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Valley susceptibility of interacting electrons and composite fermions

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Abstract

We report magnetotransport measurements of integer and fractional quantum Hall states in an AlAs quantum well where two conduction band valleys are occupied. By monitoring the valley level crossings for these states as a function of applied symmetry-breaking strain, we determine the "valley susceptibility" (the change of valley population with strain) for both electrons and composite Fermions. The data reveal that these valley susceptibilities are significantly enhanced over the band values, reflecting the role of strong interaction. Moreover, the measured valley susceptibilities are quite similar to the values of spin susceptibility, establishing the analogy between the spin and valley degrees of freedom.

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Currently there is considerable interest in quantum Hall effect in multi-valley two-dimensional electron systems (2DESs) [1]. The interest partly stems from the recent magnetotransport results in graphene [2,3] where there is a twofold valley degeneracy. In 2DESs confined to certain semi-conductors, such as Si or AlAs, the carriers possess a valley degree of freedom, and the role of valley degeneracy in the interaction induced integer and fractional quantum Hall effects (IQHE and FQHE) were indeed experimentally studied recently in these systems [4–7]. Here we report measurements of IQHE and FQHE states in a 2DES confined to an AlAs quantum well. This system has the rather unique property that its valley degeneracy can be controlled via the application of symmetry-breaking in-plane strain [4,5]. We focus on the IQHE at Landau level (LL) filling $\nu > 1$ and FQHE states around $\nu = \frac{3}{2}$ and measure their strengths as a function of strain. The FQHE data can be well described in a composite Fermion (CF) picture [8–10] where the CFs have an additional (valley) degree of freedom. From the experimental data we deduce the "valley susceptibility" [11,12], defined as the change in valley polarization as a function of strain, for both electrons and CFs. The results reveal that this susceptibility is significantly enhanced over the band value for both electrons and CFs. Comparison of our data with the results of *spin* susceptibility measurements [12,13] reveals the remarkable similarity of the spin and valley degrees of freedom.

We performed experiments on a 2DES confined to an 11 nm thick layer of AlAs, and modulation-doped with Si. The sample was grown by molecular beam epitaxy on a semi-insulating (0 0 1) GaAs substrate. In this sample, electrons occupy two in-plane conduction-band minima (valleys) at the X point in the Brillouin zone, with elliptical Fermi contours as schematically shown in Fig. 1(a). We refer to these valleys by the direction of their major axis ([1 0 0] and [0 1 0]). We deposited AuGeNi contacts on a lithographically defined Hall-bar mesa, aligned along the [1 0 0] crystal direction, as shown in Fig. 1(b). Mounting the sample on a piezoelectric stack (Fig. 1(a)) with its [1 0 0] axis along the stack's poling direction allows us to apply controllable, symmetry-breaking strain, by changing the voltage (V_P) on the stack. When positive (negative) V_P is applied, e.g., the piezo stack expands (shrinks) along its poling direction and shrinks (expands) in the perpendicular

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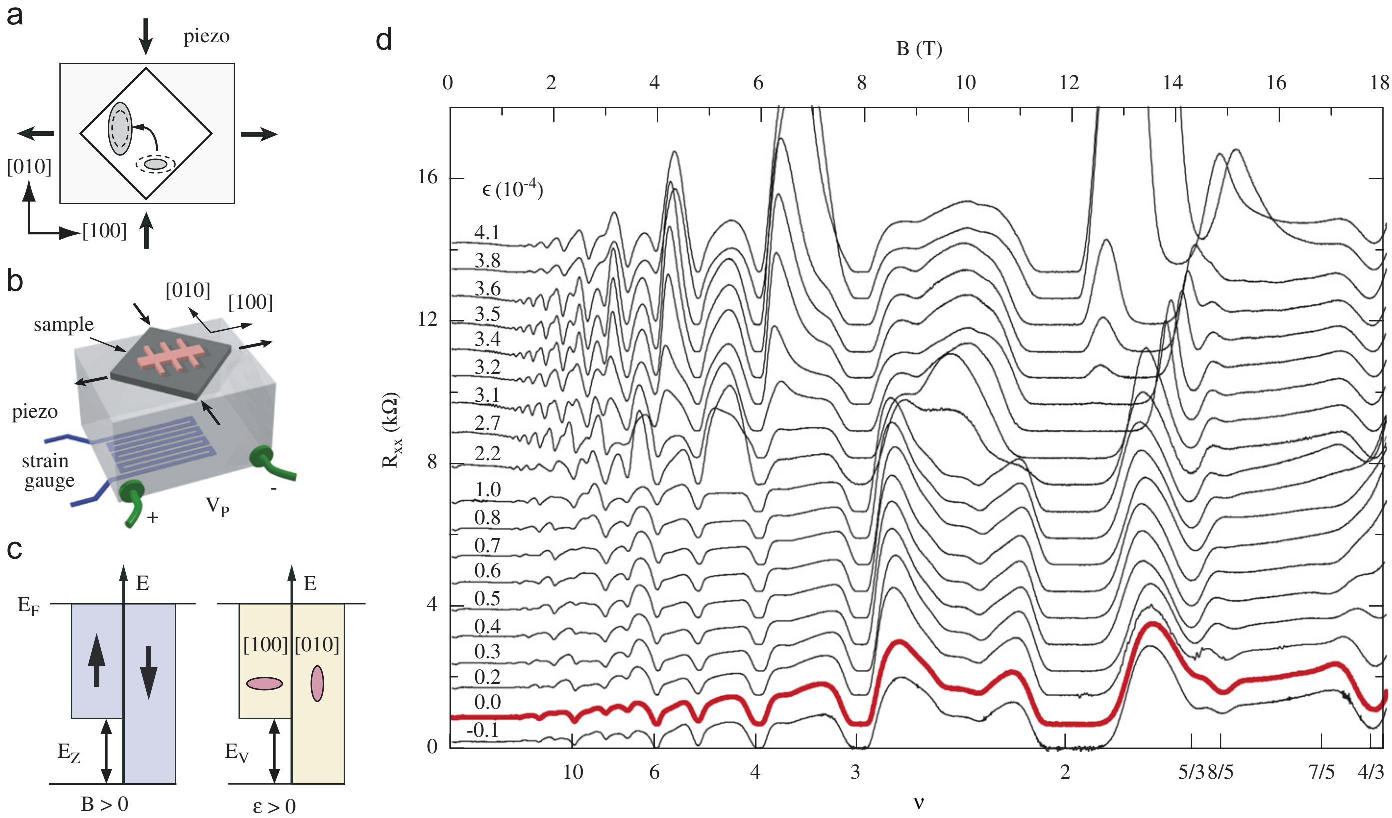

Fig. 1. (a) Schematic diagram showing that electrons are transferred from the [1 0 0] to the [0 1 0] valley upon the application of strain while the total 2DES density is independent of strain. (b) Experimental setup for the valley susceptibility measurements. (c) Energy diagram showing the spin (E_Z) and valley (E_V) subband splittings with applied magnetic field or strain, respectively. (d) Magnetoresistance traces at a density of $5.7 \times 10^{11}\,\mathrm{cm}^{-2}$, taken at $T \simeq 50\,\mathrm{mK}$, for different values of applied strain, as indicated on the left. The traces are vertically offset for clarity.

direction, straining the sample. We define this strain as $\varepsilon = \varepsilon_{[1\,0\,0]} - \varepsilon_{[0\,1\,0]}$, where $\varepsilon_{[1\,0\,0]}$ and $\varepsilon_{[0\,1\,0]}$ are the strains along the [1 0 0] and [0 1 0] directions, respectively. Such strain transfers electrons from the [1 0 0] valley to the [0 1 0] valley while the total density remains constant, as schematically shown in Fig. 1(a). The applied strain was measured using a strain gauge glued to the other side of the piezo (see Fig. 1(b)). All measurements were done in a top-loading dilution refrigerator with a base temperature of $\simeq 50\,\mathrm{mK}$ in an 18 T superconducting magnet.

Fig. 1(d) gives an overview of our magnetoresistance data. The strengths of both the IQHE and FQHE states clearly vary with applied strain. It is from this variation that we determine valley susceptibilities for electrons and CFs. We first discuss the simpler case of the IQHE data. A magnetic field (B) applied perpendicular to a 2DES quantizes the allowed energies into LLs, separated by the cyclotron energy $\hbar\omega_c$. Each level is further split into spin up and spin down levels, separated by the Zeeman energy $\Delta E_Z = g^* \mu_B \cdot B$, where g^* is the effective g-factor and μ_B is the Bohr magneton [14]. By applying strain to the system, each of the spin-split LLs splits again into [1 0 0] and [0 1 0] valley levels, separated by the valley splitting energy $\Delta E_v = E_2^* \cdot \varepsilon$, where E_2^* is the effective conduction band deformation potential [15]. This is illustrated in Fig. 2(a), showing the LLs behavior at constant B under applied strain [15]. As clearly seen, for certain strain values, LLs with opposite valley polarization coincide, and this coincidence happens periodically as the strain is increased. As is well known, in a transport measurement, resistance is high when two energy levels are coincident at the Fermi energy, and decreases as the system moves away from coincidence. Fig. 2(b) shows the measured resistance as a function of strain at the $\nu = 10$ IQHE state, which is consistent with the behavior predicted by the simple LL picture [16].

Before analyzing the CF coincidence data, some discussion of the details of CF states would be helpful. The CFs around $\nu = \frac{3}{2}$ are holes in the second LL, that is, the carrier component of the flux-carrier composite particle is a hole, even though at $B = 0$ the carriers are electrons. In contrast to CFs around $\nu = \frac{1}{2}$, the density of $\nu = \frac{3}{2}$ CFs (n_{CF}) is not equal to the density of electrons (n_{el}), and increases with decreasing ν. At $\nu = \frac{3}{2}$, $n_{CF} = n_{el}/3$. Since each CF carries two flux quanta ($2h/e$) of the gauge field, which opposes the applied field, the CFs experience no net magnetic field at $\nu = \frac{3}{2}$. Thanks to the variation of n_{CF} with magnetic field, the CFs feel an effective magnetic field $B_{eff} = 3(B - B_{3/2})$, where $B_{3/2}$ is the magnetic field at $\nu = \frac{3}{2}$ [9,17]. The CFs form LLs under this B_{eff}, and thus the FQHE states around