Ferromagnetic fractional quantum Hall states in a valley degenerate two-dimensional electron system

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We study a two-dimensional electron system where the electrons occupy two conduction band valleys with anisotropic Fermi contours and strain-tunable occupation. We observe persistent quantum Hall states at filling factors $\nu = 1/3$ and $5/3$ even at zero strain when the two valleys are degenerate. This is reminiscent of the quantum Hall ferromagnet formed at $\nu = 1$ in the same system at zero strain. In the absence of a theory for a system with anisotropic valleys, we compare the energy gaps measured at $\nu = 1/3$ and $5/3$ to the available theory developed for single-valley, two-spin systems, and find that the gaps and their rates of rise with strain are much smaller than predicted.

In a single-electron picture, there should be no quantum Hall effect (QHE) at odd-integer Landau level (LL) filling factors (ν) in a two-dimensional electron system (2DES) with a vanishing Lande g-factor. In an interacting 2DES, however, a QH state exists at $\nu = 1$ even in the limit $g = 0$ [1, 2]. The ground state is a ferromagnet, and it is the large Coulomb (exchange) energy cost of a spin flip that leads to a sizable energy gap separating this ground state from its excitations. These charged excitations, called skyrmions, have a nontrivial, long-range spin texture with a slow rotation of the spin as a function of distance to minimize the Coulomb energy cost [1–5].

A question naturally arises as to whether there are similar ferromagnetic ground states in the *fractional* quantum Hall effect (FQHE) regime. The presence of such a state with finite energy gap at $g = 0$ along with skyrmionic excitations was theoretically predicted for $\nu = 1/3$ [1, 6]. Experimentally, it is challenging to tune the g-factor to zero while keeping the quality of the 2DES sufficiently high to exhibit FQHE. There has been only one study [7] to date probing the state at $\nu = 1/3$ under the condition of $g \to 0$, which was achieved via applying hydrostatic pressure. The data revealed no FQH resistance minimum at $\nu = 1/3$ when $g \simeq 0$ [8], but from measurements at non-zero values of g, a finite but small energy gap was deduced for the $\nu = 1/3$ FQH state.

Here we report magnetotransport measurements for 2DESs confined to AlAs quantum wells where the electrons occupy two conduction band minima (valleys). In this system, the energy splitting between the two valleys can be controlled *in situ* via applying in-plane strain. Considering the valley degree of freedom as an isospin, the condition of zero valley splitting is identical to the limit of $g = 0$ in a two-spin system. Under this condition, a ferromagnetic ground state and skyrmionic excitations have already been reported at $\nu = 1$ [9–11]. Here we report the observation of a well-developed QH resistance minimum at $\nu = 1/3$ as we tune the valley splitting through zero. We also observe a pronounced resistance minimum at $\nu = 5/3$ which is the particle-hole conjugate state of $\nu = 1/3$ in our two-component (two-valley) system. These observations strongly suggest the presence of ferromagnetic FQH states at these fillings. From the temperature (T) dependence of the resistance minima, we deduce energy gaps for these states as a function of applied strain. The gaps increase initially and then saturate, as expected qualitatively. Quantitatively, however, both the gaps and their dependencies on strain are much weaker than the predictions of theories which were developed for the single-valley, two-spin systems.

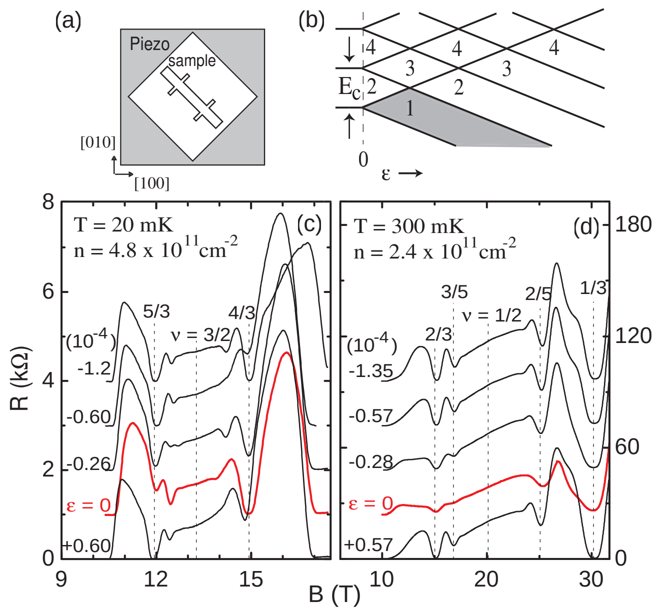

FIG. 1. (a) Experimental setup with the sample glued to a piezo. (b) Simple energy level fan diagram showing the splitting of electron LLs in response to strain. (c) and (d) Magnetoresistance traces for sample A around $\nu = 3/2$ and $\nu = 1/2$ taken at different ϵ.

Our samples are AlAs quantum wells grown by molecular beam epitaxy [10]. Contacts were made with GeAuNi alloy and Hall bars were defined. Metallic front and back gates were deposited on the samples, thus allowing us to control the 2D electron density, n. We report results for three samples from two wafers. The quantum well in sample A is 12 nm wide while samples B and C have well