A Self Assembled Nanoelectronic Quantum Computer
Based on the Rashba Effect in Quantum Dots

S. Bandyopadhyay*

Department of Electrical Engineering
University of Nebraska
Lincoln, Nebraska 68588-0511, USA

Abstract

Quantum computers promise vastly enhanced computational power and an un
canny ability to solve classically intractable problems. However, few proposals exist
for robust, solid state implementation of such computers where the quantum gates are
sufficiently miniaturized to have nanometer-scale dimensions. Here I present a new
design for a nanoscale universal quantum gate. It consists of two adjacent quantum
dots each containing a single electron. The spin of each electron encodes a qubit. Ferromagnetic contacts are used to coherently inject an electron into each dot with
a definite spin orientation, thus defining the initial state of the qubit. To rotate the
qubit, we exploit the fact that the ground state of the electron is spin-split because
of the magnetic field caused by the ferromagnetic contacts, as well as the Rashba in-
teraction arising from spin-orbit coupling. Arbitrary qubit rotations are effected by
modulating the Rashba splitting with an external electrostatic potential and bringing
the total spin splitting energy in a target quantum dot in resonance with a global ac
magnetic field. The controlled dynamics of the universal 2-qubit rotation operation
can be realized by controlling the exchange coupling between the two dots with yet
another gate potential which changes the overlap between the wavefunctions of the
two electrons. The qubit (spin orientation) is read via the current induced between
the ferromagnetic layers under an applied potential. The ferromagnetic layers act as
“polarizers” and “analyzers” for spin injection and detection. A complete prescription
for initialization of the computer and data input/output operations is presented. Fi-
nally, we define a clear pathway towards self assembling this structure using chemical
synthesis and some lithography.

*Corresponding author. E-mail: bandy@quantum1.unl.edu
1 Introduction

There is significant current interest in quantum computers because they possess vastly enhanced capabilities accruing from quantum parallelism \[1, 2\]. Some quantum computing algorithms \[3, 4\] have been shown to be able to solve classically intractable problems, i.e. perform tasks that no classical algorithm could perform efficiently or tractably. Quantum computers and quantum memories are also the backbone of quantum repeaters and teleportation networks.

Experimental effort in realizing quantum computers has been geared towards synthesizing universal quantum logic gates from which quantum computers can be built. A universal gate is a 2 qubit-gate \[5, 6, 7\] and has basically two attributes. First, it allows arbitrary unitary rotations on each qubit and second, it performs the quantum controlled rotation operation whereby one of the qubits (the target qubit) is rotated through an arbitrary angle, if, and only if, the other qubit (the control qubit) is oriented in a specified direction. The orientation of the control qubit is left unchanged. It is this conditional dynamics of the controlled rotation operation that is challenging to implement experimentally.

Recently, it has been shown \[8, 9, 10\] that there exist universal fault-tolerant computers that can operate in a non-ideal noisy environment. They are usually a circuit composed of one- or two-qubit gates performing various unitary rotations on a qubit (e.g Hadamard, Pauli rotations through rational or irrational angles, etc.). They too can, in principle, be realized from the basic gate that we discuss here.

The most vexing problem in experimentally realizing quantum computers is the issue of decoherence. Qubits are coherent superpositions of two-level states and, as such, are delicate entities. Any coupling to the environment will destroy the coherence of the superposition state and corrupt the qubit. Were it not for the recent discovery of quantum error correcting codes \[11\] that can correct errors due to decoherence through the use of appropriate software, quantum computing would have remained a theoretical curiosity.

In the past, atomic systems were proposed as ideal testbeds for experimental quantum logic gates because of the relatively long coherence times associated with the quantum states of trapped atoms and ions \[12\]. Experimental demonstrations of quantum logic gates were carried out in atomic systems \[13, 14\]. Recently, nuclear magnetic resonance (NMR) spectroscopy has been shown to be an attractive alternative \[15, 16\] and there has been some reports of experimental demonstrations involving NMR \[17\]. However, there are also some doubts regarding the efficacy of NMR based approaches when dealing with many qubits \[18\].

The major drawback of both atomic and NMR systems is of course that they are unwieldy, expensive and inconvenient. Solid state (especially nanoelectronic) implementations would be much more desirable because they are amenable to miniaturization. One would like a quantum gate that is one nanometer long and not one meter long. The technology base that exists in the solid-state area with regards to miniaturization is unparalleled.

While it is understood that solid state systems will be preferable vehicles for quantum computation, it is also well-known that the phase memory time of charge carriers in solids saturate to only a few nanoseconds as the lattice or carrier temperature is lowered to a few
millikelvins (this is caused by coupling of carriers to the zero-point motion of phonons). Thus, solid state implementations of quantum gates where the qubits are coupled to charge degrees of freedom will be always dogged by serious decoherence problems. Even though such systems have been proposed in the past, they will require clock speeds in the far infra-red frequency range to meet Preskill’s criterion for fault-tolerant computing.

A possible solution of this problem is to use the spin degrees of freedom in solid state systems to encode qubits since the spin is not coupled to electromagnetic noise and hence should have much longer coherence times than charge. It has been shown that electronic and nuclear spins of phosphorus dopant atoms $^{31}$P in silicon have very long spin-flip times (or the co-called $T_1$ times in the language of spectroscopy) of about an hour. Consequently, nuclear spins of $^{31}$P dopant atoms in silicon have been advocated as preferable vehicles for qubits. However, the actual coherence time (or $T_2$ time) of electron spin in P-doped silicon may be on the order of a millisecond. Compound semiconductors may exhibit somewhat shorter spin coherence times, but spin coherence times as long as 100 ns have been experimentally demonstrated in n-type GaAs at the relatively balmy temperature of 5 K. Thus, it is practical to contemplate solid state quantum computers based on single electron spins.

Not all semiconductors however are suitable hosts for qubits. Pyroelectric materials (uniaxial crystals without inversion symmetry) usually exhibit electric dipole spin resonance which can increase the spin flip rate significantly by strongly coupling the spin to phonons. An advantage of quantum dots is that the spin-phonon interaction may be reduced because of a constriction of the phase space for scattering. Moreover, the phonon-bottleneck effect may block phonon-induced spin-flip transitions. Another obvious strategy to increase the coherence time is to decrease the phonon population by reducing the temperature. The temperature must be low in any case since the time to complete a quantum calculation should not significantly exceed the thermal time scale $\hbar/kT$ irrespective of any other consideration.

Quantum gates based on spin polarized single electrons housed in quantum dots have been proposed by us in the past and more recently by Loss and DiVincenzo. Here we adopt a different idea - which is still based on spin-polarized single electrons - to provide a realistic paradigm for the realization of a self-assembled solid-state, nanoelectronic universal quantum gate.

2 A Self Assembled Universal Quantum Gate

Consider two adjacent penta-layered quantum dot structures shown in Fig. 1(a). In each dot, the two outer layers are ferromagnetic and the middle layer is a semiconductor. Insulating layers separate the ferromagnetic layers from the semiconductor layer in order to provide a potential barrier for an electron injected into the semiconductor layer. We will describe later how one can self-assemble this structure.
Figure 1: (a) Cross-section of a penta-layered quantum dot. FM refers to ferromagnet, SC refers to semiconductor, and I refers to insulator. (b) The top view showing the ohmic contacts for measuring spin polarized current in the target (T) and control (C) dots, and the Schottky contacts $A_1$, $A_2$, $A'_1$ and $A'_2$. These contacts are defined by fine-line lithography. (c) a “spin-wire” for transmitting quantum information is made out of exchange coupled single electron cells, which induce the Rashab effect and turn exchange coupling between C and T on and off. (d) The energy band diagram for the structure along the x-direction (perpendicular to heterointerfaces) showing the spin-split states and the corresponding spatial wavefunctions.
A dc potential pulse is applied between the two outer (ferromagnetic) layers to inject a
single spin-polarized electron coherently from one of the outer layers into the middle layer.
We will discuss the ramifications of such spin injection later. In the middle layer, the
electron’s ground state is spin-split because of Rashba interaction \cite{34, 35, 36}. The Rashba
effect arises from spin-orbit coupling in the presence of a transverse electric field which is
always present at the interface of two dissimilar materials owing to the conduction band
discontinuity. It is possible to electrostatically modulate this spin splitting \cite{38} by applying
a transverse potential using lithographically delineated gate contacts. The applied potential
alters the interface field that causes the Rashba effect and hence changes the spin-splitting
energy.

2.1 Single qubit rotation

A target qubit is selected for rotation by bringing its spin-splitting energy in resonance
with the external global ac magnetic field by applying a suitable potential pulse to the gate
contacts. Arbitrary qubit (spin) rotation is achieved by varying the pulse duration, i.e.
the duration of resonance with the ac magnetic field. Such a procedure realizes the first
ingredient of a universal quantum gate, namely arbitrary single qubit rotations.

2.2 Two qubit controlled dynamics

In order to achieve the second and last ingredient of a universal quantum gate - namely
the conditional dynamics of a universal 2-qubit gate - we need to couple the rotation of one
qubit (target qubit) with the orientation of another qubit (control qubit). This can be done
by exploiting the exchange coupling between two single electrons in two neighboring dots.
The spin-splitting energy in any dot depends, among other things, on the spin orientation
in the neighboring dot if the two dots are exchange coupled. It is obvious that the total
spin splitting $\Delta_{\text{target}}$ in the target dot depends on the exchange interaction $J$ with the
neighboring (control) dot (and hence on the spin orientation of the control qubit) if the two
dots are exchange coupled. After all, the exchange term will appear in the Hamitonian of the
coupled two-dot system. For instance, without the exchange interaction, the spin splitting
energy in the target dot is

$$E_\downarrow - E_\uparrow = \Delta$$  \hspace{1cm} (1)

Now, let us turn the exchange interaction on which lowers the energy of the singlet state
with respect to that of the triplet state. Thus, if the control dot’s spin is pointing “up”,
the target dot’s spin will prefer to be “down” if the exchange interaction is operative. This
decreases $\Delta$. On the other hand, if the control dot’s spin is pointing “down”, then $\Delta$ is
increased. The energy levels are shown in Fig. 2. Thus, the potential $V_{\text{target}}$ that brings
the total spin splitting energy $\Delta_{\text{target}}$ in the target dot in resonance with the ac magnetic
field $B_{ac}$ depends on the spin orientation in the control dot. Herein lies the possibility of
conditional dynamics. We can find the $V_{\text{target}}$ that will rotate the target qubit through an
arbitrary angle only if the control qubit is in the specified orientation. Application of this
potential $V_{\text{target}}$ to the target dot realizes the operation of a quantum controlled rotation gate.

To turn the exchange “on” and “off”, one can apply a differential potential between the target and control dots which will skew the wavefunctions and change the overlap between the wavefunctions of the target and control electrons. Alternately, one can apply positive potentials to all Rashba contacts $A_1$, $A_2$, $A_1'$ and $A_2'$. In this case, there is no differential potential, and the Rashba effect is not modified, but the positive potential will attract the electrons into the insulating layers surrounding the quantum dots, thus increasing the overlap between the wavefunctions and the exchange interaction.

### 2.3 Reading the qubit

Finally, we have to “read” a qubit for data output. The qubit (spin orientation in a dot) is read directly via the current induced between the dot’s spin polarized outer layers (ferromagnetic contacts) when a sufficiently strong potential is applied to overcome the Coulomb blockade. The magnitude of the current tells us the electron’s spin orientation because it depends on the angle between the electron’s spin orientation and the direction of magnetization in the ferromagnetic contact (which is known \textit{apriori}). This principle was prescribed for measuring spin precession in the so-called spin-transistor proposed more than ten years ago [36]. It is the same principle that is used in tunneling magnetoresistance devices [39]. The single electron current is small, but can be measured using sensitive electrometers. There are alternative schemes for reading single electron spins that rely on single electron transistors and the use of the Pauli exclusion principle [27]. They are much more complicated and are
not discussed here.

3 Rashba effect in a quantum dot

We will now derive the total spin-splitting in a quantum dot, including the Rashba splitting. Consider the system shown in Fig. 1. The ferromagnetic contacts give rise to an in-built magnetic field in the x-direction which can be quite strong in realistic structures (∼ 1 Tesla). There may be an electric field in the x-direction as well to maintain single electron occupancy and an electric field in the y-direction to induce the Rashba effect.

The total Hamiltonian for an electron in the semiconductor layer is

\[
H = \frac{(\vec{p} - e\vec{A})^2}{2m^*} - e\mathcal{E}_x x - e\mathcal{E}_y y + \frac{(g/2)\mu_B B_x \sigma_x}{2m^*} + H_R
\]

where \( g \) is the Landé g-factor, \( e \) is the electronic charge, \( \mu_B \) is the Bohr magneton, \( \sigma_x \) is the x-component of the Pauli spin matrix, and \( H_R \) is the Rashba interaction given by

\[
H_R = i\frac{\hbar^2}{2m^*c^2} \nabla V \cdot [\vec{\sigma} \times \nabla] = \frac{e\hbar}{2m^*c^2} \vec{\mathcal{E}} \cdot \vec{\sigma} \times \vec{p}
\]

where \( \vec{\sigma} \) is the Pauli spin matrix, \( \vec{p} \) is the momentum operator, and \( \vec{\mathcal{E}} \) is the electric field inducing the Rashba effect.

We will neglect the effect of the x-directed electric field on the Rashba effect and include only the effect of the y-directed field which is much larger since the potential applied along the x-direction must be smaller than \( e/2C \) to maintain Coulomb blockade. In any case, the x-directed field has no Rashba effect on x-polarized spins, and we are interested in the energy splitting between the +x and -x-polarized spins. Therefore,

\[
H_R = \frac{e\hbar}{2m^*c^2} \mathcal{E}_y [\sigma_z p_x - \sigma_x p_z]
\]

The Zeeman term \((g/2)\mu_B B_x \sigma_x\) introduces an Zeeman splitting between the +x-polarized spin (\( |\uparrow>\)) and the -x-polarized spin (\( |\downarrow>\)). If the potential confining the electron in the semiconductor quantum dot is finite (the conduction band offset between the semiconductor and the surrounding material is finite), then the spatial parts of the “upspin” (+x-polarized) and “downspin” (-x-polarized) states are slightly different. The wavefunction of the higher energy state will be spread out a little bit more. This is shown in Fig. 1(d). Thus, if the downspin state is at a higher energy, then the spatial parts of the wavefunctions of the two spin states in the lowest spin-split subband of the quantum dot can be written as

\[
\phi \uparrow = \left( \frac{2\sqrt{2}}{W_x W_y W_z} \right) \sin \left( \frac{\pi x}{W_x} \right) \sin \left( \frac{\pi y}{W_y} \right) \sin \left( \frac{\pi z}{W_z} \right)
\]

\[
\phi \downarrow = \left( \frac{2\sqrt{2}}{W'_x W'_y W'_z} \right) \sin \left( \frac{\pi x}{W'_x} \right) \sin \left( \frac{\pi y}{W'_y} \right) \sin \left( \frac{\pi z}{W'_z} \right)
\]
where $W'_x > W_x$, $W'_y > W_y$ and $W'_z > W_z$. These widths are larger than the physical dimensions of the quantum dot since the wavefunctions will leak out into the barrier as long as the barrier is not of infinite height. The point of this exercise is to show that the spatial parts of the two spin states are different because of the Zeeman splitting. This is a critical requirement for the Rashba splitting.

Next, we will evaluate the total spin splitting ($\Delta$) which is a combination of the Zeeman and Rashba splitting. The latter can be modulated by the transverse gate potential.

The time-independent Schrödinger equation describing the ground state of the system is

$$ (H_0 + H_R) \psi = E\psi \quad (6) $$

We will expand $\psi$ in the basis functions of the two lowest spin-resolved subband states. We can neglect the higher subband states as long as the Rashba spin splitting $\Delta_R$ is much smaller than the energy separation between the lowest two subbands in the quantum dot. If the effective mass is equal to the free electron mass and the dimensions of the quantum dot in all directions is about 10 nm, then the energy separation between the two lowest subbands is 33 meV. This is obviously much larger than any reasonable Rashba splitting which scarcely exceeds 1 meV. Hence, neglecting the higher subbands is justified.

Hence

$$ \psi = a_\uparrow \phi \uparrow + a_\downarrow \phi \downarrow \quad (7) $$

Using the above in Equation (6) we get

$$ \begin{bmatrix} <H_1> + <H_R>_{11} & <H_R>_{12} \\ <H_R>_{21} & <H_2> + <H_R>_{22} \end{bmatrix} \begin{bmatrix} a_\uparrow \\ a_\downarrow \end{bmatrix} = E_{\text{ground}} \begin{bmatrix} a_\uparrow \\ a_\downarrow \end{bmatrix}, \quad (8) $$

where $<H_1> = <\phi \uparrow | H_0 | \phi \uparrow>$, $<H_2> = <\phi \downarrow | H_0 | \phi \downarrow>$, $<H_R>_{11} = <\phi \uparrow | H_R | \phi \uparrow>$, $<H_R>_{22} = <\phi \downarrow | H_R | \phi \downarrow>$, $<H_R>_{12} = <\phi \uparrow | H_R | \phi \downarrow>$, and $<H_R>_{21} = <\phi \downarrow | H_R | \phi \uparrow>$.

Diagonalizing the above Hamiltonian, we get that the total splitting between the upspin and downspin states is

$$ E_\downarrow - E_\uparrow = 2 \sqrt{\left( \frac{<H_1> - <H_2> + <H_R>_{11} - <H_R>_{22}}{2} \right)^2} + <H_R>_{12} <H_R>_{21} \quad (9) $$

where $<p_x> = <\phi \uparrow | -i\hbar(\partial/\partial x)\phi \uparrow> = <\phi \downarrow | -i\hbar(\partial/\partial x)\phi \downarrow> = 0$ and $<p_z> = <\phi \uparrow | -i\hbar(\partial/\partial z)\phi \downarrow> = \frac{\sinh(\pi W_x / W'_x)}{\sqrt{W_x W'_x}} \cos^2 \left( \frac{\pi W_x}{W'_x} \right)$.

Therefore the total splitting is

$$ \Delta = E_\downarrow - E_\uparrow = 2 \sqrt{\left( \frac{g\mu_B B}{2} \right)^2 + \frac{e\hbar}{2m^* c^2} \mathcal{E}_y <p_x>^2 + \frac{e\hbar}{2m^* c^2} \mathcal{E}_y <p_z>^2} \quad (10) $$
The last term under the radical is the Rashba effect which can be varied by the electric field $E_y$. Note that this term would have vanished if $W_x = W'_x$, that is, if the spatial parts of the upspin and downspin wavefunctions were identical. Here, we have made the spatial parts different by using a finite potential barrier and a magnetic field to raise the energy of the downspin state above that of the upspin state.

3.1 Coherent spin injection from spin polarized contacts

We mentioned earlier that we wish to inject an electron into the quantum dot with a definite spin orientation so that we know the initial state of the qubit at time $t = 0$. However, coherent spin injection from a spin-polarized (ferromagnetic) contact into the semiconductor is not critical for this purpose. If the spin-injection does not work, one could still select a definite initial spin using the principle of the spin-RTD. Since the subbands in the quantum dot are spin split, one can align the Fermi level in the contact with one of the spin-split levels and therefore preferentially inject into that level. This will assign a definite spin orientation to the qubit. If even that does not work, one can inject an electron with arbitrary spin and wait till the electron decays to the lowest state (by a spin flip transition if necessary). Since the spin degeneracy is lifted by a combination of the Zeeman and Rashba effect (see last equation), the ground state always has a definite spin polarization. In the latter two scenarios, ferromagnetic contacts are not necessary.

Even though coherent spin “injection” is not critical, coherent spin “detection” is absolutely critical since it provides the mechanism for reading a qubit. The injector is a spin-polarizer and the detector is a spin-analyzer. We can do away with the polarizer, but not the analyzer. Thus, coherent spin injection across one of the ferromagnetic interfaces is necessary. If the analyzer does not work either, we have to rely on the mechanisms proposed in ref. [27] for reading spin which are much more complicated.

Coherent spin injection from a metal into a semiconductor is a difficult problem [40] and has been recently addressed theoretically [11]. There have been some scattered reports of spin injection from a ferromagnet into a semiconductor [12] and between two semiconductors of widely different bandgaps [13]. Recently, spin polarized hole injection was demonstrated from GaMnAs into GaAs [15] at around a temperature of 120 K. Prior to that, spin polarized injection from CdMnTe into CdTe was demonstrated [14], but the disadvantage in that case is that CdMnTe is not a permanent ferromagnet; the spin polarization needs to be maintained by a globally applied dc magnetic field which introduces a Zeeman splitting in CdMnTe. However, only a very small field is required since the effective Landé g-factor for electrons in dilute magnetic semiconductors is huge ($\sim 100$). On the other hand, the advantage of CdMnTe is that it is lattice matched to CdTe and hence interface scattering is less of a problem. Most recently, 90% spin polarized electron injection was demonstrated from the dilute magnetic semiconductor $\text{Be}_x\text{Mn}_y\text{Zn}_{1-x-y}\text{Se}$ into GaAs at a temperature below 5 K [46] and at a relatively large magnetic field which induces a Zeeman splitting in the magnetic semiconductor. While the temperature is high enough for quantum computing applications, the applied magnetic field is too large and may flip the spin in the semiconductor quantum
dot, thus corrupting the qubit. The problem of coherent spin injection from a ferromagnetic material into a semiconductor is a topic of much current research. It has a long history and rapid strides are being made in this field.

Another important question is how easy will it be to maintain single electron occupancy in each dot. As long as the energy cost to add an additional electron \( (= e^2/2C; C \) is the capacitance of the dot) significantly exceeds the thermal energy \( kT \), only a single electron will occupy each dot. Uniform electron occupancy in arrays of \( > 10^8 \) dots has been shown experimentally \([17]\).

### 3.2 Spin measurement

After quantum computation is over, we need to read the result by measuring the qubits. During this process, the qubits will collapse to classical bits. These classical bits are the measured spin orientations in relevant dots. They are measured by measuring the current that results when the potential over the dot is raised over the Coulomb blockade threshold. If we assume that the differential phase-shift suffered by the spin in traversing the dot is negligible; in other words, transport through the dot does not rotate the spin, then the magnitude of the measured current can tell us the spin orientation \([36]\). It was shown in ref. \([36]\) that the spin-polarized contacts act as electronic analogs of optical polarizers and analyzers, so the current will depend on the projection of the spin of the quantum dot’s resident electron on the spin orientation in the contacts. Thus, by measuring the current, we can tell the spin orientation in any quantum dot.

### 3.3 Calibration

For each dot, the potential \( V \) that needs to be applied to flip the spin by bringing the dot in resonance with \( B_{ac} \) can be calibrated following the procedure outlined by Kane \([25]\). With \( B_{ac} = 0 \), we measure the spin in a quantum dot. Then we switch on \( B_{ac} \) and sweep \( V \) over a range. Next \( B_{ac} \) is switched off and the spin is measured. The range of \( V \) is progressively increased till we find that the spin has flipped. We then proceed to narrow the range with successive iteration while making sure that the spin does flip in each iteration. Finally this allows us to ascertain \( V \) with an arbitrary degree of accuracy. As pointed out by Kane \([25]\), the calibration procedure can, in principle, be carried out in parallel over several dots simultaneously and the voltages stored in adjacent capacitors. External circuitry will thus be needed only to control the timing of the biases (application of \( V_{target} \)) and not their magnitudes. While this is definitely an advantage, fabricating nanoscale capacitors adjacent to each individual dot is outside the scope of self-assembly. Moreover, capacitors discharge over time, requiring frequent recalibration through refresh cycles, so that this may not be a significant advantage.
3.4 Input and Output Operations

Any computer is of course useless unless we are able to input and output data successfully. Since we are using spin-polarized contacts to inject an electron in each dot, we know the initial orientation. Those dots where the initial orientation is the one we want are left unperturbed while the spins in the remaining dots are flipped by resonating with $B_{ac}$. This process prepares the quantum computer in the initial state for a computation and can be viewed as the act of “writing” the input data. Computation then proceeds on this initial state by carrying out a desired sequence of controlled rotation operations. Reading the data is achieved as described in subsection 2.3.

3.5 Comparisons with similar proposals

Proposals similar to that presented in this paper, which envision nanoelectronic spin-based implementations of universal quantum gates, have been forwarded in the past by Privman [26], Kane [25] and more recently by Vrijen, et al. [27]. Our proposal is distinct from those previous versions in many ways. The first two of the previous proposals envision qubits as being encoded by nuclear spins and a delicate transduction between electron- and nuclear-spins is required for data communication. Both Vrijen and we have eliminated the role of nuclear spins (and the need for coupling between electron and nuclear spins), but perhaps at the cost of a somewhat smaller $T_2$ time (spin coherence time). The major difference between our proposal and all others is that we do not need any dc magnetic field at all. All previous versions split the spins using the Zeeman effect induced by a strong dc magnetic field. We use the Rashba effect instead (which is purely electrostatic). Since we only need a small ac magnetic field (supplied by a microwave source), there is some hope of a “lightweight” implementation where heavy electro-magnets for generating strong dc magnetic fields are not required. There is nonetheless a cryogenic requirement which is the main obstacle to realizing a truly “portable” quantum computer. This obstacle is not easy to overcome.

Another major difference with previous proposals is that our structure can be mostly self-assembled thus eliminating the requirement of performing Herculean feats in lithography. In the next section, we briefly describe how it may be possible to self-assemble a quantum computer.

4 Self Assembly

The self-assembly process that we propose is relatively standard and has been successfully applied by a number of groups, including us, for fabricating ordered two-dimensional arrays of quantum dots or nanowires [18]. The synthesis proceeds as follows.

First an Al foil is dc anodized in 15% sulfuric acid for several hours with a current density of 40 mA/cm². This produces a nanoporous alumina film on the surface of the foil with a quasi-ordered arrangement of pores. The film is stripped off and the foil is re-anodized for a few minutes. The alumina film that forms on the surface after the second anodization step
Figure 3: Raw atomic force micrograph of pore morphologies produced by anodization of an aluminum foil in oxalic acid. The average pore diameter is 52 nm with a 5% standard deviation. This structure acts as a self-assembled template for self-assembling a quantum computer.

has a very well ordered arrangement of nanopores. Fig. 3 shows a raw atomic force micrograph of pores formed by anodizing in oxalic acid. The pore diameter is 52 nm and the thickness of the wall separating two adjacent pores is of the same order. If the anodization is carried out in sulfuric acid, the pores that self-assemble have a much smaller diameter of $10 \pm 1$ nm with a wall thickness of the same order. Cross-section TEM of the pores have revealed that they are cylindrical with very uniform diameter along the length. The length of the pores is of course the thickness of the alumina film and depends on the duration of anodization. Typically, the length is a few thousands of angstroms.

Multilayered quantum dots as shown in Fig. 1 are formed by sequentially electodepositing the constituent layers selectively within the pores. However, in order to have appreciable overlap of the wavefunctions in neighboring dots for exchange coupling, we must first decrease the thickness of the alumina walls separating two adjacent dots. The separation can be decreased to as small as $\sim 1$ nm by widening the pores. This is accomplished by soaking the porous alumina film in phosphoric acid which dissolves the alumina from the walls of the pores.

Electrodeposition of the constituent layers of a multi-layered quantum dot (or quantum dash) is carried out in steps. In Fig. 1(a), we show a penta-layered dot of Co-ZnSe-InAs-ZnSe-Co where Co acts as the spin polarized material (it has a 34% spin polarization). For depositing the first Co layer, the alumina film is immersed in a solution of CoSO$_4$ and an ac signal of 20 V rms amplitude and 250 Hz frequency is imposed between the aluminum substrate and a graphite counter electrode. During the cathodic half cycle of the ac signal,
the Co\(^{++}\) ion is reduced to zero-valent Co metal which goes into pores selectively since they offer the least impedance path for the ac current to flow. Since alumina is a valve metal oxide, the zero-valent Co is not re-oxidized to Co\(^{++}\) during the anodic half-cycle. After a few seconds of electrodeposition, we are left with a \(\sim 10\)-nm layer of Co at the bottom of the pore [51].

The partially filled alumina film is then ac electrolysed in selenic acid for a few seconds which leaves behind the Se\(^{--}\) ions adsorbed on the walls of the pores. Next, the sample is immersed in a boiling aqueous solution containing the Zn\(^{++}\) ion. The Zn\(^{++}\) ion reacts with the Se\(^{--}\) in the walls of the pore to produce a \(\sim 10\)-nm thick layer of ZnSe on top of the Fe layer. This material is a wide gap semiconductor and acts as the insulator layer. The pores are then washed in de-ionized water to remove excess Se\(^{--}\). Next, the narrow gap semiconductor InAs (which has a strong Rashba coupling because of the low effective mass), is deposited over the ZnSe layer by carrying out ac electrolysis in arsenic acid followed by immersion in a boiling solution containing In\(^{+++}\) ion. This deposits the InAs layer. Finally, ZnSe and Co depositions are repeated. This results in the structure of Fig. 1(a). Note that the spin-polarized contacts (Co) are automatically self-aligned to the semiconductor dot (InAs) in this approach.

It should be pointed out that one is not limited by material. Almost anything can be deposited selectively within the pores, one way or another. Even silicon can be deposited by slow deposition using chemical vapor deposition and Group V elements like carbon have been deposited within the pores employing essentially gas-phase epitaxy [52]. Plasma-enhanced chemical vapor deposition is another promising approach.

Material purity is of extreme concern in any electrochemical synthesis. Chemical reagents are never very pure and we certainly do not want a magnetic impurity in the semiconductor dot that will tend to cause unwanted spin flips. Since it is possible to fill the pores using very slow deposition in a CVD set-up, one could use this approach to guarantee vastly improved material purity with a commensurate increase in fabrication cost.

### 4.1 Wiring the gates to make a computer

Arbitrary electrical (classical) connections will have to be made between different gates in order to make a computer. The lithographic challenge associated with this task is daunting; however, there is an alternate. We can deposit Au over the top Co contact in the same way as we deposit Co itself. Gold sulfide is an appropriate electrochemical source for gold. Conjugated organic molecules such as biphenyl dithiol and gold clusters can be co-evaporated on the surface after each pore is sealed with a top Au layer. The end-group in the organic molecule self-attaches to Au acting as “alligator-clips” [53, 54]. The molecules bridged by Au clusters (Fig. 4a) are electrically conducting with a resistance of 10-40 M\(\Omega\) per molecule [55, 56]. They are called “molecular ribbons” and provide self-assembled electrical connection between the quantum dots (Fig. 4a) [57]. However, the connection exists between every dot and hence must be surgically modified to realize a specific interconnection pattern. For this purpose, one will need to remove the unwanted connections with an STM tip. This is a slow
and laborious process but still beats lithography.

The electrical interconnects transmit electrical signals such as Rashba voltages and spin currents. However, they do not transport quantum signal such as the state of spin polarization. For this purpose, we need “spin wires” which transmit quantum information about spin polarization. Fortunately, making “spin wires” is somewhat easier. A line of exchange coupled quantum dots is a “spin wire” since its ground state is anti-ferromagnetic \cite{58, 59} so that the spin repeats itself every other dot. This allows spin state to be transmitted down a line consisting of an odd number of dots. Such a spin wire is shown in Fig. 4b. Unfortunately such wires are not “unidirectional” and do not transmit signal (spin orientation) from the input end to the output end unidirectionally \cite{58, 60}. We had shown in ref. \cite{60} that unidirectionality in time effectively also imposes unidirectionality in space. Temporal (and consequently spatial) unidirectionality can be achieved by sequential clocking (this is the technique adopted to transmit charge packets in conventional charge coupled devices \cite{61}). We turn the exchange interaction between neighboring dots “on” sequentially by propagating a positive pulse down a line connected to contacts interposed between adjacent dots as shown in Fig. 4(b).

The above lines will have to be delineated by lithography. However, since much of the pattern is periodic, it may be possible to use techniques such as achromatic interferometric x-ray lithography which have a much faster throughput than direct write lithography to delineate the clocking connections. Direct writing is not completely unavoidable, however. Connections to the external world for data input/output to the entire chip must be delineated with direct-write lithography. This is however not as demanding as making all the internal connections (dot-to-dot connections) with lithography.

5 Conclusions

In this paper, we foresee the application of a great advance in materials technology, nanoscale self-assembly, to realize a great advance in information technology - the quantum computer. Past proposals of semiconductor implementations of quantum computers \cite{25, 27} required extremely challenging fabrication methodologies and at least some of them relied on delicate interaction between nuclear and electron spins to transduce the qubit into a measurable signal. The present paradigm is much simpler, probably more robust, and the possibility of self-assembly makes it very attractive.

6 Acknowledgement

I am indebted to many individuals for insightful discussion, but especially to Profs. P. F. Williams and D. J. Sellmyer.
Figure 4: Wiring the quantum computer. Dot-to-dot connections are self-assembled using conjugated organic molecules with appropriate end-groups that self-adhere to gold. Gold clusters act as links in the bridge. Every Au contact is connected to others via the linked molecules and the unwanted connections are subsequently removed with an STM tip.
References

[1] B. Schumacher, Phys. Rev. A, 51, 2738-2747 (1995).

[2] A. Steane, Rep. Prog. Phys., 61, 117-173 (1998).

[3] P. W. Shor, in Proc. 35th. Ann. Symp. Foundations of Computer Science, Ed. S. Goldwasser, pp. 124-134 (IEEE Computer Society, Los Alamitos, CA, 1994).

[4] L. K. Grover, Phys. Rev. Lett., 79, 325-328 (1997); L. K. Grover, Phys. Rev. Lett., 79, 4709-4712 (1997).

[5] D. P. DiVincenzo, Phys. Rev. A, 51, 1015-1021 (1995).

[6] S. Lloyd, Phys. Rev. Lett., 75, 346-349 (1995).

[7] A. Barenco, Proc. R. Soc. London, A449, 679-683 (1995).

[8] P. W. Shor in Proc. 37th Ann. Symp. Foundations of Comp. Sci., IEEE Computer Society Press, pp. 56-65 (1996).

[9] A. Kitaev, Russian Math Surveys, 52, 1191 (1997).

[10] P. O. Boykin, T. Mor, M. Pulver, V. Roychowdhury and F. Vatan, LANL e-print quant-ph #9906054.

[11] A. R. Calderbank and P. W. Shor, Phys. Rev. A, 54, 1098-1105 (1996).

[12] J. I. Cirac and P. Zoller, Phys. Rev. Lett., 74, 4091-4094 (1995).

[13] Q. A. Turchette, C. J. Hood, W. Lange, H. Mabuchi and H. J. Kimble, Phys. Rev. Lett., 75, 4710-4713 (1995).

[14] C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano and D. J. Wineland, Phys. Rev. Lett., 75, 4714-4717 (1995).

[15] D. G. Cory, A. F. Fahmy T. F. and Havel, in Proc. 4th Workshop. on Physics and Computation, (Complex Systems Institute, Boston, MA, 1996). See also, D. G. Cory, M. G. Price and T. F. Havel, Proc. Natl. Acad. Sci., USA, 94, 1634-1639 (1997).

[16] N. A. Gershenfeld and I. L. Chuang, Science, 275, 350-356 (1997).

[17] J. A. Jones and M. Mosca, Phys. Rev. Lett., 83, 1050-1053 (1999).

[18] S. L. Braunstein, C. M. Caves, R. Josza, N. Linden, S. Popescu and R. Schack, Phys. Rev. Lett., 83, 1054-1057 (1999).

[19] P. Mohanty, E. M. Q. Jariwalla and R. A. Webb, Phys. Rev. Lett., 78, 3366-3369 (1997).
[20] A. Barenco, D. Deutsch and A. Ekert, Phys. Rev. Lett., 74, 4083-4087 (1995).

[21] S. Bandyopadhyay, A. Balandin, V. P. Roychowdhury and F. Vatan, Superlat. Microstruct., 23, 445-464 (1998).

[22] A. Balandin and K. L. Wang, Superlat. Microstruct., 25, 509 (1999).

[23] J. Preskill, Proc. Royal Soc. London A, 454, 385 (1998).

[24] G. Feher, Phys. Rev., 114, 1219 (1959).

[25] B. E. Kane, Nature (London), 393, 133-137 (1998).

[26] V. Privman, I. D. Vagner and G. Kventsel, Phys. Lett. A, 239, 141 (1998).

[27] R. Vrijen, E. Yablonovitch, K. Wang, H. W. Jianh, A. Balandin, V. Roychowdhury, T. Mor and D. DiVincenzo, Phys. Rev. A, 62 12306 (2000).

[28] J. M. Kikkawa and D. D. Awschalom, Phys. Rev. Lett., 80, 4313 (1998).

[29] R. Romestain, S. Geschwind and G. E. Devlin, Phys. Rev. Lett., 39, 1583 (1977).

[30] H. Benisty, C. M. Sotomayor-Torres and C. Weisbuch, Phys. Rev. B, 44, 10945 (1991).

[31] W. G. Unruh, Phys. Rev. A, 51, 992 (1995).

[32] S. Bandyopadhyay and V. P. Roychowdhury, Superlat. Microstruct., 22, 411 (1997).

[33] D. Loss and D. P. DiVincenzo, Phys. Rev. A, 57, 120 (1998).

[34] E. I. Rashba, Sov. Phys. Semicond., 2, 1109-1122 (1960); Y. A. Bychkov and E. I. Rashba, J. Phys. C, 17, 6039-6045 (1984).

[35] G. Lommer, F. Malcher, and U. Rössler, Phys. Rev. Lett., 60, 728-731 (1988).

[36] S. Datta and B. Das, Appl. Phys. Lett., 56, 665-667 (1990).

[37] B. Das, D. C. Miller and S. Datta, Phys. Rev. B, 39, 1411 (1989).

[38] J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett. 78, 1335-1339 (1997).

[39] R. Meservey and P. M. Tedrow, Phys. Rep., 238, 173 (1994).

[40] H. X. Tang, F. G. Monzon, Ron Lifshitz, M. C. Cross and M. L. Roukes, Phys. Rev. B, 61, 4437 (2000).

[41] G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip and B. J. van Wees, Phys. rev. B, 62, R4790 (2000).
[42] P. R. Hammar, B. R. Bennett, M. J. Yang and M. Johnson, *Phys. Rev. Lett.*, **83**, 203 (1999).

[43] I. Malajovich, J. M. Kikkawa, D. D. Awschalom, J. J. Berry and N. Samarth, *Phys. Rev. Lett.*, **84**, 1015 (2000).

[44] M. Oestreich, J. Hübner, D. Hägele, P. J. Klar, W. Heimbrodlt, W. W. Rühle, D. E. Ashenford and B. Lunn, *Appl. Phys. Lett.*, **74**, 1251-1253 (1999).

[45] Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno and D. D. Awschalom, *Nature* (London), **402**, 790 (1999).

[46] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag and L. W. Molenkamp, *Nature* (London), **402**, 787 (1999).

[47] B. Muerer, D. Heitman and K. Ploog, *Phys. Rev. Lett.*, **68**, 1371 (1988).

[48] See, for example, S. Bandyopadhyay, A. E. Miller, H-C Chang, G. Banerjee, V. Yuzhakov, D-F Yue, R. E. Ricker, S. Jones, J. A. Eastman, E. Baugher and M. Chandrasekhar, *Nanotechnology*, **7**, 360-371 (1996) and references therein.

[49] H. Masuda and M. Satoh, *Jpn. J. Appl. Phys.*, **35**, L126 (1996).

[50] See, for example, G. A. Prinz, *Physics Today*, **48**, 58 (1995).

[51] L. Menon, M. Zheng, H. Zeng, Sellmyer and S. Bandyopadhyay, in *Advanced Luminescent Materials and Quantum Confinement*, Eds. M. Cahay, S. Bandyopadhyay, D. J. Lockwood, N. Koshida, J-P Leburton, M. Meyyapan and T. Sakamoto (The Electrochemical Society, Inc., Pennington, New Jersey, 1999), pp. 413-424.

[52] J. Li, C. Papadopoulos, J. M. Xu and M. Moskovitz, *Appl. Phys. Lett.*, **75**, 367 (1999).

[53] J. M. Tour and J. S. Schumm, *Polymer*, **34**, 368 (1993).

[54] J. I. Henderson, S. Feng, G. M. Ferrence, T. Bein and C. P. Kubiak, *Inorg. Chim. Acta*, **242**, 115 (1996).

[55] R. P. Andres, T. Bein, M. Dorogi, S. Feng, J. I. Henderson, C. P. Kubiak, W. J. Mahoney, R. G. Osifchin and R. Reifenberger, *Science*, **272**, 1323 (1996).

[56] R. P. Andres, J. D. Bielefeld, J. I. Henderson, D. B. Janes, V. R. Kolagunta, C. P. Kubiak, W. J. Mahoney and R. G. Osifchin, *Science*, **273**, 1690 (1996).

[57] S. Datta, D. B. Janes, R. Andres, C. P. Kubiak and R. Reifenberger, *Semicond. Sci. Technol.*, **13**, 1347 (1998).

[58] S. Bandyopadhyay, B. Das and A. E. Miller, *Nanotechnology*, **5**, 113 (1994).
[59] S. N. Molotkov and S. S. Nazin, *JETP Lett.*, **62**, 272 (1995).

[60] S. Bandyopadhyay and V. P. Roychowdhury, *Jpn. J. Appl. Phys.*, Pt. 1, **35**, 3350 (1996).

[61] D. K. Schröder, *Advanced MOS Devices*, Modular Series on Solid State Devices, Vol. VII, Eds. R. F. Pierret and G. W. Neudeck, (Addison Wesley, Reading, Massachusetts, 1988).