# Research Proposal

## 1. Title of the project

Gate controlled spin-orbit interaction: a way to spin manipulation

## 2. Applicant

Andrii Rudavskyi (under supervision of Prof. Caspar van der Wal)

## 3. Institute

Zernike Institute for Advanced Materials
University of Groningen
Nijeborgh 4, 9747 AG
Groningen
The Netherlands

Contact: Prof. Caspar van der Wal
Telephone: +31 50 363 4555
Fax: +31 50 363 4879
E-Mail: c.h.van.der.wal@rug.nl

## 4. Abstract

Spin-orbit interaction is a main source of the spin-dephasing in the crystals with zinc-blend structure. It leads to the energy spin splitting, which is felt as an effective magnetic field by each individual spin with nonzero k-vector. Although spin-dephasing is highly undesirable process, spin-orbit field itself may be used for manipulation of the spin. We propose to investigate spin-dephasing processes in 2DEG as a function of structural asymmetry of the heterostructure, by applying electric field to the heterostructure and thus changing its band structure. The principal experimental method we are going to use is a Shubnikov de Haas magnetotransport measurements. We want to study tunability of the spin-orbit interaction by means of the external electric field perpendicular to the plane of the 2DEG. By using front gate (FG) and back gate (BG) electrodes independent control of both electric field within the quantum well and carrier sheet density can be achieved.

## 5. Duration of the Project

4 years, starting November 2009

## 6. Personnel

### 6.1 Senior-scientists

| Name | Task in project | Time |
|---|---|---|
| Prof. Dr. Ir. B.J. van Wees | Supervision and management | 5 % |
| Prof. Dr. Ir. Caspar H. van der Wal | Supervision and analysis | 10 % |

### 6.2 Junior-scientists and technicians

| Name | Task in project | Time |
|---|---|---|
| PhD student (OIO) | Experiments and analysis | 90 % |
| B. Wolffs | technical support | 5 % |
| Ing. S. Bakker | technical support | 5% |

# 7. Cost estimates

## 7.1 Personnel positions

One 'onderzoeker in opleiding' position for four years.

## 7.2 Running budget

20 k€/year

## 7.3 Equipment

No equipment is required

## 7.4 Budget summery (in k€)

| | 2009 | 2010 | 2011 | 2012 | 2013 | TOTAL |
|---|---|---|---|---|---|---|
| Personnel (positions) | | | | | | |
| PhD students | 18 | 43 | 43 | 43 | 33 | 180 |
| Postdocs | - | - | - | - | - | - |
| Technicians | - | - | - | - | - | - |
| guests | - | - | - | - | - | - |
| personnel(costs) | 18 | 43 | 43 | 43 | 33 | 180 |
| running budget | 16 | 20 | 20 | 20 | 20 | 96 |
| equipment FOM-part | - | - | - | - | - | - |
| TOTAL(requested from FOM) | 34 | 63 | 63 | 63 | 53 | 276 |

# 8. Research programme

### Introduction

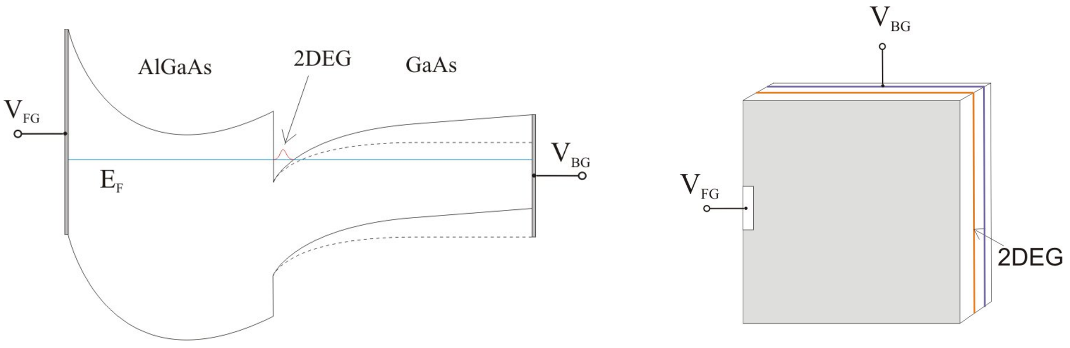
Most III-V semiconductors have zinc-bland lattice structure that is asymmetric with respect to inversion. The intrinsic crystal fields lead to the conduction band spin splitting proportional to the third power of electron wave vector, even at zero external magnetic field. This spin-orbit field is called Dresselhaus field. Spin-orbit coupling can also be induced by electric field on the interface of the heterostructure. As a result, carriers confined to moving within an asymmetric quantum well will experience an effective magnetic field called Rashba field. Both these fields induce spin precession. The strength of the Rashba component of the spin-orbit field should tunable through and external gate voltage inducing a static electric field perpendicular to QW that can serve to alter built-in confinement potential of the heterostructure. The strength of the Rashba spin-orbit interaction is given by the Hamiltonian [1]:

$$H_R = \alpha\left[\vec{\sigma}\times\vec{k}\right]\cdot\vec{e}_z$$

where $\alpha$ is a parameter of the spin-orbit interaction which linearly depends on built-in electric field $E_z$, $\sigma$ represents Pauli spin matrices, $\vec{e}_z$ is a direction of the electric field (coincides with the crystal growth direction). Assuming that Rashba field dominates in spin-orbit interaction the total Hamiltonian is given by $H_{tot} = H_k + H_R$, where $H_k$ is a kinetic energy part of the Hamiltonian. The eigenstates for up and down spins are then given by:

$$E^{\pm}(k) = \frac{\hbar^2 k^2}{2m^*} \pm \alpha|k|$$

The last term defines energy spin splitting at zero magnetic field $\Delta_R = 2\alpha k_F$. The tunability of spin-orbit coupling can be obtained by tuning the value of $\alpha$ by an external gate. By experimentally measuring energy spin-splitting we would be able to estimate the strength of the spin-orbit interaction as function of gate voltage.



*a)* *b)*

Figure 1 (a) Scheme of the band structure of the AlGaAs/GaAs heterostructure. 2DEG is confined within asymmetric quantum well. (b) Parameters of the quantum well (slope of the potential and electron density) are controlled by external gates. $V_{FG}$ and $V_{FG}$ are the voltages applied to front and back gates accordingly

Spin-orbit coupling parameter is proportional to the interface electric field in quantum well which in its turn is proportional to the slope built-in potential within heterostructure (Figure **1**). By applying voltage to either front or back gate the slope of the potential can be controlled. But by applying gate voltage Fermi level of the whole heterostructure is shifted that results in adrift of the carrier density within quantum well. To insure constant carrier density, $V_{FG}$ and $V_{FG}$ are adjusted in such a way that carrier density is constant, with slope of the potential being changed.

Another important issue for the construction of the spintronic device is the possibility to control spin-dephasing time, since spin-dephasing is the main process leading to the loss of spin orientation. Recently it was shown, both numerically and experimentally [2], [3], that confinement of the two dimensional electron ensembles within quasi one-dimensional channels leads to increase of the spin-dephasing time $T_2^*$ for certain orientation of the confinement. This is explained by the fact that for these directions both Rashba and Dresselhaus components of the spin-orbit field cancel each other. Since the motion of the electrons along direction of confinement is reduced, spin-dephasing time for such confined system increases. In theory, if these two components exactly cancel each other $T_2^*$ tends to infinity. If we learn how to tune Rashba field by means of gate control, we would be able to further study a possibility of the gate control of the spin-dephasing. This is a big goal of this project.

## Experimental techniques

Gate control of the spin orbit interaction has already been studied in a number of two dimensional electron gas systems. Apart from theoretical investigation of spin splitting of the conduction band of zinc blend compounds, many experimental techniques have been employed. With some of them it became possible to get value of spin splitting through extrapolation to zero magnetic field of magnetotransport data (Shubnickov de Haas measurements [4]) or through electron spin-resonance experiments [5]. Among other experimental methods used to study gate-controlled spin-orbit interaction were spin-precession technique [6], zero-field Raman scattering experiment [7] and so called weak localization magnetotransport measurements [8].

Our group, Physics of Nanodevices in Zernike Institute for Advanced Materials, is highly experienced in performing electric transport measurements in nanostructures. That is why we are going to chose magnetotransport technique for spin-splitting measurements as basic tool for this project. Another part of the group is operating time resolved Kerr rotation measurements setup, which is an optical tool to measure spin dephasing processes is spin system, which in its turn are determined by spin orbit interaction.

## Shubnikov de Haas measurements

Shubnikov de Haas (SdH) effect consists in oscillation of the conductivity of a material in intense time varying magnetic field and occurs at low temperatures. Motion of electron in strong magnetic field is quantized. The resulting energy spectrum is made up of so called Landau levels which are the levels of quantum harmonic oscillator and are equally separated. The distance between two nearest Landau level is determined by cyclotron frequency and is proportional to the magnetic field. By gradually altering magnetic field distance between levels will chance and at some fields Landau levels will cross Fermi level of the system. This results in the local maxima of the conductivity and is observed as a Shubnikov de Haas oscillation on experiment (Figure 2). Oscillation frequency is determined by the density of two dimensional electron gas. This effect is widely used for the electrical characterization of two dimensional electron and hole systems. Carrier density may be calculated from the period of oscillations.

Spin-orbit fields lead to splitting of Landau levels which leads to the beating pattern of the Shubnikov de Haas oscillations. By detecting beating patter of SdH oscillation Papadakis [6] managed to observe control of the spin-splitting by the external magnetic electric field by applying gate voltage to heterostructure in two dimensional hole gas. The results are presented on Figure 2. Beating pattern is different for different gate voltages which indicates that spin splitting is changing when gate voltage is changed. Fourier transform (Figure 2 B) of the SdH data reveal that spin splitting changes from positive, through zero, to negative values as is the case with electric field at the interface.

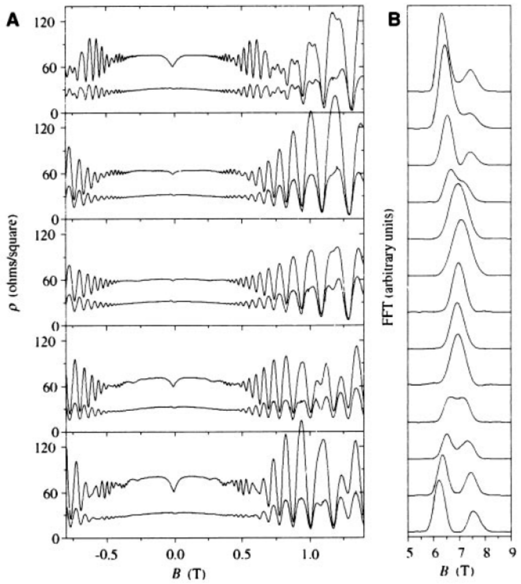


Figure 2 Shubnikov de Haas oscillations in two dimensional hole gas show clearly visible beating pattern that proves presence of the spin-splitting. SdH oscillations are plotted for a range of gate voltages applied to the heterostructure, with 2D electron density kept constant (A). Fast Fourier transform (B) shows shift of two frequencies with respect to each other as function of applied voltage. Plot taken from [6]

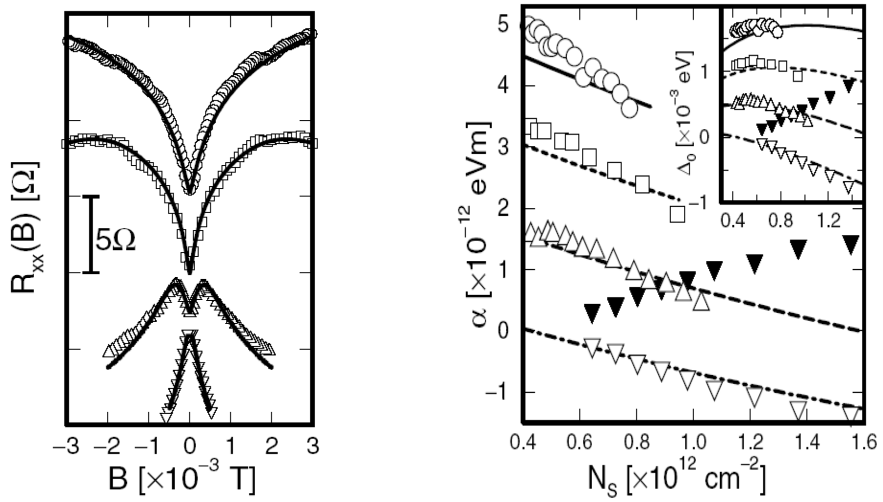
We are going to use SdH technique for measurements of the tunability of the spin-orbit interaction in this project.

## Weak antilocalization magnetotransport analysis

There are a few problems that may occur while determining spin orbit coupling constant $\alpha$ by means of presented experimental method. While existence of the spin splitting $\Delta$ suggests beating in SdH oscillations, the value $\Delta$ deduced from the position of the beating node is usually different from the value of zero-field spin splitting $\Delta_R$ since $\Delta$ includes the effect of the Zeeman spin splitting which always present in finite magnetic field. In addition, in order for beatings to be observed the value of spin splitting must be sufficiently large, so that the beating node would be visible within the range of accessible magnetic fields. Also there may be other effects that lead to beating like pattern of SdH oscillations, such as contributions from second Landau level. Therefore we are going also to exploit also another method to study spin splitting due to the SO interaction. This is so called weak antilocalization magnetotransport measurements [10].

The effect of the weak localization in metals and semiconductors is caused by the interference of two electron waves, which are scattered by the same centers (defects or impurities) but propagate in the opposite direction along the same closed trajectory, and therefore return to the origin with equal phases. This effect increases the effective scattering cross section and therefore leads to the suppression of the conductivity. In magnetic field two wave propagating in opposite direction gain phase difference, which is proportional to the magnetic flux through the area enclosed within electron trajectory. This phase difference breaks the constructive interference and restores conductivity to the value it would have without quantum interference corrections. This is observed as an increase in conductivity with magnetic field and this effect is known as positive magnetoconductivity. A theory for such magnetotransport was developed by Iordanskii, Lyanda-Geller and Pikus and resulted into the dependence of magnetoconductivity of magnetic field [11].

This theory has already been tested and has shown good agreement with the experiment. Four asymmetric quantum wells with different degree of asymmetry were prepared in work [10]. One gate was used only for the carrier density control. Magnetoresistance curves for all samples are shown on Figure 3. Totally different behaviour of magnetoresistance for different samples is a result of different spin-orbit splitting. Fitting performed using Iordanskii, Lyanda-Geller and Pikus theory allowed to deduce values of the spin splitting constant α. It has shown excellent agreement with theoretical calculations. It was also shown that for one of the samples spin splitting has opposite sign which is in agreement with band structure calculations.



*a)* *b)*

Figure 3 (a) Low-field magnetoresistance data for four different sample with different built-in electric field. Solid line: fitting using Iordanskii, Lyanda-Geller and Pikus theory. (b) Values of spin-orbit coupling constant α from weak antilocalization analysis for four samples. Dashed black curves obtained from **p·k** calculations. Figures are taken from [10].

Weak antilocalization analysis is a good method for estimation of the spin splitting due to asymmetry of quantum well and it is the next tool we are going to use in this project.

## 9. Project steps

- Calculation of the heterostructure with needed properties of quantum well and two dimensional electron gas

- Sample with MBE-grown AlGaAs/GaAs quantum well will be prepared by group in Ruhr-Universität in Bochum
- Before making gates we are going to characterize our sample. For that, using photolithography and etching, we are going to make Ohmic contacts to 2DEG and perform Hall and SdH measurements.
- On the top of the sample we deposit metal gate.
- All the measurements are performed in cryostat at Helium temperature.

## 10.Collaboration

We are collaborating with Applied Solid State Physics group at the Ruhr-University of Bochum in Germany, where our sample is going to be grown. We are also collaborating with Optical Condensed Matter Physics group in our institute. Zero-field Raman scattering experiments may be also done there if needed in course of the project, as an independent tool for measurements of the spin-splitting [7].

## 11.Research questions and goals

The aim of the project is to investigate possibility of tuning of the spin splitting by changing interface electric field in quantum well via external gates. A few different techniques are going to be applied, to reach maximum consistency with theory and previous experiments. In case of positive result, a possibility of gate control of the spin-dephasing is going to be investigated.

## 12.Scientific interest

The concept of a spin-polarized field effect transistor has been proposed by Datta and Das [9]. The spin-polarized carriers are injected and collected by the ferromagnetic electrodes. The key idea of the above device is that a spin-orbit interaction in a narrow gap semiconductor quantum well causes the spins of the carriers to precess. The modulation of current can be expected by controlling the alignment of a carrier's spin with respect to the orientation of the magnetization in the drain of the transistor. The gate electrode on the top of the device can be used for controlling the spin-orbit interaction since the spin-orbit interaction is dependent on the interface electric field. One of the problems to be solved is to what extent the spin-orbit interaction can be controlled by the gate voltage. In this project we propose to investigate this issue.

## 13.References

[1] R. H. Silsbee, J. Phys.: Condens. Matter **16**, R179 (2004)
[2] J. Liu *et al.*, arXiv:0810.1413
[3] S. Z. Denega *et al.*, arXiv:0910.2336
[4] S. J. Papadakis et al., Science **283**, 2056 (1999)
[5] D. Stein *et al.*, Phys. Rev. Lett. **51**, 130 (1983)
[6] H. Riechert *et al.*, Phys. Rev. B **38**, 4136 (1988)
[7] B. Jusserand et al., Phys. Rev. Lett. **69**, 848 (1992)
[8] P. D. Dresselhaus et al., Phys. Rev. Lett. 68, 106 (1992)
[9] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990)
[10] T. Koga *et al.*, Phys. Rev. Lett. **89**, 046801 (2002)
[11] W. Knap *et al*, Phys. Rev. B **53**, 3912 (1996)