Probing the Electrostatics of Integer Quantum Hall Edges with Momentum-Resolved Tunnel Spectroscopy

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Abstract

We present measurements of momentum-resolved magneto-tunneling from a perpendicular two-dimensional (2D) contact into integer quantum Hall (QH) edges at a sharp edge potential created by cleaved edge overgrowth. Resonances in the tunnel conductance correspond to coincidences of electronic states of the QH edge and the 2D contact in energy-momentum space. With this dispersion relation reflecting the potential distribution at the edge we can directly measure the band bending at our cleaved edge under the influence of an external voltage bias. At finite bias we observe significant deviations from the flat-band condition in agreement with self-consistent calculations of the edge potential.

Key words: quantum Hall effect, edge, tunneling, momentum-resolved

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1. Introduction

The quantum Hall (QH) effect arises due to energy gaps developing in the spectrum of two-dimensional electron systems with a perpendicular magnetic field. At specific ratios of electron sheet density and magnetic field, when the Fermi-energy is in such a gap, the only low-energy excitations in a finite quantum Hall sample are located at the boundary, where the energetically bent Landau-levels intersect the Fermi-energy. These states at the sample edge exhibit one-dimensional (1D) chiral transport behavior, i.e. quantized conductance, independent of the exact electrostatics at the sample boundary. Typical transport measurements therefore do not provide information about the edge electrostatics (e.g. depletion lengths or edge reconstructions) or the exact spectrum of the edge excitations. Therefore different techniques like tunneling into the QH edge were introduced to study electron correlation in QH edges.

Due to the atomic precision of confinement potentials and tunnel barriers, the method of cleaved-edge overgrowth (CEO) \cite{1} is of particular interest for fabricating low dimensional tunnel structures. 2D-3D tunneling at a sharp edge was used to study the density of states of fractional quantum Hall edges \cite{2}. In such a geometry the fingerprint of non-Fermi-liquid behaviour was power law behaviour in the tunneling density of...
states over a continuum of fractional quantum Hall edge channels \cite{3}. Subsequent experiments showed evidence for plateau structure at \( \nu = 1/3 \) \cite{4} as well as a drastically shifted power law plot \cite{5} indicating sample dependence in the observed characteristics. In this context it was suggested that the exact potential shape at the edge might be crucial for defining the correlations at the QH edge. In this paper we present a new geometry where the 3D tunnel contact is replaced by a high mobility 2D system \cite{6}. This allows momentum resolved tunnel spectroscopy of the QH edge. In the fractional QH regime this geometry is predicted to probe the spectral function of charged and neutral modes at specific filling factors \cite{7}. In this paper we study the edge dispersion of Landau levels in the integer QH regime and deduce information about the potential distribution at the edge. In contrast to the geometry presented by W. Kang, et al. \cite{8}, where tunneling between two quantum Hall edges is studied, in our sample the contact probing the quantum Hall edge is a simple Fermi system whose properties are not affected by the magnetic field.

2. Sample design

The samples consist of two separately contacted perpendicular high mobility quantum wells (QW\( ^\perp \) and QW\( ^\parallel \)) forming a T-shaped structure (Fig. 1), where \( ^\perp \) and \( ^\parallel \) are defined relative to the quantizing \( B \) field. These QWs consist of GaAs embedded in Al\(_{0.32}\)Ga\(_{0.78}\)As. Using cleaved-edge overgrowth (CEO), a 150 \( \AA \) thick (001)-quantum well (QW\( ^\perp \)) is cleaved along the perpendicular (110)-plane and overgrown with a 200 \( \AA \) thick (110)-quantum well (QW\( ^\parallel \)) in a second epitaxial growth step. The quantum wells are separated from each other by a 50 \( \AA \) thick 320 meV high Al\(_{0.32}\)Ga\(_{0.78}\)As tunnel barrier. Both QWs are modulation doped with a Si-\( \delta \) layer 500 \( \AA \) and 400 \( \AA \) away from the respective QWs. The electron sheet density in the bulk of QW\( ^\perp \) and QW\( ^\parallel \) after illumination is \( 2 \times 10^{11} \) cm\(^{-2} \) for both and they are 5000 \( \AA \) and 3600 \( \AA \) below the surface, respectively. In the \( y \)-direction the sample geometry is translationally invariant and the tunnel junction extends about 20 \( \mu m \) in width.

3. Experimental Results

For our measurement we apply a magnetic field \( B \) in the \( z \)-direction perpendicular to QW\( ^\perp \) where it causes Landau quantization and the formation of edge channels close to the tunnel junction (schematically shown in Fig. 1). Applying a voltage bias \( V \) to QW\( ^\parallel \) with QW\( ^\perp \) grounded, we measure the differential tunnel conductance \( G = dI/dV \) in a \(^3\)He cryostat at temperatures of about 400 mK. Fig. 2 shows several conductance traces plotted against applied voltage bias for a series of \( B \)-values between 2 T and 10 T. At \( B \) fields above 2.5 T we observe clear maxima and minima at low negative voltages. They become more pronounced and shift towards negative bias at higher magnetic fields, with their separation increasing with magnetic field from about 10 mV at 3.5 T to more than 50 mV at 7 T. The conductance at zero bias disappears beyond a \( B \)-field of 4 T and the voltage range of suppressed conductance around zero bias increases with higher \( B \)-fields. At 10 T the conductance is suppressed down to almost \(-60 \) mV.

4. Discussion

In the presence of a magnetic field the electronic states in the QW\( ^\perp \) are quantized to Landau levels with energy gaps proportional to \( B \). With an applied junction bias \( V \) the confining edge potential \( \Phi(x, V) \) leads to a dispersion of the Landau level energy \( E_n^\pm (k_y) \) (see Fig. 3, left) in the vicinity of the tunnel barrier through the Schrodinger equation

\[
\left[ \left( \frac{\hbar^2}{2m^*} \right)^2 + \Phi(x, V) \right] \Psi_n(x, y) = E_n^\pm \Psi_n(x, y). \quad (1)
\]
Fig. 2. a) Differential conductance $dI/dV$ plotted against voltage bias $(V)$ between $QW^\perp$ and $QW^\parallel$, with successive traces shifted by +6 µS. The resonances due to tunneling into the lowest two Landau levels are marked by arrows. b) Positions of $dI/dV$ maxima for the lowest two Landau levels plotted in the $V - B$ plane. The experimental results (circles) differ significantly from the values determined from a flat edge potential (dashed line) but are well described by a self-consistently calculated edge potential (solid line).

With a Landau gauge $A(x, y) = x B \hat{y}$, where $x = 0$ in the center of $QW^\parallel$, and taking advantage of the translational invariance in $y$-direction by expressing $\Psi_n(x, y) = \psi(x) e^{i k_y y}$, we can solve for the motion in $x$:

$$\left[ \frac{p_x^2}{2m^*} + \frac{1}{2} \frac{e^2}{\hbar^2} (x - \bar{x})^2 + \Phi(x, V) \right] \psi_n(x) = E_n^\parallel(k_y) \psi_n(x)$$

where $\bar{x} = k_y l_B^2$ is the electron orbit guiding center and $l_B = \sqrt{\hbar/eB}$ defines the magnetic length. Fig. 3 shows the calculated $E_n^\parallel(k_y)$ assuming a simple step function edge potential.

Alternatively the $k$-space dispersion $E_n^\parallel(k_y)$ of $QW^\parallel$ exhibits a parabolic shape with a well defined Fermi point $FP^\parallel$. From our choice of Landau gauge, the mass parabola will always be centered at $k_y = 0$, as shown in Fig. 3. Since Zeeman splitting in GaAs is small we neglect the influence of the in-plane magnetic field on $QW^\parallel$.

The translational invariance of the geometry in $y$-direction together with the high mobility of the 2DEGs and the high uniformity of the tunnel barrier causes both momentum $k_y$ and energy $E$ to be conserved during tunneling. Graphically, this means that tunneling is only allowed where the dispersion curves intersect. Resonances in the tunnel conductance correspond to coincidences of one of the quasi-Fermi-points ($FP^\perp$, $FP^\parallel$) with such a crossing point. Applying a voltage bias the dispersion curves are shifted in energy, and the magnetic field shifts them in momentum space with respect to each other through the Lorentz impulse acquired by tunneling the effective distance $\Delta \bar{x}$ through the barrier: $\Delta k_y = eB \Delta \bar{x}/\hbar$. Magnetic fields above 4 T separate the occupied states of both systems in the $k_y$ space and therefore tunneling at zero bias is no longer possible. In Fig. 3 we have depicted the situation at finite negative bias where the Fermi point $FP^\parallel$ matches the dispersion curve of the lowest Landau level at the QH edge resulting in a conductance peak. At even higher bias further peaks are observed when $FP^\parallel$ touches the higher Landau levels. Scanning both the voltage bias and the magnetic field we can map out the entire $E_n^\perp$ vs. $k_y$ space using $FP^\parallel$ as a probe for the Landau level dispersion $E_n^\parallel(k_y)$. The conductance maxima for the lowest two Landau levels are indicated by little arrows in Fig. 2a and their positions are plotted in the $V - B$ plane (Fig. 2b) for comparison with model calculations. Spin splitting is not resolved in these measurements.

From the measured $V - B$ relation we can deduce information about the real space edge potential $\Phi(x, V)$ with B-field. For comparison we have performed a self-consistent Schroedinger-Poisson calculation of the edge potential at a biased tunnel junction without magnetic field and plotted the result in Fig. 4. There we have plotted $\Phi(x, V)$ as the lowest 2D subband in $QW^\perp$ as a function of position $x$. The subband is occupied...
up to the Fermi energy designated by the dashed line. Even at zero bias the potential close to the edge is not flat. Negative bias lifts the subband energy above the Fermi level resulting in edge depletion of order 750 Å at -100 mV, for example.

![Fig. 4. Self-consistently calculated potential $\Phi(x, V)$ at the edge of QW$_{\perp}$ for a series of applied bias voltages $V$ (denoted in mV) at $B = 0$. The plotted lines represent the local bottom of the 2D-subband in QW$_{\perp}$. Electronic states are filled up to the Fermi level $E_{F}^\perp$. Note the onset of a depletion region at 10 mV bias.](image)

5. Conclusion

With the presented measurement we are able to directly probe the dispersion relation $E_n^\perp(k)$ of QH edge states. In this paper we focused on the regime at high magnetic fields and moderate negative bias where only the lowest Landau level is occupied and the probed states are empty. We observe a shift in the location of the conductance maxima that directly reveals the band bending under bias at the tunnel junction, and is in excellent agreement with a self-consistent model calculation.

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