Quantum computer hardware

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One of the interesting characteristics of Quantum Information Computation (QIC)[1] is to gather scientists from very different backgrounds, from Physicists to Mathematicians, from Computer Scientists to Chemists. This provides a wide variety of methodologies and scientific languages, and it allows for an approach to problems from unorthodox perspectives, which in the past years have proved very fruitful and have definitely enriched the involved community.

My personal background is in Physics and I think that, for a Physicist, the main spell cast by QIC is the thrill of exploring the very same foundations of Quantum Mechanics. This subject has always been perceived as very abstract, yet, through QIC and the potential for everyday-use of quantum computers, it has assumed a very concrete and practical connotation.

The basic advantage of QIC in respect to classical computation, is to benefit from the natural parallelism of quantum mechanics, the so-called superposition principle. The computational unit in QIC is the 'qubit', which can be in principle implemented by any two-level quantum system. Qubit levels are usually indicated as $|0>$ and $|1>$; the general state of a qubit is then $a|0> +b|1>$, where $a,\ b$ are complex numbers. This shows that, while the classical bit can store either state 0 or state 1, each qubit can store $|0>$ and $|1>$ *simultaneously*. As a consequence N qubits can store 2^N numbers and in general calculations can be performed simultaneously on each of these numbers (quantum parallelism).

It has been demonstrated that a quantum computer could solve 'hard' mathematical problems such as the factorization of large integer numbers or a large database search. Additionally, being explicitly governed by quantum mechanics, it should allow for simulation of very complex systems, such as many-particle quantum systems.

In general a quantum computation scheme requires (1) the preparation of the initial state, (2) its coherent propagation and manipulation (the 'computation' stage), and (3) the detection or measurement of the final result.

There are unfortunately many practical problems connected to this apparently simple '1-2-3' sequence and the reason for this becomes clear if we think that our computational units are among the smallest possible physical systems and that in order to perform meaningful computation, we must be able to address in some general sense the single qubit and to drive and perfectly control the single qubit as well as the global dynamics.

The most dreadful of these problems is decoherence. This is due to interaction of the computational system with the environment and/or with non computational degrees of freedom, i.e. background charges, phonons, additional energy levels. Such an interaction alters the system dynamics, ultimately spoiling the computation results. Other problematic requirements are the system/computational scheme scalability (due to the necessity of building and addressing/controlling thousands of qubits) and the possibility of implementing error-detecting and error-correcting codes. Last but not least, the choice of hardware deserves a particular place in this list. Indeed, even if very many papers have been written on potential quantum computers, a definite optimal hardware is still far from being selected. Many different possibilities have been partially explored, from molecules dispersed in a fluid, to specially designed ion traps to semiconductor-based nanostructures. Each one of the proposed implementations has both some advantage and some drawbacks in respect to the others.

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Maybe due to my background, my personal preference goes to semiconductor-based QIC schemes. The advantage of using semiconductors lies principally in the fact that traditional electronics is semiconductor based and by now there is a good understanding and characterisation of semiconductor materials and structures. The related technology is also well developed, so that a semiconductor based quantum computer has more chances to be easily integrated with traditional electronics components, which will be important for example for interfacing the quantum computer with the external world.

Some of the most famous semiconductor-based proposals include the use of nuclear spins of phosphorus impurities embedded in a doped silicon structure[3] or electrically driven electron spins in gate-defined quantum dots[4]; we have concentrated instead on schemes based on self-assembled quantum dots[2], and completely optically driven[5].

A quantum dot is the real counterpart of the 'quantum box' model. It is a quasi 0-dimensional structure, i.e. its confining lengths in all the three dimensions are of the order of the carrier De Broglie wavelength (nanometer scale). Such a structure is then characterised by a discrete energy spectrum which resembles the atomic one. Due to the small size and to the absence of screening, the interactions among confined charges are strong, while, due to the discreteness of the spectrum, interactions with the environmental degrees of freedom are relatively weak. One interesting feature of these structures is the potential for controlling and engineering their electronic structure by tailoring their parameters. Additionally self-assembled semiconductor quantum dots feature coupling to (optical) laser fields. Laser pulses can in fact (i) excite electron-hole correlated pairs (excitons) inside such structures and (ii) drive their coherent dynamics. Our schemes exploit this feature by using excitonic degrees of freedom either as qubits or as ancillary states. We propose fully optical gating schemes, which use energy selective addressing. The advantage of such all-optical proposals is first of all the possibility of generating and manipulating excitons on a sub-picosecond time scale. This is important in order to overcome the decoherence problem, decoherence times of the order of a nanosecond have been in fact measured for excitonic states. Our proposals also avoid the presence of slowly varying external fields, which may induce charge fluctuations and in general tend to slow down the operational time. Self-assembled quantum dots can be grown in arrays of vertically stacked dots in a controlled way, and this natural identification of a quantum array helps to face the scalability problem. Technological improvements are still needed though to (i) perfect the design of vertical and horizontal arrays during the growth process, (ii) characterise the single quantum dot and (iii) to increase further the array length.

At the present stage, nobody can predict with certainty when the first quantum computer will be built nor if quantum dots and semiconductor nanostructures in general will be the selected hardware. One certain and important outcome though is that in these past years, quantum computation has been a driving force for the functional study and for the improvement of the overall quality of semiconductor nanostructures. In fact as a by-product, several nano-devices have been proposed and great improvements in the experimental mastering of related processes have been achieved.

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[1] See, e.g., M.Nielsen and I. Chuang, *Quantum computation and quantum information*, (Cambridge Univ. Press, 2000)

[2] See, e.g., L. Jacak, P. Hawrylak,A. Wojs, *Quantum Dots* (Springer, Berlin 1998).

[3] B.E.Kane, Nature 393,133(1998).

[4] D.Loss and D.P.DiVincenzo, PRA 57, 120 (1998).

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