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A pseudo-spin surface-acoustic-wave quantum computer

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A modification to the surface-acoustic-wave quantum computer is described. The use of pseudo-spin qubits is introduced as a way to simplify the fabrication and programming of the computer. A form of optical readout that relies on the electrons in each surface-acoustic-wave minimum recombining with holes in a two-dimensional hole gas is suggested as a means to measure the output. The suggested modification would allow the quantum computer to be made smaller and to operate faster.

Keywords: SAW; quantum computation; nanotechnology

1. Introduction

The notion that a quantum computer is capable of storing and manipulating vectors with vast numbers of elements has captured the attention of academics, industry and government. These communities are now actively engaged in an attempt to identify $N$-particle systems that not only satisfy the DiVincenzo criteria (DiVincenzo et al. 1999) but that will also minimize time and cost of production of even a single quantum computer. This paper suggests two refinements to the surface-acoustic-wave (SAW) quantum computer (Barnes et al. 2000) that will make it faster, easier to construct, easier to program and easier to read-out the final state. In addition, these modifications make it more attractive for use as a component in a quantum communication network because the output is in the form of photons and can be in the form of entangled photons.

The simplest design for the SAW quantum computer consists of a set of $N$ long, narrow, parallel channels. The magnetic field inside the channels is modified with a distributed pattern of single-domain magnetic-surface gates (Cowburn & Welland 2000). Tunnelling between channels is controlled using a set of electrostatic gates. $N$ electrons are captured in each cycle of the SAW, so that each SAW minimum has one electron trapped in each of the parallel channels. Each set of $N$ electrons in each SAW minimum is used as a single quantum computer. Each of these quantum computers is put into the same initial state, through the physics of their electron-capture process, and the state of each is manipulated in exactly the same way as it passes through the electromagnetic environment produced by the magnetic and electrostatic surface gates. Measurement is continuous and therefore an average of the

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final quantum state of each quantum computer is determined. This measurement is the same as the ensemble measurement made in NMR quantum computation, where a large number of identical systems are prepared, manipulated and then measured. The most important difference between an SAW quantum processor and an NMR quantum processor is that it is possible to make sure that the initial state of each SAW quantum computer is identical and pure.

The modifications that are proposed and discussed in this paper are to use a pseudo-spin, derived from the spin of three electrons, as the qubit, and to use optical means for readout.

2. The pseudo-spin qubit

Many solid-state approaches to producing a quantum computer use electron spin as the qubit. In particular, this is the case for the SAW quantum computer. Within this architecture, single-qubit operations can be performed by placing split, single-domain magnetic gates across a channel, or perpendicular to it, at the location at which the rotation is required. Since only rotation about two perpendicular axes is required to move a spin to an arbitrary point on its Bloch sphere, this combination is sufficient to produce universal single-qubit gates. The main problems with such gates are that: fairly large magnetic fields are required if the length of each magnetic gate is not to be longer than the spin-dephasing length (typical gate lengths in GaAs, for 1 T surface fields, exceed 1 μm); once the magnetic gates have been patterned, there is no easy way to change their magnetic field strength, especially if there is a distributed pattern of similar magnetic gates nearby; each single-domain magnet would produce unwanted stray fields affecting other channels and the orientation of domains in other magnets; and owing to the nature of their fabrication, evaporation through a mask, it is very difficult to determine the field strength that will be achieved for a magnetic gate produced using a given mask. A degree of control over single-qubit rotation can be achieved if electromagnets are used in place of permanent magnets but, in order to achieve sufficient field strengths, very high currents in very short pulses are required.

The two-qubit operation for electron spins in an SAW quantum computer is based on the exchange interaction. Where a barrier is reduced to allow tunnelling between adjacent channels, the electrons trapped in these channels will interact via the exchange interaction. The reduction in the barrier is achieved by evaporating a short metallic Schottky gate onto the barrier and by applying a suitable potential to it. These gates are typically an order of magnitude faster than the single-qubit magnetic gates. The necessary gate length for root-of-swap operations can be tens of nanometres. The effect of each gate can be made very local, since the tunnelling probability is exponentially dependent on surface gate voltage. The use of electrostatic gates is therefore preferable to magnetic gates. They are shorter and faster and therefore allow more operations to be packed in before decoherence begins to affect the computation.

It is unfortunate that, if electron spin is used as the qubit, the exchange interaction is not universal. However, the exchange interaction is universal for a particular pseudo-spin qubit defined using three electron spins (DiVincenzo et al. 2000). Convenient basis states for this pseudo-spin qubit are

$$|0_P\rangle = |S\rangle |\uparrow\rangle$$ and $$|1_P\rangle = \sqrt{\frac{2}{3}} |T_+\rangle |\downarrow\rangle - \sqrt{\frac{1}{3}} |T_0\rangle |\uparrow\rangle,$$

where $|S\rangle = \sqrt{\frac{1}{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ is the singlet state of the first two spins that make up the pseudo-spin qubit and

$$|T_+\rangle = |\uparrow\uparrow\rangle \quad \text{and} \quad |T_0\rangle = \sqrt{\frac{1}{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

are two of the triplet states for the same two spins. For SAW quantum computation these pseudo-spin qubits require three parallel channels to define a single qubit. The technology required for producing many parallel channels in a GaAs/AlGaAs heterostructure device is very mature and is regularly used in the fabrication of quantum devices (Kardynal et al. 1997). Such pseudo-spin qubits are therefore ideal for SAW quantum computation.

3. The pseudo-spin quantum computer

A schematic of a pseudo-spin SAW quantum computer is shown in figure 1. The vertical light and dark lines represent SAW maxima and minima. On the left of the figure, the light modulated region represents a two-dimensional electron gas. It acts as a source of electrons for the quantum computer. On the right, the dark modulated region represents a two-dimensional hole gas which, as we will discuss, acts as a source of holes. The light grey horizontal lines represent barriers between channels and the dark grey rectangles represent tunnel barriers between channels. The grey spheres represent individual electrons. Each vertical line of electrons in a single SAW minimum represents a single pseudo-spin quantum computer. The figure shows six channels which define two qubits in each SAW minimum. Single-qubit rotations occur when tunnelling between channels in the same pseudo-spin qubit occurs (upper and lower two grey rectangles in figure 1). Two-qubit operations occur when tunnelling between first and last electron spins in adjacent pseudo-spin qubits occurs (central grey rectangle in figure 1).

In order to be able to apply an arbitrary quantum algorithm to an SAW computer, the metallic surface gates should be placed in a regular array along its length. Where a gate is not needed, a suitable potential is applied to prevent tunnelling between channels. Where a gate is needed, a suitable voltage is applied to allow tunnelling. Because each gate will have slightly different properties owing to the ways gates...
are made, each would have to be individually calibrated in order to determine the dependence of tunnelling probability on gate voltage.

A single computation is performed by each SAW minimum as it passes across the network, dragging a set of $N$ qubits along with it. The qubits in each SAW minimum are prepared in the same way and perform the same computation. At the readout stage, each qubit passes into a separate readout gate. The SAW performs $ca. 3.0 \times 10^9$ computations per second and each calculation contributes to produce a measurable averaged output signal.

Each quantum computer in each SAW minimum must be put into some pure state before computation can begin. For the pseudo-spin qubits we are considering, it is possible to capture each set of three electrons in the $|0_p\rangle$ state. This state is the ground state of three electrons trapped in adjacent quantum dots when the coupling between the first two electron spins is turned on and a weak magnetic field is applied. If, as is shown in figure 1, the barrier between the first two channels of each trio of channels is removed, and the potential in the entrance region is modified, it is possible to capture two electrons in each SAW cycle. The decoherence that accompanies the capture process (Robinson & Barnes 2001) should then ensure that they are reduced to their ground state: a singlet state $|S\rangle$. The presence of an external magnetic field will then ensure that the third electron is captured in a spin-polarized state $|\uparrow\rangle$. Spin splitting causes the spin-up and spin-down population in the two-dimensional electron gas to be separated in energy, and screening prevents the formation of a quantum dot of sufficient depth to capture the spins of higher energies.

4. Optical readout

Readout for the pseudo-spin qubit may be done either using a charge detection method (Field et al. 1993) or by optical means. When a general pseudo-spin state $|\psi\rangle = \alpha|0_p\rangle + \beta|1_p\rangle$ is measured, there is a probability $|\alpha|^2$ that the first two spins of the trio will be in a singlet state and a probability $|\beta|^2$ that they will be found in a triplet state (DiVincenzo et al. 1999). If the two spins are in a singlet state, an electric field placed between the two channels will cause the lower-energy channel to become doubly occupied (Kane 1998; Barnes et al. 2000) and this double occupation can be measured using a nearby single electron transistor or narrow constriction (Field et al. 1993). If the two spins are in a triplet state, the same electric field will not cause any charge redistribution.

Optical readout of the pseudo-spin qubit is made possible by the fact that a two-dimensional hole gas can be induced at the end of each SAW quantum-processor channel (North et al. 1999; Vijendran et al. 1999) so that electrons from the processor can recombine with the holes and produce output photons (Foden et al. 2000; Sogawa et al. 2001). An electric field is then placed between the first two channels of each qubit and only light emission from the first channel is measured. If the input state is $|0_p\rangle$, the output light will have a maximum intensity, since in each cycle there will be two electrons injected into the hole gas. If the state is $|1_p\rangle$, only one electron per cycle will be injected into the hole gas and therefore the light intensity will be a minimum. For states that are a linear combination of $|0_p\rangle$ and $|1_p\rangle$, the light intensity will be somewhere in between the minimum and maximum intensity. Many of the emitted photons will not be detected and therefore the minimum and maximum intensities would need to be determined empirically.

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If it is possible to measure the intensity of light from each channel independently, then it is possible to use a novel property of GaAs band structure to make a measurement of the spin of each electron in each pseudo-spin qubit and thereby make a more accurate determination of the state of the pseudo-spin qubit. In GaAs, the optical selection rules (D’yakonov & Perel 1971) require a spin-$+\frac{1}{2}$ electron to recombine with a spin-$+\frac{3}{2}$ hole to produce a left-handed circularly polarized photon ($m_j = -1$) (Pierce et al. 1975; Vrijen & Yablonovitch 2000). Similarly a spin-$-\frac{1}{2}$ electron will recombine with a spin-$-\frac{3}{2}$ hole to produce a right-handed circularly polarized photon. As each electron enters the hole gas it will be decohered by elastic collisions with holes so that its state will be spin-up with probability $|\alpha|^2$ and spin-down state with probability $|\beta|^2$. The two hole species occur with equal probability and therefore the numbers of left and right circularly polarized photons emitted will be in direct relation to these probabilities. The output light from each channel is passed through a beam splitter and perpendicular polarizing elements to measure the ratio $|\alpha|^2 : |\beta|^2$.

Neither of the two optical readout methods described above preserve the state of entanglement of the output electrons in the emitted photon field. For quantum communication this would clearly be an advantage if possible. Vrijen & Yablonovitch (2000) have suggested two methods to achieve this that would require placing each hole gas in a high-finesse cavity, straining the GaAs and applying an external magnetic field. A suitable high-finesse cavity can be produced during molecular beam epitaxy growth. Alternating layers of material with different dielectric constants are grown in bands above and below the hole gas. These layers then act as Bragg reflectors. The introduction of strain is possible through introducing layers of material with different dielectric constants. Imamoglu et al. (1999) have suggested an alternative method for preserving entanglement that involves the use of conduction-band-hole Raman transitions induced by classical laser fields.

5. Summary

We have suggested a way in which the SAW quantum computer proposed by Barnes et al. (2000) can be modified to be faster, easier to construct, easier to program and easier to read out. In addition, the modifications make it more attractive for use in conjunction with proposed quantum communication protocols. The two modifications are to use a pseudo-spin constructed from three electron spins; and to use electron–hole recombination as a means to convert the final calculated quantum state to either a classical photon state or an entangled many-photon state. The important issues of error production and decoherence for this type of quantum computer are discussed in Barnes et al. (2000).

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References
