2.15 Ballistic transport at nonuniform magnetic fields in cross junctions of a curved two-dimensional electron gas

The self-rolling of thin pseudomorphically strained semiconductor bilayer systems allows to realize the motion of electrons on curved surfaces. There are two complementary points of interest: (i) the effect of the local curvature of the surface on the electron motion, for which the most prominent modification is the motion subjected to an effectively nonuniform normal-to-surface component of the magnetic field, and (ii) the impact of the global topology on the quantum-mechanical wave functions — the electron changes its direction while being confined in the quantum well.

To study the relevant ballistic motion in curved two-dimensional electron gases (2DEG), the low-temperature mean free path of the electrons l_{mfp} has to be comparable with both, the typical structure size, and the curvature radius r. To realize large values of l_{mfp}, we used a heterojunction, where the high-mobility 2DEG is located in a 13-nm-wide single quantum well (SQW) with barriers consisting of AlAs/GaAs short-period superlattices (SPSL). X-like conduction-band states are formed in the AlAs compound of the SPSL, thereby effectively smoothing the fluctuations of the scattering potential, which result from the surface of the tube. As a result, we obtained curved high-mobility 2DEG structures, which are just as wide as their curvature radius. In addition, l_{mfp} is as large as r. In this case, for an electron motion along the curvature, free electron trajectories bend in space by about 60° while being confined in the SQW.

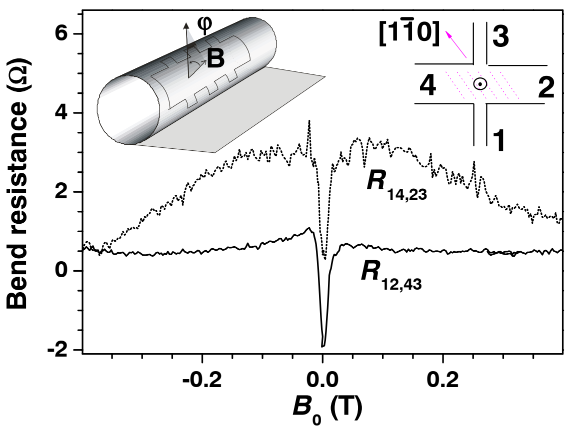

Fig. 39. Bend resistances in a cross junction with a magnetic field **B** normal to the surface at the center of the junction, i.e., $\varphi = 0°$, at $T = 0.3$ K. The insets demonstrate schematically the geometry of our experiments. The right inset shows the direction of the interface corrugations along $[1\bar{1}0]$.

The high mobility in our structures allows for the observation of a new class of trajectories in the ballistic motion of electrons in curved 2DEGs. To demonstrate this ballistic motion, we investigated the magnetoresistance in cross junctions as shown by the insets in Fig. 39. The magnetic field component perpendicular to the surface changes along the circumference of the curved 2DEG (along the direction of the narrow leads). We measure the resistance $R_{ij,kl}$, which indicates the current along the leads i and j, while the voltage is measured between k and l.

First, we consider the configuration, where the magnetic field **B** is perpendicular to the surface at the center of the Hall bar arc. With a curvature radius of about 20 μm, the Hall bar, which is 20 μm wide, spans over $\Delta\varphi = 57°$. Correspondingly, the perpendicular magnetic field components $B_\perp = B_0 \cos(\varphi)$ at the narrow lead positions is only by 12% lower than B_0. Figure 39 illustrates the results of the ballistic four-terminal magnetotransport measurement, which are qualitatively similar to the ones for the flat, unrolled cross junctions. At zero magnetic field, the bend resistance $R_B = R_{12,43}$ is negative, indicating the preferential transmission T_F of electrons into the opposite leads of the junction. At high magnetic fields, electrons will bend to the left (T_L) or to the right (T_R) arms of the junction dependening on the magnetic field direction. As a result, the bend resistance becomes zero according to the conventional analysis of the Landauer-Büttiker equation:

$$R_B^{LB} = \frac{h}{2e^2} \frac{T_L T_R - T_F^2}{D} \,, \tag{3}$$

where h denotes the Planck constant and e the elementary charge. The denominator D depends on T_L, T_R, and T_F, but does not influence the sign of R_B^{LB}. The difference between $R_{14,23}$ and $R_{12,43}$ is related to the well known structural anisotropy along the $[1\bar{1}0]$ and $[110]$ directions.

We observed a dramatically different behavior when the magnetic field was tilted away from the surface normal at the center of the Hall bar by an angle φ. Figure 40 shows $R_{12,43}$ and $R_{14,23}$ as a function of the magnetic field for $\varphi = 29°$. In this case, the magnetic-field gradient along the circumference is large, which causes a more than two times larger perpendicular magnetic field component on the high-magnetic-field side of the Hall bar at lead 3 as compared to the low-magnetic-field side at lead 1. As a result, the magnetoresistance becomes extremely asymmetric with respect to the orientation of the magnetic field, which is not observed in unrolled flat samples. $R_{12,43}$ is zero for high positive magnetic fields, while the resistance turns to negative values at $B_0 = 0$. In contrast, by reversing the direction of the magnetic field, a positive resistance $R_{12,43}$ appears, which increases monotonically with $|B_0|$. In accordance, $R_{14,23}$ becomes nearly the mirror image of $R_{12,43}$ with respect to the field direction.

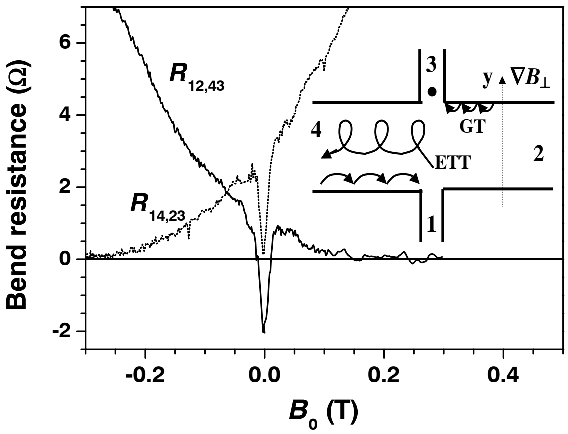

Fig. 40. Bend resistances in a cross junction with a magnetic field **B** perpendicular to the surface at lead 3, i.e., $\varphi = 29°$, at T= 0.3 K. The inset shows ETT and GT.

The asymmetric bend resistance in curved 2DEGs results from ballistic trajectories, for which the electron motion is modified by an instantaneously varying cyclotron radius L_C. In particular, extended trochoid-like trajectories (ETT) form, which drift into the opposite direction as compared to the guided trajectories (GT) on the low-magnetic-field side of the Hall bar. Consequently, at high fields, this results in non-zero values of $T_R^{GT} T_L^{ETT}$ or $T_L^{GT} T_R^{ETT}$ for the corresponding magnetic field directions, for which T_R^{GT} or T_L^{GT} are non-zero. Therefore, according to Eq. (3), R_B is non-zero — in contrast to the magnetic field directions for which the corresponding T_R^{GT} or T_L^{GT} are zero.

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