# Progress review:

## Background

### State of the art

One of the hottest topics in condensed matter physics is the realization of a quantum computer. The main advantage of such a quantum computer would be its ability to solve specific classes of algorithms orders of magnitudes faster than classical computers. A classical computer is based on deterministic two level states called bits. A quantum computer is also based on two level states (basis states) called quantum bits (qubits). However, a qubit unlike a classical bit exploits the quantum effect of superposition. As a consequence, a quantum system can be simultaneously in both basis states.

There have been several proposals for implementing such a qubit, with just some solid state realizations listed below:

* Electrons on Helium (He) [1]
* Semiconductors:
  + - Nuclear spin qubits [2]
    - Electron (hole) spin qubits [3]
* Superconductors:
  + - Flux qubits [4]
    - Charge qubits [5]

One of the above mentioned suggestions, which came in 1998 by Loss and DiVincenzo, was to use the spin of electrons (holes) for the realization of a qubit. The spin, an intrinsic quantum mechanical property of every elementary particle, lifts the degeneracy of an orbital energy level in the presence of an external magnetic field. The orbital level splits into two, typically labelled as spin-up and spin-down. This two level system can then act as a qubit, the so-called spin qubit.

However, for creating and manipulating the spin qubit, one must first confine the charge particle into a region, which is in size comparable to the charge particle wavelength. Such a confinement can take place in a structure called quantum dot (QD). QDs are very small structures (their diameters can reach tens of nanometers) and because of their almost zero dimensionality, the energy levels for a charge particle are discrete and far away from each other.

Not every two level system can create a useful qubit for the realization of a scalable quantum computer. In 1998 DiVincenzo published a list of conditions which a qubit should fulfill for a quantum computer to work correctly [6]:

The 5 necessary criteria are:

* **The qubit should be well-defined:** A well defined qubit is a two level (two state) system whose levels are distinguishable and highly controllable.
* **It should allow reliable state preparation:** The qubits need to be deterministically driven into the initial state so that the next computational step can take place**.**
* **It should show low decoherence times (long coherence times):** Because of the several noise sources to which a qubit is exposed its initially prepared state is lost (it does decohere) with time. It is desirable to have coherence times as long as possible.
* **A “universal” set of quantum gates which perform the state manipulations, should exist:** In the classical logic the Boolean function set (set of gates) is functionally complete or universal if any other function (gate) can be represented by it. The same functional universality applies for the quantum logic.
* **A qubit measurement capability (state readout) should exist:** After several state manipulations have been applied to the qubit, one should be able to read the computed result, it’s quantum state.

**For all types of qubits there is a battle between the manipulation time on one side and the coherence time on the other side. This is so because for performing quantum computation, many single operations need to be done before the system will decohere. The benchmark for the manipulation time is the minimum time needed for going from one state to the other.**

**For the spin qubits, which this proposal deals with, different materials have been investigated aiming to find the material with the highest coherence vs manipulation time ratio.**

**Materials**

Silicon **(Si)** has emerged as a promising material for the realization of spin qubits because it can be isotopically purified and left just with the 28Si isotope which is a zero nuclear spin element. Thus the nuclear noise can be eliminated and the coherence time boosted in comparison to the broadly used gallium arsenide (GaAs) [7]. The additional big advantage of Si is its compatibility with current CMOS technology. This could become very important when moving towards the realization of a large number of qubits as required by quantum algorithms.

There are several approaches of defining QDs in silicon.

One way is by means of a phosphorous (P) dopant. In that case a P atom behaves as an electron QD because of its confining potential. Andrea Morello’s Group at UNSW in Australia, by applying the spin echo pulse sequence, has measured electron spin coherence time T2ECHO exceeding 200 microseconds, in a non – isotopically purified Si:P system, while the duration of one full spin rotation (τπ) in this case was τπ = 150 ns [3]. By using isotopically purified 28Si:P samples and the nuclear spin of a P atom as a qubit, the same group has achieved nuclear spin coherence time of T2ECHO = 60 milliseconds and τπ ≈ 25 μs [2].

M. Veldhorst et al. by using lithographically defined electron QDs in Si have measured spin coherence times using the CPMG pulsing technique of T2CPMG = 28 ms and τπ = 1.5 μs [8]. Finally, E. Kawakami et al. by using a single-electron QD in a Si/SiGe heterostructure qubit, have measured T2ECHO = 40 μs, while τπ = 0.15 μs [9].

One limitation of Si is the difficulty to perform fast gate operations while maintaining the good coherence. One way around this problem is to use the spin-orbit interaction of holes instead of electrons and perform spin manipulation via electric fields (as described in more detail in the *Spin dynamics experiments* section). Using this approach R. Maurand et al., realized very recently the first CMOS spin qubit by using a hole confined in a transistor made out of p-type Si. Indeed, the time for a full spin rotation was much reduced τπ ≈ 6 ns but also the reported T2ECHO ≈245 ns. [10].

**Holes in** **germanium** **(Ge)**, have an even higher spin orbit coupling which should allow thus much **faster spin manipulation times**. In addition, for purely heavy-hole (HH) states the **dephasing time should be very long** [11].

In our group we study qubits in Ge self-assembled nanostructures [12], which are created by epitaxial growth of Ge on Si. Such a growth can lead to various types of nanostructures. In this project the so-called Ge hut-wires are going to be studied. Very recently magnetotransport measurements have shown that holes, in this type of structures, are of HH character [12], suggesting long coherence times for this material system.

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Figure 1: Stability diagram of a SiGe hut-wire single QD (left). Scanning electron micrograph of a Ge hut-wire contacted by palladium Pd source and drain electrodes (right) [12]

### Measurement techniques

Different type of measurement techniques have been used in order to extract the state of a spin qubit and its coherence time:

* DC current readout: The DC current readout is sensing the electron transport through the qubit by means of current measurement. It is prone to low frequency 1/f noise and the bandwidth (BW) is low because of heavy filtering necessary for achieving low effective electron temperatures.
* Differential measurement (AC current readout): The differential measurement (AC current readout) has a similar drawbacks as the DC current readout. It is typically done with a low frequency lock-in technique. Because of the low frequency noise, a lock-in amplifier usually operates on a very narrow bandwidth (BW) around the measurement frequency, which leads to long measurement times.
* Ohmic reflectometry: Ohmic reflectometry is a technique which indirectly senses the impedance change of a QD by monitoring the amplitude or phase of the reflected wave from the QD (see Figure 2 for a more detailed explanation). It is usually performed by high frequency lock-in techniques and is not prone to 1/f noise.
* Gate reflectometry: Similar to the ohmic reflectometry but it is connected to a gate electrode and not to a source or a drain. **It’s big advantage is that it does neither require charge transport through the QD hosting the qubit nor the existence of a charge sensor typically used with ohmic reflectometry.**

## What is done so far

During the first year of my PhD I have already prepared a 4K dip stick (Figure 3) for reflectometry measurements. Particular attention was paid to the sample holder, fabricated out of a printed circuit board (PCB). DC electrical signals are sent to the sample through low thermal conductive wires twisted in pairs finishing in a PCB connector; radio frequency (RF) signals are sent through the coaxial cables. The DC signals are low pass filtered with surface mounted RC filters (Figure 4) to reduce thermal noise from the wires. After low pass filtering, the DC signals are routed to the gold plated bonding pads around the area in the middle of the PCB (sample area) on which a typically 5x5 mm2 sample is glued with the silver paste (Figure 4). The RF coaxial lines are finishing on the PCB mounted SMP connectors (Figure 4). After the SMP connector, a DC signal is added to the RF signal using a bias tee. From there the signal is routed to the PCB bonding pads. Electrical contacts from the PCB bonding pads to the sample bonding pads are achieved by wedge wire bonding.

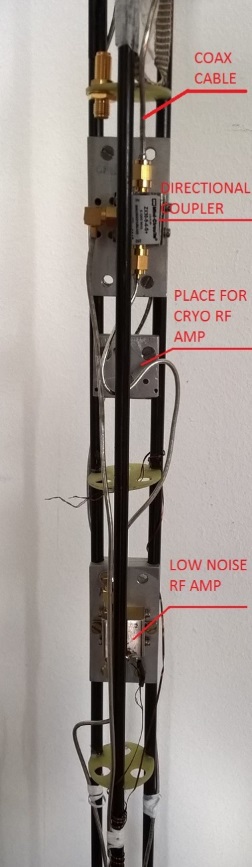
Figure 3: The plexiglas 4K dip-stick used for cooling down the samples to 4K and performing the reflectometry measurements. The left picture shows the whole stick, while the right is a zoom-in, highlighting the directional coupler and the low noise Minicircuits ZX60-33LN-S+ RF amplifier. An additional low noise cryogenic RF amplifier CITLF2 from Sander Weinreb’s Caltech Microwave Research Group can be added in order to increase the SNR of the measured signal.

Figure 4: Initial version of the PCB sample holder for the ohmic reflectometry. The upper figure shows the upper view of the PCB while the lower figure focuses on the back side.

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The resonant circuit consists of a matching circuit (Figure 4) and the SHT. The SHT is schematically presented as the resistance RS in parallel to the capacitance CS, as can be seen in the simple circuit model in Figure 2. For the matching circuit, the surface mounted inductor Murata 1.2 μH and the varactor MACOM MA46H070-1056 were used. The Varactor – a voltage tunable capacitor - was used in order to

Figure 5: Simplified schematic of the overall ohmic reflectometry measurement circuit

be able to always achieve a good matching condition.

For performing the ohmic reflectometry measurements the RF signal was sent down the coax line (Figure 3, right) towards the QD device. The signal which gets reflected from the resonant circuit is sent via the directional coupler to the amplifiers. The amplifiers configuration, shown in Figure 3 (right), is used to preserve the signal to noise ratio (SNR). After the sample, the very low noise cryogenic amplifier, Weinreb’s CITLF2, is used to amplify both signal and noise by the same amount (around 20 dB), adding a very small amount of itself noise, thus almost equalizing the SNR on its input with the SNR on its output. Thus higher noise level on the output of the CITLF2 amplifier allows the second, noisier amplifier to achieve the SNR on its output approximately the same as the SNR on its input. Such an amplifier chain enables non – degrading propagation of the SNR from the sample stage to the higher noise, room temperature electronics.

For conducting the measurements several instruments have been used.

* Reflection coefficient measurement: vector network analyzer (VNA) from Rohde and Schwarz, model ZNB20
* DC biasing of the single hole transistor: auxiliary bias outputs of a Stanford Research SR830 lock-in amplifier
* DC current measurements: current amplifier from Stanford Research SR570
* For attenuating the RF signal sent to the sample: Minicircuit’s attenuator
* For amplifying the reflected from the sample RF signal: series of CITLF2 and Minicircuit’s low noise amplifier
* Instrument control and data retrieval to the PC: Python application.

### Low temperature electronic transport measurements with the initial version reflectometry setup

The SHT sample was fabricated by H. Watzinger and the nanofabrication description can be found in [12]. Using the setup described in the previous chapter, the SHT (single QD) formed in the germanium hut-wire (Figure 6, left) was tuned in the Coulomb blockade regime applying DC voltages on source, drain and gate electrodes (Figure 5). Charge stability measurements were conducted in the Coulomb blockade regime showing a Coulomb diamond pattern. A comparison of the DC current and the ohmic reflectometry measurements has been done. The DC current was measured by applying a bias on the source and reading the current from the drain contact (Figure 5), while for the reflectometry measurement the LC matching circuit was connected to the SHT source contact (Figure 5).



Figure 6: (Left) 3D model of a SiGe nanowire-based single QD sample - SHT, designed by H. Watzinger. A single QD which confines holes is formed in the nanowire beneath the gate (green). Comparison of the DC current transport (middle) and the ohmic reflectometry (right) measurements on the SHT in a Ge hut-wire.

By adjusting the integration time to be similar for both measurements, it can be seen that the reflectometry technique enables us to see more features like the excited orbital energy states of the SHT (Figure 6, middle and right).

We have compared our reflectometry setup with the one of D. J. Reilly et al. for which they reported conductance sensitivity of 5\*10-6 e2/h Hz−1/2 by performing reflectometry on a quantum point contact in a dilution fridge with electron temperature of 120 mK [18].

We have measured a just around five times lower sensitivity despite the much higher temperature of 4K. This is quite good when considering that the thermal broadening of the energy levels at 4K leads to a much wider coulomb peaks. Such results in a much smaller resistance change for a small gate voltage modulation and thus a smaller sensitivity.

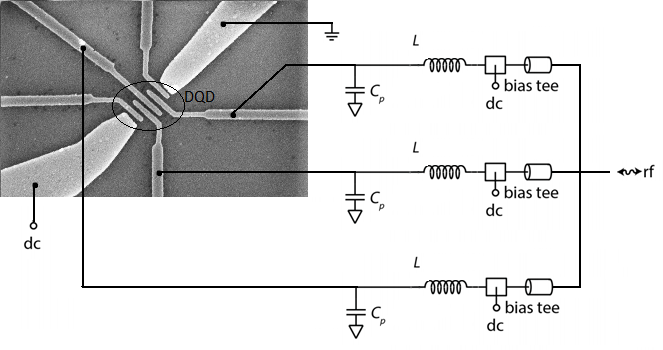
## Working plan for the future

### Towards gate reflectometry

The first generation of the used setup and the PCB board aimed to verify that indeed we have the knowhow to perform RF reflectometry measurements. The second generation of the reflectometry setup will be developed during this project and installed in a dilution fridge reaching temperatures down to 10 mK.

For the purpose of measuring several samples and due to the necessity for a higher number of RF lines dictated by the experiments of spin manipulation, a new PCB will be designed. The new design will allow frequency multiplexing of four different reflectometry resonant circuits enabling the measurement of four devices by using just one RF line and amplification stage. We will install in the dilution fridge insert a similar reflectometry system like the one used in the 4K dip-stick. However there will be several improvements. There will be an upgrade in terms of using lower thermal conducting stainless steel cables, attenuators, and additional DC filtering of all the DC wires. In addition, a Niobium titanium superconducting cable is going to be used between the input of the cryogenic amplifier and the sample stage because of its very low thermal conduction, to avoid heating of the mixing chamber stage of the fridge which has a cooling power of a few tens of μW in the insert.

The vector network analyzer which was used so far for the measurements will be replaced with a Zurich Instruments UHF lock in amplifier which enables faster and longer data acquisition, more inputs and generally more measurement flexibility. For the spin relaxation time and the spin manipulation measurements, to be described below, arbitrary waveform microsecond pulses with a nanosecond rise time are needed. Those are generated using a Tektronix arbitrary waveform generator (AWG) 5014C. The measurements will be conducted using the QTLab measurement application developed in Python initially by the Delft Quantum Transport (QT) laboratory. We modified it according to our needs. All the codes can be found on the GitHub: <https://github.com/nanoelectronics-new/qtlab>

Figure 7. Gate reflectometry schematic on the Ge hut-wire DQD sample, fabricated in our group. LC resonators are connected to the three gates. Because of the different inductor L values, the resonance frequencies of the three matching circuits are different enabling thus the so-called frequency multiplexing technique.

As in the ohmic reflectometry, also for the gate reflectometry the readout parameters are the phase shift ∆φ and the amplitude change ∆γ of the reflected signal due to the charge configuration change in a QD or a DQD. They are expressed as: , , , where Q is the quality factor of the resonant circuit, Cp is the parasitic capacitance, Cg is the gate to dot coupling capacitance and CΣ is the overall QD capacitance [15]. The capacitance Cg can be approximated with a parallel plate capacitor since the gate electrode and the hut-wire separated by a thin dielectric, form such a capacitor. From the above expressions it can be seen that a higher coupling between a gate and a QD (higher Cg) leads to higher sensitivity of both ∆φ and ∆γ.

From the equation for ∆φ, it is clear that there are two factors which are critical for getting a sensitive gate reflectometry setup. Firstly to **reduce the parasitic capacitance** **Cp** as much as possible by engineering the sample holder. Secondly, to **achieve high quality factor Q** of the resonant circuit.

For **reducing the parasitic capacitance Cp,,** simulations of the PCB RF lines and bonding pads geometric capacitance in respect to their dimensions, routing configuration and PCB dielectric will be performed.

**The quality factor Q** dependence on different inductors and capacitors will be examined.

There are some additional losses apart from those directly influencing the resonant circuit, namely, PCB dielectric losses and losses in the PCB RF transmission lines [15].

Losses in the PCB dielectric will be addressed by using a dielectric with lower dielectric loss then the currently used FR4, e.g. some of the Rogers Corporation laminates.

RF lines transmission losses come probably from the unwanted reflections due to the transmission line routing and splitting needed to connect more reflectometry readout circuits – frequency multiplexing. This assumption should be tested and the **optimum configuration of the PCB RF lines** could be achieved by using the Sonnet software for simulating the RF line scattering parameters.

*Since I have already obtained quite some experience with reflectometry setups I expect that it will be feasible to realize a state of the art gate reflectometry setup within one year. In particular, since the group has three dilution refrigerators, I will have enough time to characterize the reflectometry and optimize it.*

### Spin dynamics experiments

Once the gate reflectometry setup will be properly working, I will focus on performing spin manipulation experiments. During my PhD I will focus on the Loss-DiVincenzo spin qubit.

For achieving good state preparation, fast manipulation and fast measurement, additional mechanisms are required beyond ones offered by single QDs. One of the most promising building block for the realization of the spin based quantum computer is the DQD system. A DQD system consists of a two neighboring QDs tunnel coupled to each other, which simply means that they can exchange charge particles via tunneling.

Figure 8: Spin state readout based on the spin blockade, shown for a gate defined DQD. The blue circles represent the individual QDs. Grey lines represent the gates and the black arrows in the QDs a spin direction. The spin can tunnel from the left to the right dot just if the spin configuration, when the charges are separated in the two dots, forms a singlet.

The main physical property which makes them attractive for the implementation of a qubit is the Pauli exclusion principle. It says that two identical fermions (in this specific case electrons or holes) cannot occupy same energy state. Figure 8 describes how the Pauli exclusion principle can be used to extract information about the spin degree of freedom in the left QD in the DQD system. If the spin configuration forms a singlet state S(1,1) (the numbers in brackets denote the hole number on the left and right dot respectively), like shown in Figure 8a, then after electrostatic pushing, by applying voltage pulses on gates L and R, the hole is allowed to tunnel to the right dot, forming a singlet S(0,2) state (Figure 8b). In the case below (Figure 8c) holes in both dots have the same spin, forming a triplet T(1,1) state, and due to Pauli exclusion principle they stay in the (1,1) configuration (Figure 8d) after electrostatic pushing because the triplet state T(0,2) is too high in energy and thus not available. This effect is known with the name Spin blockade.

#### Measuring the spin relaxation time T1

For measuring the spin relaxation time, an approach similar to the approach of Koppens et al. [19] will be used. The DQD will be tuned to the (0,1)-(1,1)-(0,2) triple point. The left dot is initially empty while the right dot is populated with a spin in its ground state, a spin down hole. First, pulsing the gate of the left dot will bring its spin up and spin down energy levels above the Fermi level, μF, of the lead, allowing lead to dot hole tunneling (holes tunnel to higher lying electrochemical potentials). Since the tunneling is most likely spin independent, the left dot is loaded with a random hole spin from the lead, during the loading time tL. The double dot is thus in either a singlet S(1,1) state or a triplet T(1,1) state and is left in that configuration for the waiting time tw. After the tw, a second pulse level is applied in order to bring the hole from the left QD to the right QD. For a S(1,1) configuration tunneling will take place. As explained above, due to the spin blockade, this will not be the case for the T(1,1) state. If charge tunneling takes place between the two QDs, a shift in a quantum capacitance (a capacitance originating from a DQD charge polarization) will take place, which can be detected by the gate reflectometry. The probability of finding the DQD system in the T(1,1) state will decay exponentially with the duration of the waiting time tw, with *T*1 being the decay constant, since for long waiting times (tw >> *T*1) the DQD will always end up in the S(1,1) state.

*The samples needed for performing the T1 experiments are already existing in the group. Hannes Watzinger, as well PhD student in the group, is currently performing DC measurements on such DQD devices. For the T1 experiments all the knowhow in the group is already existing thus 6 months seem a realistic time for performing this experiment.*

#### Measuring the spin dephasing time T2\*

Quantum gate operations for a spin qubit system imply spin manipulation. Basically such manipulations are spin rotations in the spin representation sphere, called Bloch sphere.

Figure 9. Bloch sphere

The spin-up and spin-down states form the basis of a hole spin qubit and they are located on the north and south pole of the Bloch sphere. Their energy splitting EZ is determined by the hole g factor g, the Bohr magneton μB and the static external magnetic field B, as . The spin vector precesses around the applied static magnetic field axis with a so-called Larmor frequency , where h is the Planck constant. For flipping the spin an external oscillatory magnetic field BAC needs to be applied perpendicular to the static one and its frequency needs to match the Larmor frequency. An intuitive understanding why the frequency of the BAC needs to match the Larmor frequency can be obtained by thinking of the example of a child on a swing. The child-swing system oscillates with its natural frequency of oscillation. If the swing is pushed by an external person with an appropriate period of pushing pulses, the amplitude of the oscillation will increase and at some point the swing will flip. In this comparison the natural frequency of a child-swing system corresponds to the Larmor frequency and the frequency of the externally applied pushing pulses to the frequency of the applied oscillatory magnetic field.

However, an oscillatory magnetic field is hard to implement, from the fabrication standpoint, since it adds more steps and thus the risk of failure. One way to avoid this problem is to a apply static instead of an oscillatory magnetic field and to apply an oscillatory voltage to the QD gate. The oscillatory electric field can modulate the hole g factor giving thus, an equivalent to the first case, oscillatory magnetic field. Modulation of the hole g factor with the electric field is possible because of the spin-orbit coupling. This technique is called g-tensor modulation technique [20] and is going to be used in the qubit I am planning to study.

Microwave sources generating high frequency signals will be needed for this experiment; for an expected in our system hole g-factor of 3 [12] and a typical magnetic field of around 0.5 T, the Larmor frequency is around 20 GHz. Actually, for this purpose a vector signal generator will be used, controlled also from the python measurement application.

In order to determine the coherence time, coherent spin manipulation is needed. In order to verify the coherent spin manipulation, Rabi oscillation experiments will be conducted. The DQD will be initialized in the T(1,1) charge configuration. Then the spin in the left dot will be rotated for an angle determined by the spin rotation time which is the time of the applied burst of the microwave signal, τBURST. In the next step, voltage pulses are going to be applied trying to push the DQD to the (0,2) charge configuration (which is a singlet S(0,2) configuration as explained already above). By linearly changing τBURST, a Rabi oscillation pattern of the S(0,2) configuration probability should be observed proving the coherent spin manipulation [10].

Following the approach of R. Maurand et al., for evaluating the inhomogeneous dephasing time T2\*, Ramsey – fringes like experiments will be conducted [10]. First, a pulse rotating the spin around the x axis for the ∏/2 angle (∏/2 pulse) will be applied to bring the spin vector from the north pole (spin down state) to the xy plane in Figure 9. It will stay there for the time τ being thus exposed to the dephasing noise. After time τ, a second ∏/2 pulse around the x axis will project the spin vector back on the z axis for the readout. If no dephasing has taken place, the spin should finish at the south pole of the Bloch sphere (spin up state). Linear increase of the τ between the measurement points will result in the exponentially decaying spin up state probability, with T2\* being the decay constant.

*I anticipate that I will need one year for determining T2\* in our qubit. For such an experiment one needs additionally a microwave signal source, one needs to synchronize the AWG with the microwave source and furthermore I will need to learn how to correctly apply the combined pulses avoiding thus gate errors.*

#### Measuring Spin echo T2ECHO

Coherence can be extended by the so called spin echo technique which can partially cancel dephasing originating, for example, from slow varying nuclear magnetic field or applied field inhomogeneities. Similar to the spin dephasing time measurement, the spin is initially oriented along the positive z axis. Then, ∏/2 pulse around the x axis rotates it to the xy plane. Because of the dephasing sources the spin will dephase in the xy plane for time τ. Then a ∏ pulse around the y axis will be applied which mirrors the spin vector around the y axis. The spin is then left to dephase for the same time, but since it will be mirrored, the direction of this dephasing will cancel the previous one, causing the so-called spin refocusing. Followed by another ∏/2pulse around x axis, the spin will be projected back to the z axis and the spin up probability will be measured. If no dephasing has occurred, after second ∏/2pulse around x axis, spin will be oriented along negative z axis. From the exponentially decaying envelope in this case the T2ECHO will be extracted.

#### Measuring T2CPMG

Finally, in order to extend further the coherence time we will use the sequence of ∏ pulses called the CPMG sequence. The ∏ pulses, rotating the spin around the y axis can be applied at the times τ, 3τ, 5τ…, instead of a single ∏ pulse, as in the spin echo experiment, for the spin refocusing. Coherence time T2CPMG will be extracted from the exponentially decaying envelope of spin up probability vs the ∏ pulses separation time τ. This method is insensitive to the ∏ pulse length errors because the rotation axis alternates between y and –y subtracting thus the pulse length errors [21].

*For measuring T2ECHO and T2CPMG one more year will be needed. In principle after determining the dephasing time it should be straight forward to measure the coherence times however always unexpected problems might appear. In addition in between the experiments I expect also to write at least two papers. One dealing with the spin relaxation time and the second one with the dephasing/decoherence times.*