the front ($n_f$) and back ($n_b$) layers can be independently controlled by applying the front and back gate voltages. Thus we can independently changes both total density $n_T = n_f + n_b$ and layer density imbalance $\sigma = (n_f - n_b)/(n_f + n_b)$. The low temperature mobility at $n_T = 1.0 \times 10^{11}\, \text{cm}^{-2}/\text{Vs}$ is $2.0 \times 10^8\, \text{cm}^2/\text{Vs}$.

3. Results and Discussions
First we measured $R_{xx}$ as a function of $n_T$ and $\sigma$ in Fig. 1. Dark and bright regions correspond to compressible state (no-QHS) and well-developed QHS regions, respectively. We find three characteristic regions in the graph. Region I is a well-developed QHS continued from BQHS at $\sigma = 0$ to monolayer QHS at $\sigma = 1$ with low $n_T$. It is considered to be a "coherent" BQHE phase where macroscopic interlayer phase coherence supports the stable QHS. Region II is a no-QHS region, where the intralayer interaction dominates the interlayer interaction and destroys interlayer phase coherence. Region III is a weakly-developed QHS called "compound" states consisting of two fractional QHSs $\nu = 1/3 + 2/3$ around $\sigma = 0.33$.

Figure 2 shows the Arrhenius plot of $R_{xx}$ for various $n_T$’s at $\sigma = 0$. $\Delta$ is determined from the temperature $T$ dependence of $R_{xx}$: $R_{xx} = R_0\exp\left(-\frac{\Delta}{2T}\right)$. Onset temperature $T^*$, below which QHS starts to develop, is defined as $T^* = \frac{\Delta}{2(\ln R_0 - \ln R_{xx}^{\text{sat}})}$, where $R_{xx}^{\text{sat}}$ is the saturated $R_{xx}$ in the high temperature limit.

Figure 3 demonstrates $\Delta$ and $T^*$ as a function of $n_T$ in the balanced state at $\sigma = 0$. The line where data were taken ($\sigma = 0$) is shown as solid line in Fig. 1. When $n_T$ increase from
2.0
1.5
1.0
0.5
0.0
∆ [K]

(a) (b)

Figure 3. (a) Activation energy ∆ and (b) onset temperature $T^*$ as a function of $n_T$ in the balanced state $\sigma = 0$.

0.4 to $1.2 \times 10^{11}$ cm$^{-2}$, ∆ increases at $n_T < 0.6 \times 10^{11}$ cm$^{-2}$, and downturns to decrease at $n_T > 0.6 \times 10^{11}$ cm$^{-2}$. At $1.2 < n_T < 1.6 \times 10^{11}$ cm$^{-2}$, ∆ = 0 where the temperature dependence of $R_{xx}$ is not thermal activation type. As for $T^*$, in contrast to the behavior of ∆, $T^*$ simply decreases as $n_T$ increases, which is a central feature of these experiments. We remark that we cannot derive it at $n_T > 1.2 \times 10^{11}$ cm$^{-2}$, because we cannot define ∆.

In Fig. 4, we observed ∆ and $T^*$ as a function of $\sigma$ for $n_T = 0.60 \times 10^{11}$ cm$^{-2}$ (dashed line in Fig. 1) and $n_T = 1.90 \times 10^{11}$ cm$^{-2}$ (dotted line in Fig. 1). At $n_T = 0.60 \times 10^{11}$ cm$^{-2}$, ∆ and $T^*$ increase as $\sigma$ increases, which indicates the BQHS becomes stabler. At $n_T = 1.90 \times 10^{11}$ cm$^{-2}$, we have three regions (no-QHS, compound QHS, coherent QHS) for changing $\sigma$. At $\sigma < 0.2$, $\Delta = 0$ and $T^*$ cannot be defined in the no-QHS region. At $0.2 < \sigma < 0.4$ around $\sigma = 0.33$, $\Delta$ and $T^*$ form local maxima in the $\nu = 1/3 + 2/3$ compound QHS. At $\sigma > 0.4$, $\Delta$ and $T^*$ increase as $\sigma$ increases in the coherent QHS. In all regions, $T^*$ has a similar behavior to $\Delta$.

Now we argue about the physical properties and interpretations of $T^*$ with relationship to $\Delta$. As for the $\sigma$ dependence of $T^*$, the behavior is similar to one of $\Delta$. However, in the case of $n_T$ dependence of $T^*$, the dependency is opposite to $\Delta$ at low $n_T$ where the mobility is also small. Essentially the $\nu = 1$ BQHS should become stabler at the lower $n_T$ at $\sigma = 0$. Considering together with the dependency on $\sigma$, we possibly employ $T^*$ as a new mobility-independent scale to evaluate the stability of BQHS instead of $\Delta$. In this regard, it is also important to consider
Figure 4. (a) Activation energy $\Delta$ and (b) onset temperature $T^*$ as a function of $\sigma$ at $n_T = 0.60 \times 10^{11}$ cm$^{-2}$ and $n_T = 1.90 \times 10^{11}$ cm$^{-2}$.

the stability of the BQHS under tilted magnetic fields, and, however, it is beyond the scope of this report. Finally it is worthwhile to compare our data with the data of Lay et al.[6] They suggest the existence of the finite-temperature transition at $T^*$ in association with $T_{KT}$ based on the theory[2]. However, their data has a problem that $\Delta_{SAS}$ also changes when $n_T$ changes, because they use a wide single quantum well. The dependency of $T^*$ on $n_T$ in our data is similar to their data. A theory[2] predicts that $T_{KT}$ decreases as the effective layer separation becomes larger and vanishes above a critical separation. These facts support the existence of the finite-temperature phase transition in the $\nu = 1$ BQHS without an ambiguity of changing $\Delta_{SAS}$, although relationship of the observed $T^*$ to $KT$ transition is needed to further investigations.

4. Conclusions
We measured the temperature dependence of the magnetoresistance in the wide range of $n_T$ and $\sigma$ in the $\nu = 1$ BQHS with tunneling energy of 1 K. We have deduced not only the activation energies but also onset temperature $T^*$ for BQHS. We have discussed finite-temperature phase transition from the data of $T^*$. We have also suggested that $T^*$ is a possible index to describe the stability of BQHS even in the low-mobility region.

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