SOLID-STATE NANOPHYSICS FOR SPIN-BASED QUANTUM COMPUTING

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Abstract: Fascinating growth in the number of transistors on a chip in the microelectronics industry requires spectacular reduction of the transistor size. Due to governance of the laws of quantum solid-state nanophysics at nanometer level , nanoscale hardware components must show quantum behaviour. Since computers are built up from these electronic components, this leading to the concept of quantum computers. In this review we highlight recent developments which point the way to quantum computing on the basis solid state nanostructures. After introducing a set of basic requirements for any quantum computer proposal, we offer a brief summary of some of several theoretical proposals for solid-state quantum computers. There are many obstacles to building such a quantum device. We address these, and survey recent theoretical, and then experimental progress in the field.One of the major direction of research on the way to quantum computing is to exploit the spin (in addition to the orbital) degree of freedom of the electron, giving birth to the field of spintronics. Perhaps the most ambitious goal of spintronics is to realize complete control over the quantum mechanical nature of the relevant spins.Thus we will focus in the paper on the spin-based solid-state proposal for quantum computing. We address some semiconductor spintronics approach based on spin orbit coupling in semiconductor nanostructures.

1. INTRODUCTION

The exponential growth (Moore's-law) of the transistor density in microchips raises the question of the possible future direction of the electronics computer industry. In particular, since small nanoscale systems are governed by the laws of quantum physics, nanoscale hardware components must show quantum behaviour. Since computers are built up from these electronic components, this leading to the concept of quantum computers (QC) and new emerging area of investigations - Quantum Information Science (QIS).

QIS is an emerging field with the perspective to cause revolutionary advances in fields of science and engineering involving computation, communication, precision measurement, and fundamental quantum science. The topics of QIS bring together ideas from information theory, computer science, and quantum physics, which are among the crowning intellectual achievements of the past century.

In the first part of the paper several general aspects of the OC are higlighting .The field of QIS began an explosive growth in the last ten years as a consequence of several stimuli:

i) the semiconductor industry realized that the improvement of computers according to Moore's law would all too soon reach the quantum limit, requiring radical changes in technology;

ii) developments in the physical sciences produced solid-state-electronics nanodevices, advanced optical cavities, quantum dots, and many other advances that made it possible to contemplate the construction of workable quantum logic devices;

iii) the need for secure communications drove the investigations of quantum communication schemes.

Information can be identifed as the most general thing which must propagate from a cause to an effect and it therefore has a fundamentally important role in the physical sciences. However, the theoretical treatment of information, especially information processing, is quite recent, when the full signifcance of information as a basic concept in physics has being discovered. The development of the theory of quantum information has lead to some profound and exciting new insights into the natural world. Among these are:

1) the use of quantum states to permit the secure transmission of classical information (quantum cryptography);
2) the use of quantum entanglement to permit reliable transmission of quantum states (teleportation);
3) the possibility of preserving quantum coherence in the presence of irreversible noise processes (quantum error correction);
4) the use of controlled quantum evolution for effcient computation (quantum computation).

The common theme of all these insights is the use of quantum entanglement and superposition of quantum states as a computational resource. In this context some aspects of QIS directed to the topics of nanophysical background of quantum computing are highlighted.

In such circumstances the new concepts and principles in electronic device architectures are a major challenge of solid-state physics. One of such concept is the spintronic ones, which is based on the quantum property of the electron known as spin, which is closely related to magnetism. Devices that rely on an electron's spin to perform their functions form the foundation of spintronics, also known as magnetoelectronics. Thus the basic concept of spintronics is the manipulation of spin currents, in contrast to mainstream electronics in which the spin of the electron is ignored.

Since the electron spin is a two-level system, it is a natural candidate for the realization of a quantum bit (qubit) . A qubit is the basic unit of information in quantumcomputation, a disciplinewhich attempts to radically improve the performance of computers by exploiting the quantum properties of the system used as hardware. The confinement of electrons in semiconductor structures like quantum dots allows for better control and isolation of the electron spin from its environment. Control and isolation are important issues to consider for the design of a quantum computer.

The present report is a tentative to review some recent developments in the fascinating area of QC, to illustrate the new possibilities and advantages of solid-state nanophysics in general and spintronics in particular in the solving of the difficult problems of QC hardware.

2. GENERAL CONSIDERATION ON QUANTUM COMPUTING

There are three fundamental questions about QCs:

1) What is a new paradigm of quantum computing? How it extends the the dimension of computation? What are the peculiarities of quantum algoritms?

2) Can QC be built? Do fundamental physical principles pose a truly serious obstacle? Can these difficulties be overcome even in principle and in practice?

3) How QC will be built ? What kind of hardware will the QC of the future use? Can this hardware be constructed via incremental improvements of existing technologies, or will truly new ideas be needed?

Formally, a quantum computation is performed through a set of transformations, called gates [1]. A gate applies unitary transformation U to a set of qubits in a quantum state $|\psi>$. At theendof the calculation, ameasurement is performed on the qubits (which are in the state $|\psi'> = U\ |\psi>$). There are many ways to choose sets of universal quantum gates. These are sets of gates from which any computation can be constructed, or at least approximated as precisely as desired.

Such a set allows one to perform any arbitrary calculation without inventing a new gate each time. The implementation of a set of universal gates is therefore of crucial importance. It can be shown that it is possible to construct such a set with gates that act only on one or two qubits at a time [2].

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The successful implementation of a quantum computer demands that some basic requirements be fulfilled. **These are known as the DiVincenzo criteria** [3] and can be summarized in the following way.

(i) Information storage—the qubit. We need to find some quantum property of a scalable physical system in which to encode our bit of information, that lives long enough to enable us to perform computations.

ii) Initial state preparation. It should be possible to set the state of the qubits to zero before each new computation.

iii) Isolation. The quantum nature of the qubits should be tenable; thiswill require enough isolation of the qubit from the environment to reduce the effects of decoherence.

iv) Gate implementation. We need to be able to manipulate the states of individual qubitswith reasonable precision, as well as to induce interactions between themin a controlled way, so that the implementation of gates is possible. Also, the gate operation time ɸs has to be much shorter than the decoherence time T2, so that ɸs/T2 _ r, where r is the maximumtolerable error rate for quantum error correction schemes to be effective.

v) Readout. It must be possible to measure the final state of our qubits once the computation is finished, to obtain the output of the computation.

These very basic and simple requirements translate into a physics language as a quantum setting:

1. A physical system with a collection of well characterized quantum two-level systems (qubits) is needed. Each qubit should be separately identi fiable and externally addressable.
2. It should be possible to, with high accuracy, completely decouple the qubits from one another, and it should be possible to start an experiment by placing each qubit in its lower (0) state.
3. The decoherence time of these qubits should be long, ultimately up to 10^4 times longer than the clock time" (see the next requirement).
4. Logic operations should be doable. This involves having the one-body Hamiltonian of each qubit under independent and precise control (this gives the one-bit gates).
5. Projective quantum measurements on the qubits must be doable. It is useful, but not absolutely necessary, for these measurements to be doable fast, within a few clock cycles.

Microelectronic mesoscopic devices will inevitably emerge, but whether they will be usable for quantum computation will depend on whether they manage to satisfy a very specific set of requirements:

1) *the machine should have a collection of bits;*
2) *it should be possible to set all the memory bits to 0 before the start of each computation;*

3) the error rate should be sufficiently low;

3) it must be possible to perform elementary logic operations between pairs of bits;

4) reliable output of the final result should be possible.

3. SPIN-BASED PROPOSAL FOR QUANTUM COMPUTING

Before even the most rudimentary quantum circuits can be built, the elementary registers (qubits) and quantum gates must be designed. There is a remarkably long list of physical systems that have been proposed, and are under active experimental investigation, for the creation of a quantum computer.The solid state physics is the most versatile branch of physics, in that almost any phenomenon possible in physics can be embodied in a correctly designed condensed matter system. The main reason is that solid state physics, being so closely allied with computer technology, has exhibited great versatility over the years in the creation of artificial structures and devices which are tailored to show a great variety of desired physical effects. This has been exploited very powerfully to produce ever more capable computational devices. It would be natural to extrapolate to say that this versatility will extend to the creation of solid state quantum computers as well.

Among a several principal directions of solid state physics dealing with the developing of different elements of QC spintronics is one of more suitable to solve the problems of quantum computing. The main concept of QC is the superposition of states which need its phase coherence. Recently it has been demonstrated that spin degree of freedom can preserve phase coherence for a much longer time than the orbital degrees connected with the particle charge. Another strong advantage of ST stem from the well-known fact that the magnetic fields present in the ambient world are significant weaker than the electric fields, and the fundamental problem of QC errors can be solved.

The outline of the ST second part of the report cover:

1) some fundamental issues for spin decoherence in different electronic systems ;
2) 2) an introduction in the ST quantum dots and spin-valves as an qubit array and how they overcome the above mentioned QC criteria;

3) an brief analysis of the spin-polarized transport in solid state hybrid structures and how the transport of quantum information can be realized, including some aspects of electron spin entanglement.

4. CONCLUSIONS

In this review paper we have discussed theoretical concepts and the present status of experimental achievements towards the implementation of quantum information processing using electron spins in solid-state quantum nanostructures. The demonstration of working single- and two-qubit gates and finally the production of quantum structure arrays that enable the application of an entire quantum algorithm including error correction are the major problems to tackle towards the goal of a solid-state nanophysics implementation of quantum information processing using electron spins in quantum nanostructures.