Research Matters SPRING 2005

Revisiting the cold world of quantum computing

In Spring 2004, Research Matters reported plans for a joint project to be carried out at the universities of Oxford and Cambridge to develop working quantum transistors. Here we examine the creation of these nanoscale circuits, which, operating at millikelvin temperatures, offer the potential for a processing power greater than that which the laws of classical physics would allow.

In classical computers, information is processed by sorting and decoding patterns of binary digits, or ‘bits’, each holding a discrete value of either 0 or 1.

A hypothetical machine with two bits can thus be used to represent one of 4 values (00, 01, 10, or 11) at any given moment. Over the past decade, nanotechnology has hurtled forward the speed with which computers process such information by scaling down device geometries, which increases circuit density and reduces the time required for a bit to ‘switch states’ to below a billionth of a second. Ultimately there are significant challenges ahead as fabrication difficulties mount. These limits are not absolute, however, as nanotechnology also offers the revolutionary promise of quantum computing.

The Quantum Difference

In a quantum computer (QC), the charge or polarisation of elemental particles, such as electrons or photons, are used to represent the 0’s and 1’s of the binary code. Electromagnetic fields are then used to switch the state of these ‘qubits’ from I0> to I1>. As the basic components of QC memory are stored in nanoscale systems, the behaviour of these systems are governed by the principles of quantum physics; most importantly superposition and entanglement. Briefly, quantum laws allow the particle to enter a superposition of states, behaving as if it were a mixture of I0> and I1> simultaneously. Entanglement also allows separated qubits to interact with each other instantaneously, regardless of distance (not limited by the speed of light), so long as they remain isolated from environmental influences.

Taken together, these principles allow the hypothetical machine with two qubits to represent four values simultaneously, rather than the single value from a choice of four in the case of a two bit classical computer. Therefore the number of computations that can be undertaken by a QC is 2n, where n is the number of qubits used. This represents an exponential increase in processing power over classical systems and a revolutionary step forward in computer technology – so long as a working quantum computer can actually be constructed.

Creating a Qubit Circuit

One of the major obstacles to developing a working QC is decoherence, a phenomenon caused by environmental interactions on a qubit system. As qubit particles interact with their surroundings, they drift from their intended phases and fall into a state of lowest energy. Eventually, each qubit will fall to a state of I0>, leading to a complete loss of information. To create functional QC, the qubit system must thus be able to hold the charged particles in their desired states long enough to perform a useful action.

In a new joint project carried out at Oxford and Cambridge Universities, a team of researchers, along with specialists from Oxford Instruments Superconductivity, Hitachi, and CCLRC have developed a generic system for running high-speed electrical measurements on quantum circuits at millikelvin temperatures. By operating the quantum processor at temperatures below 1 K, and by using low-noise, high-speed control and measurement electronics, it is believed that the effects of decoherence can be effectively relieved.

Using solid-state microfabrication techniques, the team constructed singleelectron transistors, such as the one shown in Figure 1 (inset), forming the qubit building blocks of a quantum scale computer. These nanoscale processors show complex behaviour as a function of

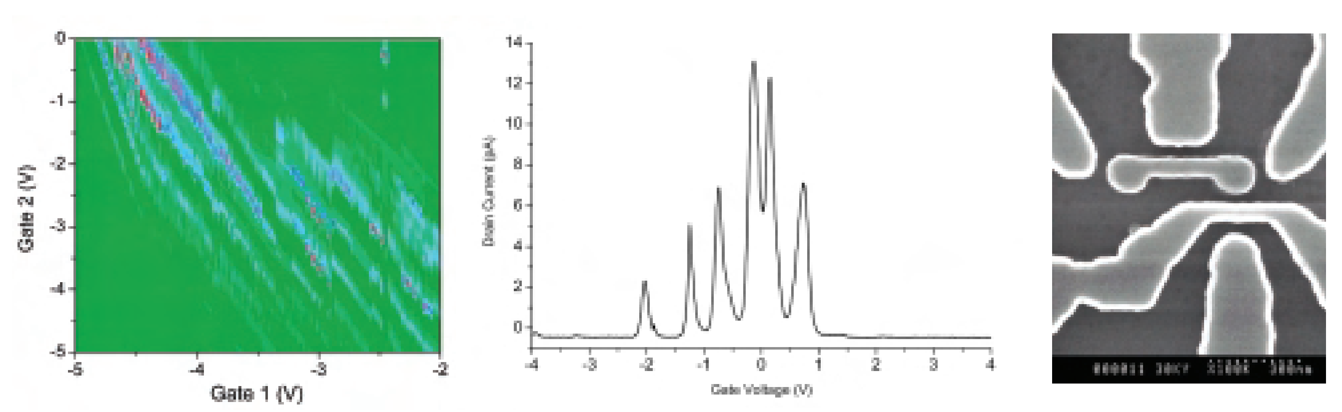


Figure 1 Gate voltage diagram of nanoscale circuitry, such as the typical model shown (inset).

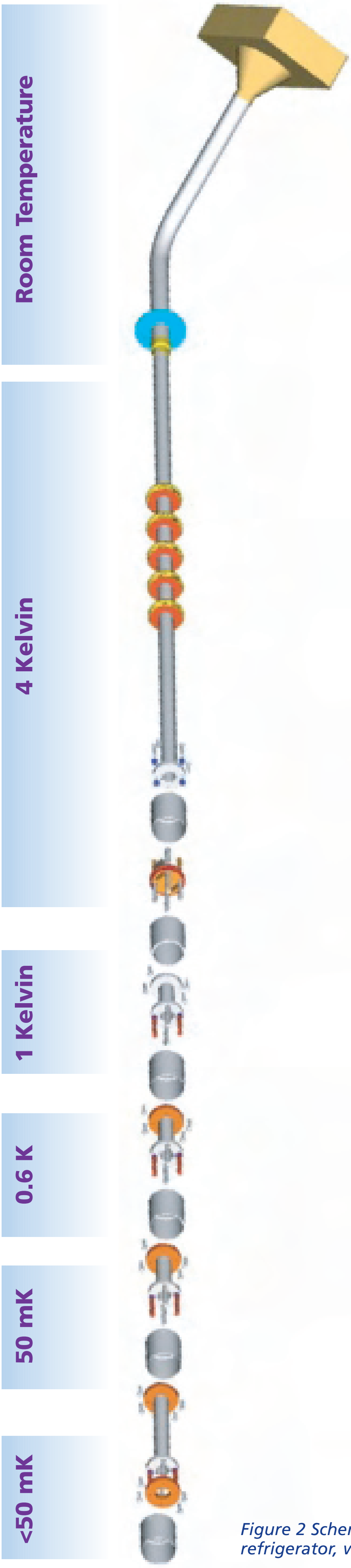


Figure 2 Schematic of the custom insert for the OI KelvinoxHA dilution refrigerator, with low temperature CMOS circuits from CCLRC

control voltage and, through the use of multiple gates, can be used to implement logic functions. To limit the effects of decoherence, however, the circuits had to be placed immediately adjacent to the system's measurement and control electronics and run at subkelvin temperatures, well outside the range of normal electronics.

Operating the system in a liquid helium temperature range was fulfilled by linking a custom dilution refrigerator, the KelvinoxHA from Oxford Instruments, to low temperature CMOS (Complementary Metal-Oxide Semiconductor) circuits from CCLRC (Figure 2). The millikelvin temperatures provided by the OI cooling unit significantly reduced the environmental influences on the quantum circuits, thereby limiting the effects of decoherence.

The performance of an SET circuit is shown in Figure 3, which displays a micrograph of a single qubit structure with a measured electrometer response curve (electrometer current versus gate voltage bias). Note the two distinct regions, upper and lower. These correspond to the situation where the electron lies predominantly on one or the other qubit island, I0> or I1>, while the middle region corresponds to a state of rapid switching – the fundamental ability required for high-speed processing.

The Next Big Step

Having designed these Phase 1 circuits, which have delivered highly interesting physics, the research group is now in the process of developing Phase 2 circuits that will offer an increased amount of sequencing and greater control. testing of these second-generation chips is anticipated to begin in 2006. Although this means that the creation of a fully functional quantum computer is still more than a decade away, these circuits offer potential gains in processing power comparable to moving from an abacus to a modern supercomputer.

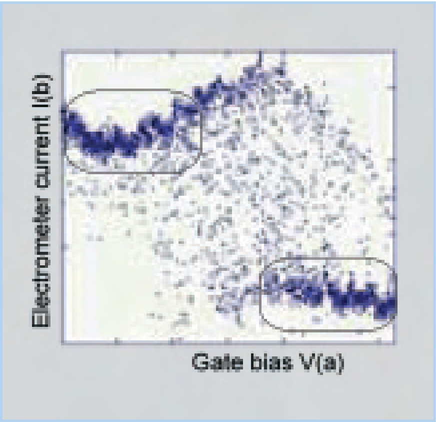
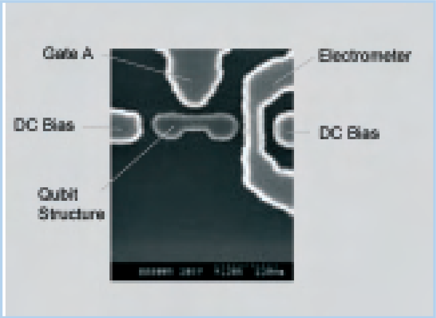


Figure 3 The micrograph shows a single qubit structure with a measured electrometer response curve (electrometer versus gate voltage bias)



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