Quantum computing based on Silicon technology

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NMR's future in quantum computing is limited. It is enjoying the spotlight now, but the technology suffers from several potentially fatal limitations. One of the most serious is lack of what is known as scalability. As the number of nuclear spins in a molecule increases, the number of molecules in the correct starting state decreases exponentially. So by the time a system gets larger than about 10 qubits, any signals are so weak that ordinary noise drowns them out. Silicon is an appealing material in several ways. Both its electron and nuclear spins have extremely long decoherence times. It is already the seminal material of computer processors. Research momentum is thus already directed toward silicon. One technological challenge, however, will be ensuring the purity of the silicon, because even a single unwanted atom could cripple the system. Silicon-based quantum computers are the focus of a mammoth research effort by a consortium including several universities.

I. Introduction

This paper explores and analyses the different advances made in the field of quantum computing that are based on the silicon technology. Traditional computers perform calculations in a basically sequential manner. Their limitations surface in the simple, yet striking, example of factoring a large number. The time a computer spends searching for a number's factors increases astronomically with the size of the number. To factor a 400-digit number, for example, would take a modern computer billions of years.

A quantum computer is a computing device that invokes intrinsically quantum-mechanical phenomena, such as interference and entanglement. These phenomena endow a quantum computer with certain capabilities that cannot be matched, even in principle, by any classical computer. The computer made of quantum particles has a built-in parallelism because quantum calculations can be performed on the particles' coexisting states simultaneously. A quantum computer, then, might factor that 400-digit number in minutes.

In a quantum computer, the fundamental unit of information (called a quantum bit or *qubit*), is not binary but rather more quaternary in nature. This qubit property arises as a direct consequence of its adherence to the laws of quantum mechanics which differ radically from the laws of classical physics. A qubit can exist not only in a state corresponding to the logical state 0 or 1 as in a classical bit, but also in states corresponding to a blend or *superposition* of these classical states. In other words, a qubit can exist as a zero, a one, or simultaneously as both 0 and 1, with a numerical coefficient representing the probability for each state. Qubits are also subject to quantum *entanglement*. When two or more are entangled, they behave as one system, so that the state of one qubit depends directly on the state of the others. If two particles are prepared, or set up, together in the right way, their wave functions become a combined system and can't be factored into separate contributions. The implication that follows may seem bizarre: If you measure some aspect of one particle, polarization, for example then its superposition of values collapses into one definite value, as expected. But the companion particle then also instantaneously assumes the same value, no matter how far apart the particles might be. Thus the potential processing power of a quantum information system increases exponentially rather than linearly with the number of qubits.

A quantum computer manipulates qubits by executing a series of quantum gates, each a unitary transformation acting on a single qubit or pair of qubits. In applying these gates in succession, a quantum computer can perform a complicated unitary transformation to a set of qubits in some initial state. The qubits can then be measured, with this measurement serving as the final computational result.

A quantum computer shares some of these traits. Many quantum-sized systems or particles have two possible configurations that could correspond to the 0 or 1 of a bit: the up or down spin of an electron or a nucleus, for example, or the polarization of a photon. But here, the quantum system departs from its classical cousin. A quantum bit, otherwise known as a qubit, can be set up to exist in both the 0 and 1 states at the same time. According to rules of quantum mechanics, the qubit will stay in this superposition of values until it is measured, at which point it "collapses" into a definite value.

The field of quantum information processing has made numerous promising advancements since its conception, including the building of two- and three-qubit quantum computers capable of some simple arithmetic and data sorting. However, a few potentially large obstacles still remain that prevent us from building a quantum computer that can rival today's modern digital computer. Among these difficulties, error correction, decoherence, and hardware architecture are probably the most formidable.

But practical quantum computers have considerable problems. First, how do we get our answer? After all, if you measure the system, it collapses into a single value that's not necessarily the right answer. Researchers have found ways to get around the problem. For example, Lov K. Grover , a theorist at Lucent Technologies' Bell Labs in Murray Hill, N.J., has developed an algorithm that manipulates the system with a series of logic gates that increases the system's wavefunction at the value you want, thereby eventually increasing--to 1, or certainty--the probability of getting that result when you measure the system. But even with a workable strategy for obtaining an answer, you still must contend with a problem known as *decoherence*, which constantly threatens to interfere with quantum computation. Because, unfortunately, it is not just a purposeful measurement that can collapse a delicate quantum system. Absolutely any sort of interaction with the environment, be it a stray photon or vibration, will do it.

Protecting a quantum system is extremely difficult. A whole subfield known as quantum error correction has sprung up to deal with the problem. And researchers have developed different strategies to protect quantum systems from decoherence and to repair damage that does occur.

The basic unit of computation is a bit, represented as either a 1 or a 0. In the solid-state world of classical computers, the bit's value corresponds to the presence or absence of current. Bits can be manipulated by what are known as logic gates, which transform bit values in designed ways. For example, a NOT gate changes a bit from 0 to 1, or vice versa. In fact, everything a computer does, from word processing to modeling the structure of the universe, can be boiled down to various combinations of these simple logic gates operating on bits.

In choosing the sort of quantum system that would make a good computer, scientists face a diifficult situation. A quantum system needs to last for a reasonably long time before it starts to become decoherent. In other words, it needs to interact weakly with its environment. But if that's the case, it generally also will interact weakly with itself, making entanglement generation and quantum computation difficult.

But by far the most well-known method for quantum computing right now is based on nuclear magnetic resonance (NMR). The advantage of NMR over other technologies is quite simply that NMR quantum computers are the only ones to have yet actually performed a quantum algorithm. When nuclei with spin are placed in a magnetic field, they align themselves either parallel or antiparallel to the field, with a slight excess in the parallel orientation. A pulse of electromagnetic radiation of the right frequency and duration will flip a nucleus. In this way, nuclear spin serves as a qubit. If another pulse of energy is given to the system at the right instant, depending on where its precessing spin is pointed, that first nucleus will then flip up or down. This two-qubit operation is one of the fundamental logic gates, known as a controlled-NOT gate, that a computer uses. The resulting NMR spectrum reveals which direction the nucleus flipped.

What's unique about NMR is that each molecule is itself a quantum computer. So a small vial of solution contains trillions of computers. A number of them can be lost to decoherence without immediately affecting the whole vial. And NMR quantum computer decoherence times are very long to begin with--up to seconds--which allows ample time to perform calculations before the system collapses completely. However, NMR's future in quantum computing is limited. It is enjoying the spotlight now, but the technology suffers from several potentially fatal limitations. One of the most serious is lack of what is known as scalability. As the number of nuclear spins in a molecule increases, the number of molecules in the correct starting state decreases exponentially. So by the time a system gets larger than about 10 qubits, any signals are so weak that ordinary noise drowns them out.

So what is the quantum computing system of the future? It will probably use some solid-state technology, and it will look much like NMR, with complicated pulse sequences and spin systems. But the pulses might be at optical frequencies, and the spins might be dopants in a crystal, instead of liquids.

There are proposals for creating a quantum computer from an array of quantum dots. Quantum dots are small, isolated collections of atoms that behave much like a single atom, sharing electrons and a common wave function. A quantum dot on the scale of about 40 nm, and with a single excess electron, could serve as a qubit, with the electron's up and down spin serving as the 0 and 1.

Silicon is an appealing material in several ways. Both its electron and nuclear spins have extremely long decoherence times. It is already the seminal material of computer processors as well as the computer would be scalable. Research momentum is thus already directed toward silicon. One technological challenge, however, will be ensuring the purity of the silicon, because even a single unwanted atom could cripple the system. Silicon-based quantum computers are the focus of a mammoth research effort by a consortium including several universities.

While a quantum computer architecture has been proposed based on donors in silicon-germanium heterostructures which uses exclusively the electron spins, no common donor exists for these semiconductors that does not possess a nuclear spin. Consequently, it is preferable to adopt an architecture which uses the properties of both the electron and nuclear spins to advantage. The electron and nuclear spins have distinct characteristics that are favorable for quantum computation. The electron spins are de-localized and mobile, and they can couple to additional nuclei via the hyperfine interaction or to other electrons via the exchange interaction. The location of the electron can be controlled by electric fields applied to gates on the Si surface, as is done in conven tional Si devices. Electron spins can also in principle be measured using device concepts based on the Pauli Principle. The nuclear spins are much more weakly coupled to the environment, have no orbital degrees of freedom, rotate much more slowly in an applied B than electron spins, and are consequently almost ideally suited to function as qubits in a quantum computer.

Checklist for quantum computation:

1. State preparation: We need a system which is manipulable from the outside.
2. Evolution without decoherence: The external interactions must be removed for the duration of the computation stage
3. Measurement: After the evolution, we need to interact with the system once more

II. Silicon Based Quantum Computer Designs

Now we look at several practical designs for quantum computers using silicon technology:

A. Silicon-based Spin Quantum Computation

This solid state quantum computer is based on the fact that spins associated with donors in silicon - the semiconductor that is the mainstay of conventional computer technology - are ideally suited to function as qubits in a quantum computer. This fact is a consequence of the high degree of isolation of electron and nuclear spins at donors in Si from their surroundings at low temperatures ($T < 4K$). This isolation means that the highly coherent manipulations of the spins necessary for quantum computation are possible if there is a suit able means of controlling the interactions of individual spins with each other and with externally applied fields. Control of individual spin dynamics is achieved by applying voltages to metal gates, located adjacent to the donors. The donors must be in prescribed locations within the silicon host to enable accurate gate control, a requirement which will pose perhaps the most significant obstacle to the implementation of the computer design.

Readout of single spin qubits (and also initialization of the qubits) is achieved by a two step process: first, a spin quantum number is transferred to a property of the charge configuration of a system. Second, the charge configuration is determined using sensitive electronic devices. Spin quantum numbers can most easily affect the charge configuration of a two electron system: the Pauli Exclusion Principle requires that two electrons can only occupy the same orbital state if they are in a mutual spin singlet state, with spins pointing in opposite directions. Sensitive electrometers now have resolution much better than a single electron charge, and are thus capable of determining whether two electrons are in a singlet or a triplet state (when the two spins are pointing in the same direction and the electrons cannot occupy the same orbital state).

ELECTRON AND NUCLEAR SPINS AT DONORS IN SILICON

The addition of Column V donors to the Si crystal results in electron states near in energy to the conduction band but weakly bound to the donor sites at low T. The electron has spin S=1/2, and all Column V donors have nonzero nuclear spin I. (In contrast all Group IV elements, including Si, have stable isotopes with I=0, which means nuclear spins can in principle be entirely eliminated from these materials by isotope refinement.) The simplest system - and the one that has been most exhaustively studied - is P doped Si, in which I=1/2.

QUANTUM OPERATIONS WITH THE Si:P SYSTEM

The Si:P system is a natural two qubit quantum computer, the controlled NOT operation, in which an electron spin flip occurs conditioned on the state of the nuclear spin, is performed by exciting the transition | ↓e↑ni ↔ | ↑e↑ni, for example. The SWAP operation is performed by exciting the transition | ↓e↑ni ↔ | ↑e↓ni. In the architecture presented here, nuclear spins are the qubits and quantum memory of the computer, while the electrons are used to mediate interactions between nuclear spins. Qubit initialization and readout is performed by a combination of transfer of spin between nuclear and electron spins (for example by using the SWAP operation) and measurement operations on the electron spins.

ENVIRONMENT NECESSARY FOR QUANTUM COMPUTATION

The long relaxation times of Si:P necessary for quantum computation only occur at T ≤ 4 K. At higher temperatures phonon scattering rapidly decreases the relaxation times. A more stringent requirement placed on the environment necessary for quantum computation is that the spins must be highly polarized. Strong polarization of the electrons requires both high magnetic fields ($B \simeq 1$ T) and very low temperatures ($T \simeq 0.1$ K).

GATE-CONTROLLED QUANTUM LOGIC

A metal “A-gate” is located directly above a donor site, separated by a barrier from the Si semiconductor material. Application of a voltage bias to the gate creates an electric field which distorts the electron wave function surrounding the donor. This distortion changes the electron density at the donor nuclear site and also the hyperfine interaction energy A. Because the energy spacings of the spin levels are sensitive to A, an A-gate can selectively bring a single Si:P system into (or out of) resonance with a globally applied external B. Single spin quantum logic can thus be performed only at selected sites. The simplest way to couple additional spins into a quantum computer architecture is to fabricate an array of Si:P sites in close proximity (Fig. 4). As the site separation becomes comparable to the Bohr radius, the electron wave functions begin to overlap. Tunneling of electrons between sites then becomes possible, leading to an exchange interaction between the electron spins and also to an indirect (or electron mediated) exchange interaction between the nuclear spins. For the case when the two electron spins are in the |↓↓i state and are each coupled to the donor nuclear spins by the same hyperfine interaction energy A, the nuclear spin exchange frequency is approximately:

$$h\nu_J = 2A^2\left(\frac{1}{\mu_B B - 2J} - \frac{1}{\mu_B B}\right),$$

where J is the electron spin exchange energy, and $2J < \mu_B B$ is assumed. The magnitude of J between electron spins on donors as a function of their separation r can be approximated from equations derived for the case of well- separated H atoms :

$$J(r) \sim E_b\left(\frac{r}{a_B}\right)^{\frac{5}{2}} \exp\left(\frac{-2r}{a_B}\right).$$

Because exchange interactions depend on the overlap of the electron wave functions, they can be effectively controlled by a voltage bias applied to a "J-gate" lying between donor sites (Fig. 4).

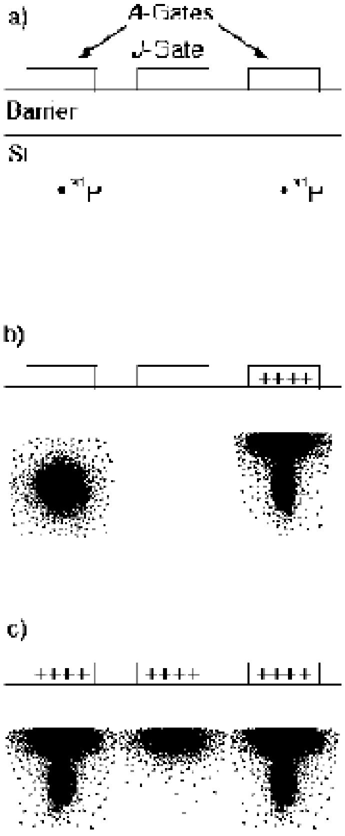


FIG. 4. (a) Configuration of gates and two donors for doing one and two qubit logical operations: in addition to *A*-gates above the donors, *J*-gates lie between donor sites. (b) One qubit logical operations are performed by applying an *A*-gate bias which brings a selected spin into resonance with an external rf magnetic field. (c) Two qubit operations are performed by lowering the potential barrier between donor sites with the *J*-gate and turning on exchange coupling between the donors. Electron mediated nuclear spin exchange will then occur between the donor nuclei.

Exchange interactions lead naturally to the SWAP operation of quantum logic, in which the spin quantum numbers of two qubits are interchanged. The SWAP operation in combination with single spin operations can be used as the primitive operations of a universal quantum computer. In the configuration shown in Fig. 4, a negative voltage bias applied to the J-gate decouples the adjacent spins. A positive voltage applied to the gate turns on the exchange interaction between the spins. A SWAP operation is performed if the voltage pulse has the appropriate length. Calculating the value of the exchange interaction as a function of separation between donors and of gate voltage in realistic device configurations is difficult and is the subject of current research. An added complication in Si is that the degenerate band structure leads to oscillatory behavior of the exchange interaction due to interference between electrons in different conduction band minima.

B. Charge-based silicon quantum computer architecture using controlled single-ion implantation

Although detection of single spins in silicon has not been achieved, fast single charge detection is already in place due to recent developments in RF single-electron transistor (SET) technology. Therefore a Si:P charge qubit architecture which is complementary to the Kane scheme, but experimentally accessible now. In this system the quantum logic states correspond to the lowest two states of the single valence electron localised in the double well formed by two donor phosphorus atoms.

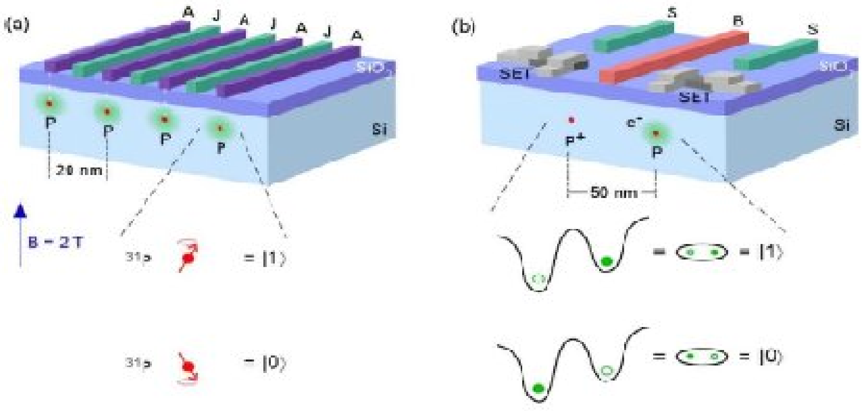


FIG. 1: Quantum computer architectures based on buried dopants in silicon. (a) Kane scheme [8], where a qubit is defined by the spin of a single ^{31}P nucleus. (b) Charge-based scheme [13], discussed here, where the position of a single electron within a double-well potential created by *two* P dopants defines logical states |0⟩ and |1⟩. Dual single electron transistors (SETs) on the surface enable qubit readout.

Gates above the buried P. P+ system allow for external control over the barrier height (B-gate) and potential symmetry (S-gates) for manipulation of localised qubit states, |0i = |Li and |1i = |Ri, while twin RF SETs facilitate qubit initialization and readout. A thin barrier layer such as SiO2 is used to isolate the gates from the donors below. The charge qubit will decohere faster than its spin-based counterpart due to stronger environmental coupling, however, calculated gate operation times of order 50 ps are commensurately faster than the µs operation times for spin qubits. Although not spin dependent, the electron transfer process in the P . P+ qubit is similar to that in the P . P system used for spin readout in the Kane scheme and as such provides a test bed for the future development of spin-based qubits.

OPERATION

To perform a single qubit operation S=1/2 rotation in the localized basis the S-gate biases are adjusted to zero, to symmetrize the potential, and the B-gate bias made negative to raise the barrier and slow the coherent oscillations (VS = 0 in). Typically, such operations will require gate bias precision down to the mV level. The time for a 1/2 rotation will depend primarily on the donor spacing and chosen B-gate bias. For a typical bias VB ~0.5 V we calculate rotation times longer than 50 ps, which are accessible using fast pulse generation technology. Before the qubit is operational it must be preinitialised after fabrication to remove one of the electrons from the P . P system. The pre-initialisation process is carried out using the S and B gates.

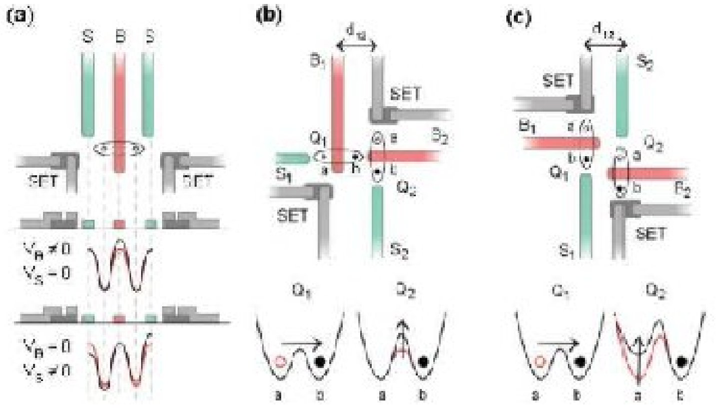


FIG. 5: (a) Operation of a single charge-qubit showing barrier (B-gate) and symmetry (S-gates) control, with twin-SET for correlated charge-position readout. (b, c) Qubit coupling schemes based on the Coulomb interaction. (b) "CNOT" configuration, where the control qubit Q_1 alters the effective barrier height as seen by the target qubit Q_2. (c) "CPHASE" configuration, where the control qubit Q_1 alters the potential symmetry at the target qubit Q_2.

C. Silicon-based quantum dot quantum bits

Spins based in silicon provide one of the most promising architectures for quantum computing. Quantum dots are an inherently scalable technology. Here, we combine these two concepts into a workable design for a silicon-germanium quantum bit. The novel structure incorporates vertical and lateral tunneling, provides controlled coupling between dots, and enables single electron occupation of each dot. Precise modeling of the design elucidates its potential for scalable quantum computing. We find that the component technologies for silicon quantum dot quantum computers are already in hand.

The fundamental goal of this design is the ability to reduce the electron occupation of an individual dot precisely to one, as in vertically coupled structures. It may be possible to use the spin of multi-electron quantum dots as qubits, but single occupation is clearly desirable. The spin state “up” = 0 or “down” = 1, stores the quantum bit of information. At the same time, it is necessary to have tunable coupling between neighboring dots. This is achieved by controlled movement of electrons along the quantum well that contains two dots. The solution is to draw on two distinct quantum dot technologies: lateral and vertical tunneling quantum dots.

The design, shown in Figure, incorporates a *back-gate* that serves as an electron reservoir, a *quantum well* that confines electrons vertically, and split *top gates* that provide lateral confinement by electrostatic repulsion. All semiconductor layers are formed of trainrelaxed $Ge_x Si_{x-1}$ except the quantum well, which is pure, strained Si. Relaxation is achieved by step-graded compositional growth on a Si wafer10. Here, we consider the composition x= 0.077, consistent with a quantum well band offset 84 meV, with respect to the barriers.

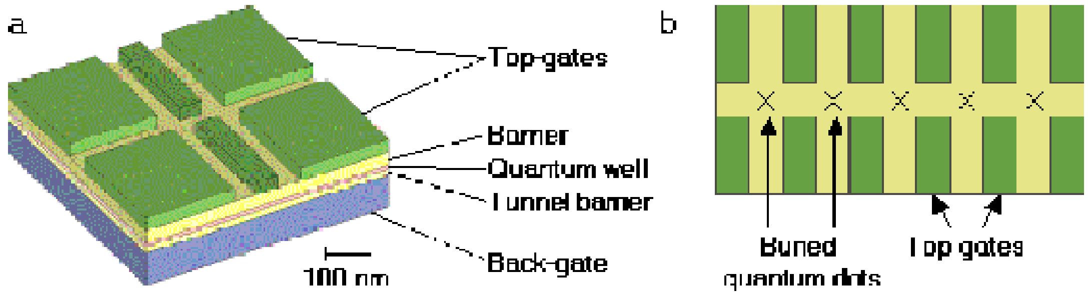


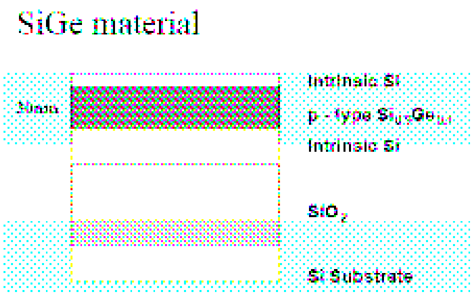
Figure 1 Two implementations of a quantum dot quantum computer. The cross-section of the heterostructure shows, from bottom to top, a thick, *n*-doped, strain-relaxed $Si_{1-x}Ge_x$ back-gate (blue), a 10 nm undoped $Si_{1-x}Ge_x$ tunnel barrier (yellow), a 6 nm undoped Si quantum well (red), a 20 nm undoped $Si_{1-x}Ge_x$ barrier (yellow), and lithographically-patterned metallic top-gates (green). All fabrication steps are based on standard technology. Not pictured is a thin Si capping layer. **a**, shows a side-view of the double quantum dot structure studied in this work. **b**, shows a top-view of a multidot device, demonstrating the scalability.

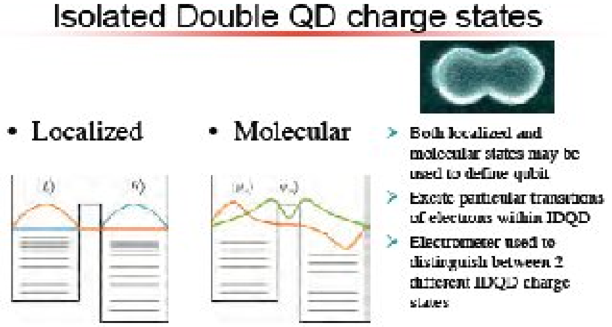
The novel feature of our design is the combined use of vertical tunnel coupling through the back gate, together with lateral coupling defined by the split top gates. To load a single electron into a dot, the gate potentials are adjusted so that single-electron filling is energetically favored In contrast with conventional, laterally coupled dots, we emphasize that no electrical connections are made to the quantum well layer. The design is scalable. Two qubits are enough for implementation of all necessary gates. Readout requires more qubits and separate consideration.

D. Silicon Device for Quantum Computing: A Quantum-Dot Charge Qubit

Hitachi Europe Ltd. announced in August, 2005 that a Hitachi-Cambridge team has developed a working silicon device for quantum computing: a quantum-dot charge qubit. This structure, based on years of work on single-electronics, is the first step in the development of a quantum computer based on conventional silicon technology.

Their approach to building a solid-state quantum computer is by exploiting quantum states of artificial atoms and molecules built in semiconductor quantum-dot systems. The team has demonstrated this with an isolated double quantum-dot as a qubit. The key challenges in producing efficient quantum circuits are to have a system with sufficiently high number of operations within the characteristic coherence time of the qubits, to control the coupling between qubits to form architectures, and to integrate the qubits with manipulation and measurement circuitry. All operations (initialisation, manipulation, and measurement) have been achieved: using electrical gates for initialisation and manipulation, and a single-electron transistor for measurement. The scheme gives a very long coherence time, (100 times longer than shown in other solid-state implementations) and also provides flexibility in design, since the qubits may be combined in a variety of two-dimensional circuits, as in conventional microprocessors. Thus it offers the possibility of scaling-up from one device to a large quantum circuit - a necessary criterion for making a useful quantum computer.

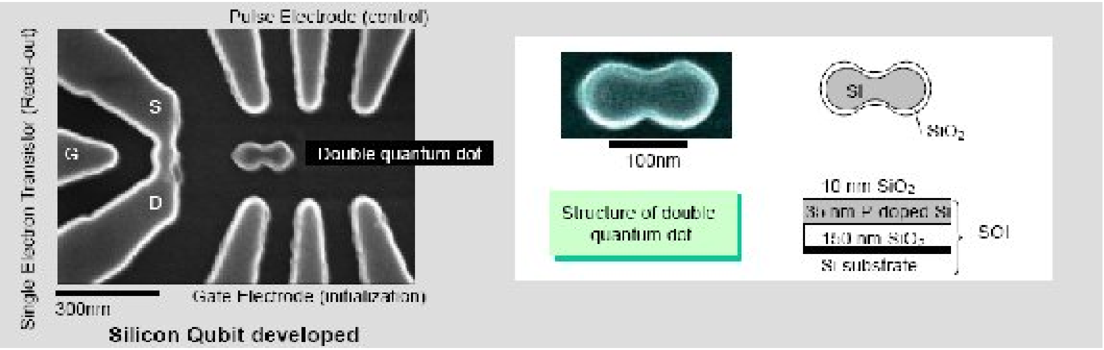

SiGe material


Isolated Double QD charge states

- Localized
- Molecular

- Both localized and molecular states may be used to define qubit
- Excite particular transitions of electrons within IDQD
- Electrometer used to distinguish between 2 different IDQD charge states

1. Gate -gate coupling is reduced
2. Two-dimensional structures are fabricabl Metal gates can also be added
3. A hard-wall confining potential is obtainable

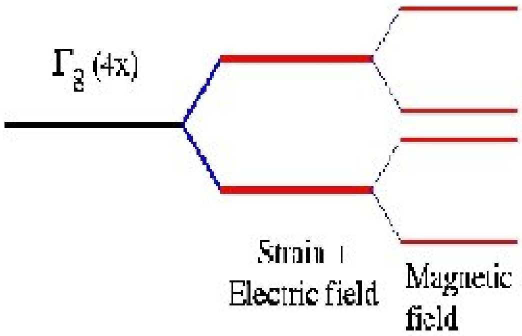


Silicon Qubit developed

E. Acceptor-based magnetic dipolar coupling silicon quantum computing

Here we describe a scalable solid-state quantum computer with “spinless” qubits. The states of the qubit are the low-lying states of a substitutional group III acceptor in silicon. The proposed system has many features in common with the NMR systems in liquids and semiconductors. It has the scalability inherent to spin-based solid state systems. However, the required spatial separation between the qubits is an *order of magnitude larger* than in the impurity-spin system, which greatly simplifies fabrication. This is made possible by strong dipolar coupling between the qubits. Measurements described here indicate a decoherence rate of order 1 kHz for this system for qubits with level separation 1-2 GHz. The frequency of gate operations is controlled by the interaction between the qubits and by the Rabi frequency in a resonant microwave field. For inter-acceptor distances of 100 nm and for moderate microwave power, the clock frequency of the quantum computer is 0.1 GHz. This implies a quality factor of 10^5, thus satisfying the criterion for quantum error correction. Different states of the proposed qubits have different charge distributions, which makes it possible to detect the state of a qubit with a capacitive measurement. Alternatively, it is possible to take advantage of the extremely narrow linewidths of acceptor-bound excitons in isotopically pure silicon for near-infrared detection.

Fig. 1. Splitting of the shallow acceptor energy levels in Si by external fields. The ground state has a 4-fold degeneracy that is split by external strain and by an electric field. It is additionally split by a magnetic field.



OPERATION

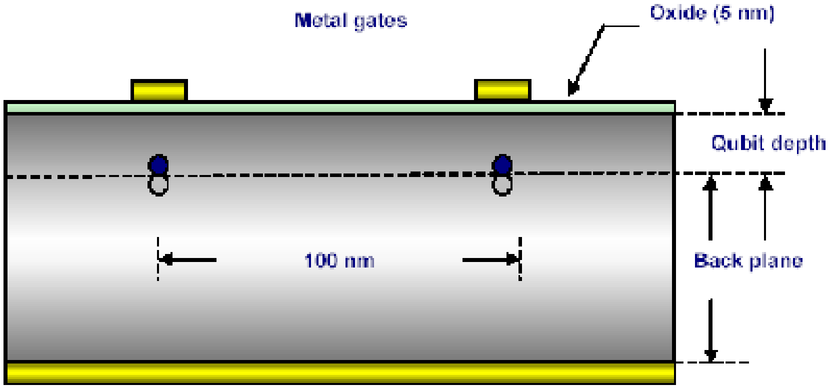


Fig. 3. Schematic diagram of the acceptor-based computer. The level splitting can be controlled by voltages applied to individual gates, shown here separated by 100 nm.

The general scheme of the acceptor-based quantum computer is shown in Fig. Using a focused ion beam and a mask, acceptors are implanted within a 10 nm lateral window at a depth ~10 nm beneath the interface. They form a regular structure, with acceptor-acceptor distances of order 100 nm. Each acceptor is addressed by a single, individual gate that imposes a static electric field, and tunes the level spacing via the Stark effect.

The different electronic states of the acceptor in an electric field are associated with different charge distributions. This allows one to measure the state populations by capacitance changes induced on the electrode and detected with an electrometer positioned adjacent to the gate. The radius of the localized electron state is much less than the distance *h* from the acceptor to the gate. Therefore a change of the state of the qubit results in the change of the dc potential on the gate, where is the dipole moment associated with difference in the charge distributions in the ground and excited states of the acceptor (see below), and 2/ˆ~ *hPVz*∑™*zP*ˆ™∑ is the dielectric constant of silicon. For readout, the static dipole moment can be enhanced momentarily by applying a strong electric field from the electrode. For ~ 10 Debye and *h* ~ 10nm, the potential *zP*ˆ*V*is of order 1 mV. The >100 nm gate separation makes SET integration relatively straightforward. Its use here has much in common with measuring charge transfer in a spin-based scheme.

TECHNIQUES FOR SINGLE SPIN MEASUREMENT

The procedures outlined above perform all of the logical operations necessary for quantum computation. The spins must also be prepared in a specified initial state and read out at the end of the calculation. In computer architecture capable of performing error correction, state preparation and measurement are necessary throughout the process of calculation. For this to be possible the measurement must be rapid, since if the measurement process during error correction were slow, the qubits would decohere during the period in which the measurement was occurring.

While the measurement of the magnetic fields induced by electron and even nuclear spins may be possible using advanced magnetic resonance force microscopy, these techniques are highly unlikely to perform measurements on a time scale comparable to logical operations. While single spin measurements are likely to be both dicult and slow, single charge measurements on a microsecond time scale are now routinely performed using single electron transistor (SET) electrometers, and SET's may be ideally suited to perform the quantum measurements necessary for quantum computation.

Measurement of a single electron spin requires that one of the two electrons be in a known spin state, for example, | ↓?i. If the state of the system is | ↓↓i then a measurement of the two electrons will yield a triplet result. If the two electrons are in the | ↑↓i state, then they may be either in a singlet (| ↑↓ . ↓↑i) or a triplet (| ↑↓ + ↓↑i) state. Scattering between | ↑↓ . ↓↑I and | ↑↓ + ↓↑i is generally much more rapid then scattering between | ↓↓i and | ↓↑i, since scattering between the latter states can only proceed via a spin flip. Consequently, a measurement which determines whether the electrons are in a singlet or triplet state can be used to infer the spin state of the second electron if the measurement

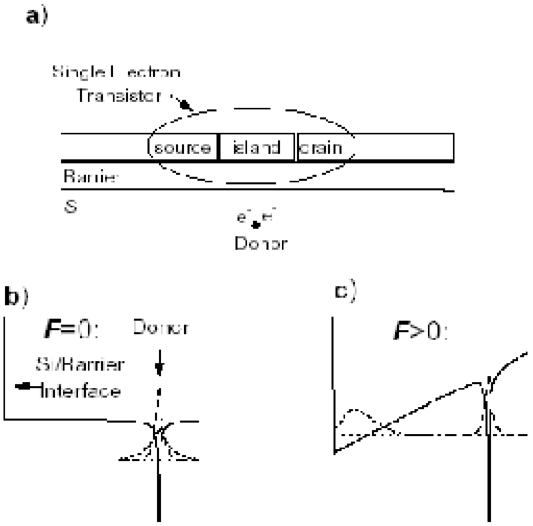


FIG. 7. (a) Possible configuration in which a single electron transistor (SET) is used as a sensitive electrometer to probe the spin state of a two electron system. The conduction across a SET depends sensitively on the potential of the island electrode. (b) In the absence of an applied electric field F the wavefunctions of both electrons (dotted lines) are localized by the attractive electrostatic potential (solid line) in the vicinity of the donor. (c) An applied electric field can draw one of the two electrons to a state at the Si-barrier interface. The value of F where this electron moves from the interface to the donor is different for electrons in singlet and triplet spin states. This charge motion affects the SET conductance, enabling the spin state of the electrons to be determined.

time exceeds the time required for scattering between the | ↑↓ . ↓↑i and | ↑↓ + ↓↑i states but is less than the time required for scattering between | ↓↓i and | ↓↑i.

TECHNIQUE FOR CHARGE MEASUREMENT

Operational issues aside, the spin- and charge-based Si:P schemes face an identical challenge for placement of individual phosphorus donors within a low disorder intrinsic-silicon (i-Si) substrate at precise array sites, accurately positioned with respect to the surface control gates and SETs. Two contrasting approaches are being developed to attain this goal. In the first, scanned probe lithography of a hydrogenated silicon surface together with epitaxial Si overgrowth may be used to construct a buried P array using a bottom-up atomic assembly approach. While potentially capable of atomic precision, a number of steps remain in the full demonstration of this technology.

IMPLEMENTING THE ARCHITECTURE IN Si/Si$_x$Ge$_{1-x}$ HETEROSTRUCTURES

In all the device structures discussed above, a barrier material must be present separating the Si containing the donors from the conducting gates. The Si/barrier interface must be almost entirely free of charge and spin defects if the devices are to perform quantum gate operations, especially if free electrons on the interface are to be used to transfer quantum information between remote donors. Silicon oxide and nitride layers used in conventional MOS structures - are amorphous materials, and their interfaces with Si will inevitably contain charge centers associated with dangling bonds, rendering their use in a quantum computer highly problematic.

Most promising for application to quantum computation, however, are the heterostructures grown with Group IV elements: Si/SixGe1-x and Si/SixC1-x. We will focus on Si/SixGe1-x heterostructures because they are the most technologically developed. Si/SixC1-x heterostructures have recently been used to perform the first direct electron spin resonance measurements on two dimensional electron systems, and they may thus also be relevant for implementing quantum logical devices. Because of the lattice mismatch between Si and Ge, SixGe1-x heterostructures must inevitably contain layers that are strained. A high quality (mobility 500,000 cm2/Vsec) has been formed in these materials by confining the electrons in a strained Si layer between unstrained layers of SixGe1-x on a (100) oriented substrate. Because the Si is strained along a (100) axis, the valley degeneracy of the conduction band is broken, and the well is occupied by electrons only in the two valleys with minima on the axis perpendicular to the layers. The electron effective mass in these valleys is anisotropic, and the contours of equal probability density of electron wavefunctions on donors in the Si well are ellipsoidal. Since the Si layer is under strain, its thickness cannot exceed a critical value without the nucleation of dislocations. For Si/Si0.85Ge0.15 this thickness is approximately 200 °A,

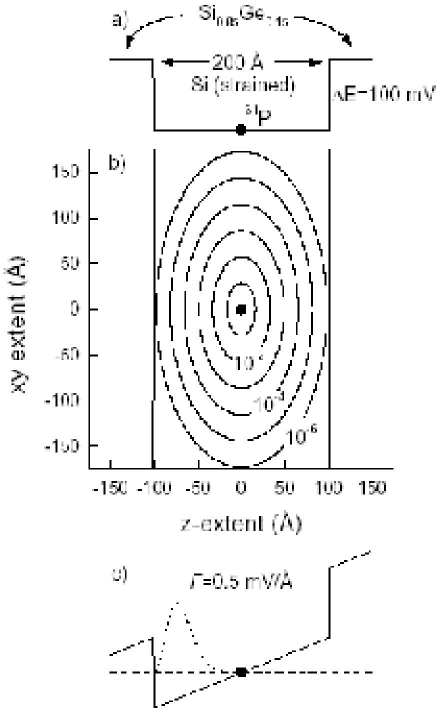


FIG. 12. (a) Possible realization of the quantum computer architecture where the electron and the donor reside in a strained Si quantum well surrounded by unstrained Si_xGe_{1-x}. (b) Because of the strain, the electron mass for motion parallel to the layers is smaller than the mass for motion perpendicular to the layers, and the contours of equal probability of the electron wavefunction are ellipsoidal. (c) An applied electric field F can draw the electron to an interface state confined in the well.

suffciently thick so that the electron wavefunction of a donor in the center of the well is almost entirely in pure Si.

STRAINED SILICON APPROACH:

Straining the silicon in a way that lowers the energy of the valleys on a single axis by an amount that makes silicon essentially a single band semiconductor, has advantages for the purpose of quantum computing. The simpler band structure minimizes the changes in donorwave function that are otherwise introduced into silicon by random strains caused by metallization and other concomitants of preparing a complex cryogenic solid-state electronic structure. The maximum separation of one type of minimum from the others occurs when the strain is uniaxial, a strain with four-fold symmetry about a (001)-type axis. A donor wave function with 0.999 single-valley content can be produced with known silicon on SiGe alloy technology.

Straining the silicon: This can be done by subjecting the silicon to a uniaxial strain around a (100) crystal axis. Strain of this kind can be induced by epitaxial growth of a thin layer of silicon on the (100) surface of a SiGe alloy substrate (Keyes 1986, Jackson *et al* 1993). The alloy has a larger lattice constant than silicon, and extends the lattice in a layer of epitaxial silicon in the (001) and (010) directions, causing a contraction in the (100) direction. As mentioned above, the technology for doing this has received considerable recent attention as a way to take advantage of the high mobility associated with the light effective mass of a valley in field-effect transistors.

Silicon is a cubic crystal. Its conduction band contains six symmetrically located points of minimum and identical energy on the + and − directions of the three cubic (100) axes. Electrons in the conduction band are clustered around these minima, often referred to as ‘valleys’. Contours of constant energy around a minimum are ellipsoids of revolution around the three (100) type axes that can be described by anisotropic effective masses. All valleys have the same minimum energy and contain the same number of electrons. Strain that destroys the cubic symmetry of the crystal removes the energy degeneracy of the valleys, allowing their occupancy by electrons to differ and the anisotropy of the valleys to become evident as marked changes in the transport parameters

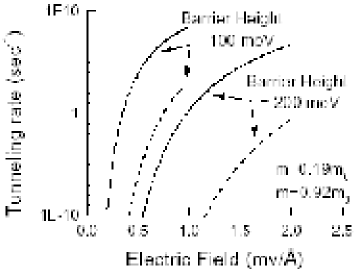


FIG. 13. Fowler Nordheim tunneling rates for electrons out of a strained Si quantum well through a Si_xGe_{1-x} barrier. Si/Si_xGe_{1-x} structures for quantum logic will need to be carefully designed so that electron tunneling out of the well is not a significant source of decoherence.

materials by confining the electrons in a strained Si layer between unstrained layers of Si_xGe_{1-x} on a (100) oriented substrate (Fig. 12a). Because the Si is strained

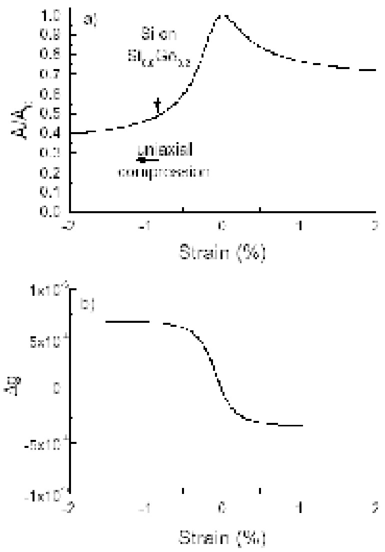


FIG. 14. The effect of strain on the hyperfine interaction frequency (a) and the g-factor anisotropy (b) in Si, using calculations in Ref. [52]. In the strained layer structure shown in Fig. 12, the hyperfine interaction will be reduced about 50% from the value observed in unstrained Si.

DOPANT INTRODUCTION BY LOW ENERGY ION IMPLANTATION

The low density of unwanted impurities introduced into the Si that is required for the computer suggests that both crystal growth and dopant incorporation should be performed in ultra high vacuum in the same apparatus. Possible approaches to dopant placement include nanoassembly using a scanned probe and ion implantation. At the temperatures necessary for optimal growth of high quality material, surface segregation of donors deposited onto a Si surface is substantial, leading to large (≥ 100°A) vertical (and presumably lateral) displacements of deposited donors from their original location. The diffusion of donors once they are incorporated into the bulk is, however, much lower. Low energy ion implantation has consequently been developed as a tool for introducing donors into semiconductors with extremely sharp (≤ 30°A) vertical profiles. A tool which could place donors into Si with the precision necessary for development of the proposed quantum computer would be a low energy focused ion beam with single ionimplantation capability incorporated into a Si MBE growth chamber.

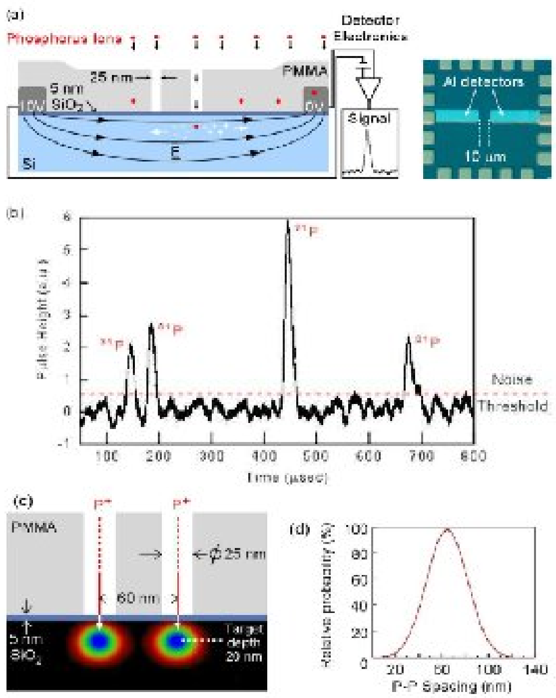


FIG. 2: (a) Schematic (not to scale) showing phosphorus implantation through a resist mask. Each ion strike creates an electron-hole plasma, producing a current pulse monitored by on chip electrodes (shown in optical micrograph at right). (b) Experimental demonstration of single ion strikes in an i-Si substrate bombarded with a 14 keV phosphorus ion beam. (c) Calculated 14 keV P^+ implant position probability for two 25 nm apertures separated by 60 nm. (d) Resulting histogram of spacings between pairs of P^+ implants through the apertures.

Figure above depicts the technique developed to localize individual phosphorus atoms at the desired qubit array sites. A nano-patterned ion-stopping resist such as polymethyl-methacrylate (PMMA) defines the array sites and a low-energy keV 31P+ ion beam is used to implant the P dopants through the thin SiO2 barrier layer to a mean depth of 20 nm into the substrate.

III. Summary

In summary, we have reviewed the different approaches to Quantum computation using Silicon technology, the ways in which the value of he qubit can be measured. Also we discussed the various methods of dopant implantation in Silicon. Simple devices can be fabricated with currently available technology, but implementing Large-scale quantum computers will need to have fluctuation and defect tolerant designs, both because of the precision that is required for doing quantum logic and because of the inevitable variations in solid state materials from device to device. The technology for donor placement will have to be developed further. Thus a lot of technological advances need to be made on many fronts for the Silicon-based quantum computers presented above to be realizable.

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