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Theoretical investigation of thermostability of incompressible channels in quantum Hall states

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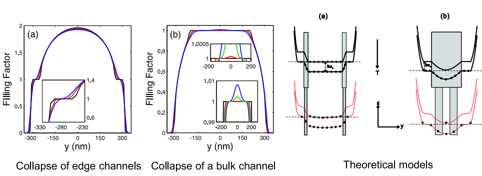
HIGHLIGHTS

- We model the thermostability of incompressible channels in quantum Hall states.
- The thermo decay of incompressible stripes depends highly on the geometry of them.
- A bulk strip will decay into two edge strips from the middle by a density ramp.
- An edge strip will reduce its size from both sides until vanishes.

GRAPHICAL ABSTRACT

The different decay mechanisms of the incompressible bulk channel and edge channels in quantum Hall states with increasing temperature are studied.



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ABSTRACT

In this work we use self-consistent method considering a two dimensional electron gas system in the integer quantum Hall regime, to calculate the temperature induced decay of incompressible stripes. There are two types of incompressible strips which can form in a Hall bar system by varying the electron density or magnetic field. We observe that the way of collapse of incompressible strips strongly depends on the type of them. With increasing temperature a bulk incompressible strip will decay from the middle and separate into two edge channels by a density ramp, while an incompressible edge channel reduces its size from both sides until vanishes.

1. Introduction

The formation of alternating strips of compressible and incompressible strips [1–3] in a gate-confined two-dimensional electron gas (2DEG) is important for understanding the mechanism of many phenomena in the quantum Hall regime, such as the transport properties of the edge states [4–7], heat transport in quantum Hall effect (QHE) samples [8], spatial distribution of local electron temperature [9,10], quantum Hall breakdown (QHBD) [11–13], topologically protected states in the fractional QHE [14] and in novel topological states at zero magnetic field [15]. Recent experimental investigation of the microscopic origin using local probe techniques [16–19] makes it possible to image these strips. Therefore, further study of the structure of the strips is important for an accurate description of QHE and related topics.

The phenomenon is induced by the screening effect of a 2DEG, characterized by the density redistribution of the electrons in response to an imposed external potential in order to minimize the total energy of the system, which is closely related to the metal–insulator transition. The screened potential is then the sum of the external potential and the Coulomb potential of the

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redistributed electrons. When the density modulation of the 2DEG is smaller than the average density, the screen is linear and the external potential is greatly reduced. With decreasing electron density, or increasing fluctuations of the disorder potential, electrons begin to be depleted locally where the external potential is not screened, which means that the screening is nonlinear. In the presence of a strong perpendicular magnetic field a 2DEG shows unusual low-temperature screening properties [20,21], since the highly degenerate quantized energy levels, i.e. Landau levels (LLs), lead to a strong variation of the density of states (DOS) with varying strength of the magnetic field. Strong localization can happen due to the Landau gaps in the energy spectrum [22]. When the chemical potential sits between two successive LLs, there is no screening if the external potential is not strong enough and the temperature is very low because the energy supplied by the disorder potential and the thermal fluctuation is not strong enough to excite electrons to higher LLs. Therefore, an incompressible region is formed. If the chemical potential is pinned in a LL we expect a nearly perfect screening at a low temperature. This happens when the amplitude of the fluctuation of the disorder potential is not large enough to cause LLs to overlap, and then only the electrons in the partially filled level are free to adjust their density. The interaction between electrons and the filling of Landau levels are important for studies in quantum anomalous Hall effect [23]. In Ref. [24] a theory for transport that includes screening effect on the IQHE were presented. Self-consistent calculations of screening properties in a Hall bar system have been developed by Gerhardts et al. [25–28]. This provides us a good tool to study the stationary screening properties of a 2DEG.

The dependence of the widths and position of compressible and incompressible strips on the filling factor [28,19], confinement potential [1,29,30] and imposed external current [28] has been widely studied both theoretically and experimentally. In this paper, we investigate the thermostability of these states in a Hall bar system under the translational invariance consideration, which is closely related to the temperature induced QHBD.

2. Self-consistent calculations

The 2DEG system in a perpendicular magnetic field **B** is actually a Hall bar system. The energy spectrum of 2DEG is split into different LLs. We denote the filling factor

$$\nu(\mathbf{r}) \doteq \rho(\mathbf{r})/n_B = 2\pi l_B^2 \rho(\mathbf{r}) \tag{1}$$

as the number of filled Landau levels, where $\rho(\mathbf{r})$ is the density distribution of electrons, $l_B = \sqrt{\hbar/eB}$ is the magnetic length and n_B is the state density of a LL. To get this result we have assumed that the magnetic field is strong enough to make complete spin polarization. To calculate the non-linear screening, we have to consider all the occupied energy levels (or the total density of electrons), and then calculate the electron density by employing the Thomas–Fermi approximation. Essentially, the screening effect has arisen because of the interaction between electrons. For a given density distribution, we will get the corresponding potential profile, and it in turn will change the density distribution until the electrostatic energy of the system is minimized. It is actually a self-consistent problem and can be described by the following equations:

$$V(\mathbf{r}) = V_{conf}(x) + V_{int}(\mathbf{r}),$$

$$\rho(\mathbf{r}) = \int d\epsilon D(\epsilon) f(\epsilon + V(\mathbf{r}) - \mu), \tag{2}$$

where μ is the chemical potential, and $f(\epsilon) = 1/(1+e^{\epsilon/k_B T})$ is the fermion distribution with k_B being the Boltzmanns constant and T being the temperature. The direct Coulomb potential is

$$V_{int}(\mathbf{r}) = \frac{e^2}{2\varepsilon} \int d^2 r' \frac{\rho(\mathbf{r})\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}, \tag{3}$$

and the confinement potential, which can be simply set as only a function of y by supposing that the system has translational invariance in the longitudinal direction (x-direction), can be written as [28]

$$V_{\rm conf} y = -\frac{2\pi e^2}{\varepsilon} \rho_{\rm bg} \sqrt{d^2 - y^2} \tag{4}$$

where d is half of the sample width, ρ_{bg} is the uniform background positive charge density. In our calculations the electron density is confined to the interval $-d \le y \le d$ in the y direction.

The bare Landau DOS without considering the broadening effect of LLs by impurities is given by

$$D(\epsilon) = \frac{1}{2\pi l_B^2} \sum_0^\infty \delta(\epsilon - \epsilon_n), \tag{5}$$

where ϵ is the energy and ϵ_n is the energy of the *nth*-LL.

The basic idea of solving Eq. (2) is that we start with a guess for the density profile, $\rho(\mathbf{r}) = \rho_0$ for example, by calculating the Coulomb potential, solve Eq. (2) to find better estimates for the density profile, and repeat the loop until the density profile ceases changing. We note that the self-consistent method is applicable for both linear and the nonlinear screening, and all kinds of external potentials in a realistic sample can be included by using this method, such as donor potential, which will not be considered in this paper.

3. Incompressible bulk and edge channels

3.1. Formation of incompressible channels

By varying the magnetic field (and hence the average filling factor), the width and position of the incompressible region change accordingly. For the filling factor $\nu \le 1/2$, there are no incompressible strips. For the filling factor $1/2 < \nu \le 1$, the system will undergo a transition from the bulk incompressible state to the incompressible edge state. We choose two typical average filling factors $\overline{\nu} = 0.55$ and $\overline{\nu} = 1$ for a sample with average electron density $\rho_0 = 4 \times 10^{11}$ cm^{-2}.

Figs. 1(a) and (b) show the results for the situation where the average filling factor is 0.55. The bulk incompressible region with $\nu = 1$ appears in the central part of the system, where the confinement potential is not screened. The confinement potential is only screened along the edges, where the screened potential is a constant. The results for $\overline{\nu} = 1$ are shown in Figs. 1(c) and (d). The screening is better when the magnetic field is applied, as can been seen by comparing this with the results in the absence of the magnetic field (dashed lines in Fig. 1). Two steps with local filling factor $\nu = 1$ appear around the edge of the system, which means the formation of incompressible edge channels and no screening in these regions. The compressible regions are separated by the edge channels. The screened potential becomes nearly constant within the central compressible region (the region between the two plateaus in Fig. 1(c)), which behaves like metal strip at constant potential. If we consider the spin degeneracy, there will be only incompressible regions with even local filling factors. A recent study [31], based on a Hall bar design on a cleaved edge overgrown wafer by the help of a side gate, shows that the widths of the incompressible strips can be changed and even made to vanish when changing the edge potential probe. Such control of the edge potential implies peculiar transport results when considering the screening theory, which includes the direct Coulomb