Operations on spin qubits

With standard semiconductor technology, billions of transistors can be integrated on a single chip.

This forms one of the key motivations for quantum dot qubits, as these qubit types are fabricated using the same technology, such that one can envision billions of quantum bits on a chip.

In this lecture we focus on the operation of these quantum dot qubits.

We will discuss how qubits are defined, how they can be initialized and readout, how the qubits can be controlled and how these qubits can be coupled to one another to execute two-qubit logic gates.

We start with an empty quantum dot connected to an electron reservoir.

The quantum dot energy levels are above the Fermi energy of the reservoir and so no electrons can tunnel from the reservoir to the dot.

We define our qubit states on the spin states of the quantum dot.

To do so, we apply a magnetic field on the order of a Tesla.

Due to the Zeeman energy, the spin states are then split by about hundred micro electron volt, assuming a g-factor around 2.

The lowest level corresponds then to the state spin down, while the upper level corresponds to the state spin up.

We can initialize our quantum dot in the state spin down, by simply lowering the energy level such that the state spin down is below the Fermi energy, while the state spin up is still above the Fermi energy.

At this position, only an electron with state spin down can tunnel from the reservoir to the quantum dot.

If we pulse the levels even deeper, the quantum dot will remain in the state spin down.

No electrons can tunnel from the reservoir to the quantum dot, since it is already occupied, and thus the state remains spin down.

If we want to readout the state, we can simply do the reverse protocol.

We align the levels such that the Fermi energy of the reservoir is in between the spin down and spin up level.

An electron will only tunnel out if the state is spin up.

This sequence converts a spin in to charge, because there is only charge movement if the state is spin up.

As quantum dot systems can also be used as highly sensitive and accurate electrometers, we can readout the spin state by measuring the charge transfer during this protocol.

In the graph below we see the current through a quantum dot electrometer.

We see that that there are different current levels.

These differences correspond to the different gate voltages that are applied to align the electron reservoir and quantum dot levels.

The middle level corresponds to the alignment for readout.

In some cases we see that there is a small bump around 1ms and in some case we don't see it.

This corresponds to the spin-to-charge conversion.

The experiment shown here is performed in GaAs.

Electrons in GaAs have a negative g-factor.

A good exercise is to verify yourself that in this particular case a bump corresponds to the state spin down and not to the state spin up, as one may expect.

This method of readout is called Elzerman readout and has been one of the central methods for readout of spin qubits.

Now that we know how to initialize and readout the spin state, we can start controlling the state and turn it into a qubit.

Qubit control can be realized by introducing an alternating magnetic field in a direction perpendicular to the applied magnetic field.

This is done by applying an ac current through a small strip close to the quantum dot system.

The AC current generates an electromagnetic wave.

When the frequency of this wave matches the resonance frequency of the qubit, photons are generated with an energy equal to the Zeeman energy of the spin states and they can flip the spin state.

If we introduce this alternating magnetic field then we will observe that the spin starts to rotate as a function of time.

These oscillations are called Rabi oscillations and they form the basis of our single qubit rotations.

This mechanism has been demonstrated with quantum dot systems and first in the material GaAs and in the figure you see that as a function of time, coherent oscillations appear with a frequency dependent on the applied electromagnetic power.

Unfortunately, these oscillations do not survive until infinity.

The oscillations decay due to qubit decoherence.

A major source of decoherence for spin qubits in GaAs is the interaction between the electron spin and nuclear spins in the environment.

GaAs has many isotopes with a nonzero nuclear spin and these can interact with the qubit through the hyperfine interaction.

These interactions vary over time.

Consequently, the qubit frequency changes over time and so the emitted photons from the stripline are not always in resonance with the electron spin.

This is a major limitation, but fortunately, it can be solved by simply changing the host material.

Silicon can be purified to an isotope with zero nuclear spin, Silicon-28.

As one can see, in this material one can just simply keep on going with rotating the electron spin.

This is of course very favourable for qubit operations.

The resulting improvement becomes even more apparent if we compare the coherence time of electron spins in different materials.

In this figure, you see three different sequences to determine the quantum coherence of a qubit.

The simplest sequence is the Ramsey experiment.

It starts by rotating the spin to the equator using a pi/2 pulse.

Then, another pi/2 pulse is applied to rotate it to the state spin up.

In the experiment, the waiting time in between these two pulses is varied.

This results typically in an exponential decay, where the time constant in the exponent defines the coherence time.

The Hahn echo and CPMG sequences are more sophisticated sequences that can extend the coherence time and they probe the ultimate quantum coherence.

From the figure it becomes clear that the quantum coherence can be greatly improved by both using sophisticated sequences and by using materials with zero nuclear spins, resulting in a maximum coherence time of tens of milliseconds.

And this is an eternity in the quantum world.

Now that we know how to initialize and read and control qubits, we can start to couple qubits together.

To do so, we use the exchange interaction.

This interaction can be controlled by tuning the electric gates of a quantum dot qubit, which modulates the potential landscape.

To turn the interaction on, the electric gates are pulsed such that the energy barrier between the qubits is short and low.

Consequently, the wave function of the two electron spins start to overlap and they hybridize.

In the figure on the left, there is no interaction.

In the figure on the right there is interaction.

Now what is crucial here, is that when the interaction is on, the resonance frequency of one qubit is determined by the state of the other qubit.

In the left figure, we see that the energy in flipping the red qubit is independent on the state of the blue qubit.

It is good to verify this yourself.

If we overlay these figures it becomes clear that the scenario is different when interaction is on.

When interaction is on, flipping the red qubit costs less energy when the blue qubit is in the state spin down, while it costs more energy when it is in the state spin up.

This is very important, as we can now control one qubit depending on the state of the other qubit, and use this, for example to create quantum entanglement.

One can also see from the figure that we have two knobs that we can use for control.

First, we can directly control the tunnel barrier.

Secondly, we can also change the relative energies of the electron spin states.

By moving towards the state where one electron spin is almost doubly occupied, the exchange interaction increases.

The first approach where one controls the tunnel barrier may be the preferred method, as operation is here at the so-called symmetry point.

At this point the qubit is the least sensitive to noise, as the slope of the energy level is to first order zero with respect to the detuning.

However, the second approach is what is typically been exploited in experiments today as this is often easier to do.

In the experiment we see here, the second option of controlling the detuning has been adopted and the experiment combines both single and two qubit gates.

The two graphs on the right show two experiments.

In the top graph, the red qubit is always in the state spin up.

In the bottom graph the red qubit is in the state spin down.

The blue qubit is initialized using the Elzerman method by aligning the electron spin to the reservoir.

Then a pi/2 pulse is executed by applying an AC current through the stripline.

Now the detuning is changed.

This detuning brings down the second empty level of the red qubit.

The state of the blue qubit hybridizes with this level and the resonance frequency changes accordingly.

This change in resonance frequency causes in-plane rotations of the blue qubit.

As we can see from the experiment, the blue qubit starts to rotate, but with a frequency that is dependent on the state of the red qubit.

A special point is reached after roughly 0.5 a microsecond, as then there is exactly a pi-rotation difference between the two states.

The experimental sequence is completed by another pi/2 pulse using the stripline.

We now see that at this special point of 0.5 microsecond, the blue qubit returns to the state spin up or spin down, depending on the state of the red qubit.

This qubit dependent controlled rotation is called a controlled not gate or CNOT gate and constitutes a very important gate in quantum computation.

Now we can combine all aspects, from readout and initialization, to single and two-qubit control, and use this implement elementary quantum algorithms.

For example, here you see an experiment where these operations are combined to demonstrate Grover's search algorithm and the Deutsch-Jozsa algorithm.

These experiments demonstrate the feasibility of quantum dot qubits, and now one of the main challenges is to up-scale the qubit number and qubit quality to go to large systems.

In the field of quantum dot quantum computation, the vision of a future quantum computer is one where small arrays of quantum dots are coupled together using long-range qubit links.

The small arrays operate using the ingredients as we discussed here.

The long-range links could be based on quantum buses, where an electron spin is transported over an array of quantum dots.

Alternatively, the electron spin can be coupled to photons in superconducting microwave cavities.

Such approaches are now actively being pursued and rapid advancements are being made, and these lay the foundation for a future quantum dot quantum computer.