Spin-dependent Transverse Magnetic Focusing in InSb- and InAs-based Heterostructures

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Abstract. Spin-dependent ballistic transport was observed in InSb/AlInSb and InAs/AlGaSb heterostructures. Split transverse magnetic focusing maxima in InSb are consistent with spin-split trajectories of carriers as well as spin-flipping events occurring when carriers reflect off a lithographic barrier. Similar results are observed in InAs. The temperature dependence reveals that the ballistic focusing maxima survive up to ~150 K for InSb and ~60 K for InAs, whereas the splitting in the maxima disappears at lower temperatures, indicating the latter's separate origin.

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INTRODUCTION

We present mesoscopic transverse magnetic focusing (TMF) experiments in high mobility InSb/AlInSb and InAs/AlGaSb heterostructures, where the large spin-orbit interaction (SOI) leads to the observation of features consistent with spin-split ballistic transport. The spin of electrons and holes in semiconductors has attracted much interest in the context of spin-dependent electronics. Further, TMF has been used to study ballistic transport, including spin-dependent transport, in semiconductors [1-3]. The narrow-gap semiconductors InSb and InAs and their heterostructures exhibit strong SOI, leading to a spin-splitting in semiclassical trajectories of carriers and to spin-dependent reflection off lithographic barriers [4]. Their large mean free paths, moreover, allow the fabrication of mesoscopic devices in which spin-dependent transport can be exploited for spin manipulation. The *n*-type InSb/AlInSb heterostructure, MBE grown on GaAs substrate [5], contains a 20-nm-wide InSb well, flanked by $Al_{0.09}In_{0.91}Sb$ barrier layers and Si δ-doped layers. At 0.4 K, the material as grown yields a mobility μ = 1.6×10^5 cm^2/Vs, and two-dimensional density N_S = 2.3×10^{11} cm^{-2}, resulting in a mobility mean-free-path $l_P \approx$ 1.3 µm. Also grown by MBE on GaAs, the undoped InAs heterostructure contains a 15-nm-wide InAs quantum well, flanked by $Al_{0.2}Ga_{0.8}Sb$ layers, with, in the experiments below, μ = 2.8×10^5 cm^2/Vs, N_S = 6.8×10^{11} cm^{-2}, and $l_P \approx$ 3.7 µm at temperature T = 0.4 K. Mesoscopic structures are patterned on the materials using standard optical and electron beam lithography and damage-less wet chemical etching.

EXPERIMENT

Figure 1 shows TMF spectra (collector voltage over injected current) of an InSb sample with injector and collector apertures spaced by 0.6 µm (geometry:

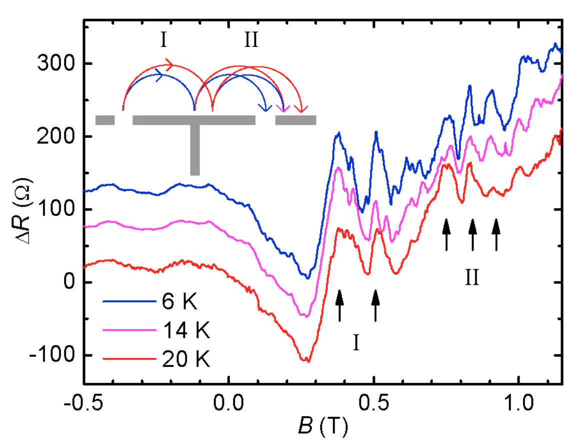

FIGURE 1. TMF spectra of the 0.6 µm InSb sample show doublet and triplet structures for the first and second focusing maxima, respectively. Traces are offset by 50 Ω. Inset: Schematic plot of the focusing structure and spin-split ballistic trajectories.

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inset in Fig. 1). A semiclassical calculation predicts focusing maxima at magnetic field multiples of B = 0.42 T, when the cyclotron orbits fit an integer multiple of times within the injector-collector separation [1-3]. Instead, we observe a doublet structure (B_1 = 0.37 T and B_2 = 0.50 T) at the position of the first maximum (0.42 T) and a triplet structure at the second maximum (0.84 T). We note that the splitting cannot originate from universal conductance fluctuations since these are not expected at T = 20 K. The doublet structure is hence likely caused by an orbital effect, namely by the presence of spin-splitting in the cyclotron orbits, themselves a result of spin-split Fermi contours due to the large SOI in InSb. A same effect has been reported on GaAs/AlGaAs heterostructures [3]. For the second maximum, electrons reflect off the lithographic barrier, which may cause electrons to flip spin states [4], creating four separate trajectories (Fig. 1 inset). Notice that the two spin-flipped trajectories land at the same location at the collector. Therefore only three peaks are expected at $2B_1$ = 0.74 T, $B_1 + B_2$ = 0.84 T, and $2B_2$ = 1.0 T, within 10% of the observed values of 0.76 T, 0.83 T, and 0.90 T, respectively. The consistency of the experimental results with spin-split ballistic trajectories and spin-dependent reflection is bolstered by the further experiments below.

Figure 2 depicts the temperature dependence of another TMF structure on InSb with 1.2 μm separation, twice that of the sample discussed above, resulting in a TMF trajectory length about twice as long as the mean-free-path. The TMF signal is hence not as pronounced as in Fig. 1, and a linear background is subtracted to extract the focusing peaks. The low-T spectra again display split TMF maxima: a peak with a strong shoulder near 0.22 T, and a triplet

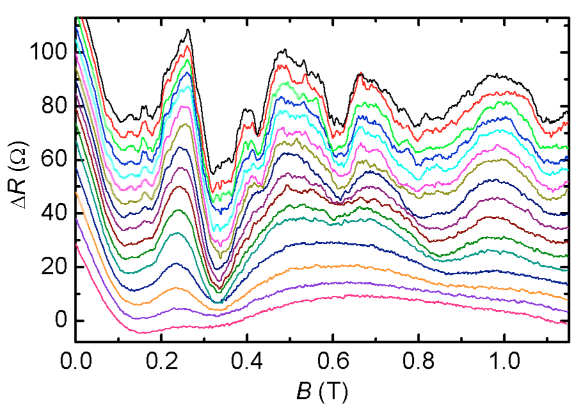

FIGURE 2. TMF spectra of the 1.2 μm InSb sample with linear background subtracted. From top to bottom, T = 4.5, 6, 8, 10, 13, 16, 20, 25, 30, 40, 50, 60, 80, 100, 125, and 150 K. Traces are offset by 5 Ω. The split maxima merge at ~80 K, at lower T than the TMF maxima smoothing out at ~150 K.

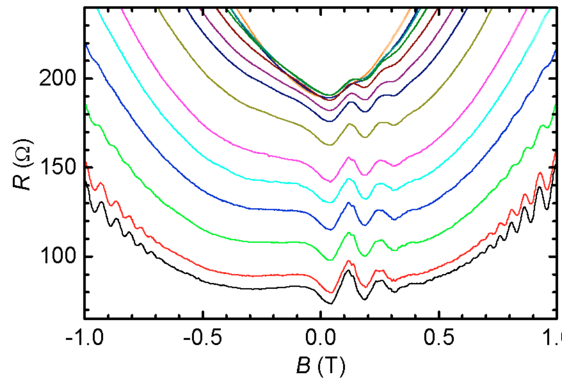

FIGURE 3. TMF spectra of the 2.0 μm InAs sample. From top to bottom, T = 60, 50, 45, 40, 35, 30, 25, 20, 15, 12.5, 10, 7.5, 5, and 4 K. The split maxima merge at ~20 K, at lower T than the TMF maxima smoothing out at ~60 K.

structure between 0.4 and 0.7 T. The fact that the splitting merges at ~80 K whereas the ballistic peaks remain discernible up to ~150 K (similar to the ballistic results in Ref. 6) confirms that the splitting is a feature additional to and of different origin than the main TMF maxima, reinforcing the spin-splitting interpretation.

Figure 3 shows TMF spectra on an InAs/AlGaSb sample with 2.0 μm separation. Low-T spectra show a doublet at the first TMF maximum and a flattening of the second maximum, indicating unresolved multiple split peaks. The splitting in InAs is less pronounced than in InSb, consistent with the latter's stronger SOI. Especially, the Dresselhaus SOI term dominates in InSb, while in our InAs heterostructures the Rashba term is expected to of double the magnitude of the Dresselhaus term. The roles of either contribution in spin-split ballistic transport merits further full study, beyond the scope of the present work. Figure 3 also exhibits a different temperature dependence of the splitting compared to the main ballistic peaks, a phenomenon hence common to our InSb as well as InAs observations.

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REFERENCES

1. H. van Houten et al. *Phys. Rev. B* **39**, 8556 (1989).
2. J. J. Heremans et al., *Appl. Phys. Lett.* **61**, 1652 (1992).
3. L. P. Rokhinson et al., *Phys. Rev. Lett.* **93**, 146601 (2004).
4. Hong Chen et al., *Appl. Phys. Lett.* **86**, 032113 (2005).
5. S. J. Chung et al., *Physica E* **7**, 809 (2000).
6. Hong Chen et al., *Appl. Phys. Lett.* **84**, 5380 (2004).