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Ballistic magnetotransport in a semiconductor microjunction with broken symmetry

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The linear and nonlinear magnetotransport response of a ballistic semiconductor cross junction with an embedded, symmetry-breaking scatterer is investigated. As a result of the broken symmetry, the so-called 'bend resistance' is no longer symmetric in the magnetic field. The experimental curve also exhibits a pronounced peak structure. In the nonlinear transport regime, both the magnitude and the position of the magnetoresistance peaks are drastically influenced by the dc current bias. We also observe new magnetoresistance peaks evolving at high lead currents in some experimental configurations.

Key words: magnetotransport, ballistic transport, symmetry-breaking, nonlinear effect.

1. Introduction

A large number of novel transport phenomena have been observed in ballistic semiconductor structures [1]. Among these intriguing phenomena is the so-called negative 'bend resistance', the four-terminal resistance of a cross-junction when current flows between adjacent probes and voltage is measured between the other two probes [2, 3]. Instead of being positive as in the diffusive transport regime, the bend resistance of a ballistic cross-junction was found to be negative at low magnetic field B. This is because ballistic electrons tend to travel straight ahead rather than 'turning the corner' [4]. Such a bend resistance was studied in the nonlinear regime where striking nonlinear behavior was observed [5]. There has also been increasing interest in effects of broken geometric symmetry in the ballistic transport regime. Ballistic magnetotransport in symmetry-breaking microjunctions has been studied by Ford *et al.* [6] and Linke *et al.* [7]. Recently, we have shown how the intentional breaking of the device geometry leads to a new rectification phenomenon at zero magnetic field [8].

Here, we investigate the magnetotransport properties of a ballistic microjunction with broken symmetry in both the linear and nonlinear transport regime. In the linear regime, the bend resistance is shown to be highly asymmetric in the magnetic field and exhibits distinctive peaks. In the nonlinear regime, we find that both the

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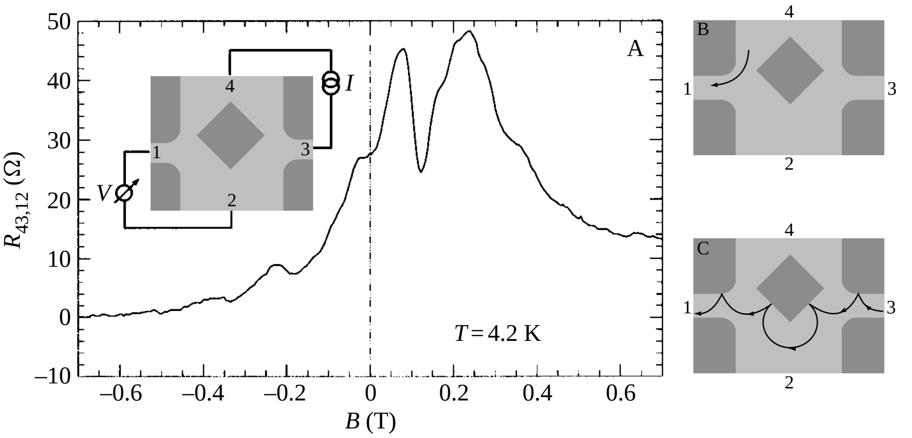

Fig. 1. A, Four-terminal bend resistance $R_{43,12}$ of a cross-junction with a symmetry-breaking scatterer. The inset is an atomic force micrograph of the device. B and C, Typical electron trajectories at positive magnetic fields.

magnitude and the position of these peaks are strongly influenced by the applied current bias and new peaks evolve at higher currents.

2. Experimental results and discussion

The sample is fabricated from a (Al)GaAs heterostructure with a shallow two-dimensional electron gas (2DEG). On the unprocessed wafer, the carrier density and mobility at temperature $T = 4.2$ K are $5 \times 10^{11}\,\text{cm}^{-2}$ and $5 \times 10^5\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$, respectively. The inset in Fig. 1A displays an atomic force micrograph of the device, which consists of two narrow leads (lithographic width 0.7 μm), two wide leads (lithographic width 3.2 μm) and a diamond-shaped scatterer fabricated using chemical etching. The leads are labeled by 1, 2, 3, and 4 counterclockwise. The scatterer is displaced by 0.5 μm towards lead 4, which thus breaks the geometric symmetry. All the measurements reported here are carried out at $T = 4.2$ K. Lock-in technique and an ac current of $I_{ac} = 1\ \mu$A are used.

We first study the transport in the linear regime. Figure 1 displays the bend resistance $R_{43,12} \equiv dV_{12}/dI_{43}$ as a function of the magnetic field B, applied perpendicular to the 2DEG. The most obvious observation is the lack of symmetry in the curve around $B = 0$. For a cross-junction without the symmetry-breaking scatterer it is easy to show that the bend resistance obeys the relation $R_{43,12}(B) = R_{43,12}(-B)$ [2–4]. So, already in the linear regime the scatterer has a pronounced effect on the transport properties. Another observation is that $R_{43,12}$ is positive at zero magnetic field and quickly decreases on the $B < 0$ side. At $B \approx -0.7$ T, $R_{43,12}$ becomes slightly negative. This is in contrast to the case of an empty cross-junction without antidot, where the bend resistance is negative at $B = 0$ and increases to positive values with B field [2–4]. The linear transport behavior can be well described using the Landauer–Büttiker formalism [9], which yields

$$R_{43,12} \propto T_{4\to1}T_{3\to2} - T_{3\to1}T_{4\to2}, \qquad (1)$$

where $T_{i\to j}$ denotes the transmission probability of electrons from lead i to lead j. The bend resistance at $B = 0$ is observed to be positive, because the direct path for carriers to travel from lead 3 to lead 1 is blocked by the antidot, i.e. $T_{3\to1} \approx 0$. From eqn (1), one straightforwardly obtains $R_{43,12} > 0$. Also remarkable in the $R_{43,12}(B)$ curve is the distinct peak structure, observed especially on the $B > 0$ side. A detailed modelling of the response, using classical ballistic transport [4] is outside the scope of this paper. A qualitative understanding of the features can, however, be obtained using typical cyclotron orbits in Fig. 1B and C. Around $B = 0$, with

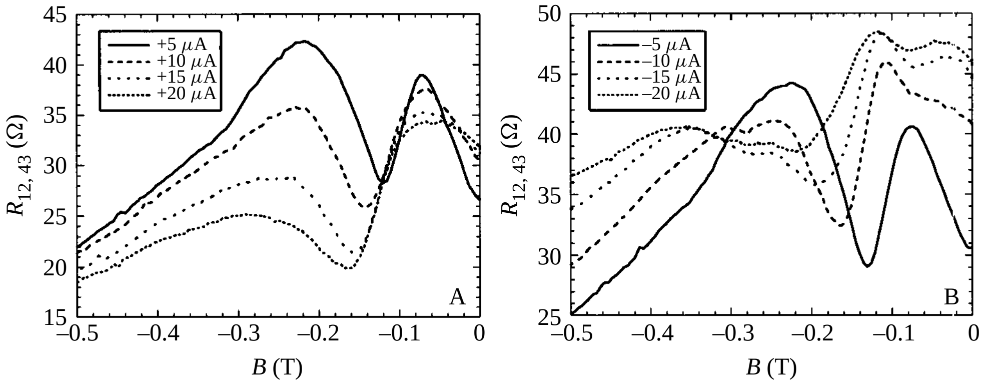

Fig. 2. Four-terminal bend resistance $R_{12,43}$ for high positive (a) and negative (b) dc currents.

increasing magnetic field, the cyclotron radius decreases. As a result, $T_{4\to 1}$ increases (see Fig. 1B), whereas all other transmission probabilities are only little affected. This remains true until $B \approx 0.08$ T, where trajectories like the one shown in Fig. 1C become relevant. The electrons ejected out of lead 3 have the possibility to 'jump' to the antidot and then into lead 1, which certainly increases $T_{3\to 1}$ and thus decreases $T_{3\to 2}$, so that $R_{43,12}$ decreases. Other features like the increase in $R_{43,12}$ around $B = 0.15$ T and the peaks at negative fields can be well understood in a similar fashion. At high B fields, transport becomes more and more dominated by skipping orbits of carriers along the edges. As a result, the symmetry-breaking influence of the scatterer becomes less important and $R_{43,12}(B) \approx R_{43,12}(-B)$ is expected. Furthermore, the skipping transport along the edges results in $T_{3\to 1}, T_{4\to 2} \to 0$. For a positive B field one finds $T_{3\to 2} \to 0$ while for a negative B field $T_{4\to 1} \to 0$. Thus, $R_{43,12}(B) \to 0$. The experimental result is in agreement with this picture.

We also measure the bend resistances in the nonlinear regime by applying constant dc currents I_{dc} to the current leads together with the ac current $I_{ac} = 1\ \mu$A. As a result, drastic changes in the differential bend resistances are observed. In Fig. 2, the differential bend resistance $R_{12,43}$ with interchanged current and voltage leads is shown for dc currents ranging from -20μA to $+20\mu$A. In this configuration, we find the strongly oscillating part of $R_{12,43}(B)$ at negative B, in good agreement with the reciprocity relation $R_{ij,kl}(B) = R_{kl,ij}(-B)$ which was derived for linear transport [9]. The agreement is best for $I_{dc} = 0$ (not shown here), but up to $I_{dc} = 5\mu$A the agreement is quite good, showing that in this current regime and for the present experimental conditions, transport can be described linearly. With further increase in current this is no longer true. Strong influence of the applied dc current biases on both the position and the magnitude of the bend resistance peaks is observed. We note that at some B fields the magnitude of $R_{12,43}$ even changes by a factor of 2 when the dc current is increased from -20μA to $+20\mu$A. In the cases of negative dc currents (net flow of electrons from lead 1 to lead 2) in Fig. 2B, we observe a more pronounced shift of the peak structure towards higher $|B|$ than we do when $I_{dc} > 0$. Surprisingly, additional peaks (e.g. at $B = 0.03$ T) appear. Whereas, at present, we do not have an explanation for the appearance of the additional structure (new peaks or peak splittings are also observed in some other measurement configurations), the shift is in good agreement with the picture of electrons being injected into the junction at a velocity which is given by both the Fermi velocity v_F and the 'excess velocity' Δv. Here, we refer to the excess velocity or the drift velocity as the mean velocity of electrons in the lead, which the electrons gain from the self-consistent field in the device induced by the applied current. At $B = 0$, only the transmissions of carriers from a contact (carrier reservoir) with higher chemical potential to another contact with lower chemical potential contribute to the lead currents of a mesoscopic conductor. A recent study on the nonlinear ballistic transport, however, shows that if there exists a finite magnetic field, transmissions of carriers from contacts with lower chemical potentials to contacts with higher chemical potentials also contribute to the lead currents and therefore should be considered when calculating the resistances of a mesoscopic conductor [10]. As the magnetic fields in this work are weak, we can expect that the transmission of carriers from the carrier injector (e.g. lead 1 for $I_{12} < 0$) would largely determine the bend resistance. In this picture, the increase in the peak position reflects the fact that for a higher injection velocity v, a higher magnetic field is necessary to achieve the same trajectory, i.e. the same cyclotron diameter $R_c \propto v/B$. It should be emphasized that this effect is much stronger for negative than for positive currents. This can be attributed to the different widths of leads 1 and 2. For the same current, Δv in lead 1 will be much higher than in lead 2. Therefore, in a configuration where lead 1 acts as an injector, the peak position will be more strongly current dependent than for the reverse configuration with lead 2 as an injector. The experimental results thus give strong support to the picture that the excess velocity in the lead, which *drains* the electron, has only little effect on the nonlinear transport in the junction. However, since this picture is strictly valid only at $B = 0$ [10], it might be the reason for the fact that some peaks almost do not shift with B or even shift to lower field.

In summary, we have investigated the influence of broken symmetry on the linear and nonlinear bend resistance of a ballistic cross junction. In the linear regime, the highly asymmetric curve, the unusual bend resistance, and the distinctive peaks are explained qualitatively by investigating the influence of the device geometry and the electron orbits on the transmission coefficients. In the nonlinear regime, the drastic change in both the position and the magnitude of the bend resistance peaks strongly suggests that (a) the excess velocity in the leads (given by the applied current) affects the transmission through the junction, and (b) the drift in the current *injecting* lead gives the strongest contribution to the nonlinear behavior at zero or low B field. We also observed new peaks in some measurement configurations which still requires further investigation.

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