

## Superconducting qubits: quantum mechanics by fabrication



### **Hans Mooij**

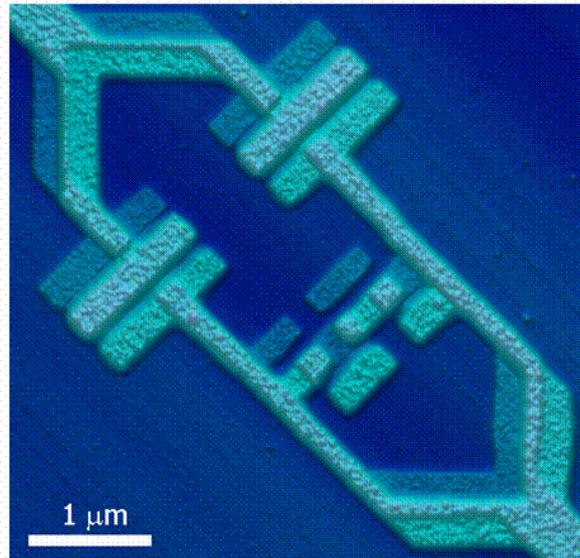
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### **Abstract**

Superconducting qubits are quantum two level systems that are fabricated with the tools of semiconductor chip technology. Because they are made of superconducting material their coherence is high. At this time single qubits of different types have been fabricated and studied, as well as two coupled qubits. They behave as true quantum bits over times as long as 4 microseconds, while the basic operations can be performed in less than a thousandth of a microsecond. The contribution to superconducting qubit research is relatively very high from Europe.

### **Introduction**

To build the large quantum computer of the future, it seems obvious to start with particles that have long-proven quantum properties, such as atoms. They are by nature well-isolated units with properties that are almost not influenced by the outside world. However, this also means that their mutual interaction is weak and completely new techniques are required to control many thousands of them. The ordinary computers that we all use contain billions of solid state devices. If one could fabricate qubits with the same technology, integration to large numbers would be relatively easy. Ten years ago, it was hard to imagine that such fabricated quantum particles could exist. Now, superconducting circuits as pictured (**Figure 1**) can be driven in the same way as the spins in an MRI-scan. Research groups in Europe, supported by the European Union in the Future and Emerging Technology program (projects SQUBIT and SQUBIT2), have been instrumental in this development.



**Figure 1**

We all take for granted that quantum mechanics must be used to describe quarks, electrons, atoms and molecules. Why does it stop there? Why not use the Schrödinger wave equations to describe a virus or an elephant? All matter is subjected to the rules of quantum mechanics, but in large objects the wave description of the multitude of constituent particles loses relevance. There is a close analogy with light. When a second light bulb is switched on in a room, the average amplitude of the light waves is not doubled, only the power. The light waves from the hot wires are not coherent, they do not have exactly the same frequency and phase. With two laser beams one can double the amplitude, because laser light is coherent. Something similar is possible with quantum mechanics of large objects. In recent years we have discovered that individual micrometer-sized objects, which have been fabricated with the tools for semiconductor chip technology, do behave as coherent quantum particles. These artificial quantum objects are very promising as quantum bits for a quantum computer, because their properties can be designed and tooled. They can be fabricated in very large numbers on a chip. To obtain the essential coherence, the objects are fabricated from superconducting material. Superconductivity is the state that occurs in many metals when they are cooled down to very low temperatures.

### **Superconductivity**

In a superconductor, the electrons are condensed into one single collective fluid. In ordinary metals or semiconductors all electrons occupy their own quantum state, of which there are millions in a small transistor. Quantum mechanics is needed to understand the average electrical and thermal properties, but the detailed control of each state that is necessary for quantum computing can only be realized when a few electrons are isolated from the others and addressed individually. In superconductors, all electrons are described with one single quantum state. A significant amount of energy is needed for an electron to escape from this collective fluid, so the single state is quite robust. The consequence is that an electrical current can flow through the metal without friction, no energy or information is transferred to the crystal lattice. This is the ideal starting point for a solid state quantum bit. To explain these superconducting qubits, a

short discussion of some elements of the theoretical description of superconductivity is needed.

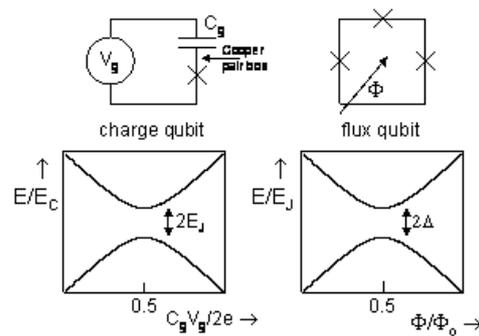
In superconductors, the electrons form pairs which are called Cooper pairs and which have double the charge of single electrons. The pairs are described with a quantum wave function. An ordinary wave has an amplitude (the maximum height of the wave) and a phase (where is the wave at what time). The amplitude of the superconducting wave function determines the number of pairs, the way the phase changes in space determines the current. As the pairs have an electrical charge, the phase is also intimately connected with the magnetic field. The quantum nature of superconductors leads to the fact that it is impossible to determine both the number of Cooper pairs and the phase accurately at the same time, in analogy with the better known Heisenberg relation for a quantum mechanical particle that says that a very accurate measurement of the velocity leads to uncertainty in its position and vice versa.

Integrated semiconductor circuits have transistors, for superconducting electronics one uses devices that are called Josephson junctions. A Josephson junction consists of two parallel metal thin films that are separated by a very thin insulator. In superconducting qubits the junctions are usually made of aluminium, with aluminium oxide as the insulator. The oxide is so thin that electrons and Cooper pairs can cross through it, in a process that is itself quantum mechanical and is called tunnelling. The Josephson tunnel junction provides a weak coupling between the two superconducting films. The engineer of superconducting electronics chooses the overlapping area of the two films and the oxide thickness to obtain the needed coupling strength. This strength is expressed as energy, the Josephson energy. The maximum current that can pass through the junction without voltage is proportional to the Josephson energy. For quantum circuits, another energy is equally important. This is the energy of the electric field in the junction when one Cooper pair is moved across the insulator from one metal electrode to the other, called the charging energy. It can be ignored in large junctions. However, in junctions that are smaller than one ten-thousandth of a millimetre a significant voltage has to be applied across the junction to provide the energy for a Cooper pair to cross the insulator. The different types of superconducting qubit are best distinguished with the relevant strength of the two energy terms.

### Superconducting qubits

A good recent review of superconducting qubits is provided by reference 1. The charge qubit uses the charging energy to define its two states, while the smaller Josephson energy provides the transfer between them. The charge qubit consists of a small superconducting volume called the Cooper pair box that is connected to the circuit by a Josephson junction. First studies of Cooper pair boxes were performed by the Quantronics group at the CEA in Saclay, with support from the European Union [2]. A voltage applied to a nearby gate influences the energy of the charges on the box (**Figure 2**). For zero gate voltage, the lowest energy is found with no electrical charge. For a specific value of the gate voltage, typically a millivolt, the box has its lowest energy when it is charged with one Cooper pair. In between, there is a value where the energy values with zero and with one pair are equal. The qubit is used in the regime near this symmetry point. Because the Josephson tunnelling provides a connection between the two charge states, two new superposition states are formed. Each superposition is a well-defined combination of the charge states. At the symmetry value of the gate

voltage, the energy values of the superposition states are different by twice the Josephson energy. The qubit in equilibrium occupies the superposition state with the lowest energy, the ground state. It can be excited to the higher energy state by the application of an AC microwave voltage to the gate, with a frequency that exactly corresponds to the energy difference. It is also possible to create superpositions of the qubit states, in the same way as with spins in nuclear magnetic resonance (NMR). In particular when a measurement is performed, one must remember that the qubit states themselves are well-known superpositions of the charge states. Measurement can be performed by measuring the electrical charge on the Cooper pair with a small on-chip measuring instrument. Such an electrometer has been developed at Chalmers University in Sweden [3]. Other measurement techniques are possible. The first time that coherent dynamics were observed in a charge qubit was at NEC in Japan.

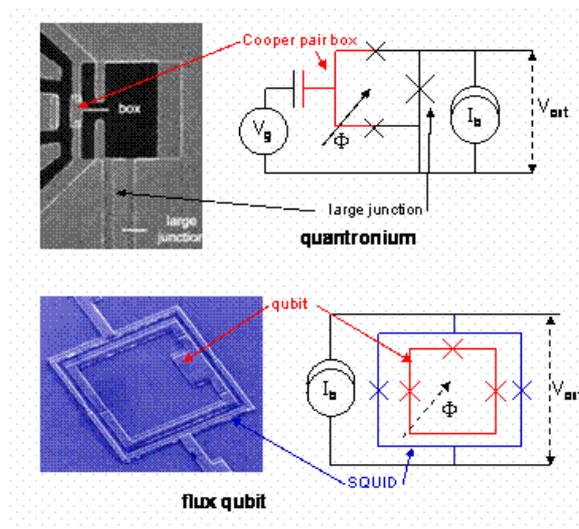


**Figure 2**

The flux qubit uses the opposite regime where the Josephson energy is significantly larger than the charging energy. The phase of the superconducting wave function is now more important than the charge. When the phase varies along the loop, a superconducting current is present. When the whole loop is traversed, the phase has to come back to its original value, or may be different by an integer number times  $2\pi$ . In a superconducting loop, a different value of the total phase change is connected with a different circulating current. For zero magnetic flux (the magnetic field times the area) through the loop, the lowest energy is obtained for a phase change zero and with zero current. When the flux through the loop is equal to the superconducting flux quantum (Planck's constant divided by the Cooper pair charge  $2e$ ), the lowest energy is found when the phase change is  $2\pi$ . There is a close analogy with the charging energy, the magnetic flux taking the role of the gate voltage. A unit  $2\pi$  of phase change is called a fluxoid. At a value of the flux equal to half a flux quantum, the states with and without a fluxoid have equal energies. The flux qubit is operated in this neighbourhood. To obtain quantum tunnelling between the fluxoid states, the Josephson energy should be not too large and the charging energy not too small. The two fluxoid states have opposite circulating current through the loop [4]. The previous discussion shows that there is a large similarity between charge and flux qubits, they are in fact each other's dual.

A very inventive extension to the charge qubit was developed by the group in Saclay [5]. The principle is indicated in **Figure 3**. The Cooper pair box has two parallel junctions and it can be calculated that the states with and without one Cooper pair have currents flowing through these two junctions with opposite direction. It is easier to detect this current than to measure the charge directly. Fine-tuning is possible by variation of the magnetic flux through the small loop. For practical reasons that have to

do with material properties, it seems unlikely that the pure charge qubit can be used for large circuits. Scaling up to large numbers of qubits is possible with the quantronium.

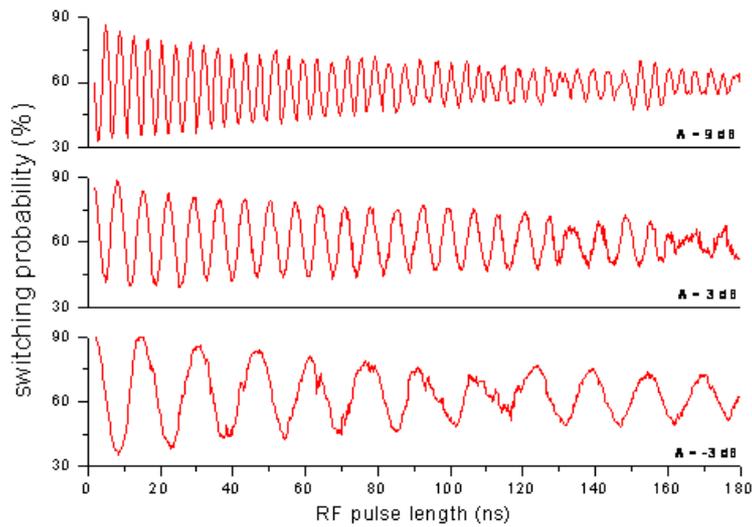


**Figure 3**

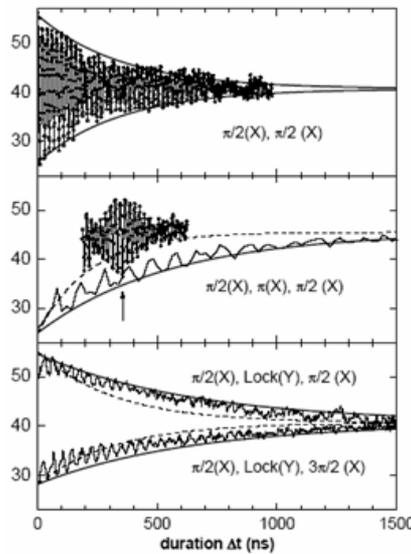
Another type of superconducting qubit, called the phase qubit, was developed by a number of groups in the United States, the group at NIST having the most developed results. This qubit employs a single Josephson junction with a large value of the Josephson energy, but the effective strength is reduced by a strong bias current close to the maximum value. With the junction acting as an inductor, an oscillation occurs which provides the qubit states. No significant work on this type of qubit is performed in Europe.

### Present status

In the last few years progress has been fast in superconducting qubits, with essential contributions from a large number of European groups. In fact, more than half of the total work in the world comes from Europe. An example of coherent oscillations between qubit states is shown in **Figure 4**. Charge qubits are studied experimentally in Sweden (Chalmers University) and Germany (PTB Braunschweig). The quantronium continues to be developed at Saclay with beautiful and very promising results. Coherence times of more than 500 nanoseconds are obtained. Detailed control of one qubit has been demonstrated, using well-known sequences of microwave pulses as developed over many years for nuclear magnetic resonance [6]. An example is shown in **Figure 5**. The next step will be the study of two qubits.

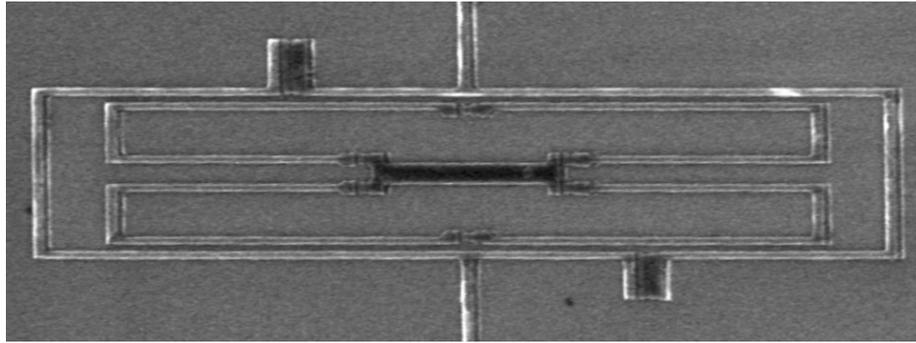


**Figure 4**



**Figure 5**

For flux qubits, the major contributions on the world scale have come from Europe, although clear activity is also present in the United States and Japan. Single qubits are now well-controlled and attention is moving towards multi-qubit systems. In Jena University in Germany, a spectroscopic technique was used to observe the behaviour of two interacting flux qubits [7]. At Delft University, The Netherlands, coherent dynamics of single and double flux qubits has been obtained. Coherence times are of the order of 400 nanoseconds, but with special compensation techniques have been increased to 4 microseconds. Qubit operations can be performed in a fraction of a nanosecond. The combination of a single flux qubit with a quantum oscillator was also brought to coherent time-evolution [8]. A picture of a 2-qubit sample is shown in **Figure 6**.



**Figure 6**

Five years ago, it was supposed by many that decoherence would be too strong in superconducting qubits for them to become practical. It remains a significant factor, but steady progress is made. Decoherence means that quantum information leaks out to uncontrolled degrees of freedom. The measurement circuit is one definite source of decoherence, but thanks to strong contributions from theoretical groups this problem is well understood. The connecting circuits can be designed in such a way that the relaxation and dephasing rates are long enough to allow 100000 operations. Theory groups in Europe have been leading the world in this area. Theory groups in Germany (Karlsruhe, Munich, and Regensburg) and Italy (Catania, Pisa) are to be mentioned specially. Unfortunately, there are other processes that induce decoherence. They are connected with microscopic materials defects in the insulating barriers of the tunnel junctions, that are unstable in time. Materials research is needed to improve the quality of fabrication. It is possible to fabricate superconducting films with perfect crystal structure and very homogeneous oxide, but it is still difficult to make the small junctions in this way. More work is needed.

Apart from the mentioned groups, in a number of places in Europe general technology for superconducting quantum electronics is developed and new effects are studied. In this context, groups in Finland (Jyväskylä and Helsinki) are important. In Grenoble, France, a special quantum system with an integrated oscillator is studied, that may well lead to a new type of qubit. All groups collaborate and exchange information on a very regular basis through the European projects SQUBIT and SQUBIT2, in the 5<sup>th</sup> and 6<sup>th</sup> Framework respectively.

### **Prospects**

Superconducting qubits are catching up with such established quantum physics fields as nuclear magnetic resonance and atom physics. The promise of scalability to large numbers of qubits is fully present for the superconducting technology, using semiconductor fabrication techniques. Among the solid state quantum systems, superconductors are clearly ahead in achieving coherent quantum dynamics. No insurmountable barrier for further progress is in sight.

### **Conclusions**

Superconducting qubits have been developed that perform the basic operations for a quantum computer. More work is needed, but the present results indicate that the

understanding of the systems is sound and that there is no principal problem to build a large quantum computer based on this type of qubit.

The operation times of superconducting qubits is of order 1 nanosecond, the coherence times are at this time around several microseconds. Coherence is still limited by materials defects and optimization of junction fabrication needs to be performed.

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### SQUBIT2

Superconducting Qubits: Quantum Computing with Josephson Junctions

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Contact Person: Goran Wendin, Chalmers University Sweden, [goran.wendin@mc2.chalmers.se](mailto:goran.wendin@mc2.chalmers.se)

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### FOM Concentration Group Quantum Information Processing

Start date: 01/06/2004

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Contact Person: Leo Kouwenhoven, [Leo@qt.tn.tudelft.nl](mailto:Leo@qt.tn.tudelft.nl)

### NanoNed Flagship Quantum Computing

Start date: 01/01/2005

End date: 01/01/2010

Web site: <http://www.stw.nl/nanoned/>

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