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Investigations towards Semiconductor/Ferromagnet Spin Transistors: Rashba Effect, Local Hall Effect and Spin Injection

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1. Introduction

Recently, the combination of semiconductors with ferromagnets has attracted considerable interest. One of the reasons is that the gate control of the carrier concentration in semiconductors can serve as a basis for novel device concepts in the emerging field of spintronics. A very prominent example is the spin transistor proposed by Datta and Das [1]. This type of transistor is based on the Rashba effect which causes the spins to precess as they move along the semiconductor structure. For the semiconductor a two-dimensional electron gas (2DEG) located in a semiconductor heterostructure is required.

However, ferromagnet/semiconductor hybrid structures are still in an immature stage. One of the reasons is that spin injection into a semiconductor remains to be problematic. One of the major problems is the insufficient matching of the conductivities between the ferromagnet and the semiconductor. Here, we will give an overview of our investigations related to the realization of a semiconductor/ferromagnet spin transistor.

2. Rashba Effect

The concept of the spin transistor proposed by Datta and Das [1] relies on the Rashba effect. Here, an energy splitting of the electron subbands is achieved, owing to spin-orbit coupling. The energy splitting is caused by the symmetry breaking due to a macroscopic electric field oriented perpendicular to the plane of the 2DEG. The degree of spin precession in the spin-transistor is quantified by the Rashba spin-orbit coupling parameter α.

In order to achieve a pronounced spin splitting, low band gap semiconductor materials are advantageous. In this respect two-dimensional electron gases based on strained InGaAs/InP heterostructures are very well suited, since the high indium content of 77% of the InGaAs channel layer guarantees a sufficiently low band gap. In order to achieve high electron mobilities, the upper barrier of the quantum well consists of a InGaAs layer lattice-matched to InP. For the lower barrier InP is used. The structures are grown by metal-organic vapor-phase epitaxy. In order to control the spin-orbit coupling, the electron concentration of the 2DEG is controlled by a gate electrode which is isolated from the semiconductor by a SiO_2 layer [2,3].

In Fig. 1 Shubnikov-de Haas measurements of a 2DEG in a InGaAs/InP heterostructure are shown for various gate voltages. The beating pattern observed in the measurements result from the subband splitting, owing to the Rashba effect. The spin-orbit coupling parameter α can be determined from the position of the nodes in the beating pattern. As shown in Fig. 1 (inset), the spin-orbit coupling parameter is increased from $4.2\cdot 10^{-12}$ eVm to $5\cdot 10^{-12}$ eVm if the gate voltage is varied from +2 V to –4 V. The underlying mechanism is the increase of the effective electric field within the quantum well if an increasing negative gate voltage is applied. The measurements shown here thus demonstrate that the spin-orbit coupling can be controlled by a gate voltage as required for the realization of a spin transistor.

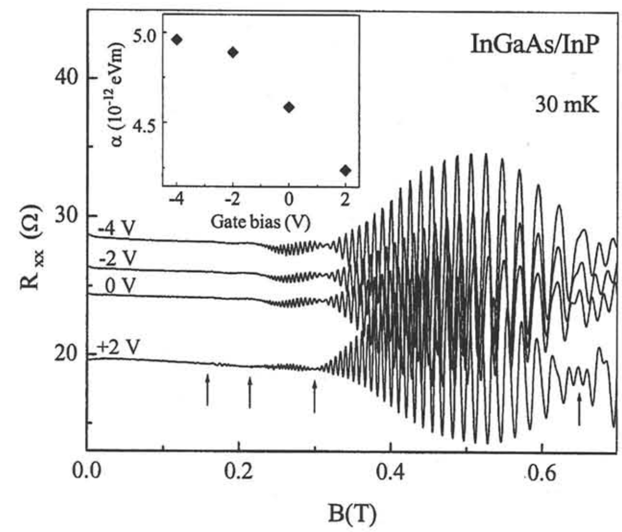

Fig. 1 Shubnikov-de Haas measurements of a 2DEG in a strained InGaAs/InP heterojunction for different gate voltages. The inset shows the spin-orbit coupling parameter α vs. gate voltage.

2. Ferromagnetic Electrodes

For a spin transistor ferromagnetic electrodes are used as spin-polarizer and spin-analyzer. Parallel as well as anti-parallel magnetization of these two ferromagnetic electrodes can be achieved if the geometry of the two electrodes, e.g. their width, is chosen differently. The magnetic properties of the electrodes can be investigated by performing local Hall effect measurements [4]. Here, the ferromagnetic electrode is placed on a micro Hall cross defined in a semiconductor heterostructure. In Fig. 2 the coercive field H_c of permalloy (NiFe) micro-magnets are shown exemplarily for various widths of the magnets [5]. It can be seen clearly that H_c increases if the width of the permalloy micro magnets is reduced. As shown in Fig. 2, the experimental results agree well with simulations based on Landau- Lifshitz-Gilbert equation [6].

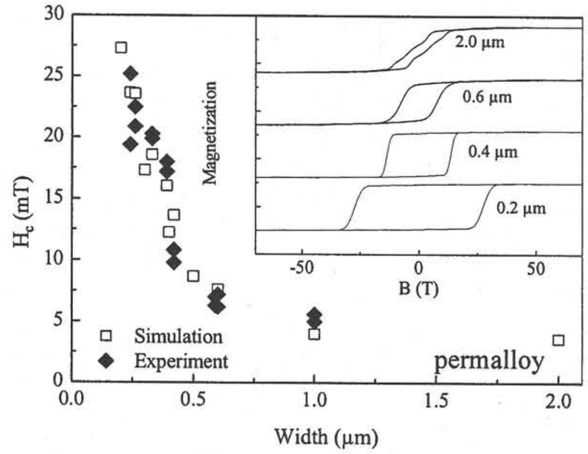

Fig. 2 Experimental results and simulations of the coercive field for different widths of the permalloy electrodes. The inset shows the calculated magnetization as a function of an external magnetic field.

3. Interference Effects

The conductivity mismatch between metallic ferromagnet electrodes and semiconductor heterostructures is considered to be a serious obstacle for spin injection into the semiconductor [7]. However, as pointed out for diffusive system by Rashba [8], this problem can be overcome if an interface barrier is introduced. A similar conclusion is drawn if a ballistic system is considered [9]. For the latter case, a plane-wave approach and a two-band model of the ferromagnet is used. In addition, interesting interference effects are expected in the ballistic case if the width of the semiconductor layer sandwiched between two ferromagnet electrodes is comparable to the Fermi wave length [10]. As can be seen in Fig. 3, the transmission probability D(E) as function of the semiconductor Fermi energy shows pronounced oscillations. Since the transmission probability depends also on the Fermi velocity of the majority and minority electrons in the ferromagnet, the relative difference of the conductance $\Delta G/G$ between parallel and anti-parallel magnetization also oscillates. Thus by adjusting the electron concentration in the semiconductor the spin signal can be improved by means of interference effects.

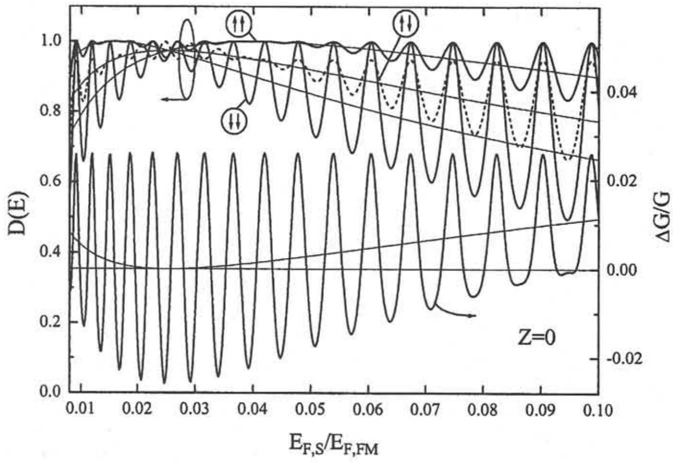

Fig. 3 Transmission probabilities D(E) of a one-dimensional ferromagnet/semiconductor/ferromagnet (FM/S/FM) structure for majority-majority (↑↑), minority-minority (↓↓) and majority-minority (↑↓) transfer as a function of the semiconductor Fermi energy. The resultingconductance difference $\Delta G/G$ is also shown.

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