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# Quasiperiodic magnetoresistance oscillations in narrow quasiballistic wire in the quantum Hall regime

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We have investigated magnetotransport behavior of a quasiballistic quantum wire in the integer quantum Hall effect (IQHE) regime. At low and high magnetic field sides of the IQHE longitudinal resistance minima of lower filling factors, we have observed quasiperiodic magnetoresistance oscillations having markedly different spectral characteristics. Oscillations at the low $B$ side of a resistance minimum were of a higher frequency than those at the high $B$ side. The analysis of the experimental data is based on the electron interference via edge current states coupled by tunneling and also on the resonant tunneling through a magnetically bound state of a potential fluctuation at the entrance to the wire. [S0163-1829(96)03620-X]

Extensive experimental investigations in the past few years have shown that magnetoresistance behavior of a quantum wire in a strong magnetic field may be quite complicated. Even though the electron mobility may be high enough for a wire to be nearly ballistic, still in some cases against the background of Shubnikov–de Haas oscillations, there can be observed aperiodic magnetoresistance fluctuations arising in the vicinity of both the $\rho_{xx}$ minima and maxima.[1,2] The origin of these fluctuations for some time remained obscure. However, with the development of the edge current states approach to the electron transport in strong magnetic fields,[3] it became clear that these effects can be explained in terms of electron interference via edge current states coupled by tunneling[4] or resonant scattering of electrons via a magnetically bound state.[4,5] In the present work, we report the observation of quasiperiodic magnetoresistance (MR) oscillations in a quantum wire in integer quantum Hall effect (IQHE) regime. We analyze our experimental data within the framework of magnetic edge states and show that the quasiperiodic MR oscillation may arise from the resonant scattering of electrons between the magnetic edge states that carry a current along the opposite boundaries of the wire via a localized state magnetically bound to an impurity potential fluctuation situated in the immediate vicinity of the wire. Relying on the period of the oscillations, we make an estimate of the spatial extent of the potential fluctuation.

The experimental device was a quantum wire with the length $L=1.5$ $\mu$m and the lithographic width $W=0.3$ $\mu$m, shallow etched from a two-dimensional (2D) electron gas in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{GaAs}$ heterostructure. The wire was positioned in the center of a Hall bar with the width 10 $\mu$m and the distance between the voltage probes 100 $\mu$m . Schematic top view of the sample is given in the inset to Fig. 1(a). The original parameters of the 2D electron gas at 4.2 K were as follows: the mobility $\mu=10^5$ cm$^2$/V s and the electron density $n=(7-9)\times10^{11}$ cm$^{-2}$. The measurements were carried out at temperatures $T\approx20$ mK and in magnetic fields up to 8 T. We measured the four-terminal resistance of the wire, using an ac lock-in technique at 30–70 Hz.

Figure 1(a) shows a variation of the quantum wire resistance as a function of the applied perpendicular magnetic field over the whole magnetic field range covered. Up to 1 T, one can observe low amplitude MR fluctuations, which actually are the universal conductance fluctuations (UCF) in the wire with the magnitude of about $e^2/h$. Their correlation function offers a means of determining the effective width $W_{\mathrm{eff}}$ of the wire from the equation $B_c\sim\Phi_0/(LW_{\mathrm{eff}})$, where $B_c$ is the correlation magnetic field and $\Phi_0$ is the magnetic flux quantum. One obtains $W_{\mathrm{eff}}\sim0.1-0.2$ $\mu$m. Hereafter, we will take $W_{\mathrm{eff}}=0.1$ $\mu$m, because the lithographical width of the wire is 0.3 $\mu$m and the depletion widths at the wire edges would be about 0.1 $\mu$m. At fields higher than 1 T Shubnikov–de Haas oscillations appear, their amplitude increasing with magnetic field, and at about 3 T and higher the $\rho_{xx}^{\mathrm{min}}\ll\rho_{xx}^{\mathrm{max}}$ condition is satisfied, suggesting that transition to the IQHE regime is taking place. Figures 1(b) and 1(c) display in more detail MR data taken in the IQHE regime for filling factors $\nu=8$ and $\nu=6$. In either case, resistance fluctuations are clearly seen which for these curves have a common feature. Indeed, the average period of fluctuations at the low $B$ side of a MR minimum (the Fermi level lies in the tail of localized states of a Landau level above) is noticeably smaller than that of fluctuations at the high $B$ side of a MR minimum when the next Landau level is approaching the Fermi level from below. MR fluctuations at higher filling factor minima show up in much narrower intervals of magnetic field, which makes their analysis impossible.

Figure 2 shows the Fourier spectra of the fluctuations to the right [2(a)] and to the left [2(b)] of $\nu=8$ minimum. Fourier analysis of MR data in the vicinity of $\nu=6$ minimum gives very similar results. In either case Fourier transform was preceded by a trend elimination in an examined part of the MR dependence. Following this procedure, the magnetic field region under study was divided into several intervals, in which Fourier transforms were independently performed. The Fourier spectra thus obtained were then averaged to produce the spectra shown in Fig. 2. As may be inferred from the general appearance of the spectra, the fluctuations from both the left and the right side of the minimum contain components periodical with magnetic field. However, while the

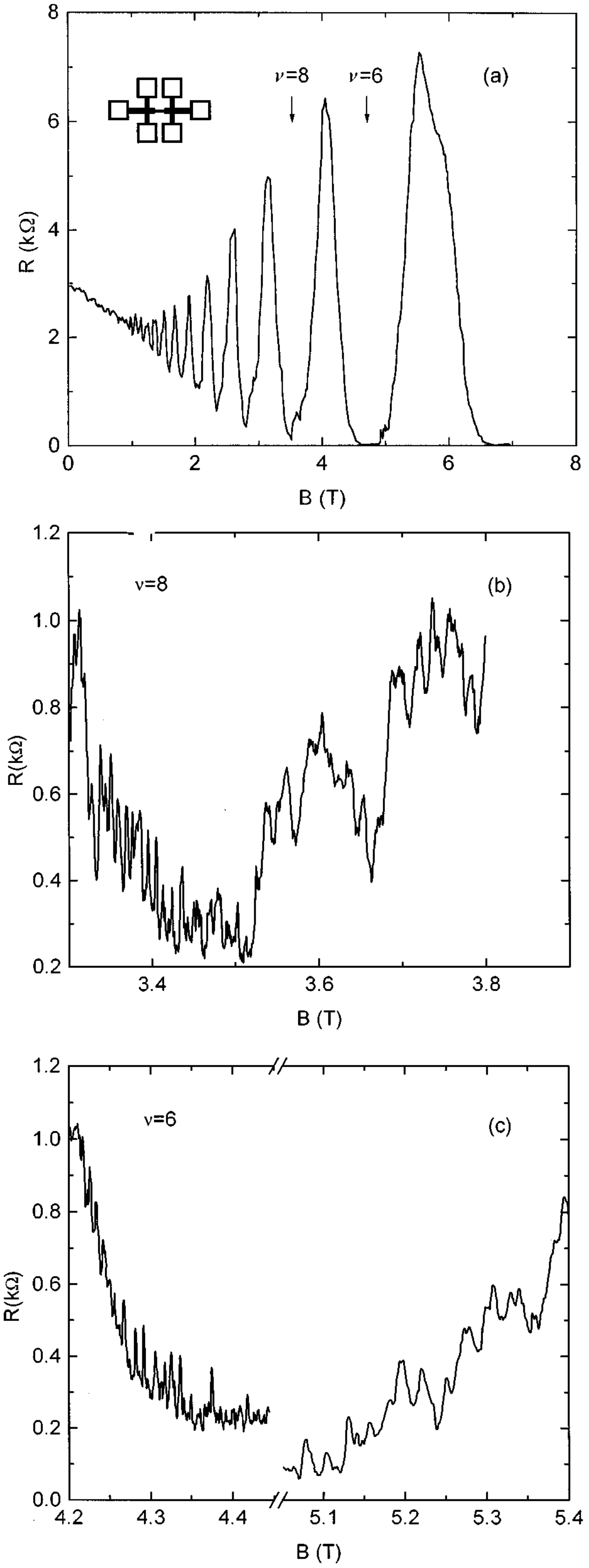

FIG. 1. The magnetoresistance of the quantum wire (a) over the whole magnetic field range studied, (b),(c) in the vicinity of the MR minima $\nu = 8$ and $\nu = 6$, respectively. Inset in (a): the cross pattern of the device.

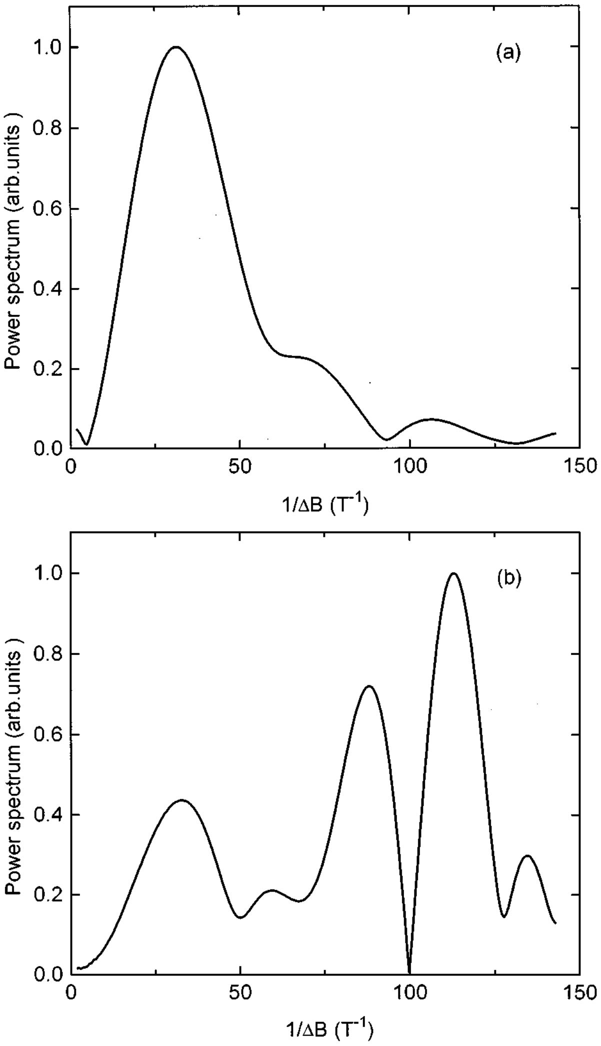

FIG. 2. Fourier spectra of the fluctuations to the right (a) and to the left (b) of $\nu = 8$ MR minimum.

high $B$ side fluctuations [2(a)] contain only one such component, the low $B$ side fluctuations [2(b)] have an additional distinct contribution of a higher frequency represented by two sharp closely spaced peaks in the Fourier spectrum. This specific structure was not destroyed by the averaging procedures mentioned above. It was also indifferent to changing (up to 10%) the width of the interval in magnetic field over which the Fourier transforms were performed. All this makes us believe that it has some physical origin. In this paper, we will, however, ignore the details of the structure and treat these high-frequency peaks further as a single feature in the spectrum, thus assuming that there are on the whole, two different periodical components: one common to both types of fluctuations, and the other, with the frequency approximately three times higher, found in the fluctuations to the left of the minimum.

We now turn to a discussion of the above results. According to the general concept of electron transport in the IQHE regime, a current is carried in a set of parallel edge states along the sides of the wire, as the electrons become confined to the edges of the sample by the Lorentz force. If there is no scattering across the wire, then there is no voltage drop along an edge and the transport is dissipationless. To account for the fluctuations observed in the vicinity of MR minima, we must consider some mechanism of electron backscattering, which is sensitive to magnetic field. Let us first consider the low-frequency component of the fluctuations. Its period is close to the UCF correlation magnetic field $B_c$ mentioned earlier and corresponds to a change of $\Phi_0$ in the magnetic flux through the area of the wire. However, the appearance of the low-frequency part of the Fourier spectra in Fig. 2 is different from a UCF Fourier spectrum.[6] A possible origin of the component in question may be an electron interference via magnetic edge states that carry the current along the opposite boundaries of the wire. It is necessary that the innermost edge states from the opposite boundaries be well separated along the whole length of the wire, except at least two (or more) places where a fluctuation of confining potential brings them close enough together to make electron backscattering sufficiently strong. In this situation, the backscattered trajectory of the electron is split in two or more alternative paths enclosing different areas. The maximum difference of the areas thus enclosed may be approximately equal to the area of the wire itself. Then the Aharonov-Bohm effect on the electron wave propagating along these paths would bring about the low-frequency component observed.

Let us now turn to the high-frequency component. In the nanostructure physics, a periodic component in MR is generally an indication that there is a well-defined area in the sample enclosed either by two different electron paths (Aharonov-Bohm effect) or by a localized magnetic edge state (resonant tunneling). In either case, the period of MR oscillations is directly related to the area thus enclosed. In the case of the high-frequency component, this area ($S$) is approximately $4\times10^{-9}$ cm$^{-2}$, which is about three times bigger than the area of the wire itself. Taking this into account, we propose a model based on the assumption that the high-frequency oscillations result from resonances associated with the discrete energy levels of a localized edge state bound to an impurity potential fluctuation in one of the precontact broadenings, Fig. 3(a). The edge states that carry current through the wire couple with the localized state where they come nearest to it [in Fig. 3(a), these are the places where the edge current lines are crossed by the dashed curve]. The resonant scattering occurs whenever the total flux through the area enclosed by the localized state is equal to a multiple of an elementary flux quantum. From the area $S$, we can get an estimate of the spatial extent of the long-range potential fluctuations in an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterostructure ($S^{1/2}\sim0.6$ $\mu$m). So big a figure (compared to the spacer setback or to the average spacing between the Si dopant atoms) might be explained by the presence in our structure of clusterlike congregations of dopant atoms in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$.

There still remains one more feature of the high-frequency oscillations that must be fitted into the model. Unlike the low-frequency component, the high-frequency oscillations can only be found at the low $B$ side of a MR minimum. To our opinion this is indicative of the nature of the impurity potential fluctuation. The MR data in Fig. 1(a) testifies that the average potential in the middle of the wire is approximately the same as in the precontact regions. Let us suppose that the potential fluctuation that is responsible for the resonant backscattering is actually a hollow near the entrance to the wire and look at what happens when the magnetic field is varied. Figure 3(b) shows the schematic diagram of the Landau levels structure along the dashed curve [Fig. 3(a)]. At the high $B$ side of a MR minimum (the Fermi level occupies the position $E_F^1$), the potential fluctuation does not produce a localized edge state and, therefore, there is no resonant backscattering. As the magnetic field increases, the Fermi level enters the shaded region, which denotes a Landau level center elsewhere in the sample, and corresponds to a MR maximum. At still higher magnetic field, the Fermi level moves into the position $E_F^2$ corresponding to the low $B$ side of the next MR minimum. In this case, there is a localized edge state originating from the upper Landau level (note, that now this Landau level does not form open edge states) and the electron resonant tunneling can take place as indicated by arrows, Fig. 3(b). Note that the high-frequency oscillations superimpose on the low-frequency fluctuations that are symmetrical with respect to MR minima.

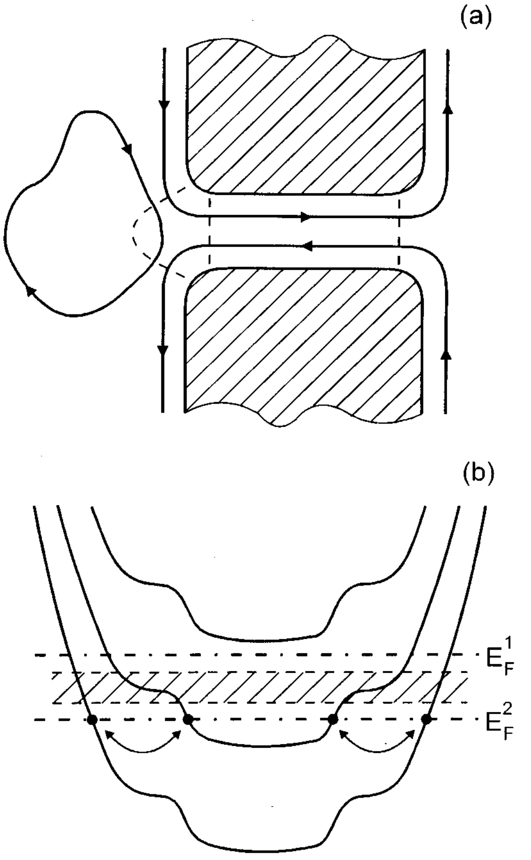

FIG. 3. (a) The edge current flow and the localized state at the entrance to the wire. (b) The schematic diagram of the Landau levels structure along the dashed curve in (a). The arrows denote the tunneling between the edge states (see the text).

In conclusion, we have observed quasiperiodic magnetoresistance fluctuations in a quantum wire in the integer quantum Hall effect regime. We have found that the Fourier spectrum of the fluctuations at the low $B$ side of a magnetoresistance minimum is markedly different from that of the high $B$ side fluctuations. We analyze our data within the framework of magnetic edge states and propose a possible model that qualitatively explains these results.

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[1] G. Timp *et al.*, Phys. Rev. Lett. **59**, 732 (1987).

[2] A. A. M. Staring *et al.*, Phys. Rev. B **45**, 9222 (1992).

[3] M. Büttiker, in *The Quantum Hall Effect in Open Conductors*, Semiconductors and Semimetals Vol. 35 (Academic Press, New York, 1992), p. 191.

[4] A. A. Bykov, E. B. Ol'shanetskii, L. V. Litvin, Yu. V. Nastaushev, V. G. Mansurov, V. P. Migal', and S. P. Moshchenko, Pis'ma Zh. Éksp. Teor. Fiz. **58**, 897 (1993) [JETP Lett. **58**, 839 (1993)].

[5] P. H. M. van Loosdreeht *et al.*, Phys. Rev. B **38**, 10 162 (1988).

[6] S. Washburn and R. A. Webb, Rep. Prog. Phys. **55**, 1311 (1992).