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Landau-Level Hybridization and the Quantum Hall Effect in InAs/(AlSb)/GaSb Electron-Hole Systems

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The quantum Hall effect in electron-hole hybridized systems is examined using back-gated InAs/(AlSb)/GaSb heterostructures with different electron-hole coupling. When the electrons and holes are strongly coupled, it is found that quantized Hall states appear when the net filling factor $[\nu_{\text{net}} = (n - p)h/eB$, where n and p are the electron and hole densities, respectively] is an integer, and that it is not a necessary condition for independent electron and hole filling factors ($\nu_e = nh/eB$ and $\nu_h = ph/eB$) to be integers simultaneously. The observed phenomena can be interpreted in terms of a simple model where the Landau-level fans associated with the electrons and holes hybridize resulting in an effective band gap at $\nu_{\text{net}} = 0$, and the quantized Hall states occur according to the number of hybridized Landau levels occupied above this gap.

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InAs/GaSb is a unique semiconductor system where the two-dimensional electron gas (2DEG) and hole gas (2DHG) can coexist in close proximity. This is due to its unusual band alignment, where the conduction band edge of InAs can lie lower in energy than the valence band edge of GaSb. This system has attracted continued attention owing to the possibilities arising from electron-hole hybridization and excitonic interactions [1], such as observed transiently in excited states of GaAs/AlGaAs systems [2]. This Letter concerns the transport properties of the system in the quantum Hall regime, where there are striking differences to the quantum Hall effect (QHE) in conventional systems [3].

It is known that, when Landau-level (LL) filling factors of the 2DEG and the 2DHG (ν_e, ν_h) become integers simultaneously, the longitudinal resistance (R_{xx}) becomes zero and the Hall resistance (R_{xy}) is quantized at a value given by the difference of the filling factors $R_{xy} = h/e^2|\nu_h - \nu_e|$ [4]. However, a global consistent interpretation has not been achieved and many questions remain concerning the nature of the QHE in this system, such as those regarding the quantization mechanism of the Hall resistance and the observation of Shubnikov–de Haas (SdH) peaks at half-integer filling of 2DEG LLs [4,5]. The situation is especially unclear when ν_e and ν_h are nonintegers. The obstacle has been due mainly to the absence of a reliable gating technology. Recently, capacitance measurements by Yang *et al.* on a gated structure found capacitance minima corresponding only to integer values of the net filling factor $\nu_{\text{net}} = n_{\text{net}}h/eB$, where $n_{\text{net}}(= n - p)$ is the net carrier density, rather than features corresponding to n and p (the electron and hole densities) seemingly in contradiction to earlier studies [6]. Highly desirable magnetoresistance measurements in the system with gate control, however, have thus far had very limited success [7].

This Letter examines the magnetotransport properties of three gated structures with different electron-hole coupling. It is shown that the phenomena observed can be interpreted in terms of a simple model where LL fans associated with the electrons and holes hybridize resulting in an effective band gap at $\nu_{\text{net}} = 0$ [8], and the quantized Hall states occur according to the number of hybridized LLs occupied above this gap. The occupancy of these levels is determined by the net carrier density.

A schematic diagram of the samples and the gate biasing is shown in Fig. 1(a). An InAs/(AlSb)/GaSb heterostructure sandwiched between $Al_{0.7}Ga_{0.3}Sb$ barriers is grown on a conductive InAs substrate which acts as a back gate [9]. The inserted AlSb layer takes the role of a barrier between the InAs conduction and GaSb valence bands, controlling the hybridization strength [9,10].

Figure 1(b) shows a contour plot of R_{xx} at 1.6 K as functions of the magnetic field (B) normal to the plane and the gate voltage (V_{G}) for a sample with a thick AlSb barrier. The InAs, AlSb, and GaSb layer thicknesses are 30, 3.6, and 18 nm, respectively. This AlSb thickness is sufficient to render the electron-hole hybridization negligible [10]. Strong R_{xx} oscillations as a function of B are observed as horizontal lines on the plot. In general, the electron density and mobility are much greater than those of the holes in the system, and the transport characteristics are determined largely by the electron characteristics. The strong R_{xx} oscillations independent of V_{G} are due to SdH oscillations of the 2DEG. The oscillation period gives a value $n = 16.2 \times 10^{15}\ \text{m}^{-2}$ for the electron density.

The dashed red lines indicate integer ν_e ($\nu_e = nh/eB$) at higher magnetic field where the electron layer is in a

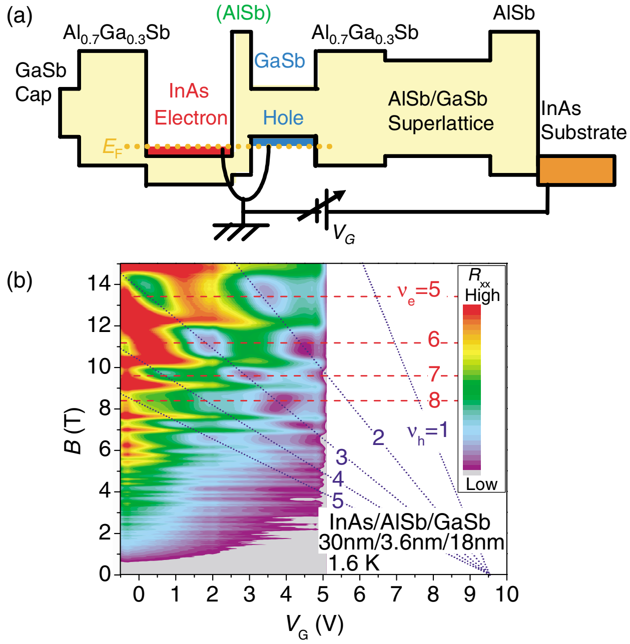

FIG. 1 (color). (a) Schematic diagram of the sample structure. The gate voltage (V_G) is applied between the substrate and the hole layer. Indium contacts were made with Ohmic characteristics for both the electron and hole layers. (b) Contour plot of the longitudinal resistance (R_{xx}) measured for a sample with independent electrons and holes. Integer filling factor of electrons (ν_e) (dashed red lines) and holes (ν_h) (dotted blue lines) are also indicated.

quantum Hall state. R_{xx} does not become very small, however, unless the hole layer is also in a quantum Hall state. The deep minima lie along diagonal lines (in dotted blue) and represent integer ν_h ($\nu_h = ph/eB$), with $p = (10.0\text{–}1.05 \times V_G) \times 10^{15}$ m^{-2} [11]. These electron and hole densities are consistent with the values evaluated by classical fitting at low magnetic field [12]. The result shows that the QHEs of the 2DEG and the 2DHG occur independently in this sample, and the main effect of changing V_G is the change in the hole density while the electron density remains relatively constant.

Figure 2 shows R_{xx} and R_{xy} for a sample with 24 nm InAs and 18 nm GaSb without an AlSb barrier so that the two layers are strongly hybridized. For R_{xx} in Fig. 2(a), at low magnetic field up to 6 T, the period of the strong SdH oscillations is not affected by the change of V_G similar to the independent system shown in Fig. 1(b), giving a value of $n = 9.61 \times 10^{15}$ m^{-2}. Integer ν_e marked by arrows in Fig. 2(a) is calculated from this value. The semiclassical behavior of R_{xy} below 3 T gives values of the hole density $p = (3.69\text{–}0.47 \times V_G) \times 10^{15}$ m^{-2}.

At high magnetic field, the resistance minima are seen to shift to higher magnetic field with increasing V_G. For R_{xy} in Fig. 2(b), clear quantized Hall plateaus are observed. The observed integer filling factor calculated from R_{xy} ($\nu = h/e^2R_{xy}$) at a given magnetic field increases with increasing V_G. Figure 2(c) shows a contour plot of R_{xx}. Integer ν_e (red dashed lines), integer ν_h (blue dotted lines), and integer ν_{net} (orange dash-dotted lines) are indicated on the plot. At high magnetic field, R_{xx} minima associated with the QHE appear along integer ν_{net}. Also, ν obtained from R_{xy} is consistent with ν_{net}.

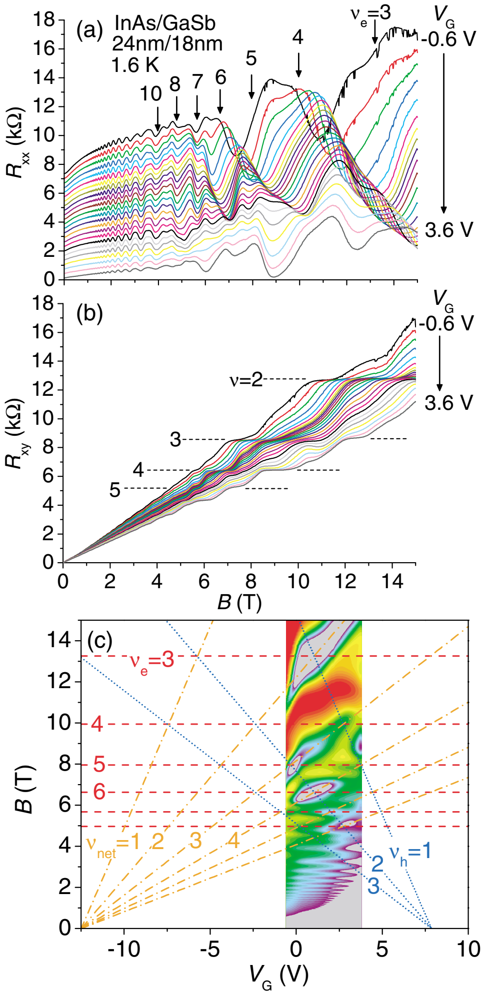

FIG. 2 (color). Measurement results for a strongly hybridized sample. (a) Longitudinal resistance (R_{xx}) (offset). Arrows indicate integer ν_e obtained from SdH oscillations at low magnetic field. (b) Hall resistance (R_{xy}). Quantized Hall resistances corresponding to integer ν are indicated as dashed lines. (c) A contour plot of R_{xx}. Orange dash-dotted lines indicate integer filling factors of net carriers (ν_{net}).

Figure 3(a) shows a contour plot of R_{xx} for a sample with 30 nm InAs and 18 nm GaSb without an AlSb barrier. The hybridization is weak in this sample due to the greater thickness of the InAs layer increasing the separation between the electron and hole wave functions. $n = 10.8 \times 10^{15}$ m^{-2} and $p = (2.25\text{–}1.23 \times V_G) \times 10^{15}$ m^{-2} were evaluated by the same methods. For this sample, we find that the R_{xx} minima corresponding to the QHE appear along integer ν_{net} and are disconnected by R_{xx} maxima corresponding to extended states of the 2DEG LLs (arrows). The quantization of R_{xy} is consistent with integer ν_{net}, rather like the strongly hybridized system.

In a strongly hybridized system, LLs derived from the original 2DEG and 2DHG are hybridized and therefore anticross [13]. Figure 4(a) shows a schematic diagram of the LL hybridization. The dotted lines show independent electron and hole LL fans. If all coincident states couple and form anticrossing gaps, regions corresponding to a given net filling factor connect, and lead to a single "fan" as shown by the solid lines. The region where the net filling is zero becomes an effective band gap, although the independent carrier densities are finite, there is no conduction [8]. The quantum Hall effect occurs through hybridized LLs occupied above this gap. Since each LL contains eB/h electronic states regardless of its conduction-band-like or valence-band-like character, at a given value of net carrier density, the Fermi level (E_F) moves through the LLs as if it were a conventional two-dimensional system [3]. The quantum Hall states therefore occur according to the filling factor calculated from the net carrier density.

Strong SdH oscillations independent of V_G were observed at low magnetic field for all our samples. This means that either E_F from the bottom of the 2DEG subband is independent of V_G or that n is constant. For the sample with independent 2DEG and 2DHG, this persists up to the highest magnetic field. V_G appears only to affect the hole density. There may be some oscillatory charge transfer between the electron and hole layers [14], but the magnetic field positions at which E_F traverses the center of LLs derived from the 2DEG remain the same (independent of V_G). The effect of the gate bias is screened by the hole layer and E_F is pinned at the surface of the sample (on the InAs electron layer side). For a hybridized system, the situation is less straightforward. When V_G is changed, the potential profile and carrier distributions rearrange to satisfy Poisson and Shrödinger equations, but this is achieved predominantly by the change of carrier density in the GaSb layer, due also to the difference in effective masses. The large effective mass of the holes implies that only small shifts in its energy levels are necessary to achieve large changes in p or n_{net}.

The situation of the LLs in the vicinity of the Fermi level is illustrated in Figs. 4(b)–4(e). When V_G is increased at a certain magnetic field, the positions of the LLs derived from the 2DEG are fixed, and those from the 2DHG go down [Fig. 4(b)]. When ν_{net} is an integer and ν_e a half integer, ν_h must also be a half integer for the independent system [Fig. 4(c)]. E_F lies in the extended states for both carrier types. Therefore, an R_{xx} maximum is observed. In contrast, for the strongly hybridized system, an anticrossing gap appears [Fig. 4(e)]. If the gap is larger than the broadening of the extended states, E_F lies in localized states and R_{xx} tends to zero. However, if the anticrossing gap is smaller than the broadening of the extended states, as is the case for the weakly hybridized system, E_F lies in extended states [Fig. 4(d), corresponding to point B in Fig. 3(a)]. Therefore, R_{xx} maxima at values of magnetic field corresponding to 2DEG half-integer filling are expected at the anticrossing point as shown in Fig. 3(a) (arrows). Around the anticrossing point, features which can be attributed to the LL derived from the 2DHG are not clearly observed. The LLs from the 2DHG are sufficiently broad and the transport properties are dominated by the LLs derived from the 2DEG, as is the case at low magnetic field.

Figure 5 shows a comparison of R_{xx} at 1.6 and 4.2 K for the strongly hybridized system. Figures 5(a) and 5(b) are contour plots at 1.6 and 4.2 K, respectively. Figures 5(c)–5(e) show data at $V_G = 0$, 1, and 2 V. An R_{xx} maximum at 8.6 T can be observed in the data for 4.2 K [arrow in Fig. 5(b) and dotted line in Figs. 5(c)–5(e)] but not in the data at 1.6 K. This maximum is known as an "anomalous peak" in Refs. [4,5]. With increasing V_G, the position of the R_{xx} minimum corresponding to $\nu_{\mathrm{net}} = 3$ shifts to

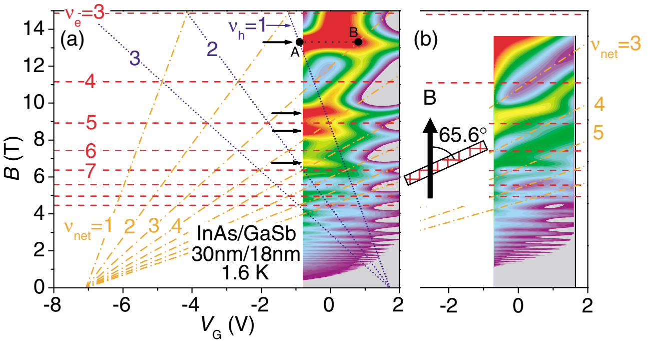

FIG. 3 (color). Contour plots of R_{xx} for a sample with weak hybridization with magnetic field (a) normal to the plane and (b) tilted to 65.6°. (Different piece from the same wafer.) The vertical axis in (b) is the magnetic field component normal to the plane. R_{xx} minima corresponding to the QHE appear along integer ν_{net} and are disconnected by R_{xx} maxima corresponding to extended states of the 2DEG LLs (arrows) in (a). Points A and B correspond to Figs. 4(b) and 4(d), respectively.

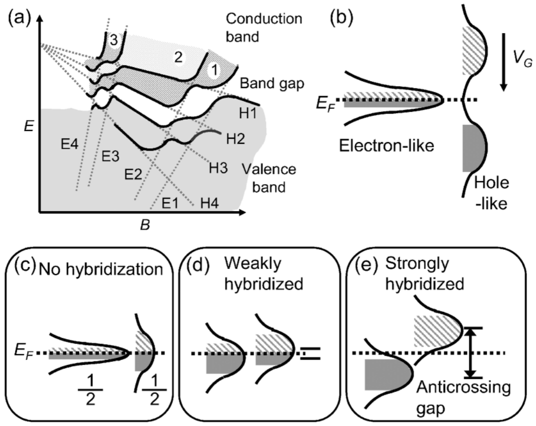

FIG. 4. (a) Schematic diagram of the LL hybridization. The dotted lines indicate LLs derived from the original 2DEG (E1-4) and 2DHG (H1-4). The solid lines indicate hybridized LLs. Indicated integers are net fillings. Relationship between the Fermi level (E_F) and the LL crossing at (b) half integer and (c)–(e) integer ν_{net}. Gray regions represent extended states.

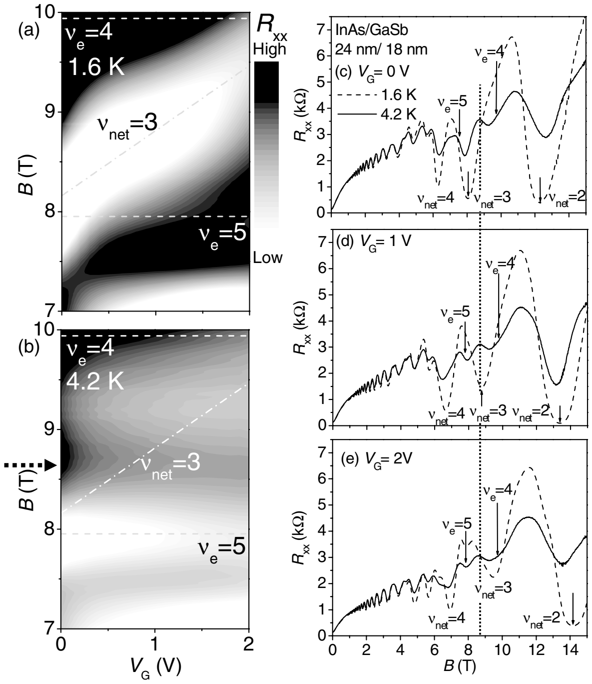

FIG. 5. Temperature dependence of the longitudinal resistance for the strongly hybridized system. Contour plots at 1.6 K (a) and 4.2 K (b). R_{xx} as a function of B with V_G = 0 V (c), 1 V (d), and 2 V (e). The position of the anomalous peak is indicated as an arrow in (b) and a dotted line in (c)–(e).

higher magnetic field, exceeding the anomalous peak. In contrast, the position of the anomalous peak is independent of V_G. In addition, the magnetic field position is consistent with that expected for an extended state of the spin-split 2DEG LL. The origin of the anomalous peak is, therefore, the same as the R_{xx} maxima corresponding to 2DEG extended states observed for the weakly hybridized system in Fig. 3. At 1.6 K, E_F lies in the localized states as shown in Fig. 4(e). With increasing temperature, the LLs are broadened and conduction is activated, leading to a peak.

In addition to measurements under a magnetic field normal to the sample plane, the magnetoresistance was measured under a tilted magnetic field. Figure 3(b) shows a contour plot of R_{xx} for the weakly hybridized sample under a tilted magnetic field at 65.6°. The vertical axis is the magnetic field component normal to the plane. At low magnetic field, the appearance is almost the same as Fig. 3(a). However, at high magnetic field, R_{xx} maxima corresponding to the 2DEG extended states disappear and R_{xx} minima along integer ν_{net} become continuous. The hybridization becomes stronger due to the increase in momentum normal to the plane. In a semiclassical picture, this phenomenon corresponds to one where, in **k** space, the outer electronlike and the inner holelike orbits shift with respect to each other and couple at the Fermi surface. However, the quantum mechanical details are yet to be clarified.

In conclusion, we have shown that the QHE in the strongly hybridized system occurs according to the net filling factor and that it is not a necessary condition for individual filling factors to be integers. When the electron filling is a half integer, quantum Hall states can be replaced by anomalous peaks at high temperature or reduced electron-hole hybridization. In a weakly coupled structure, the application of an in-plane field appears to strengthen the hybridization.

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