Imaging the quantum Hall incompressible strip influenced by disorder

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While the disorder-induced quantum Hall (QH) effect has been studied previously, the effect of disorder potential on microscopic features of the integer QH effect remains unclear, particularly for the incompressible (IC) strip. In this research, a scanning gate microscope incorporated with the non-equilibrium transport technique is used to study the influence of potential disorder on the QH IC strip emerging near the sample edge. It was found that different mobility samples with different disorder potentials showed the same spatial dependence of the IC strip on the filling factor, while in the low-mobility sample alone, strong pattern modulations such as bright and dark spots appeared in the IC strip. This pattern is related to the stronger potential disorder inherent to the low-mobility sample. It could be concluded that this disorder strongly affects the QH state, and the applied technique can be effectively used to detect the IC strip in a low-mobility sample.

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Under a strong magnetic field, two-dimensional electron gas (2DEG) forms quantum Hall (QH) phases, such as insulating incompressible (IC) and metallic compressible (C) phases. The microscopic configuration of these phases, determined by both the nonlinear screening effect and electrostatic potential landscape in the 2DEG plane, plays an essential role for the QH effect. When the filling factor (ν) is close to the integer ν, the IC region covering the interior of the 2DEG protects the counter propagating C edge channels from backscattering in between the channels [1]. The bulk IC phase emerges owing to potential disorder at ν, deviating slightly from the exact integer ν, inducing the quantized Hall conductance that is widely persistent around an integer ν. This disorder-induced QH effect has been microscopically confirmed through scanning probe measurement [2,3] that showed compressible paddles interspersed with the IC bulk phase, namely, localized states. On the other hand, the IC along the edge of the 2DEG governed by edge confinement potential [4] and its robust ν-dependence have recently been microscopically demonstrated for the high mobility Hall bar device by our nonequilibrium-transport assisted scanning gate imaging [5].

While the disorder stabilizes integer QH effect, further strong disorder may significantly disturb the QH state. The localized states in the integer QH effect may be delocalized owing to disorder scattering [6]. When the disorder strength is sufficiently high, QH plateaus begin to collapse and finally cease the existence of the integer QH effect [6]. However, it is not clear how disorder potential disturbs microscopic features of the integer QH effect, particularly for the IC strip and its movement. In this study, we address influence of potential disorder on the IC strips in GaAs quantum wells with the different mobility samples. To the end, a non-equilibrium transport assisted scanning probe technique, which was previous used for the high-mobility sample, is applied to the low-mobility sample. It was found that the disorder strongly modulated the QH state, particularly the IC strip, for the low-mobility sample.

The samples we used were 10 μm width Hall bars, which were fabricated using the 20 nm GaAs/AlGaAs quantum wells. High- and low-mobility samples were chosen with the mobility of 130 m²V⁻¹s⁻¹ and 25.6 m²V⁻¹s⁻¹, respectively, at an electron density of n = 1.8 × 10¹⁵ m⁻² to ensure different potential disorder.
Fig. 1(a) depicts the set-up of our scanning gate method. The metallic tip, mounted on an atomic force microscope, was positioned at a constant distance from the surface. In the conventional scanning gate imaging technique, the large $V_{\text{tip}}$ is applied to obtain sufficient signal strength by deforming the QH states and thereby inducing backscattering between chiral edge channels [8]. In contrast, we minimized tip-induced global depletion (or accumulation) by setting $V_{\text{tip}}$, typically $0.2 \text{ V}$, to compensate for the potential mismatch between the tip potential and global potential of the sample surface. The current was tuned up to approach the critical point of breakdown regime to drive the inter-LL tunneling through the innermost IC strip, inducing the electron tunneling from the edge to the bulk. This current-induced non-equilibrium transport technique induced the backscattering with minimizing influence of current heating [9]. Meanwhile, the imposed excess Hall voltage deviated the local chemical potential from the ground level of the 2DEG. Hence, the tip (a nanoscale top gate) could perturb a microscopic landscape of the potential, resulting in a modification of the inter-LL tunneling. In the case of a high-mobility sample, the nanoscale top gate reduces the width of the IC region by bending the LLs locally and enhancing the inter LL tunneling, particularly through the innermost IC [5], leading to a further enhancement in the longitudinal resistance. Here, the tip-induced resistance change was measured as the longitudinal voltage ($V_{xx}$) at the constant source-drain current ($I_{\text{sd}}$) by a DC amplifier during scanning. This scanning gate microscopy technique enables robust imaging of the QH IC strip in the non-equilibrium condition [5]. By using a dilution refrigerator and a superconductor magnet, measurements were performed at a temperature of $100-300 \text{ mK}$, while varying $\nu$ near $\nu = 1$ by tuning the electron density of the 2DEG via back gating at a constant magnetic field $B = 8 \text{ T}$. The experimental results obtained for high- and low-mobility samples were then compared.

Figure 1(b) and 1(c) show the SGM images of $\Delta V_{xx}$ plotted after subtracting the background. The current flows from down to up, and the magnetic field is applied perpendicular to the 2DEG plan. For the high-mobility
sample (Fig. 1(b)), at the higher chemical potential side, a bright line strip can be observed along and near the left Hall-bar edge, which is attributed to the IC strip [5]. For the low-mobility sample (Fig. 1(c)), a similar pattern appears along and near the left Hall-bar edge, although it comprises of alternating bright and dark spots which differ significantly from the monotonic contrast in the pattern for the high-mobility sample.

We measured the SGM image at different $\nu$ values around $\nu = 1$. The resultant images for the low-mobility sample (Fig. 2(a)) show a line pattern that moves from the edge to the interior of the Hall bar with reduction of the filling factor toward $\nu = 1$. To compare this position of the line pattern with that for the high-mobility sample, we took the line profile across the Hall bar and then spatially averaged the line profile within the measurement area shown in Fig. 2(a) for the low-mobility sample and almost the same size of the area for the high-mobility sample (data used in our previous work [5]). The resulting line profiles for the high-mobility sample (the upper panel of Fig. 2(b)) show a peak structure that moves to the interior of the Hall bar as the $\nu$ value reduces toward the exact integer $\nu$. This was identified in our previous work [5] as the innermost IC region dependent on $\nu$. In contrast, the line profiles for the low-mobility sample (the upper panel of Fig. 2(c)) show, instead of such a clear peak structure, an oscillatory feature which strengthens near the higher chemical potential side edge. We speculate that spatial averaging partially canceled out the original oscillatory pattern derived from the positive and negative peaks that originate from the bright and dark spots observed in the 2D image (Fig. 2(a)).

To clarify this point, we performed a statics analysis on the distribution of the bright and dark spots in the SGM image. Figure 2(d) shows the intensity histogram of the SGM images for the high- and low-mobility samples at $\nu = 1.07$. The skewness ($S$) value [7] for the high-mobility sample is $S = 2.6$ (positive asymmetry), indicating that the bright region dominates in the SGM image. In contrast, for the low-mobility sample, $S = 0.1$ (almost symmetric distribution), indicating that the dark and bright spot regions are almost equivalent. These results lead to the conclusion that the positive and negative peak structures observed in the low-mobility sample were canceled out after spatial averaging and are faint. To determine the point of the highest intensity of both the positive and negative peaks, the absolute value of $\Delta V_{xx}$ in the line profile was taken, followed by spatially averaging over $x$-direction. The resultant line profiles for the high- and low-mobility samples, respectively, are shown in the bottom panels of Fig. 2(b) and 2(c). The absolute line profiles for the high-mobility sample (bottom panel of Fig. 2(b)) show a peak structure and $\nu$ dependence that are almost identical to those of the unprocessed line profile (upper panel). By contrast, the line profiles for the low-mobility sample (Fig. 2(c)) significantly change by taking absolute values, such that the peak structure near the high chemical potential side edge becomes obvious (bottom panel). For further quantitative comparison of the peak structures in the absolute line profile, the full width at half maximum (FWHM) and the position of the peak structures were estimated, as shown in the inset of Fig. 2(c) and plotted as the horizontal bars and dots as a function of the bulk $\nu$ and position ($y$) (Fig. 2(c)). This verifies that the $\nu$-dependence of the position are identical for the high- and low-mobility samples in the range $\nu > 1.05$, proving that the peak structure in the absolute line profile for the low-mobility sample is the innermost IC strip.

Closer examination of the SGM pattern, as marked by circles in Fig. 3(a) and 3(b), shows that the size of the bright spot for the low-mobility sample is smaller than that for the high-mobility sample. To analyze this trend quantitatively, the two-dimensional autocorrelation function ($G(x,y)$) [5] of the SGM image was calculated. The right insets of Fig. 3(a) and 3(b) show the representative $G(x,y)$ values which were calculated for the SGM images taken at the $\nu = 1.07$. The resulting $G(x,y)$ exhibits a disk pattern which reflects the bright spots observed in the real-space images (marked by the red circle in Fig. 3(a) and (b)). Note that a line pattern overlapping the disk pattern for the high-mobility sample (inset of Fig. 3(a)) is caused by the real-space line pattern overlapping bright spots. To compare the char-
acteristics of the real-space bright spots for the high- and low-mobility samples, the $G(x, y)$ section was extracted across the disk pattern along the dashed line. Figure 3(c) and 3(d) show the obtained main peak around $R = 0$ with the small satellite peaks. The averaged radius ($r$) of the bright spot and averaged spacing ($D$) between the spots were estimated from the peak width at half maximum of the main peak and the separation between satellite peak (Fig.3(c) and (d)), respectively defined by $2r$ and $2D − 4r$ [10, 11]. The estimated values are $r = 441$ nm and $D = 2.77$ $\mu$m for the high-mobility sample and $r = 386$ nm and $D = 1.97$ $\mu$m for the low-mobility sample. These results indicate that the fine pattern in the IC strip for the low-mobility sample is $12\%$ smaller and $28\%$ denser than those for the high-mobility sample.

The obtained fine structures can be interpreted as the inter-LL scattering center induced by the disorder potential which can have sharper potential gradient and be denser in the low-mobility sample. Such potential disorder is primarily induced by the ionized impurity distributed inhomogeneously inside the low-mobility sample. The disorder-induced potential gradient is significant in the IC region, while being screened in the compressible region. For instance, in Fig. 2(a), the bright spot marked by the red arrow appears at the same position at $\nu = 1.07$ and $\nu = 1.01$ only when IC strip overlaps the corresponding position, but it remains invisible at the $\nu = 1.13$. The sharper potential disorder causes larger potential fluctuation. Tip-induced modification sometimes enhances (suppresses) tunneling through IC strip. Therefore, bright and dark patterns appear with almost the same probability. Such scenarios are likely to occur for the low-mobility sample in which the ionized impurities located in/near the 2DEG layer play an important role. In contrast, although there are smaller amounts of impurities in/near the quantum well, those that act as the dominant source of disorder potential in the high-mobility sample can be located relatively far from the 2DEG layer, for instance, in the barrier layers. These types of impurities may induce a potential gradient that is relatively smaller than that induced by the excess Hall voltage imposed by non-equilibrium transport. Therefore, the bright IC strip is pivotal for the high-mobility sample.

In conclusion, non-equilibrium transport assisted scanning gate microscopy was successfully applied to detect IC strip in a low-mobility sample as well as high-mobility sample. The disorder potential strongly modulates the QH IC phase, providing sharply different microscopic perspectives for different mobility samples. This work can be extended to study the microscopic influences of potential disorder on fractional quantum Hall (FQH) IC strips and IC domain structures [12].

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