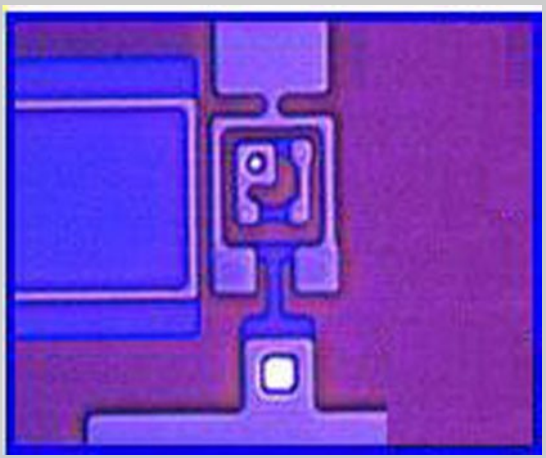
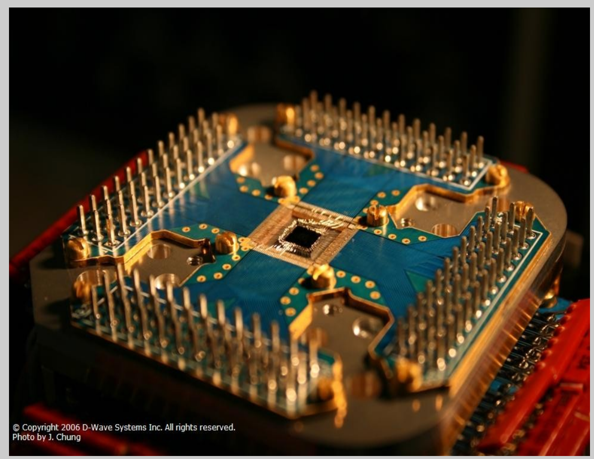
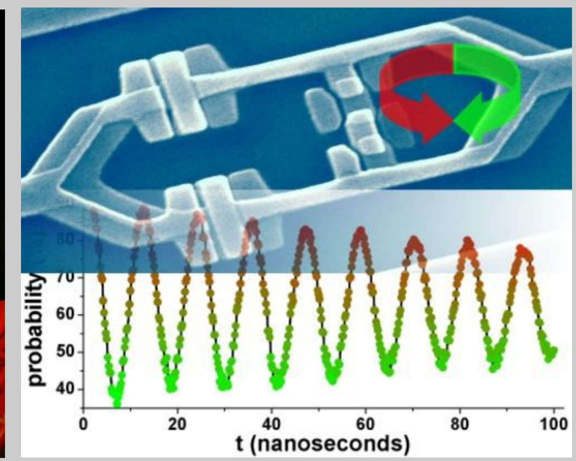
# Quantum Computing for Beginners: Building Qubits






Suzanne Gildert
Condensed Matter Physics Research (Quantum Devices Group)
University of Birmingham

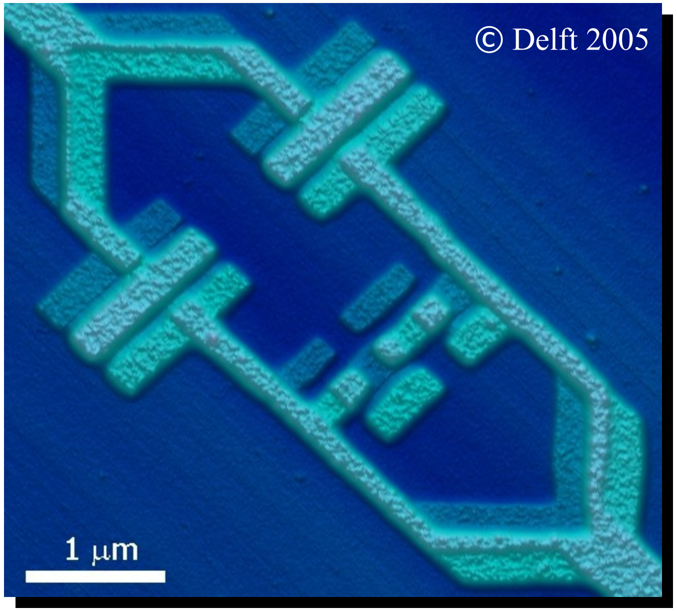
28/03/2007

# Overview of this presentation

What is a Qubit?

What are the 'basic' principles of the qubit system?

What are the design rules?




What's so great about them?!

How are they fabricated?

How do researchers test them?

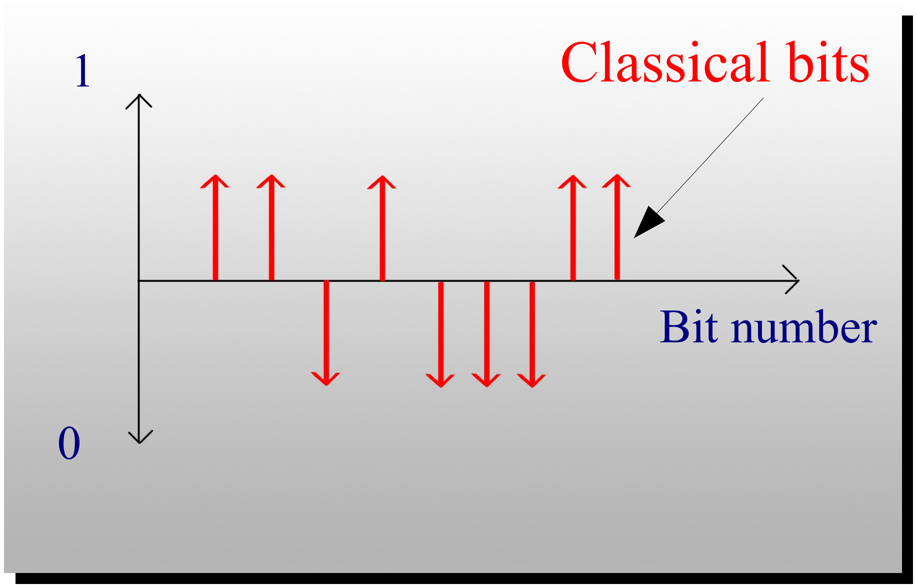
What are the applications?

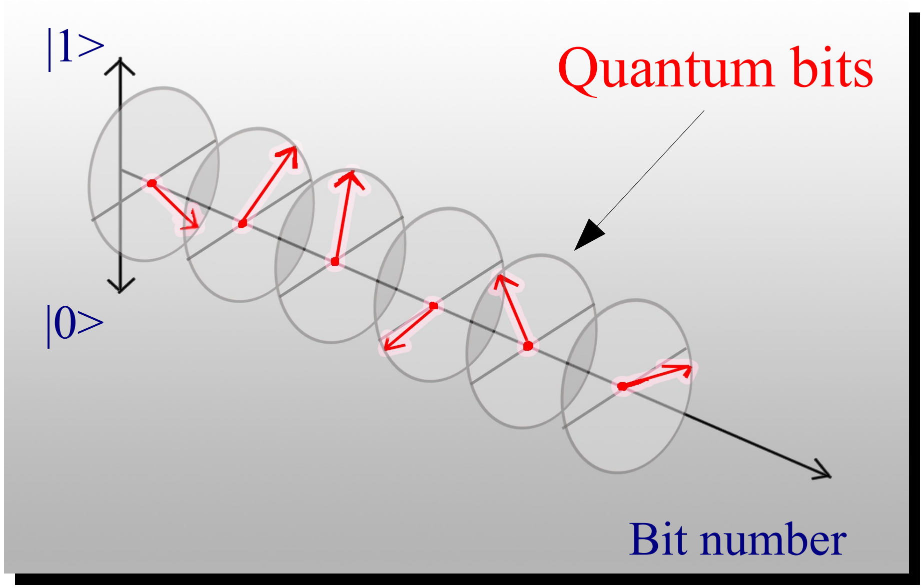
# What is a Qubit?

What is a Qubit?

- A qubit (or QUantum BIT) is similar in concept to a standard 'bit' - it is a memory element. It can hold not only the states '0' and '1' but a linear superposition of both states, α|0> +β |1>
- In physicicts terms, we denote the states |0> and |1> respectively.

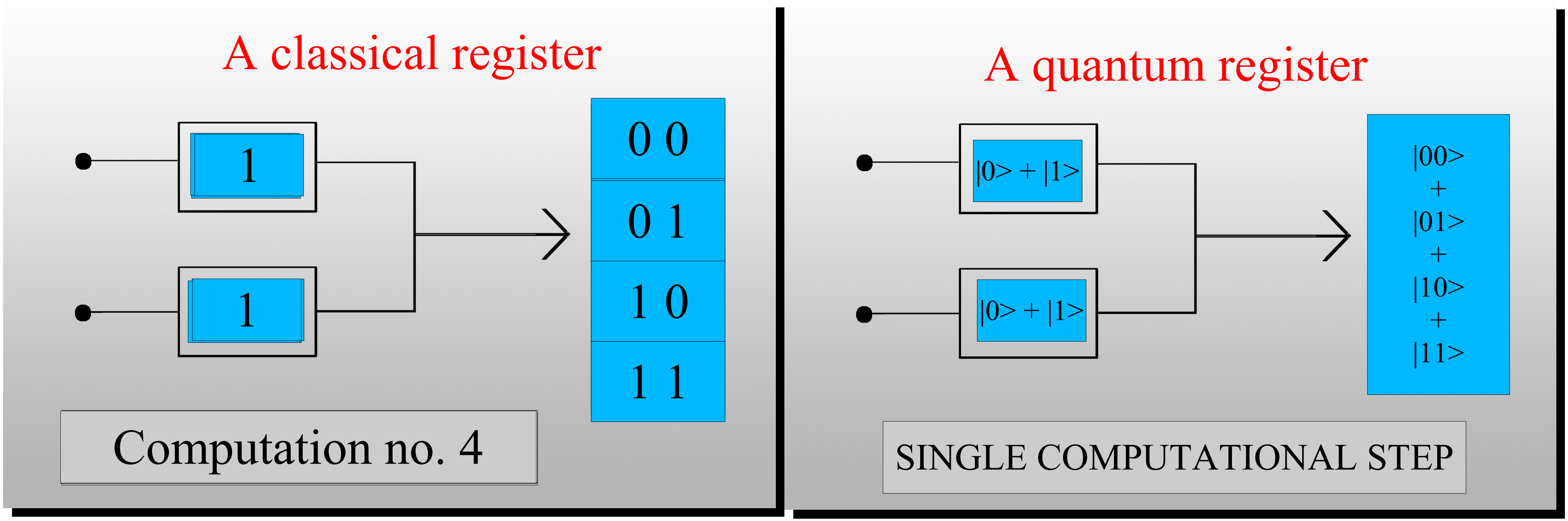
**QUBIT vs. CLASSICAL BIT**



# What's so good about the Qubit?

- Qubits are useful for quantum computation
- Useful when lots of permutations need to be tried
- Suppose we want to calculate and store all possible outcomes of a particular calculation...



# Choosing your Qubit

- Qubits can be realised using many different methods:
Photonic systems
Laser Ion traps / NMR systems
Quantum Dots / artificial atoms

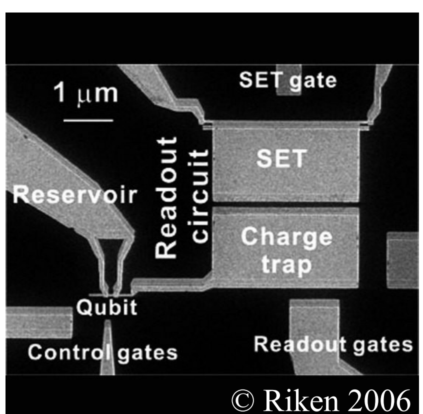
- We are working towards Solid State Qubits, using *Superconductor* technology

It is widely believed that the only way to realise large scale integration of qubits will be with solid state technologies, in the same way that current computation can be scaled up by using transistors.

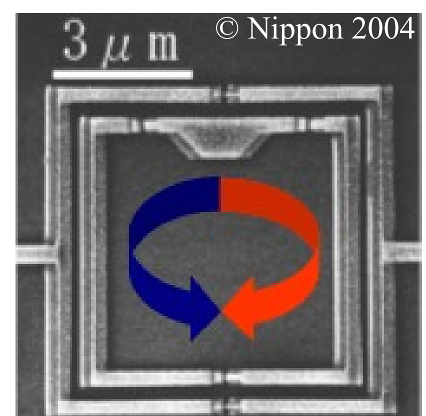
There are 2 main families of Superconducting Qubits:

- Charge Qubit and Flux/Phase Qubit

**CHARGE QUBIT**



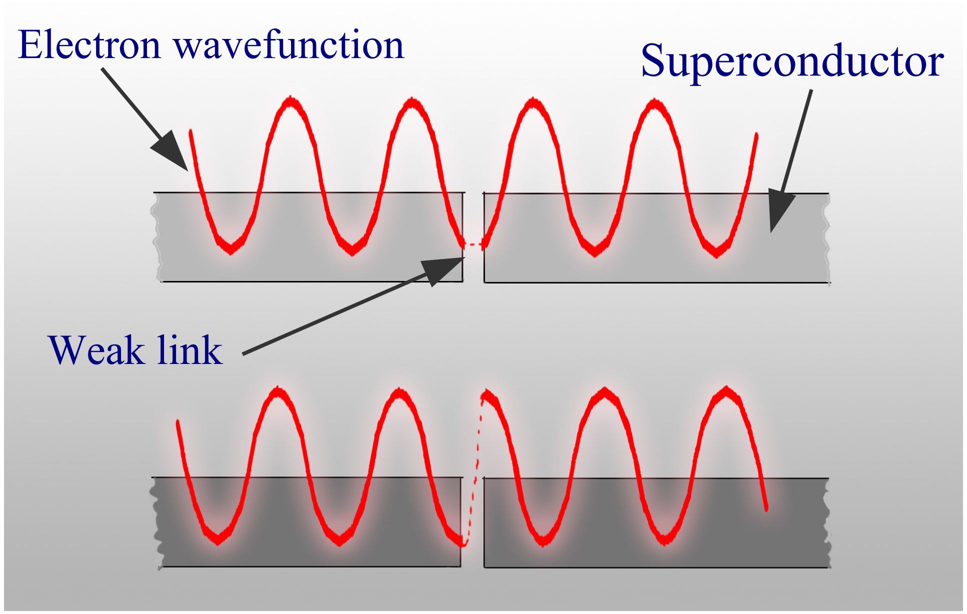

**FLUX QUBIT**

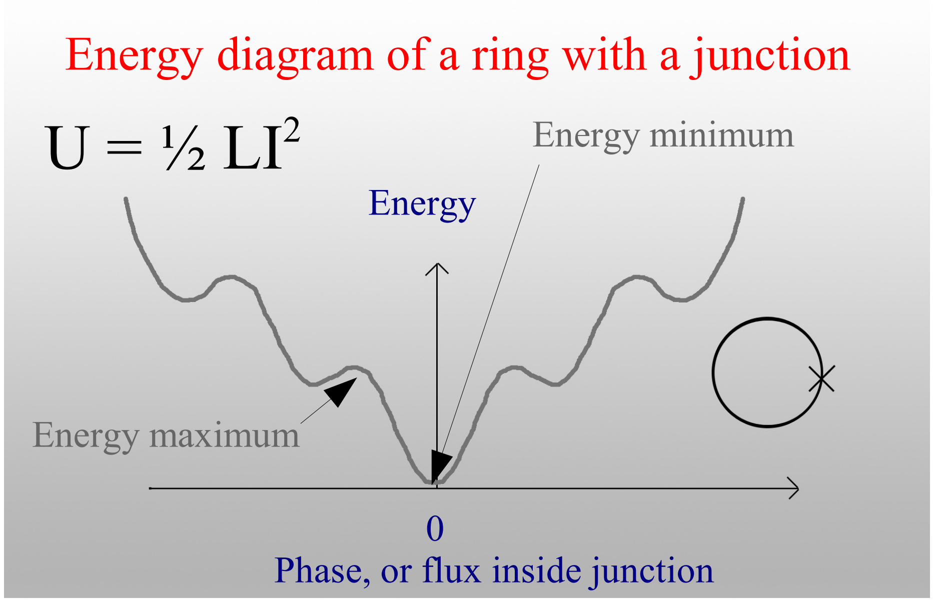



UNIVERSITY OF BIRMINGHAM

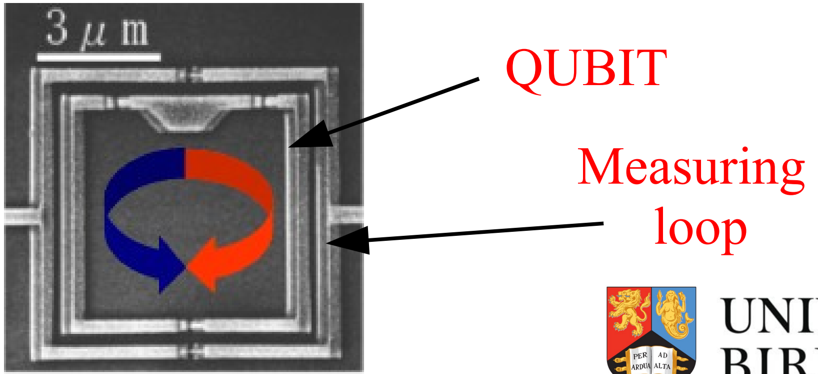
# What are the basic principles?

- The Josephson Junction is the basic building block of a superconducting qubit, and thus a quantum computer.
- Junction consists of 2 superconducting regions separated by a weak link (usually an insulator)



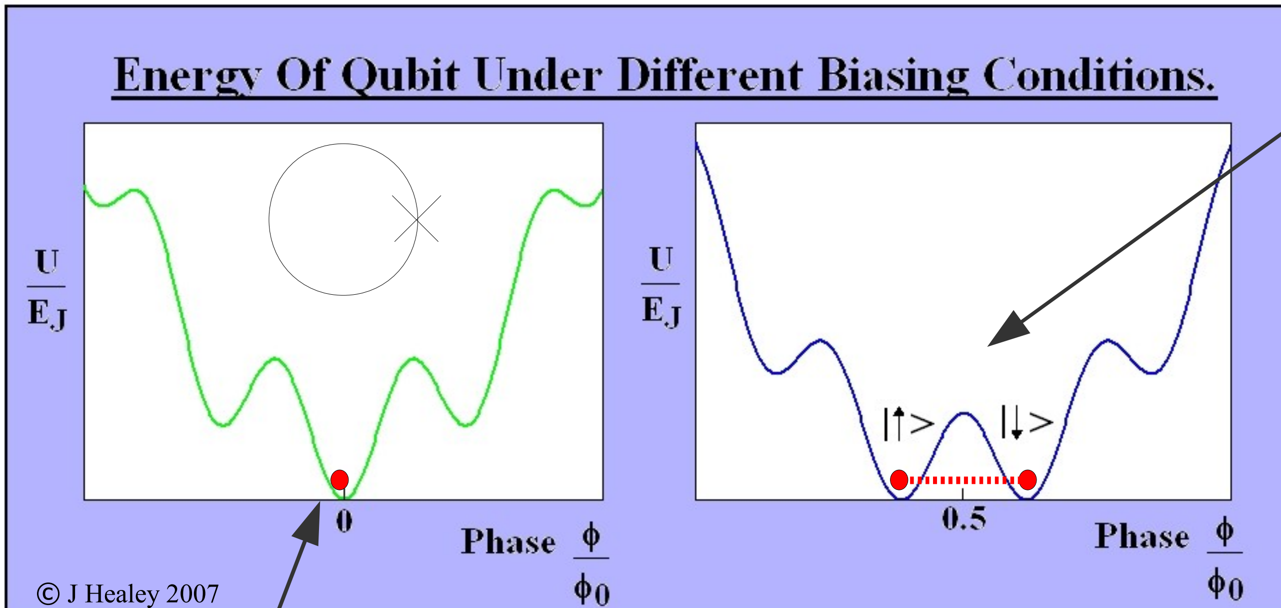




- The qubit consists of a ring of 1 or more superconducting Josephson Junctions, with this same energy landscape.



# Designing Qubits

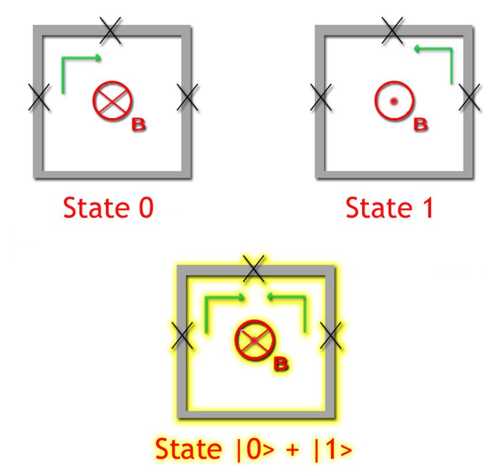
- When the energy of the system is correctly chosen (by carefully choosing the capacitance and inductance of the device), quantum mechanics dominates the junction behaviour...



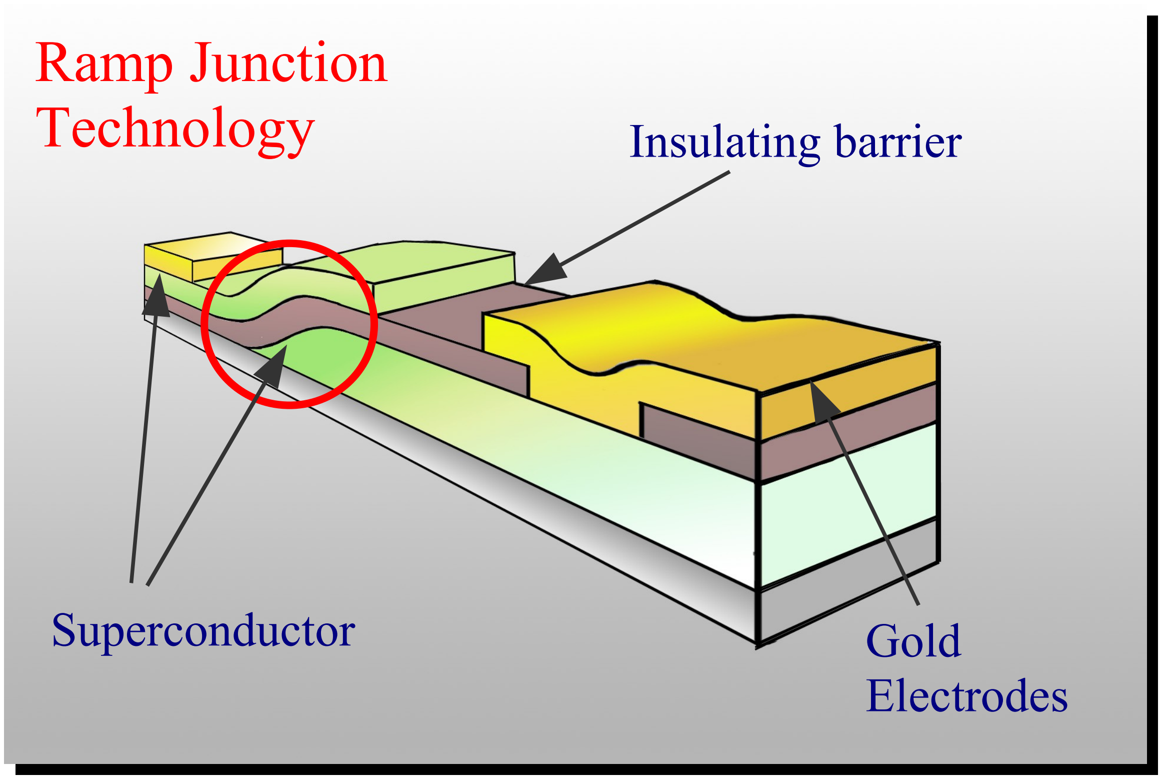

- Apply a *particular* magnetic field, and both energy states are equally favourable.
- What's more – they become quantum mechanically 'linked' through the barrier!

- The 'ground state' of the system - no currents flow. Apply a magnetic field, currents will start to flow around the loop.

- The qubit can support currents flowing in both directions at once!
- We can encode our data, |0> and |1>, into these two states.



# How do you make one?

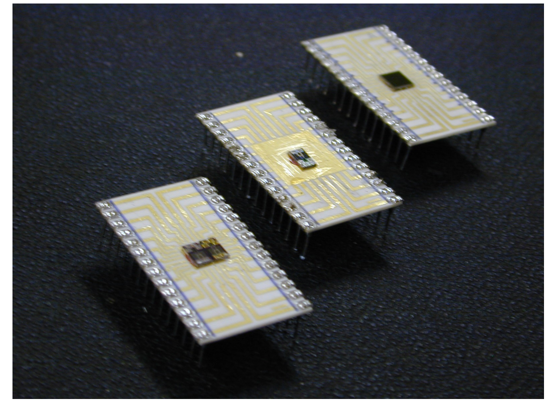


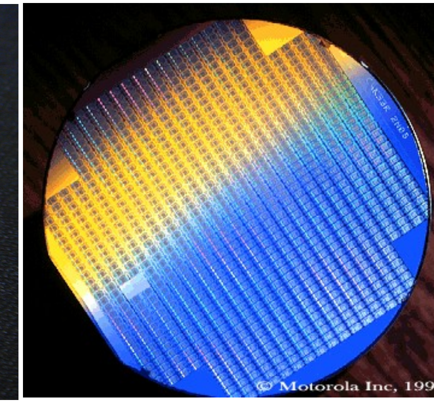

- Use material deposition techniques to place a layer of superconductor
- Pattern a ramp into the superconductor
- Oxidise the surface of the superconductor (or deposit an insulating layer on top) to form the Josephson barrier

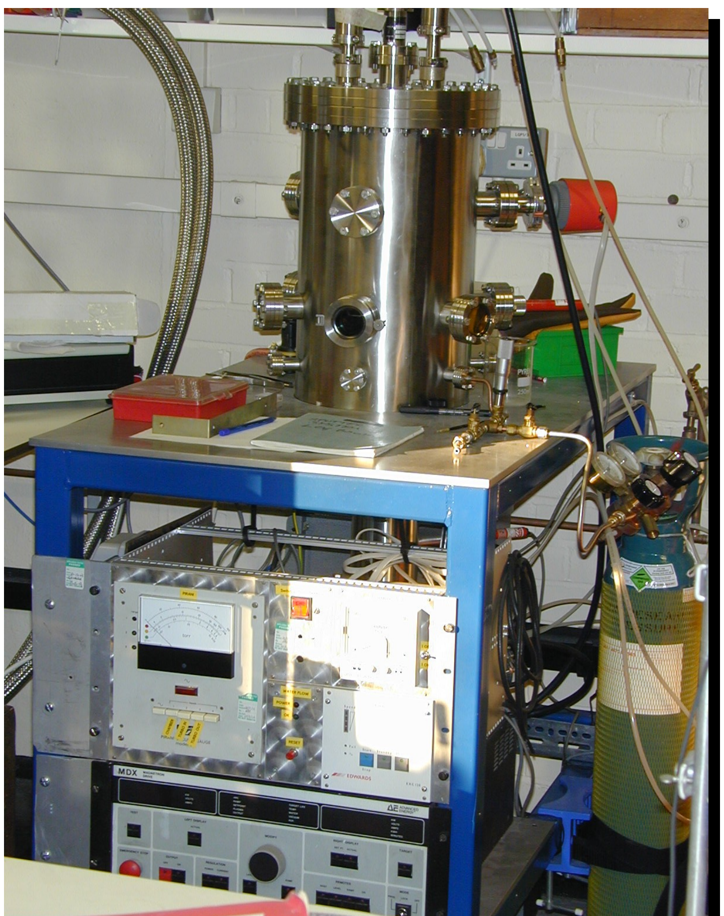
- Make a via (hole) into the insulating layer and attach electrodes to each side of the junction
- Different superconductors can be used for the two layers, to investigate interesting effects

# How do you make lots?

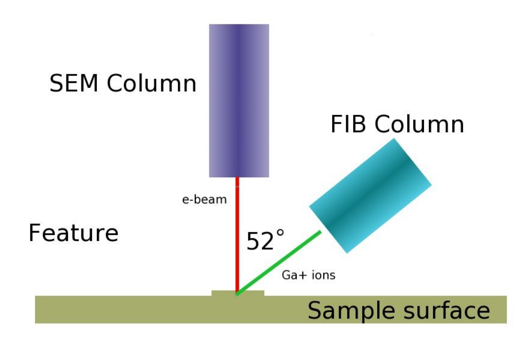
- Single device vs. VLSI techniques
- Single device is OK for research...
- ...But VLSI needed for anything  useful!





- Standard fabrication techniques in device physics/engineering to make Junctions
- Metal sputtering / Pulsed Laser deposition
- FIB etching - to produce a single device.... or an e-beam mask for multiple devices...

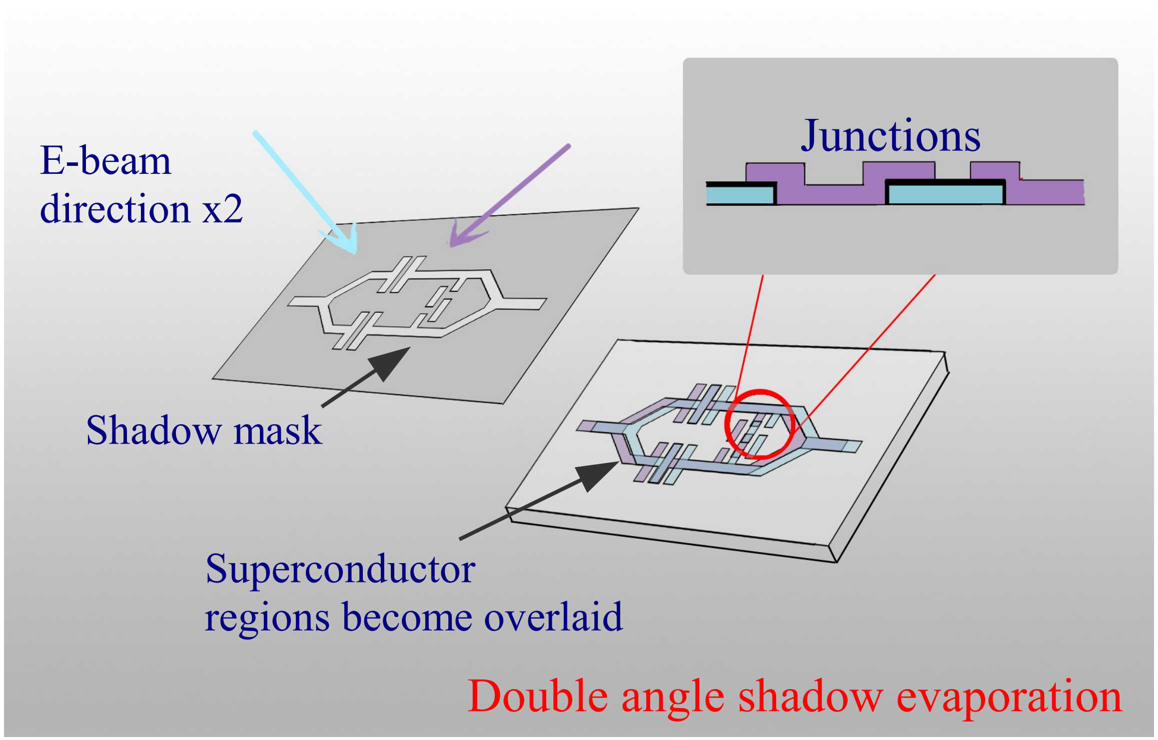





UNIVERSITY OF BIRMINGHAM

# Our fabrication plan

- We will employ a double-angle shadow technique - simple, quick and can reproduce junctions to within a small tolerance



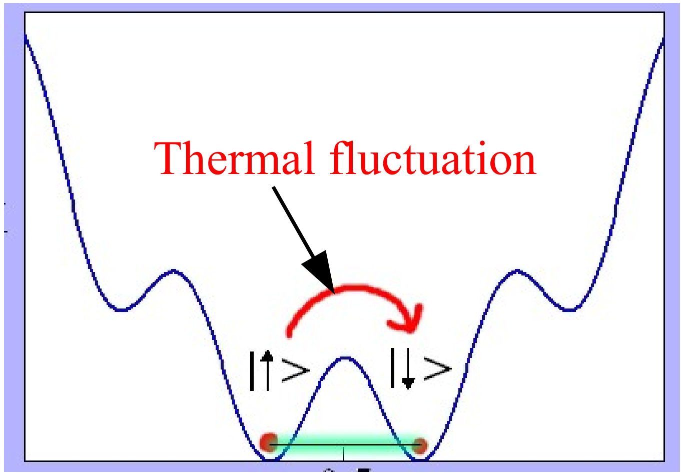

- However, we will also be looking at other, more novel fabrication techniques in the meantime - there are lots!

Self-alignment
Single crystal whisker stacks?
Ramp Junctions?

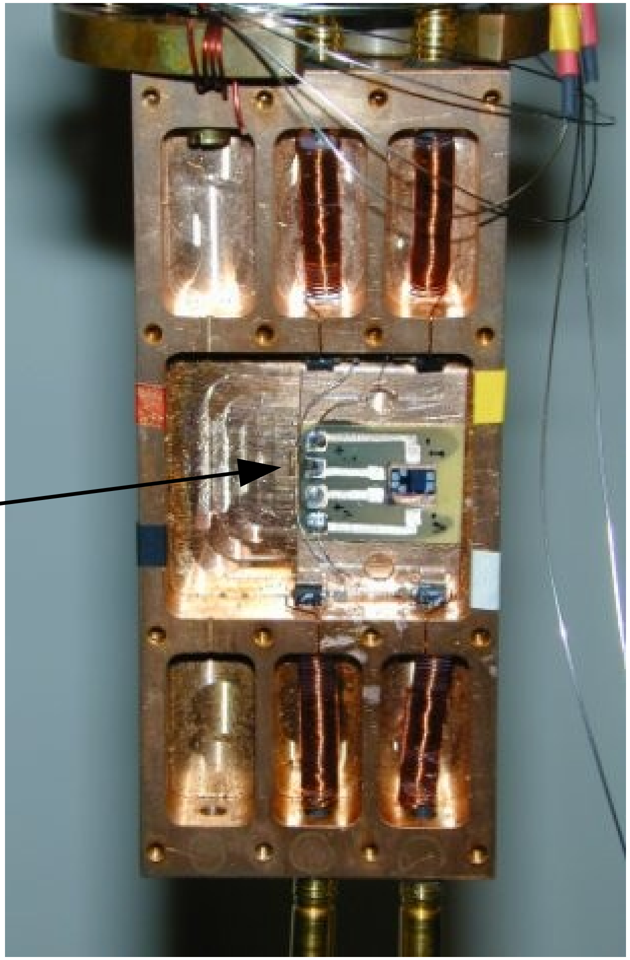
# Testing and measuring qubits

What temperatures do the qubits operate at?

- They need to be in the superconducting regime
- They need to be cold enough that thermal fluctuations are unimportant.
- So in the energy well diagram, the energy of the system is unlikely to be accidentally 'excited' over the barrier.



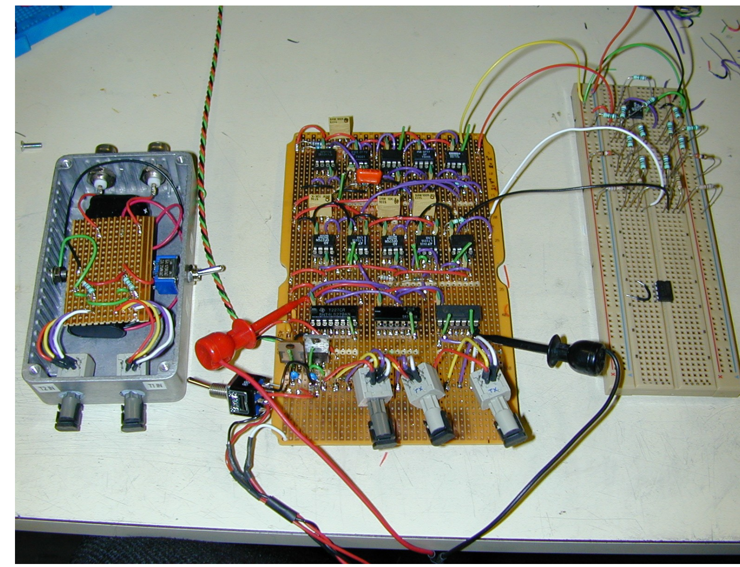

- The qubit sits in a copper box, which reaches the lowest temperatures – here approx. 30mK, (or 0.03 of a degree above absolute zero!)



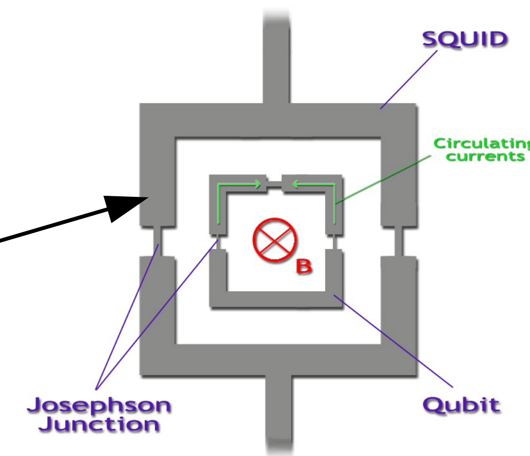
QUBIT MYTH:
Even if you had Room Temperature Superconductors, qubits would still need to be refrigerated down to very low temperatures.

# Why is it difficult to investigate qubits?

- Qubit research is difficult – you have to be really careful... 2 main problems.



  - Noise can affect your experiment – as explained earlier. Many steps taken to reduce the noise level...
    - Specialist amplifiers & comparators
    - Custom designed shielded electronics systems
    - Take many, many measurements to compile a good average
    - Great care is taken to calculate the effect of noise so that it can be eliminated

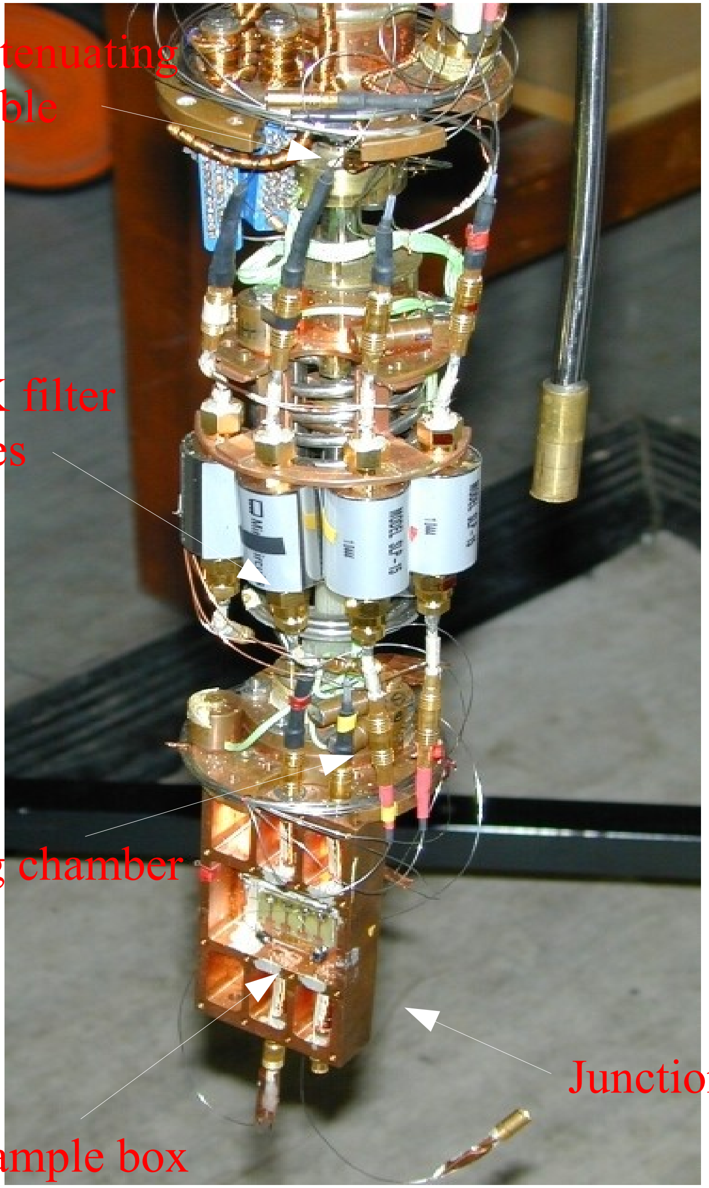



  - The measurement problem – reading a qubit without disturbing it....
  - Most people use either a SQUID loop or a resonant coil to infer the state of the qubit

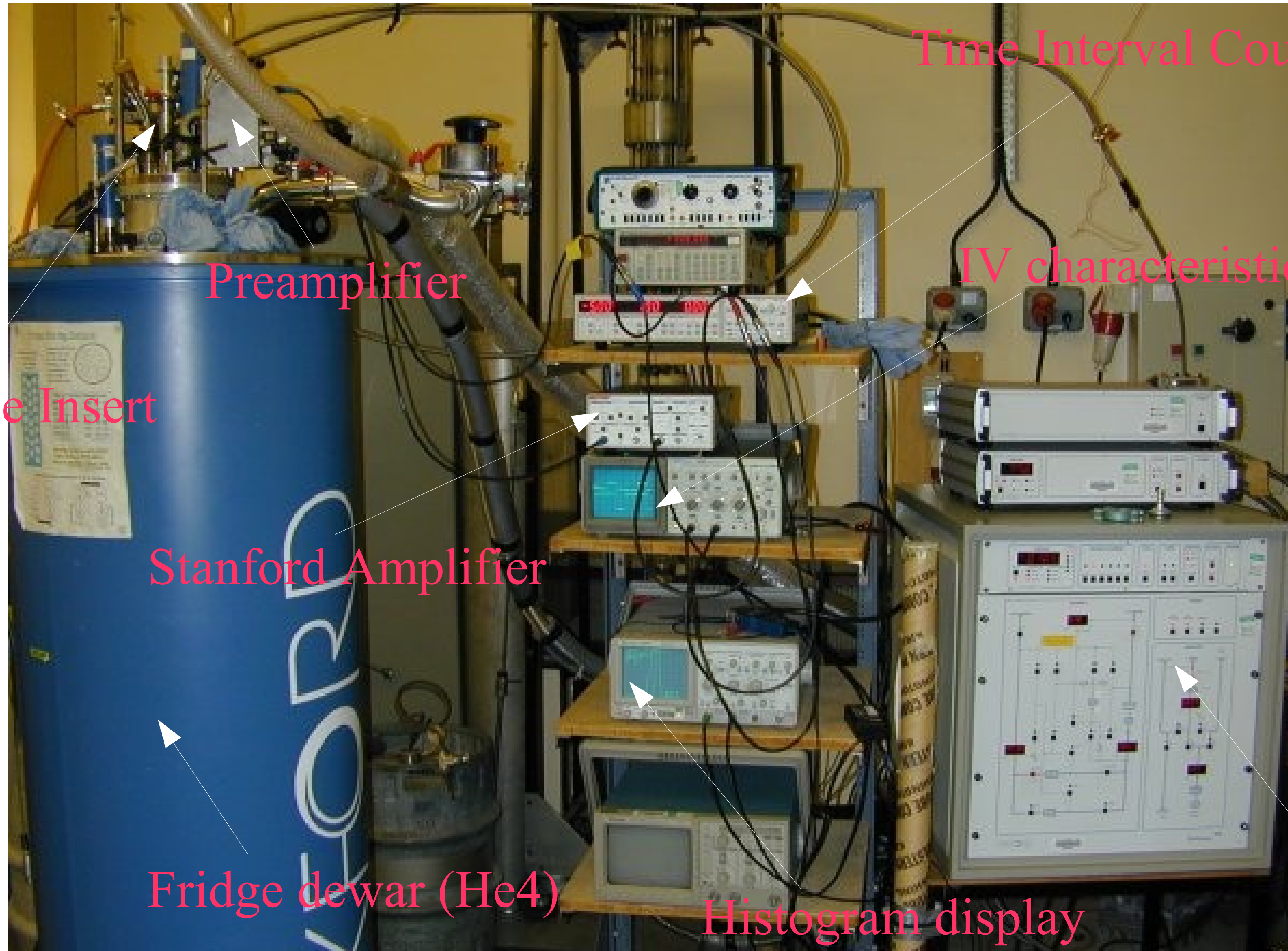
# A typical experimental set-up

What does it look like?

- The lower section of the apparatus is housed within a vacuum can
- Filter modules at various temperatures along the length of the cryostat
- Run apparatus from battery power and send signals through fibre optic (non electrical) links
- Fully shielded cables and fully shielded ground

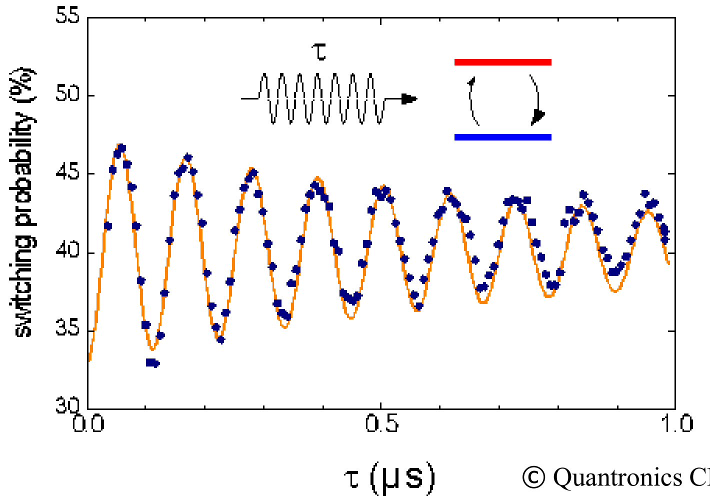


# Experimental Setup (2)

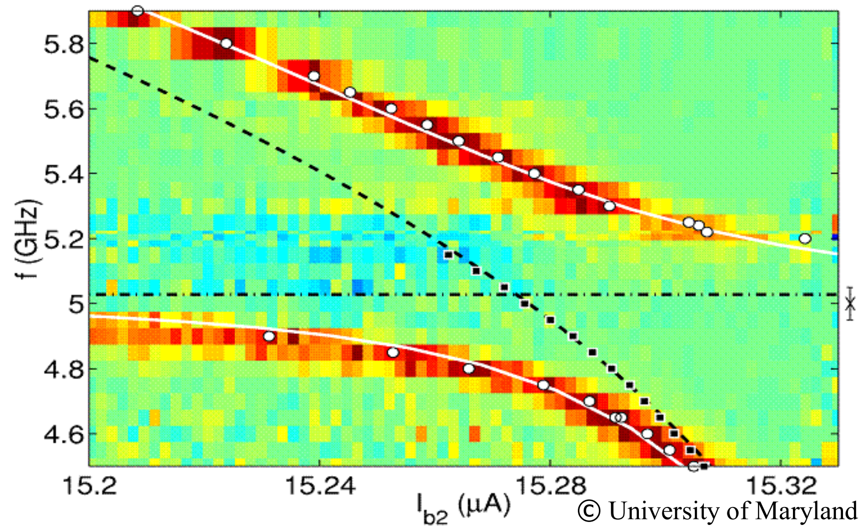


# What can you actually measure?

- Rabi oscillations & Ramsey fringes can illustrate the quantum coherence (showing that the two states, |0> and |1>, really are in co-existence
- Microwave spectroscopy can probe the energy levels of the qubit and help us to understand the potential of these devices









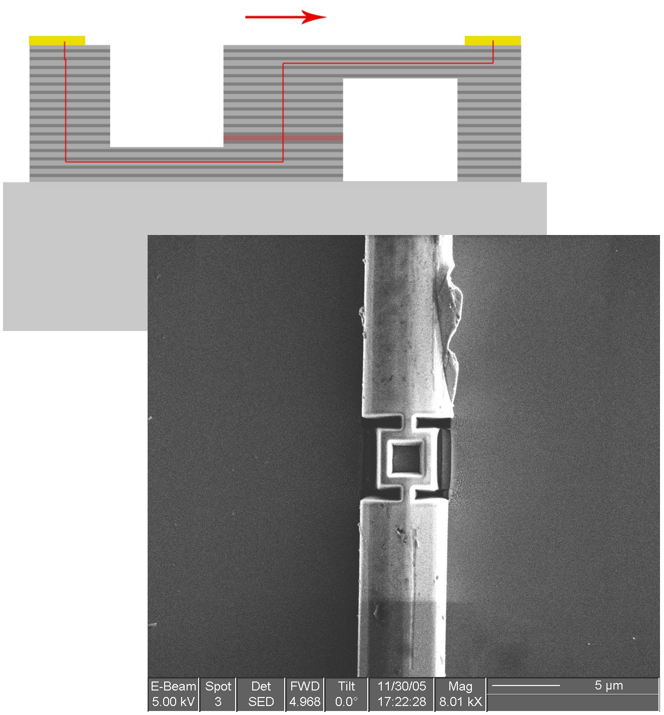
These experiments show very fundamental quantum properties which signify a working qubit, before trying to couple the devices together

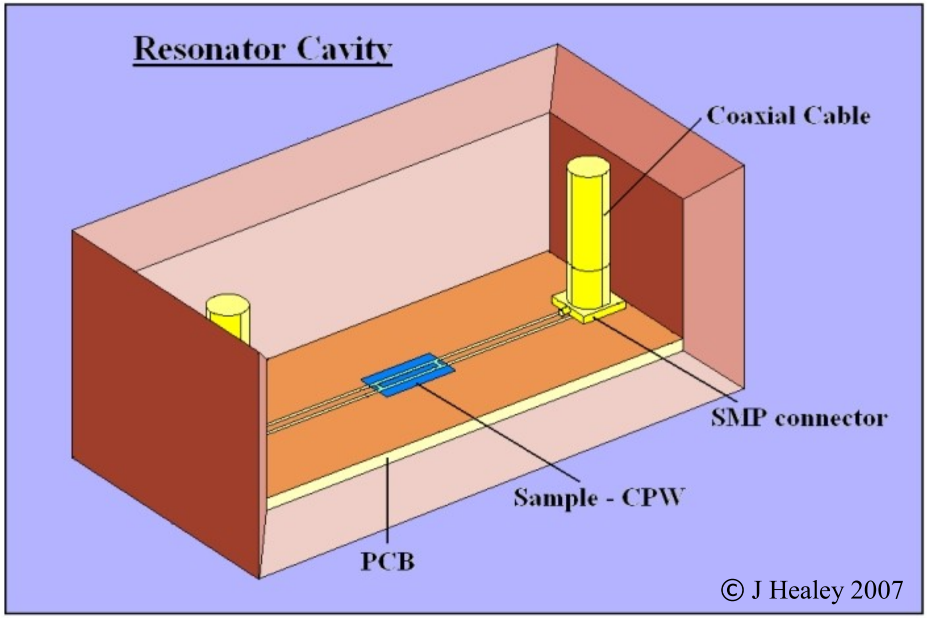
# New experiments – our contribution

Cutting edge qubit technology!

High Tc experiments

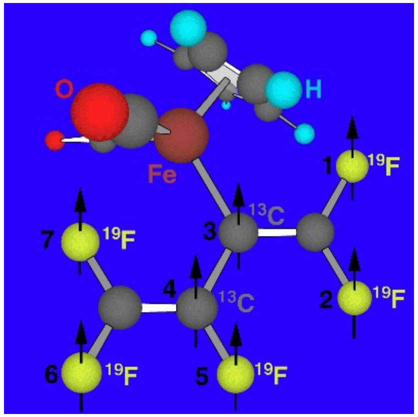
Microwave cavity experiments



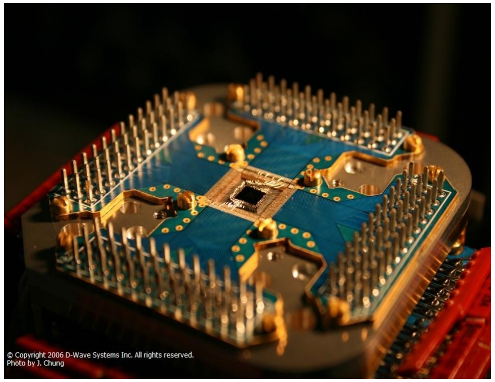



# Applications
## (...so can I factorise 15 with your qubits?)

- Unfotunately.....not (yet)
- May have heard of the IBM 'quantum computer' *factorising* the number 15 – the system uses an NMR technique – ensemble quantum computer
- This is currently beyond the reach of solid state quantum computers (you need at least 7 qubits)
- However solid state qubit technology is progressing very rapidly indeed, and hopefully there will be more and more results and demonstrations in the next few years
- D-wave systems 'The quantum Computing company' are in the process of producing a large scale qubit system using similar Josephson Junction technology
- Possible cryptography applications, and integrating with current optical quantum technology




IBM's 7 qubit 'molecule'



D-wave's 16 qubit device



UNIVERSITY OF BIRMINGHAM

# Conclusions

- Qubits are interesting both from a physicist and an engineer's point of view, and are definitely worth investigating further.
- With enough qubits, it is possible to run quantum computations, which can outperform current technology in some specific cases, and may provide other means of replacing (or enhancing) semiconductor systems.
- The fabrication technology is improving all the time and soon qubits will be routinely implemented into superconducting circuits
- New materials are being discovered all the time which may improve the operation of the qubits further - in the same way that the semiconductor industry is progressing now.
- The applications are somewhat limited at the moment, but hopefully the field will continue to advance in the future.

# Quantum computing for beginners: Building Qubits

## Thank you for your attention - Any Questions?

**Further Reading for interested audience members:**

- *M. Tinkham 'Introduction to Superconductivity', Chapter 7*
- *D-wave systems: http://www.dwavesys.com/*
- *Some nice introductions to quantum computing:*
  - *http://www.cm.ph.bham.ac.uk/scondintro/qubitsintro.html*
  - *http://www.cs.caltech.edu/~westside/quantum-intro.html*
  - *http://en.wikipedia.org/wiki/Qubits*
  - *http://www.csr.umd.edu/csrpage/research/quantum/index.htm*

Suzanne Gildert
Condensed Matter Physics Research (Devices Group)
University of Birmingham