11th International Workshop on Computational Electronics
TU Wien, 25-27 May 2006

The Rashba Effect and Non-Abelian Phase in Quantum Wire Devices

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The study of the phase acquired by propagation in a mesoscopic device can be important for determining the presence/absence of phase interference in re-entrant geometries. While the study of the Aharonov-Bohm phase, due to a magnetic flux, has been studied for some time, it only recently has been realized that an additional geometric (topological) phase can be introduced through the presence of the Rashba spin-orbit interaction in a heterostructure [1,2]. In the presence of both fields, a more complicated behavior can be present [3]. It is still somewhat controversial as to whether the spin dynamics follows the orbital motion adiabatically or even whether the geometrical phase can be detected in interference experiments. Nevertheless, the phase shifts introduced by the spin-orbit interactions produce non-Abelian phases in the network, and the general use of non-Abelian statistics has become of interest for quantum computation [4,5].

In this paper, we report the results of simulations of quantum wire networks present at the interface of a GaAs/AlGaAs heterostructure. The spin-orbit interaction appears through the interfacial electric field (normal to the interface) and is assumed to be modulated through the use of surface gates. This leads to an additional term in the Hamiltonian. We solve the transport problem through the use of a recursive scattering matrix formulation for the total wave function [6]. The quantum wire network is assumed to be defined by a set of surface gates, as shown in Fig. 1. Illustration of the spin precession in a straight quantum wire is shown in Fig. 2. The *z*-field couples via the y-component of momentum to the s_x spin matrix, giving spin precession around the s_x axis. This rotation of the spin vector around the Bloch sphere is illustrated in Fig. 3 for this configuration. Here, an applied electric field has been used to introduce the spin-orbit phase shifts necessary for the spin precession.

We consider a ring of radius 100 nm, with wires that have width of 100 nm, as shown in Fig. 1. The magneto-conductance of this ring is shown in Fig. 4, with no Rashba term present. Here, we see normal Aharonov-Bohm interference for transport around the ring. The Rashba term is characterized by the factor $\alpha \cong ehE_z/4\pi m^{*2}$ (in appropriate units). In Fig. 5, we plot the variation of the conductance through the ring as the electric field is varied, with no magnetic field. Now, we see resonances in the transmission due to the geometrical phase introduced by the Rashba effect. In Fig. 6, we plot how the magneto-conductance changes for a Rashba field giving α = 6.25 μeV-μm. The conductance is now more complicated due to the contributions from both phase factors. The two sharp drops in conductance near $|B|$ = 0.3 T are due to localization resonances where the ring connects to the wires.

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ISBN 3-901578-16-1

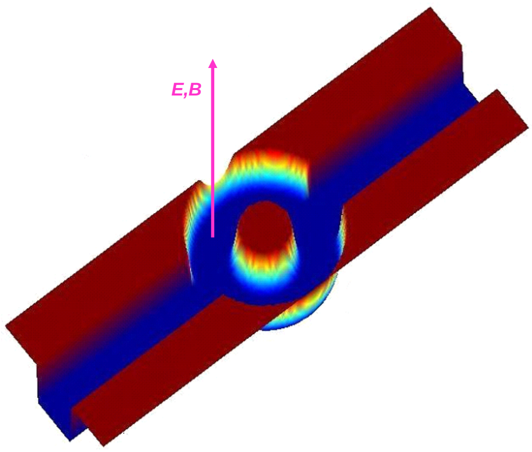

Fig. 1. Structure of the quantum wire network, which is assumed to exist at the interface of a GaAs/AlGaAs heterostructures. The ring radius and wire width are both 100 nm.

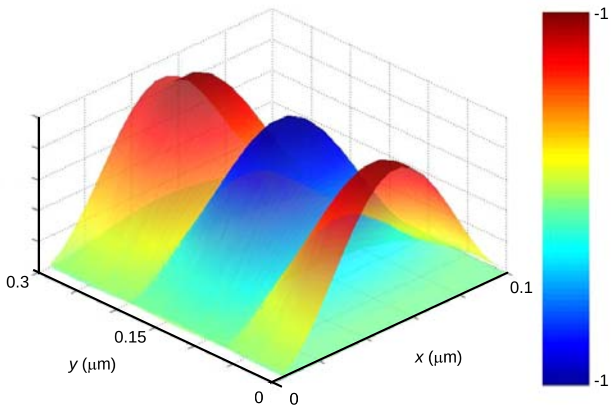

Fig. 2. Propagation in a single quantum wire. The color coding gives the spin orientation, which is in the *z*-direction.

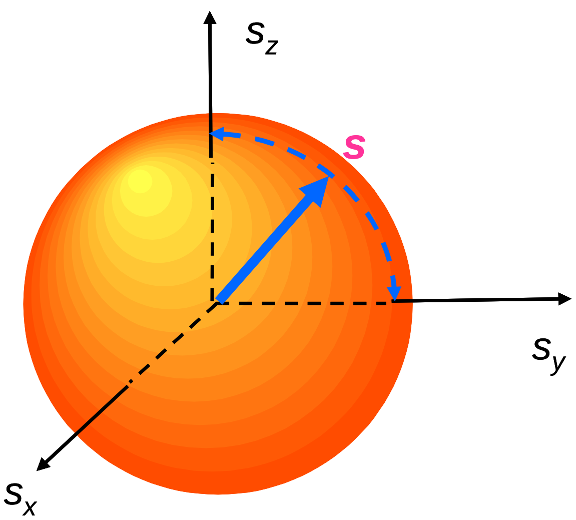

Fig. 3. Rotation of the spin vector around the Bloch sphere for the case shown in Fig. 2.

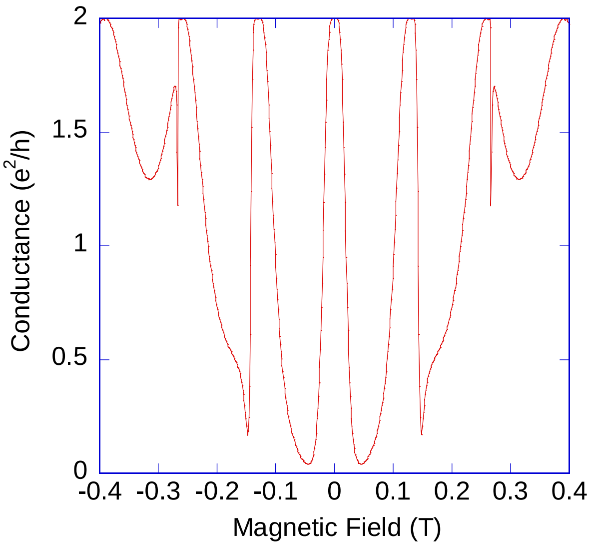

Fig. 4. Ring conductance as a function of the magnetic field, with no Rashba electric field applied.

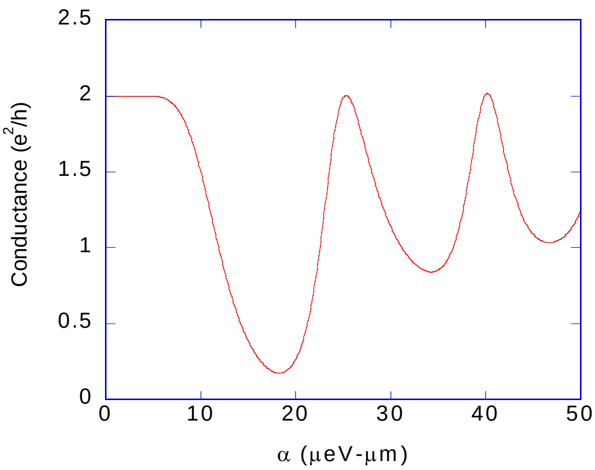

Fig. 5. Ring conductance as a function of the Rashba coupling term, with no magnetic field.

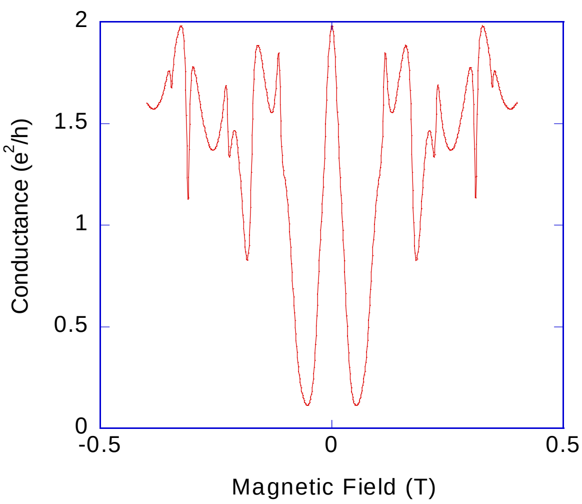

Fig. 6. Ring conductance as a function of magnetic field for the Rashba coupling term equal to 6.25 μeV-μm.