Spin Quantum Beating in the Conductance of Ballistic Rings

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We propose and demonstrate experimentally a novel configuration for observing spin interference effects in the conductance of quantum rings. Using this configuration, in which the conducting ring and the tangential current lead form a single collimating contact, we have observed the spin quantum beating in the Aharonov-Bohm (AB) conductance oscillations. We demonstrate that the beating is the result of the superposition of two independent interference signals associated with the chiral states arising from intrinsic spin-orbit interactions. Our work provides conclusive evidence of the spin Berry phase in the ring conductance.

When a quantum system evolves adiabatically under a cyclic variation of its parameters, the quantum state acquires dynamical and geometric phases. In contrast to the dynamical phase that records the cycle duration, the geometric phase depends only on the path traced out in the parameter space. It has been proposed that AB ring geometry provide a physical setting in which the spin Berry phase can be observed as a result of spin-orbit (SO) interactions. In the earlier attempts to probe Berry's phase, two-contact rings have been used. However, there are two drawbacks inherited in this configuration, including multi-mode transport and spin rotation in the contact regions. The proposed one collimating contact (OCC) ring overcomes these challenges so that the observed interference effect comes solely from two spin states originated from a single transverse mode.

In this work, we use newly developed nanofabrication technique to process four pairs of OCC rings on AlGaSb/InAs/AlGaSb single quantum wells with radii, r = 150, 250, 350, 500nm. While all devices show AB oscillations at low magnetic field (B_{ext}), two pairs of rings with r = 250 and 350nm exhibit clear double frequency ($h/2e$) component in the raw conductance data. More specifically, the AB interference for r = 250nm at 1.9K displays two distinct features: (1) the unambiguous $h/2e$ oscillations around $B_{ext} = 0$, and (2) the quantum beating pattern with visible transition to the fundamental frequency, h/e, where the noticeable nodes are aperiodic on B_{ext}. With the support of a conductance simulation, we demonstrate that the observed quantum beating features in AB oscillations result from the superposition of conductance signals originating from two spin states. The interplay of the Berry's and dynamical phases leads to characteristic transitions in AB conductance between double and single frequency oscillations. The prominent $h/2e$ oscillations around $B_{ext} = 0$ not only constitute a direct observation of the zero-magnetic field spin splitting, but also prove the effectiveness of momentum filtering at the collimating contact. By comparing data with simulations, we show that the spin Berry's phase has a profound impact on the AB oscillations and on their Fourier power spectrum when B_{ext} is less than the effective SO magnetic field. The observations of quantum beating and double-frequency oscillations also indicate a long spin coherent length, more than 3 μm at a relatively high temperature of 1.9K.

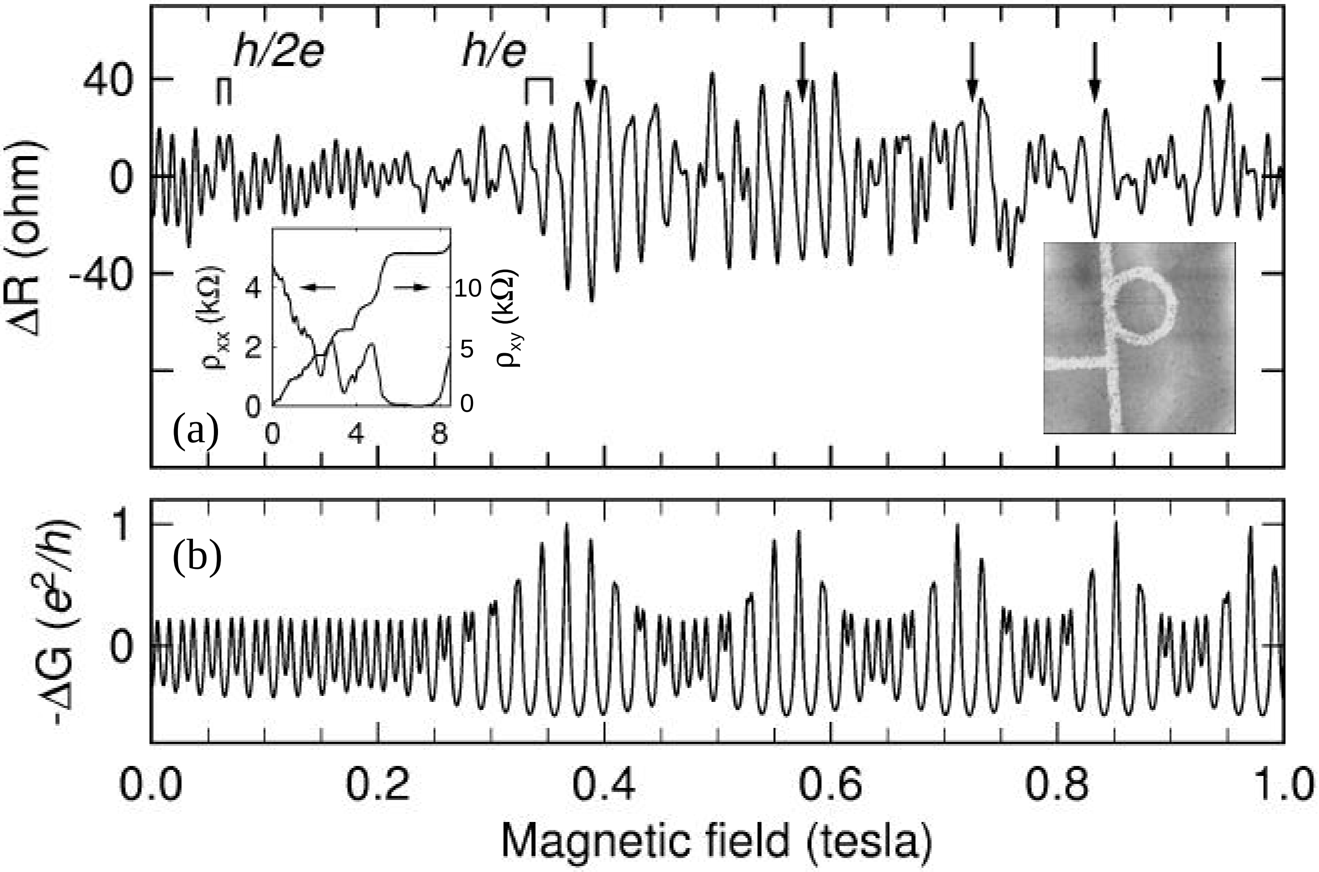

Fig. 1 (a) The experimental quantum beating pattern for an OCC InAs ring with a radius of 250 nm at 1.9K. The arrows indicate the in-phase nodes for two spin chiral states. The right inset is a 2µm× 2µm atomic force micrograph. The left inset show the magnetoresistance of a ring. (b) The simulated conductance.

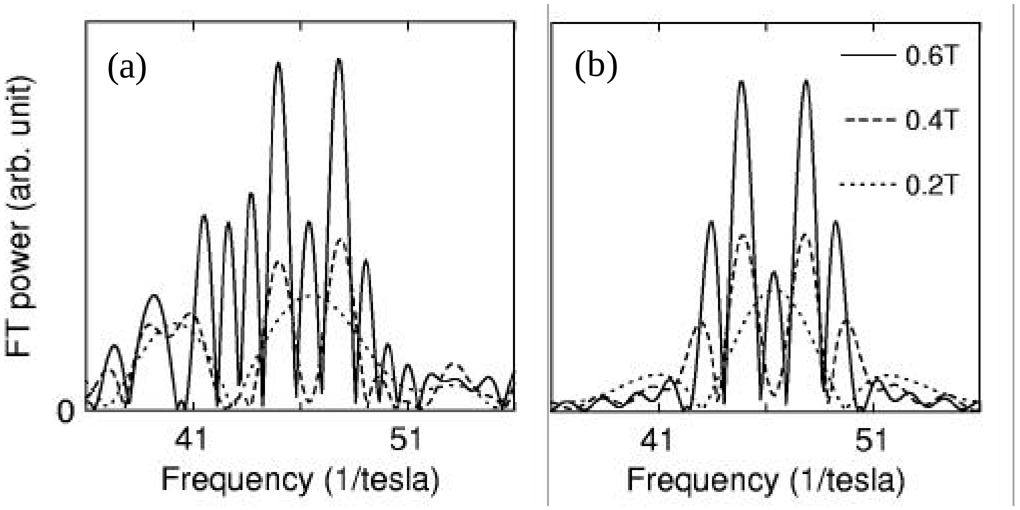

Fig. 2 The evolution of the Fourier Transform spectra, where the transforms were performed with different ranges of magnetic filed for (a) the experimental data and (b) the simulation.