**Instrumentation setup**

******

Figure 6: Simplified schematic of the overall measurement circuit

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 Minicircuit’s and CITLF3 low noise amplifier
* Instrument control and data retrieval to the PC: Python application.

#### Germanium nanowire based, hole spin single quantum dot tuning and characterization with the initial version reflectometry setup



Figure 7: 3D model of a silicon germanium nanowire-based single quantum dot sample SHT, designed by H. Watzinger. A single quantum dot which confines holes is formed in the nanowire beneath the gate (green).

The single hole transistor sample was fabricated by H. Watzinger and the nanofabrication description can be found in [10].

Using the setup described in the previous chapter, the SHT (single QD) formed in the germanium hut-wire (Figure 7) was tuned in the Coulomb blockade regime applying DC voltages on source, drain and gate electrodes (Figure 6). Charge stability measurements were conducted in the Coulomb blockade regime showing a Coulomb diamond pattern. A Comparison of the DC current and ohmic reflectometry measurements has been done. The DC current was measured by applying a bias on source and reading the current from drain contact (Figure 6), while for the reflectometry measurement the LC matching circuit was connected to the SHT source contact (Figure 6).



Figure 8: Comparison of the DC current transport (left) and the ohmic reflectometry (right) measurements for 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 8).

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 [19].

By using the same methodology as in [19] for characterizing the reflectometry setup we have measured a just around five times lower sensitivity despite the much higher temperature of 4K. This is a quite good when considering that the thermal broadening of the energy levels at 4K, leads to much wider coulomb peaks. Such results in a much smaller resistance change for a small gate voltage modulation and thus a smaller sensitivity

#### Second generation of the reflectometry setup

The first generation of the used setup and 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 installed in dilution fridges allowing us to achieve 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 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 samples 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 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 spin manipulation measurements, to be described below, arbitrary waveform microsecond pulses with a nanosecond rise time are needed. Those are generated using a Tektronix AWG5014C. The measurement 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>

#### Moving towards gate reflectometry C:\Users\jkukucka\Desktop\IST\DOC Fellowship\DQD_reflectometry.tif

Figure 2. Gate reflectometry schematic on the Ge nanowire DQD sample, nanofabricated in our group. LC resonators are connected to the three gates. Because of different inductor values, resonance frequencies of three matching circuits above are different enabling 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 the quantum dot or double quantum dot system. , , , 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 [12]. The capacitance can be approximated with that of a parallel plate capacitor since the gate electrode and the nanowire separated by a thin dielectric, form a capacitor. From the above expressions it can be seen that a higher coupling between the gate and the QD (higher Cg) leads to higher sensitivity of both ∆φ and ∆γ.

Using gate reflectometry in a gate defined GaAs DQD J.I. Colless et al., achieved charge sensitivity of 6.3 meHz-1/2, having Cg/CΣ ≈ 0.05 [14]. Using 1.9 nm HfSiON oxide as dielectric in a silicon nanowire field effect transistor, M.F. Gonzalez – Zalba et al. achieved a charge sensitivity of 37 μeHz-1/2, with Cg/CΣ = 0.92 [12]. For comparison, the sensitivity achieved using ohmic reflectometry and a rf-QPC (rf-SET) as a charge sensor is 100 μeHz-1/2 (0.9 μeHz-1/2) [12]. Thus the performance of gate reflectometry is very close to that of ohmic reflectometry. In our system using by using ~ 4nm HfO2 as a dielectric, which has εroxide = 24, we expect to have a Cg/CΣ comparable to that reported in [12].

From the equation for ∆φ, it is clear that there are two additional things to be done which are critical for getting a sensitive gate reflectometry setup. Firstly to reduce the parasitic capacitance as much as possible by engineering the sample holder. Secondly, to tune the reflectometry to the good matching condition by changing the inductor values in the resonant circuit. Explanation why the good matching condition is wanted can be found at the end of the “State of the art” chapter (question: is the quality factor, i.e. the sharpness of the dip depending on whether you have chosen you elements to match perfectly 50 Ohm or does it depend mainly on the material properties of the used lumped elements?). Q factor dependence about L and C values will be examined (what do this mean, different material? Like you describe below?).

**The first generation of the gate reflectometry setup will emerge from the second generation of the ohmic reflectometry** by **changing inductor values** and by trying inductors of different core material and size in order to reduce inductor losses.

#### Optimizing the gate reflectometry (already above you speak about optimization, all the parts where you speak about optimization should be in one logical paragrap

There are several sources for signal loss in a gate reflectometry system: inductor losses, PCB dielectric losses, losses in PCB RF transmission lines, losses caused by the geometric parasitic capacitance [12].

The inductor losses come from the dissipation on the ohmic resistance of the wire wound and core losses from the hysteresis of the core magnetization curve and dissipation caused by eddy currents. The overall loss can be represented by adding next to the inductor a series resistance – an equivalent series resistance. Inductors with air core have smaller core losses but for achieving high inductor values they need to have more wounds and they are bigger, lowering their self – resonant frequency and increasing the wire resistance. As a part of this work, the **examination of the inductor influence** on the gate reflectometry sensitivity regarding the core material and the inductance value will be conducted.

For **minimizing the geometric parasitic capacitance** coming from the coupling of the PCB RF lines and bonding pads to the ground planes, the Sonnet software can be used. Simulations of the PCB RF lines and bonding pads geometric capacitance in respect to their dimensions, routing configuration and PCB dielectric will be performed.

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.

The 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 again the Sonnet software for simulating the RF line scattering parameters.

**Try to get used in writing smooth links between paragraphs. A text is not a collection of nicely written paragraphs ☺ Took me also very long to get used to it!**

### Spin dynamics expermients (make this title compatible)

#### 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 qubit quantum computer based on QDs is a serial double quantum dot (DQD) system. A DQD system consists of two neighboring QDs tunnel coupled to each other, which simply means that they can exchange charge particles by tunneling. The



Figure 1: Spin state readout based on spin blockade shown for gate defined double quantum dot. The blue circles represents the individual quantum dots, the grey lines the gates and the black arrows in the QDs the electron spin direction in the left and the right dot.

main physical property which makes them favorable for the realization 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 1 (adapt to the correct figure number after merging the text) describes how spin blockade 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, Figure 1a), 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)). In the other case, Figure 1c), holes in the (1,1) state have the same spin, they form a triplet, and due to Pauli exclusion principle they stay in the (1,1) configuration after electrostatic pushing because the triplet state T(0,2) is too high in energy and thus not available.

#### Measuring the spin relaxation time T1

In the description below try to speak from the moment when you have two charges on the DQD about singlet and triplet states. You do not align any more to a single energy level but either to a singlet or a triplet. For measuring the spin relaxation time, an approach similar to the approach of Koppens et al. [20] will be used. The DQD will be tuned to a 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 (1,1) state or a triplet (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 an S(1,1) configuration tunneling will take place. As explained above due to spin blockade this will not be the case for the T(1,1) state. If charge tunneling takes place, a shift in the quantum capacitance (capacitance originating from the DQD charge polarization) will take place, which is read 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 the DQD will always end in the S(11) state. (Check it once more carefully if it makes sense).

#### Spin manipulation measurements

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



Figure 10. Bloch sphere

The spin-up and spin-down states form the basis of the 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 a 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 quantum dot gate. The oscillatory electric field can modulate the hole g factor giving thus an equivalent to the first case oscillatory magnetic field. This technique is called g-tensor modulation technique and is going to be used in the qubit I am planning to study.

For generating such high frequency signals, microwave sources are needed because of high Larmor frequencies (10 – 20 GHz, *not sure if you meant that I need to exactly calculate some Larmor frequencies. Explain that for g~3 B=0.5 Tesla Ez = 3\*0.5\*57=85~20GHz*). For this purpose a signal will be used, controlled also from the python measurement application.

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

In order to determine coherence times, coherent manipulation of the spin is needed. In order to verify coherent manipulation of the spin, Rabi oscillation experiments will be conducted. The DQD will be initialized in T(1,1) charge configuration. Then the spin in the left dot will be rotated for an angle determined by the spin rotation time τBURST , followed by spin readout by trying to push the DQD to the (0,2) charge configuration (which is a singlet (0,2) configuration as explained already above). If the S(0,2) configuration is achieved, it means that the spin has been rotated. By linearly changing τBURST a Rabi oscillation pattern [11] should be observed proving the coherent spin manipulation.

Following the approach of R. Maurand et al., for evaluating the inhomogeneous dephasing time T2\*, Ramsey – fringes like experiments will be conducted [11]. First, a ∏/2 pulse around the x axis is applied to bring the spin vector from the north pole (positive z axis) to the xy plane in Figure 10. It stays there for the time τ being exposed to the dephasing noise. After time τ, a second ∏/2 pulse around x axis projects 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 results in the exponentially decaying spin up state probability, with T2\* being the dephasing time. (Check throught the proposal, for Ge spin down is the ground state)

#### Spin coherence time experiments:

##### Hahn echo T2

Coherence can be extended by the so called Hahn 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, after the first ∏/2 pulse around the x axis the spin vector lays in 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 is 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 is projected back to the z axis and a spin up probability is measured. From its exponentially decaying envelope in this case the T2ECHO will be extracted.

##### CPMG pulse sequence 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 Hahn echo experiment, for the spin refocusing. Coherence time T2CPMG will be extracted from the exponentially decaying envelope of spin up probability vs ∏ pulses separation time τ. This method is insensitive to the ∏ pulse length errors because the rotation axis alternates between y and –y subtracting the pulse length errors [15].

### Innovative aspects of the proposed project:

There has been a huge interest in the past few years in the realization of electron Si spin qubits . In this project a hole spin qubit in a DQD formed in a Ge hut wire will be studied. Despite the interesting electronic properties of this type of nanostructure nothing is known about the spin lifetimes of the confined holes. Due to the low hyperfine interaction and the heavy hole character of the wavefunction very long dephasing times are actually expected [10],[21]. In addition, easy and fast spin state manipulation should be possible because of the in situ present **large spin orbit coupling** for holes in Ge. This will also eliminate the necessity for an oscillatory magnetic field. Such a manipulation by means of oscillatory electric fields in combination with the gate reflectometry will dramatically reduce the fabrication complexity since no extra structures (charge sensor, stripline) are required except of the already defined and necessary gates. Thus this approach has high chances of **addressing the challenge of scalability**.

Finally we aim to achieve the highest reported sensitivity in the gate reflectometry setup. The gates in our DQD system (Figure 2) are positioned very closely to the hut wire (less than 4nm – defined simply by the thickness of the dielectric) in which the QDs are formed. This implies **high capacitive coupling between gate and QDs and as a consequence high speed of the gate reflectometry setup** as explained in the *Moving to the gate reflectometry* chapter.

### International collaboration:

We are collaborating with the spin qubit team in the group of C. Marcus in Copenhagen, led by **Ferdinand Kuemmeth (to ask the GO; should you here also state that Ferdinand will be in your thesis committee?)**. Actually I have been visiting them for three months end of 2015. Since they are a leading group with a vast knowledge in instrumentation and in the physics of spin dynamics, this collaboration will help me a lot in realizing the proposed project. It would be helpful to visit them once per year to discuss with the technical and physics related questions thus I am requesting 1000 Euro (I think you can ask max 500 Euro, ask the GO about it) per year as travel expenses.

The other significant collaboration is with Prof. **J.J. Zhang** who is working in the Chinese Academy of Science, in the Institute of Physics in Beijing, China. He is a material scientist providing us with the very high quality Ge hut wires which very few groups around the world can grow.

### Work table

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Task | 1st-6th month | 7th-12th month | 13th-18th month | 19th-24th month | 25th- 31st month | 32nd- 36th month |
| Second generation of the reflectometry setup | X |  |  |  |  |  |
| Moving to the gate reflectometry  Optimizing the gate reflectometry |  | X |  |  |  |  |
| Measuring the spin relaxation time T1 |  |  | X |  |  |  |
| Determining the various spin coherence times |  |  |  | X | X | X |



After each successful experiment a publication will be submitted to an high impact factor journal.

### Contingency plan:

In case it turns out that the gate reflectometry technique is not sensitive/fast enough we are going to use ohmic reflectometry. For that reason a charge sensor proximate to the double quantum dot should be added during the nanofabrication process of the samples. Charge sensing has been recently demonstrated in our group for hut wires [22]. For the charge sensor a single QD located very closely and capacitively coupled to the DQD is going to be used. Whenever the charge configuration in the DQD will change, the impedance of the charge sensor will change and thus the reflected signal amplitude.

### Personal qualification:

I permormed my undergratduate studies at the *f*aculty of electrical and computer engineering, at the University of Zagreb, Croatia. During my undergraduate studies I was a teaching assistant in the course “Electronics” which is mandatory course for all students on the faculty. This allowed my to deepen my knowledge in electronic instrumentation? Sth like this. For my master thesis, performed with professor Tomislav Suligoj I focused on …, which gave me a strong background in …. .

Fascinated by the idea of quantum computation, I moved in April

*April 2015*the Johannes Kepler University to work as a research assistant in the group of Georgios Katsaros. There I started working on the development of an ohmic reflectometry system for charge readout of SiGe QDs. The realization of printed circuit board designs, the development of python codes for controlling various DC and high frequency signal instruments were among my tasks. I also performed 4K measurements on single hole transistors based on SiGe nanowire QDs fabricated in our group by Hannes Watzinger. During that time I had the chance to attend also an important conference in the field: SpinTech VIII – Basel, Switzerland, 10-13 August 2015. (sispin is an internal meeting so typically one does not mention them). In October 2015, and for three months, I went on a *r*esearch visit to the Center for Quantum Devices, Niels Bohr Institute, Copenhagen. I worked in the group of Ferdinand Kuemmeth. This group is developing spin based qubits in GaAs and Si/SiGe lithographically defined double and triple quantum dots. They are one of the biggest and most successful groups in the field of quantum computation. During my research stay, I learned about high end laboratory equipment including cryogen free dilution refrigerators, waveform and signal generators, RF equipment (amplifiers, filters, special type of coaxial cables… ). I was also following the experiment of Filip Malinowski – tuning the GaAs double and triple QD for coherent spin manipulation and readout using a charge sensor ohmic reflectometry setup. Since 2016 I am a PhD student of Georgios Katsaros, at the Institute of Science and Technology (IST), Austria, currently working on a second version of a reflectometry readout system for spin relaxation experiments. (Here I would not give many details so that they do not say that you have already developed too much).

*Somehow I feel that the conference is not needed here.*

So now just the abstract is missing and the merging of the two parts. Once you do it check it once more to see that we are not repeating things and send it to me. I will try to read it as fast as I can so that next week you can send it to the GO.

I think it would be nice if you can fit your picture Figure 2 (which appears in the next pages where you show the SEM image of the Double dot with the multiple gate reflectometry tank circuits)

**What is still missing is a kind of one page description of the project in the beginning, an abstract**

THINGS THAT ARE KICKED OUT, BUT MAYBE SOME OF THOSE CAN BE IMPLEMENTED ABOVE:

### Overall goal of the project:

To implement one of the Loss and DiVincenzo’s criteria:

* **strong quantum measurements**,

and conducting **experiments of spin manipulation**.

Strong quantum measurements can be achieved by implementing gate reflectometry in our type of qubit structures. After having state readout solved, spin manipulation experiments can be done by applying bursts of microwave signal on electrostatic gates *(as explained in research methods).*

Spin manipulation experiments will be guideline for achieving second of the Loss and DiVincenzo’s criteria:

* accurate quantum gate operations

## Specific aims

### Clear aims:

Samples are done in cleanroom… *(take from someone in group)*

All experiments are done on DQD and TQD samples placed on the printed circuit board (PCB) sample holder *(put the picture)* in the dilution refrigerator with a base temperature of 10 mK.



Fig. x1. PCB holder (green) with mounted nanowire based sample (middle, grey) fabricated in our group by Lada Vukušić. Altogether mounted on golden plated copper fork on the dilution fridge insert. Copper wires are coaxial cables providing high frequency connection for spin manipulation and readout. Nanometer gates and ohmic contacts on the sample are connected by wedge wire bonding.

Electrical connection with the sample is achieved through thermally low conductive looms for DC signals and coaxial cables for RF and microwave signals. *(put the picture of the probe)* All cables finish in PCB connector and further electrical contact with the sample is achieved by wedge wire bonding.

On room temperature side there are several instruments for sending and receiving the signals from the sample. Firstly, DQD and TQD needs to be tune in correct electrostatic configuration what is achieved through the low-noise, optically isolated, voltage DC sources.

Sequences of high-speed pulses (ranging from hundreds of nanoseconds to several milliseconds) coordinated together with bursts of microwave signals (several GHz up to several tens of GHz) are sent via coaxial cables to manipulate DQD and TQD charge and spin state thus **providing spin qubit manipulations**.

Pulses are generated by arbitrary waveform generator (Tektronix AWG5014C) and microwave signals by microwave signal source (Rohde & Schwarz SMF100A).

**Qubit state is read-out** by probing radio-frequency (RF) signal reflected from resonant circuit consisted of discrete inductor and capacitor and gate capacitance between DQD and TQD top gates and confined charge area in those. Probing is done by high frequency lock-in measurement technique using Zurich Instruments UHFLI lock-in amplifier.

### Hypoteses:

*(Don’t know what to put here and what in research metodology)*

Main hypotheses is that our gate reflectometry is sensitive enough to achieve fast quantum state readout. Read out parameter (one which needs to be boosted) by gate reflectometry is resonance frequency shift ∆f due to hole tunneling form one to another dot in DQD or TQD system: . Resonant frequency, , of resonance circuit depend on externally added lumped inductance L which is externally added, and parasitic capacitance Cp. Because L is easily tunable and Cp can be reduced to some level by engineering, main hypotheses is that quantum capacitance due to a hole tunneling, CQ is big. It is given by our sample and we expect it to be relatively high because of the following reasons.

*(This need to be changed according to Csigma)*

CQ depends on capacitive coupling of reflectometry readout gate to QDs in a qubit Cg, and parasitic capacitances Cp, according to:

Previous expression suggest that pathway for boosting sensitivity of gate reflectometry is to have Cg high and Cp low.

Since in our types of structures gates are positioned on the top of the nanowire (d is small, l and w are relatively large) consisting QDs (Fig 1.) we expect high Cg ,according to:

Small parasitic capacitance we are going to achieve by engineering our sample holder (PCB). Isolating PCB sample area from the ground by removing ground planes and decoupling RF and DC ground by putting relatively large resistors in DC line around that area. On Fig.x.1. around the sample PCB is translucent indicating that there is no copper ground plane.



Figure 1. Nanowire based single quantum dot, predecessor of double quantum dot on Fig.x.

## Research methods

Here we are proposing integration of two qubit Loss and DiVincenzo’s criteria in our type of qubit. First is **qubit state (spin) readout**. Other one is **spin state manipulation**.

### Qubit state readout:

C:\Users\jkukucka\Desktop\IST\DOC Fellowship\DQD_reflectometry.tif

Figure 2. Gate reflectometry schematic on the DQD sample from Fig.x1. LC resonators are connected to three of the gates. Signal from different gates are distinguished by frequency multiplexing since resonant frequencies are different because of different inductor values.

**What is reflectometry?**

Reflectometry is readout technique based on change of wave reflection coefficient Γ. It comes from electromagnetic wave principle – if the wave is travelling in media with impedance Z0  (e.g. coax cable) and it encounters change of impedance (e.g. coax end) to Z, portion of the wave will be reflected back according to the expression: , where Ar is amplitude and ᵠ( Ar) phase of the reflected, and Ain amplitude and ᵠ(Ain) phase of incoming wave. Reflection coefficient phase is ᵠ(Γ).

Putting resonant circuit with incorporated device instead of coax cable end one can measure change in impedance (capacitance) of that device. If elements of a resonant circuit – inductance L and capacitance C are properly chosen, on the resonant frequency of that circuit, , wave reflection coefficient Γ is minimized and it’s phase has inflection point and highest slope, Fig 2. top right blue and red.

In case of resonant LC circuit consisted of just L and C with very small R, Z is almost purely imaginary consisting of inductive and capacitive reactance. Thus if capacitance of sensed device changes -> ᵠ(Γ) changes and so phase of reflected wave ᵠ( Ar). Thus, by measuring phase of reflected wave ᵠ( Ar) and comparing it with ᵠ(Ain) one can get information of the impedance (capacitance) of sensed device.



Fig 3. S11 parameter vs frequency for different capacitors *(put something from qucs instead of this one)*

**Our plan:**

RF wave (tens to hundreds of MHz) is generated and sent from UHFLI out port down the coax cable. Going through directional coupler and encountering three resonant circuit frequency multiplexed on different resonance frequencies by choosing different values for surface mount inductors L1, L2, L3. Each of this inductors will be wire bonded to finger like gates, as shown in Fig 2. Here is an example for nanowire, double quantum dot based qubit. Gates LP (left plunger) and RP (right plunger) are capacitively coupled to the left and right quantum dot respectively. When electron undergo tunneling between the dots there is an onset of quantum capacitance, changing overall capacitance seen by the resonant circuit, which changes resonance frequency (according to expression for f0) and consequently amplitude and phase of reflected wave which is then measured.

### Spin state manipulation:

*Write something about it*

# References:

J.I.Colless, Dispersive Readout of a Few-Electron Double Quantum Dot with Fast rf Gate-Sensors”

Some lecture: <http://www.physics.udel.edu/~msafrono/650/Lecture19.pdf>

About inductors: <http://info.ee.surrey.ac.uk/Workshop/advice/coils/air_coils.html>,

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