1 Title of the Project

Optical investigation of quantum well and Landau level dynamics in heterojunction quantum well structures and the realization of a ballistic spin filter.

2 Applicant

Msc Abraham Slachter

References:

Master thesis
Time resolved Kerr rotation and reflectance on 2D and 1D confined electronic spins in an AlGaAs/GaAs heterojunction. Rijks*universiteit* Groningen, The Netherlands 2006

3 FOM-researchgroup

GM-10

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5 Abstract

In the field of spintronics[1][2][3] many interesting devices have been proposed. This project encompasses the experimental realization of one of these devices: the ballistic spin filter[4]. By sending a current through this 3 terminal device electronic spins will get separated in two of the leads. This can be measured optically by Kerr microscopy. By spectrally filtering the beams in the optical experiments it should be possible to see quantum well and Landau level dynamics which is to be measured in this project as well. The realization of such a device will be a big step towards functional spintronic devices.

6 Duration of the Project

4 years, starting from January 2007.

7 Personnel

7.1 Senior-scientists

Name	Task in project	Time
Prof. Dr. Ir. Paul van Loosdrecht	Supervision and management	5%
Dr. Ir. C. H. van der Wal	Supervision and analysis	10%

7.2 Junior-scientists and Technicians

Name	Task in project	Time
1 OIO position	Experiments and analysis	90%
B. Wolffs	technical support	10%
A. Kamp	technical support	10 %

8 Cost Estimates

8.1 Personnel Positions

One 'onderzoeker in opleiding' position for four years.

8.2 Running Budget

15 k€/year for conferences, summer schools and maintenance optical setup (periodic replacement mirrors etc.).

8.3 Equipment

8.4 Other Support

The project is part of a larger research programme of the MSC^{plus}. Involved personnel described above is employed via the MSC^{plus} or associated research programmes.

8.5 Budget Summary (in k€)

The expenses are summarized in the following table

9 Research programme

9.1 Introduction

Present day electronic devices are mainly based on classical electrodynamics. By continuous miniaturization of these electronic devices, they will eventually end up in the realm of quantum mechanics. This compromises their device operation giving rise to all sorts of unwanted effects such as increased power consumption or unreliable computations.

Equipment	Price (k€)
4 Liquid Crystal Tunable Band Pass Filters ΔE=0.2, 1, 10, 10 meV bandwidth with controller (www.sci-sol.com)	∼ 20
2 Avalanche photodiodes or photomultiplier tubes with temperature control	∼ 10
Newport 4 ns Delay Line with 0.67 fs stepsize	∼ 10
Set of customized fixed band pass filter filters ΔE=5, 10 meV	∼ 2
New Focus Chopper with multiple TTL outputs (up till 6.4 kHz sum and difference frequency etc)	∼ 2
Stanford Research Systems SR830 DSP lock-in	4.5
Hinds Near IR Photo Elastic Modulator with controller	25
2 Newport Glan-Thompson calcite polarizers	2.6
1 Newport /2 Quarz waveplate 800 nm (05RP04-01)	0.67
1 Newport /4 Quarz waveplate 800 nm (05RP04-01)	0.67
Total	∼ 77.44

	2007	2008	2009	2010	TOTAL
Personnel (positions)					
PhD students	0.25	0.25	0.25	0.25	1
postdocs	-	-	-	-	-
technicians	-	-	-	-	-
guests	-	-	-	-	-
personnel (costs)	43	43	43	43	172
running budget	15	15	15	15	60
equipment FOM-part	77.44	-	-	-	57.44
TOTAL(requested from FOM)	138	58	58	58	309.44

The electronic spin degree of freedom in solid state systems can be used to construct devices which not only overcome this barrier towards miniaturization but even add additional functionality. This area of research is called spintronics[1][2][3].

Since the advent of this field many interesting devices were proposed such as the spin FET[5] or various spin filters[4][6][7]. Most of these devices rely on the manipulation of spins with magnetic fields. External magnetic fields applied to these devices are difficult to confine and have long switching times which compromises their practical feasibility. Control of intrinsic magnetic fields by applied electric fields should avoid these problems[5]

With the semiconductor technology of today, the creation of dense 2D confined electron gasses (2DEG) is possible (see figure 1(a)). An important feature is that the electrons residing in the gas have very low scattering rates. From the theory of relativity we know that if the speed (wavevector) of these electrons is high enough, an applied or intrinsic electric field can be seen as an effective magnetic field. The electrons in the gas precess can around this magnetic field(see figure 1(b)).

2DEGs contain intrinsic electric fields which arise from the polarity and asymmetry of the GaAs crystal and the 1D band structure shown in figure 1(a). These contributions are called the Dresselhaus and Rashba spin orbit interaction respectively. If the intrinsic scattering rate is low enough and the structure is confined to 1 or even 0 dimensions the confinement walls dominate all scattering.

By engineering the geometry and applying electric fields the scattering and spin orbit interaction can be altered in such a way to produce useful devices[1].

We propose the experimental realization of a spin filter using these principles. Several different geometries have been proposed of which two are shown in figure 2.

Now the question arises as to how to detect the spin polarization such a device would produce. Electrical detection through ferromagnetic contacts as proposed by [5] suffer from weak injection and detection known as the conduction mismatch problem between semiconductors and metals [10]. This makes electrical detection hard. Optical carrier injection and detection however is quite easy in theory[11].

9.2 Kerr Spectroscopy

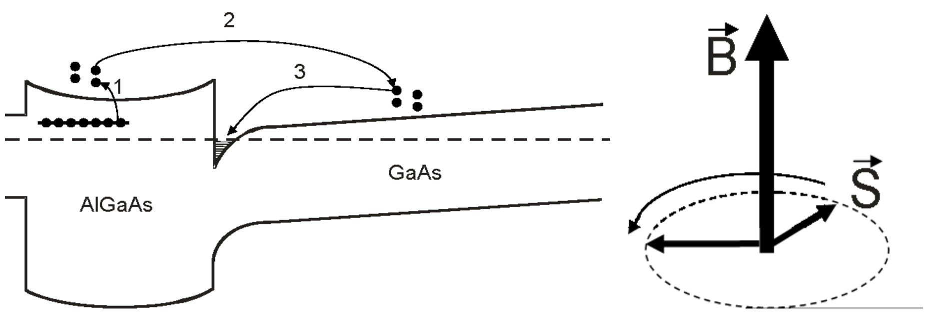
If a linearly polarized probe pulse is directed at one of the arms of the device the polarization of the reflected pulse is rotated depending on the spin polarization. This effect is known as the Magneto Optical Kerr Effect (MOKE) and gives a way to measure the spins created by the spin filter. The spectroscopy based on this principle is called Kerr spectroscopy and has been used in literature before to measure for example the spin Hall effect[12]. We will use this technique to characterize the spin splitting properties of our device.

9.3 Pump-Probe Spectroscopy

By splitting the ∼100 fs wide pulse coming from an ultrafast Ti:Sapphire laser and delaying these pulses with respect to each other very precise, it is possible to pump carriers into a semiconductor with one pulse and with the other pulse analyze the amount of carriers which still remain. This is known as pump probe spectroscopy and has been done numerous times before in literature[3].

By selecting spectrally a very narrow bandwidth (0.1 meV) for the pump and probe pulses it is possible to selectively excite and probe quantum well levels and even Landau levels on the ps timescale. However, the selective observation of Landau levels depends a lot on the strength of the Stark effect present in an heterojunction quantum. It very likely smears optical spectra

[1] Examples of a prediction and actual realization are found in [8] and [9].



(a) (b)

Fig. 1: (a) 1D band structure of an AlGaAs/GaAs heterojunction illustrating the creation of a high moblity 2 dimensional electron gas. The structure consists of a AlGaAs/GaAs interface where the AlGaAs is n-doped several nanometers away from the GaAs. The electrons which are ionized from these dopants(1) fall into the GaAs(2) and are attracted towards the interface by the electric field created by the remaining positive dopants(3). A high density electron gas is created which are free from impurities creating extremely high mobilities and very long scattering lengths. (b) When a magnetic field is applied perpendicular to the electronic spin orientation spins start to precess. This is the basis for many device proposals in spintronics.

which might complicate the observation for the 2DEG sample. Nevertheless, we expect it can be observed in symmetric quantum wells. Such samples are already available which can be measured as a reference to interpret the possibly complicated Landau level dynamics in the heterojunction quantum well.

By altering the polarization of the pump pulse from linear to circular, it is possible to excite electrons from the valence to the conduction band with a well defined spin. By observing the reflected and rotated probe pulse it is then possible to very directly follow spin orientation in time. In literature this has already been used to observe for example electronic spins transported by an electric field[13] or to study spin transfer between different semiconductors[14]. The applicant has used this to measure electron spin and carrier dynamics before in and AlGaAs/GaAs heterojunction which is described in his Master thesis. The setup to measure the spin polarization our device should produce is shown schematically in figure 3.

We propose to use these optical techniques to first examine in more detail the carrier and spin dynamics in a normal heterojunction 2DEG as has been done earlier (see master report applicant). With the spectrally narrow filters, Landau level dynamics may also be observed indicating the strength of this spectroscopy.

9.4 Goal of the Proposal

The goal of the proposal is to produce and optically measure a ballistic spin filter as proposed by [4]. It is motivated by several observations and recent publications:

- It has been experimentally shown in InGaAs, where Rashba is the dominant mechanism, that it is possible to alter spin orbit interaction by more then a factor of two either without changing the electron density[15]. When the electron density is changed as well, this can be even done more dramatic (factor 10). Together with the fact that mean free path lengths can be in excess of 1 μm in InGaAs and Rashba spin flip lengths being $\sim$ 80 nm-200nm depending on the gate voltage the experimental realizations of these proposals are possible but hard. This is because the complete device needs to be smaller then 1 μm for ballistic transport. The optical resolution of the Kerr microscope is at maximum $\sim$1 μm which makes it hard to detect the spin polarization optically.

- For the AlGaAs/GaAs heterojunction, the spin orbit interaction is more complicated due to a significant Dresselhaus spin orbit effect. Nevertheless, very long electron mean free path lengths (13 μm) can be present in this heterojunction which makes the experimental

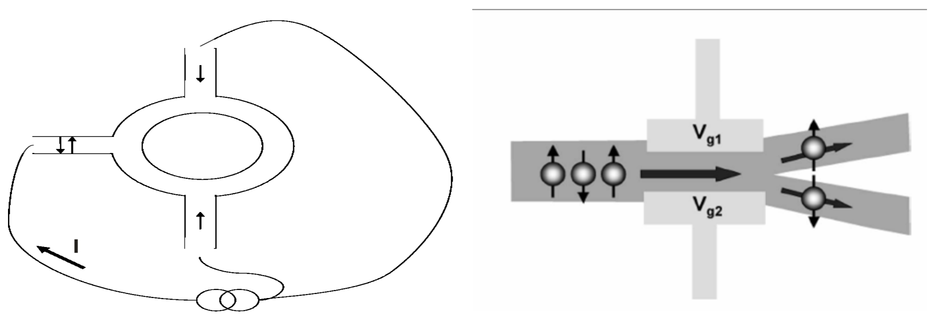


Fig. 2: (a) Spin filter proposal using a resonator ring[4]. If a current is sent from one wire (A) to the other two, spins will get separated due to quantum interference effects in the ring which is induced by Rashba spin orbit interaction. (b) A similar device where a T-bar is influenced by a gate which alters Rashba coupling[7]. Both devices promise nearly 100% spin polarization.

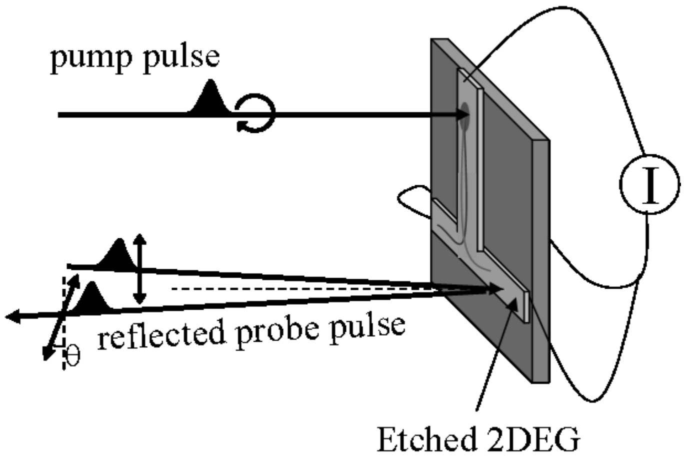


Fig. 3: Schematic drawing showing the optical way to investigate spin transport. Without the pump pulse a linearly polarized probe pulse may be directed at one of the arms of the spin filter. If a spin polarization is present, the reflected pulse gets rotated which can be observed using a polarization bridge. When the pump and probe pulse are very narrowly filtered in their spectra, it is possible to study very detailed transport throughout all the quantized channels originating from the confinement of the 2DEG. With Lock in techniques and current or pump polarization modulation very precise rotation measurements possible which is shown by the success to measure the weak Spin Hall effect[12].

realization of such devices much easier. It is predicted that wires pointing in the correct crystal orientation can have an extremely low spin orbit interaction[16] which causes practically no precession at all. By altering the Rashba coefficient in these wires with electrical gates[15] it should then be possible to realize the proposed device experimentally.

- Magnetoconductance measurements show that it is possible to significantly alter the Rashba and Dresselhaus coefficients by applying a gate voltage on a deposited gate on top of the AlGaAs/GaAs 2DEG[17]. However, it has not been experimentally shown yet the Rashba effect can be significantly altered by applying electric fields without altering the electron density as has been done in [15]. Measuring and indicating this will be one of the tasks in this project.

- Standard Kerr spectroscopy has a typical resolution of $\sim 1\mu$m. With a 13μm mean free path lengths measured in our GaAs/AlGaAs Heterojunction (see master thesis applicant) we know that the proposed structure should be smaller then this to achieve ballistic transport. This estimation shows it is possible to do Kerr rotation microscopy with the already available techniques present at the MSC^{plus}.

If in our GaAs/AlGaAs structure the Dresselhaus spin orbit interaction is too much of a nuisance or it turns out it is very hard to alter the Rashba spin orbit interaction it is possible to switch to InGaAs/InAlAs 2DEG systems. In these systems the Dresselhaus contribution is known to be irrelevant and Rashba spin orbit interaction can be altered strongly. A Hurricane amplified Ti:Sapphire system with TOPAS is available to achieve the correct optical wavelengths for these measurements.

Prior to these measurements, the carrier and spin dynamics of Landau and quantum well levels are investigated in more detail on the AlGaAs/GaAs heterojunction. At the same time magnetoconductance[17] and Quantum Hall measurements[15] will be performed to characterize the relevant Rashba and Dresselhaus spin orbit parameters. With this knowledge, ballistic transport simulations similar to [4] (or even more advanced as done in [18]) will be performed depending on need to accurately guess the final conditions for the proper operation of the spin filter.

Earlier optical measurements done on the AlGaAs/GaAs 2DEG reported on in the master report of the applicant indicated that a parallel channel was formed in the AlGaAs rendering electrical gate measurements impossible due to screening. These 2DEG samples are therefore not suitable for our purposes. To overcome this problem it is suggested to grow a new AlGaAs/GaAs heterostructure with less doping density. At the same time an AlAs stopping layer for the etching process can also be used to produce front and back gates to repeat the measurements of [15] on our GaAs/AlGaAs system.

9.5 Plan of Work

The plan of work is summarized in the following table:

Time (Months)	Activity
0-6	Fabrication of several AlGaAs/GaAs samples by MBE. Test their photoconductivity by the electrical measurement apparatus available at the MSC^{plus}.
6-12	Building the optical setup of which all parts should have arrived by this time. This is basically a replication of an optical setup already available (but highly occupied) at the MSC^{plus} with the exception of the usage of photomultiplier tubes or avalanche photodiodes for the setup. The choice between these will be made after a more extensive noise analysis.
12-24	Measuring Landau and quantum well level dynamics on the plain 2DEG. If necessary time resolved photoluminescence measurements can be done to analyze the various recombination mechanisms involved in the 2DEG sample.
24-30	Fabrication of Hall bars on the most suitable MBE grown heterostructure and deposition of front and back gates. Quantum Hall[15] and magnetoconductance measurements[17] to determine the various spin orbit parameters and how they can be varied.
30-33	Determining how to exactly produce the device by performing calculations using the results obtained from measurements.
33-36	Fabrication of the final spin filter.
36-42	Kerr microscopy measurements on the final spin filter.
42-45	Pump probe measurements on the spin filter.
45-48	Thesis writing.

Off course, deviations from this scheme might occur depending on the problems or interesting new physics encountered. If an InGaAs/InAlAs 2DEG is necessary to produce the final device the measurements will be similar.

10 Infrastructure

A variety of instruments are available at the MSC^{plus} to produce the desired structures such as:

- A cleanroom with general processing facilities such as an e-gun evaporator, resist spinners, ovens, reactive ion etching etc.
- Raith electron beam lithography system.
- JEOL scanning electron microscope.

To realize the optical experiments the following setup is available:

- A temperature controllable optical flow cryostat (2-300K) with a controllable superconducting magnet (0-7T).
- A cryostat insert with a special low temperature 1 cm focal distance lens with an Attocube xyz positioner (2.5 nm precision, 3mm range) for spatial measurements may be borrowed.
- Optical table with a pulsed 150 fs tunable Ti:Sapphire laser.
- Home built 'IV meetkast' for electrical measurements.

The Optical Condensed Matter group at the MSC^{plus} has a variety of optical measurement setups such as a THz setup for time resolved measurements in the IR or a time resolved photoluminescence setup to study recombination processes. These may also be used depending on need.

11 Application perspective in industry, other disciplines or society

The experimental realization of a spin filter will be a big step forwards in spintronics. Together with the engineering of wires which should have no or very low spin dephasing[17] this may be one of the first steps towards commercially viable devices which will solve the miniaturization problem in conventional electronics. However, poor electrical detection remains a problem which must be solved separately[10] before this will be practically used. Even if the experimental realization has not been achieved at the end of this project much fundamental information has at least been gained in quantum well and Landau level dynamics, as well as spin transport itself in quantum wells.

References

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