Quantized magnetoresistance in multiply connected perimeters in two-dimensional systems

F. F. Fang
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

P. J. Stiles
Brown University, Providence, Rhode Island 02912
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It is shown that multiply connected perimeter contacts of a two-dimenisonal system in the quantized-Hall-effect (QHE) regime have two-terminal resistance values equal to a well-defined rational fraction of h/e^2, depending on the interconnection configurations. A phenomenological model is presented to account for the results which is consistent with quantized dissipation in the vicinity of current-carrying contacts. It is further demonstrated that the interior of the system is dissipationless and the effect is not affected by the inclusion of macroscopic inhomogeneities.

In a previous paper[1] we reported the quantization magnetoresistance (QMR), the two-terminal resistance of a two-dimensional (2D) electron gas (2DEG) of any shape and size between any well-resolved magnetic levels, has plateaus exactly equal (to the acuracy of our measurements $1/10^5$) to the quantized-Hall resistance.[2] This result has the same origin as the quantized Hall effect. In the quantized-Hall regime, the current carriers are completely quantized in all three dimensions and all states below ith Landau level are occupied. There should be vanishing σ_{xx} and zero ρ_{xx} at $T=0$ for this system.[3] The system becomes nondissipative in the bulk of the 2D domain. However, the system as a whole dissipates power I^2R_Q, where $R_Q=h/ei^2$, regardless of the size and shape and contact geometry. One must conclude that the dissipation occurs only in the vicinities of the current-carrying probes. In this paper, we further generalize the universality of this result in multiple connections in the 2DEG open domain periphery.

It will be shown that by various interconnections among these peripheral terminals, two-terminal resistance of many rational-number multiple values of R_Q are obtained. It will also be shown that the two-terminal QMR results are not affected by the macroscopic areal inhomogenieties inside the 2DEG open domain.

Samples used for the multiply connected peripheral terminals are the six-probe Hall bridges and in some cases van der Pauw[4] circular disk geometry. The substrates are (100) oriented 100-Ω cm p-type Si. The gate oxide thickness is about 1 μm. The peak mobility is over 10^4 cm^2/V s. Figure 1(a) shows seven configurations of peripheral terminal connections. Corresponding resistances between the terminals indicated by open circles in each configuration at $H=15$ T and $T=1.6$ K, are shown in Fig. 1(b). The QMR plateaus are preserved for each case, but the values of these plateaus have various rational number of multiples of the h/ie^2. So far, rational number factors of 3, 2, $\frac{3}{2}$, 1 , $\frac{2}{3}$, $\frac{1}{2}$, and $\frac{1}{3}$ have been obtained as shown by configurations a to f. The accuracy of these rational multipliers is generally better than a few parts in 10^4 which in part is due to the finite resistances of the interconnections which were made externally. The results are independent of size, shape, and peripheral probe positions. We speculate that with $2n$ connections, one may obtain quantized resistances given by l/m, where $l=1,2,\ldots,n$ and $m=1,2,\ldots,n$.

The observed results may be understood by a phenomenological model based on the two-terminal QMR at the quantized-Hall plateaus. Consider an open domain 2DEG in quantized-Hall regime with multiple peripheral contacts as shown in Fig. 2. Each peripheral contact is asso-

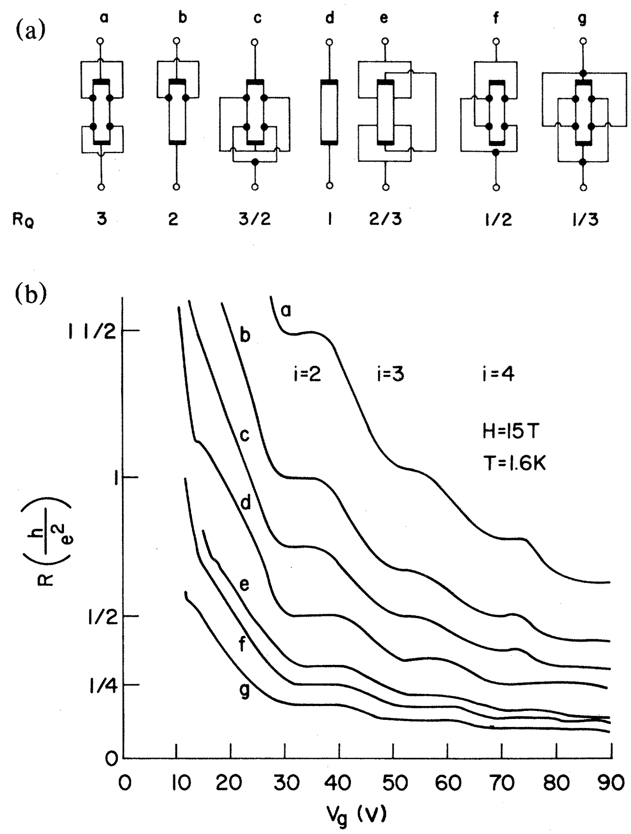

FIG. 1. (a) Perimeter interconnection configurations of a six-contact sample. The two-terminal QMR is measured between terminals designated by open circles. The rational multipliers of the QMR are indicated below each configuration. (b) Two-terminal resistance for each configuration as a function of gate voltage at $H=15$ T. The resistances are in units of h/e^2.

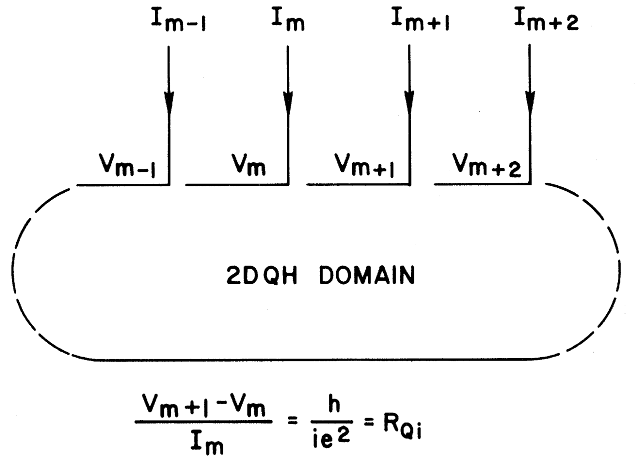

FIG. 2. Phenomenological representation of a 2D domain in quantized-Hall domain with multiple perimeter terminals.

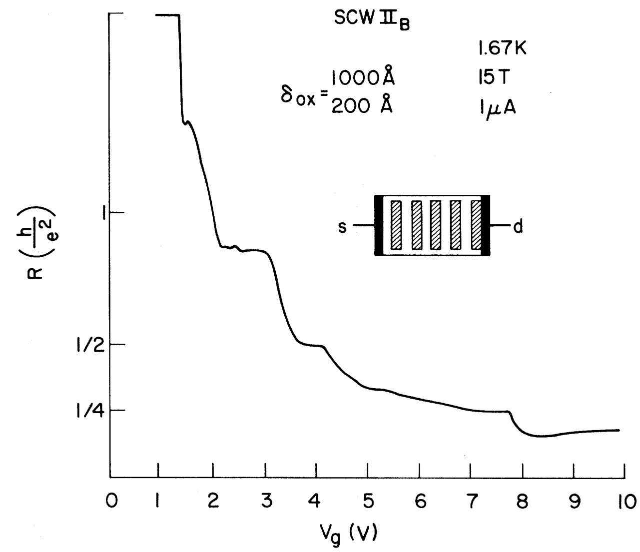

FIG. 3. Two-terminal resistance of a 2D domain with periodic islands (see text) at $H=15$ T as a function of gate voltage.

ciated with a current I_m and voltage V_m where m identifies the contacts. According to our QMR results, only dissipative regions are in the vicinity of the current probes. The vanishingly small dissipation inside a 2DEG for large σ_{xy}/σ_{xx} ratio was first pointed out by Kawaji[5] in a general analysis of the quantum galvanomagnetic transport, although by itself it does not imply QHE and absolute dissipationless transport state. Let these regions be in one side of each current probe; there are voltage drops only in these regions. In general, each adjacent pair of the contact is represented by the potential difference between the probes, e.g., $V_{m+1}-V_m$, and the current I_m associated with the region. Furthermore, the resistance of this pair of terminals must satisfy the QMR conditions, i.e.,

$$\frac{V_{m+1}-V_m}{I_m}=\frac{h}{ie^2}=R_{Qi} \ . \tag{1}$$

For multiple connected peripheral contacts, there are specific boundary conditions, depending on the external connections. For instance, for shorted k and l terminals, $V_k=V_l$ and $I_k=-I_l$, etc. The two-terminal resistance between contacts a and b is then given by $R_{ab}=(V_b-V_a)/I_a$ which must be a rational multiple of R_{Qi} and can be readily solved from the general condition (1) and the boundary conditions describe the specific connections.

The experimental results and the phenomenological model agree with what one would calculate for topologically different connection schemes. For example, two points connected together with no intervening connection are equivalent to a single connection. Any change in potential along the perimeter must be accompanied by a current given by that change in voltage divided by the quantized resistance at that point. In evaluating the two-terminal resistance of the configuration, one describes the voltage drop on the perimeter at a contact point as being on the same side for all contacts on the perimeter either clockwise or counterclockwise (as in Fig. 2) for a given direction of the magnetic field as long as they are consistent in each configuration.

The dissipationless transport in the QHE regime in the 2DEG domain implies that the QMR is not affected by the macroscopic inclusion or edge inhomogeneities as long as the inhomogeneous regions are themselves not in the QHE regime. Clearly, if the inhomogeneous regions are dissipative, all current fluxes are excluded in these regions. We have measured the metal-oxide-semiconductor-field-effect-transistor samples with well-defined islands in the channel. The islands are formed by different thicknesses of gate oxide. Figure 3 shows a typical result of the two-terminal resistance at $H=15$ T of such a sample. The resistance between the source and the drain contacts has a plateau with $1/i$ multiples of h/e^2 at appropriate gate voltages which induces inversion layer electron density in the neighborhood of ieH/hc for the thick oxide area. A schematic of the areal view of the sample is shown in the inset. There are ten 250×6-μm periodic islands under the 20-nm-thin oxide gate. The islands are included inside the 100-nm-thick gate area with 6 μm between islands and edges. Notice also that the drain electrode contacts the thick gate inversion layer as well as one of the islands. The plateaus between $i=1$ and 2 is probably due to the fact that both the thick and thin gates are in the QHE regime with different Landau level filling integers i and i', respectively, or, alternatively, due to the nonvanishing value of ρ_{xx}, at $i=1$ in the thick gate region[6] so that both thick and thin gate regions contribute to the conduction.

In this paper we have demonstrated the nondissipative nature of the 2DEG in the QHE regime. We also demonstrated the local dissipation in the vicinities of the current-carrying contacts at the 2DEG perimeter. With this model, we can predict two-terminal resistance in any interconnected configurations of multiple perimeter contacts in a single QHE regime. The resulting two-terminal resistances are rational fractions of QMR. The results are also shown to be independent of macroscopic inhomogeneities as expected.

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