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VIEWPOINT

Limitations of silicon devices for quantum computing

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Abstract
There is considerable interest in the use of silicon devices as qubits for quantum computing. The existence of nuclear spin in a silicon isotope and the complex band structure of silicon are unfavourable for this application of silicon devices.

Quantum computing uses qubits, elementary physical systems that may be in either of two distinct quantum states, to represent information. The most successful physical embodiments of qubits have been based on the phenomenon of superconductivity and have made demonstrations of interactions between two qubits possible (Pashkin *et al* 2003, Berkley *et al* 2003). The use of solid state devices as qubits has the potential advantage that devices can be fabricated in large numbers with techniques developed by the electronics industry for manufacturing integrated circuits.

An innovative proposal of Kane (1998) used nuclei of spin one-half phosphorus donor atoms in silicon as qubits. The two qubit states were the two possible orientations of the nuclear magnetic moment of phosphorus in a magnetic field. The nuclei could be influenced and made to interact through their contact with the wavefunction of the electron trapped at the donor. Kane's proposal stimulated considerable additional interest in the possibility of realizing qubits that used spin in silicon (Vrijen *et al* 2000, Shlimak *et al* 2001, Berman *et al* 2001, O'Brien *et al* 2001, Ladd *et al* 2002). The fabrication of qubits in silicon is attractive as it takes maximum advantage of the existing integrated circuit technology, which uses the unique properties of silicon and a set of silicon compounds and compatible materials.

However, the requirements for qubits are rather different from those for the devices in integrated circuits now used for digital information processing. There are two aspects of silicon that threaten its application to quantum computing with qubits.

First, natural silicon is a mixture of several isotopes. The presence of isotope ^{29}Si, which has a nuclear spin and a magnetic moment, will hinder manipulation of the spins of intentionally added nuclei and the electrons with which they interact. Kane's (1998) influential proposal contemplated the use of isotopically pure ^{28}Si that has no nuclear moment. However, the numbers suggest that achieving isotopic purity in a substantial number of qubits will be a formidable task. Natural silicon contains 4.67% ^{29}Si. The Bohr radius of the hydrogen-like wavefunction of an electron bound to a donor nucleus is 3 nm (Kohn 1957) and the volume encompassed by a sphere of this radius contains about 2×10^4 silicon atoms. In natural silicon approximately 1000 of these are therefore randomly distributed ^{29}Si atoms. Enrichment by a factor of 10^4 or 10^5 will be needed to provide a reasonable probability of obtaining an interesting number of ^{29}Si-free bound electron states.

Second, silicon is a multivalley semiconductor. There are six equivalent minima of energy (the valleys) in the crystal momentum space of the conduction band (Kittel and Mitchell 1954, Kohn and Luttinger 1955, Kohn 1957). Ideally, the wavefunction of an electron trapped on a donor is formed as a combination of equal contributions from each of the six minima. However, the processes that form devices on the surface of the silicon introduce unintended strains into the crystal (Shen *et al* 1996, Noyan *et al* 1999). Strain destroys the perfect crystal symmetry and the equivalence of the energy minima and changes their contributions to the bound electron state (Wilson and Feher 1961). The erratic changes in the electronic wavefunctions caused by the strains will prevent the use of predictable interactions between wavefunctions and nuclei and between wavefunctions for quantum computing.

The binary digital logic used in today's computers refers signal voltages to standard values intended to represent zeros and ones at each step, correcting errors introduced by device variability at each step in a procedure (Keyes 2001). Quantum computing deals with superpositions of quantum states described by a continuum of numbers (Barenco 1996, Monroe 2002) and has no comparable method for standardizing physical variables.

An approach outside the mainstream of those referred to above (Stoneham *et al* 2003) that proposes to exploit the differences between devices has been called to the author's attention. This method uses a set of qubits that differ from one another and that are therefore characterized by different excitation and interaction energies. Electromagnetic radiation at an appropriate frequency can then be used to address and control the excitations and interactions of a single qubit or single qubit pair.

In summary, silicon technology offers a tempting path for the fabrication of the large number of qubits that will be needed for a quantum computer. However, it is less favourable for the use of these qubits in quantum computation. Unwanted nuclear spins will interfere with the operation of spin-based qubits. Fabrication processes produce strains in the silicon that cause variability between nominally identical devices that quantum computation is ill-equipped to handle.

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