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The Quantum Computing Hardware

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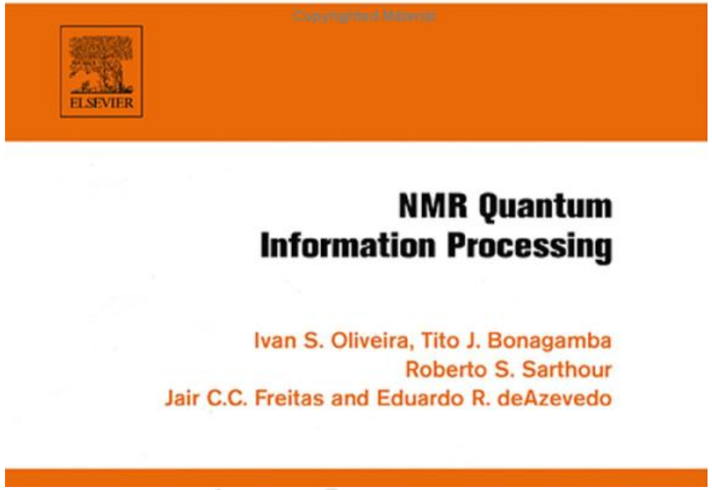

Team

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Physics

Physics **2**, 34 (2009)

Trends

Is a room-temperature, solid-state quantum computer mere fantasy?

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Published April 27, 2009

Creating a practical solid-state quantum computer is seriously hard. Getting such a computer to operate at room temperature is even more challenging. Is such a quantum computer possible at all? If so, which schemes might have a chance of success?

Vol 464|4 March 2010|**doi:10.1038/nature08812** nature

REVIEWS

Quantum computers

T. D. Ladd[1]†, F. Jelezko[2], R. Laflamme[3,4,5], Y. Nakamura[6,7], C. Monroe[8,9] & J. L. O'Brien[10]

Over the past several decades, quantum information science has emerged to seek answers to the question: can we gain some advantage by storing, transmitting and processing information encoded in systems that exhibit unique quantum properties? Today it is understood that the answer is yes, and many research groups around the world are working towards the highly ambitious technological goal of building a quantum computer, which would dramatically improve computational power for particular tasks. A number of physical systems, spanning much of modern physics, are being developed for quantum computation. However, it remains unclear which technology, if any, will ultimately prove successful. Here we describe the latest developments for each of the leading approaches and explain the major challenges for the future.

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Basic (tricky) requirements

- The QC must be isolated from the enviroment, but allow external operations!
- The Hilbert space must grow exponentially, but the resources to operate on it cannot grow that rate!
- Any quantum state on the Hilbert space must be acessible by a finite set of universal quantum gates;
- It must be possible to implement quantum error correction codes.

"We have to find ways to build quantum computers in the solid state at room temperature – that's the challenge!"

Anton Zeillinger – In his 2008 Newton Medal talk.

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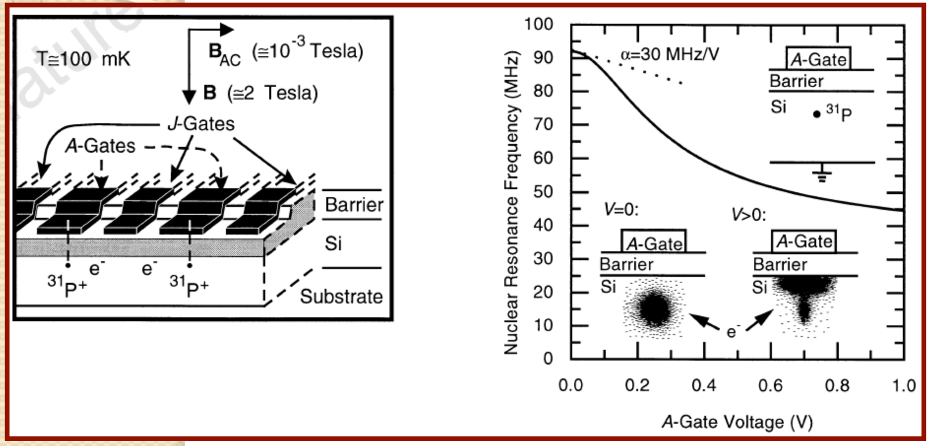
Semiconductors



A silicon-based nuclear spin quantum computer

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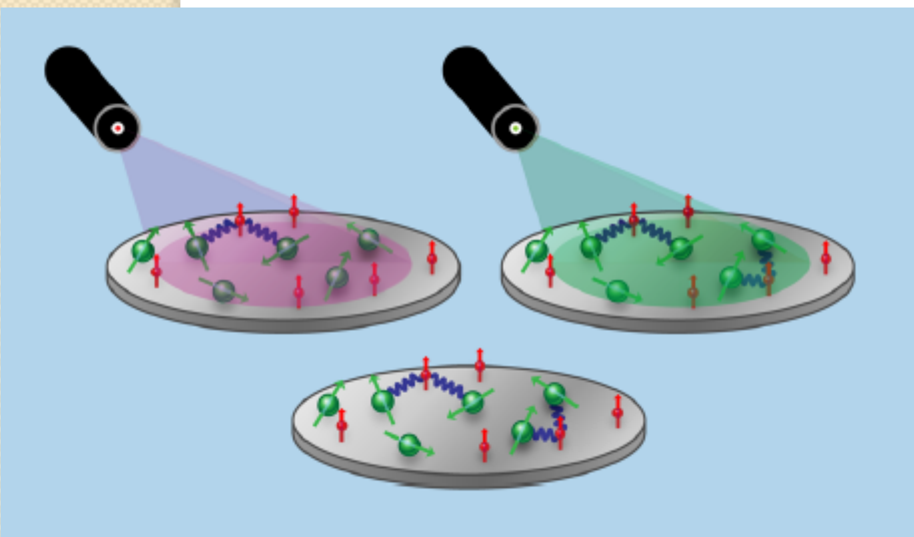
Quantum computers promise to exceed the computational efficiency of ordinary classical machines because quantum algorithms allow the execution of certain tasks in fewer steps. But practical implementation of these machines poses a formidable challenge. Here I present a scheme for implementing a quantum-mechanical computer. Information is encoded onto the nuclear spins of donor atoms in doped silicon electronic devices. Logical operations on individual spins are performed using externally applied electric fields, and spin measurements are made using currents of spin-polarized electrons. The realization of such a computer is dependent on future refinements of conventional silicon electronics.



INSTITUTE OF PHYSICS PUBLISHING | JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **15** (2003) L447–L451 | PII: S0953-8984(03)64964-7

LETTER TO THE EDITOR

Optically driven silicon-based quantum gates with potential for high-temperature operation

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Abstract

We propose a new approach to constructing gates for quantum information processing, exploiting the properties of impurities in silicon. Quantum information, embodied in electron spins bound to deep donors, is coupled via optically induced electronic excitation. Gates are manipulated by magnetic fields and optical light pulses; individual gates are addressed by exploiting spatial and spectroscopic selectivity. Such quantum gates do not rely on small energy scales for operation, so might function at or near room temperature. We show the scheme can produce the classes of gates necessary to construct a universal quantum computer.

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LETTERS

Solid-state quantum memory using the ^{31}P nuclear spin

John J. L. Morton[1,2], Alexei M. Tyryshkin[3], Richard M. Brown[1], Shyam Shankar[3], Brendon W. Lovett[1], Arzhang Ardavan[2], Thomas Schenkel[4], Eugene E. Haller[4,5], Joel W. Ager[4] & S. A. Lyon[3]

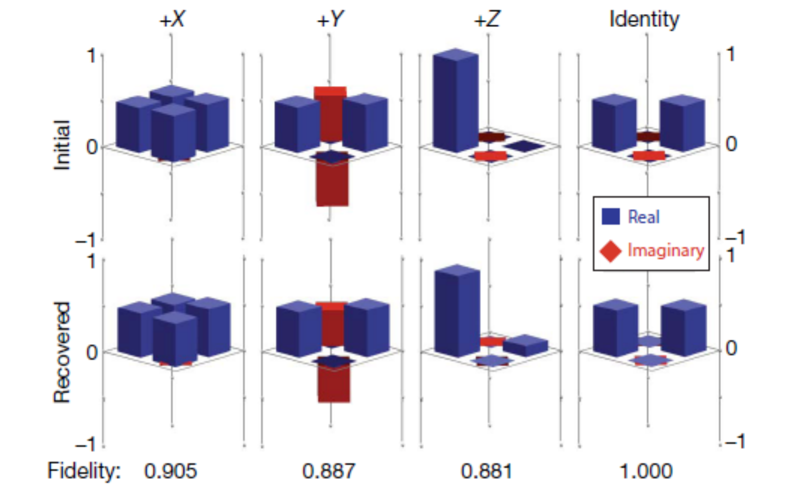

Figure 4 | Density matrix tomography for original and recovered states. Pseudopure states $+X$, $+Y$ and $+Z$ and the identity were prepared in the electron-spin qubit and measured (first row, initial). These states were then stored in the nuclear-spin degree of freedom and then returned to the electron spin and measured (second row, recovered). Tomography was performed by measuring the qubit in the $(\sigma_x, \sigma_y, \sigma_z)$ basis. The fidelity of the quantum memory was obtained by comparing the initial and recovered density matrices.

VOLUME 89, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 2002

All-Silicon Quantum Computer

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(Received 10 September 2001; published 12 June 2002)

A solid-state implementation of a quantum computer composed entirely of silicon is proposed. Qubits are ^{29}Si nuclear spins arranged as chains in a ^{28}Si (spin-0) matrix with Larmor frequencies separated by a large magnetic field gradient. No impurity dopants or electrical contacts are needed. Initialization is accomplished by optical pumping, algorithmic cooling, and pseudo-pure state techniques. Magnetic resonance force microscopy is used for ensemble measurement.

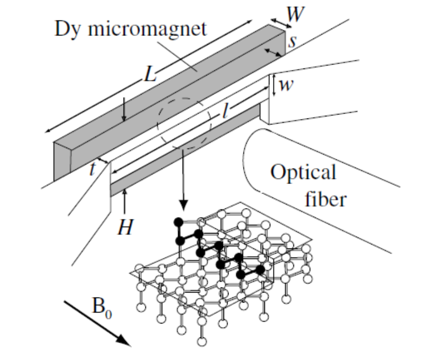

FIG. 1. The integrated micromagnet and bridge structure. The bridge has length $l = 300\ \mu$m, width $w = 4\ \mu$m, and thickness $t = 0.25\ \mu$m. The micromagnet, a distance $s = 2.1\ \mu$m from the bridge, has length $L = 400\ \mu$m, width $W = 4\ \mu$m, and height $H = 10\ \mu$m. The inset shows the structure of the silicon matrix and the terrace edge. The darkened spheres represent the ^{29}Si nuclei, which preferentially bind at the edge of the Si step.

nature materials

LETTERS

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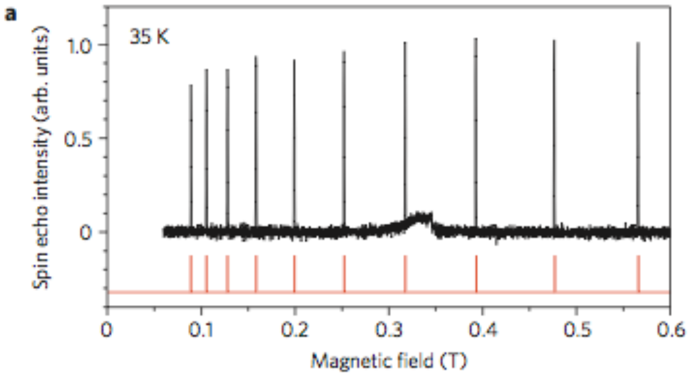
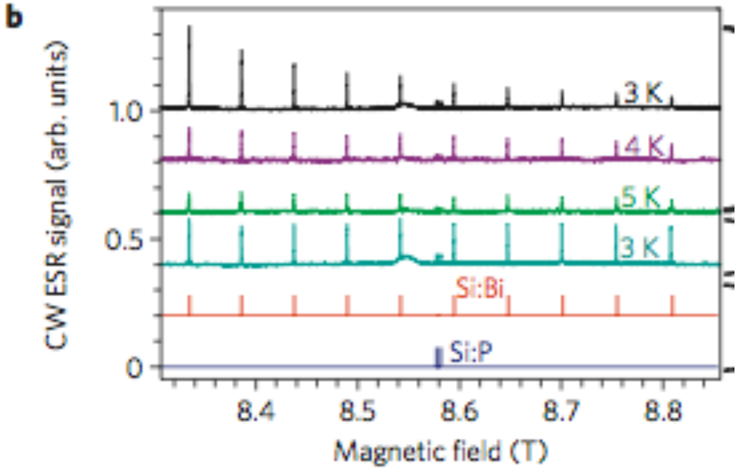
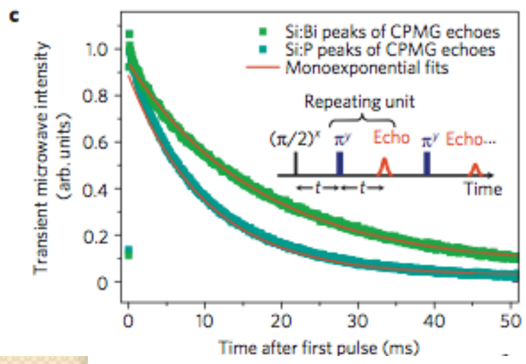
The initialization and manipulation of quantum information stored in silicon by bismuth dopants

Gavin W. Morley[1,2]*, Marc Warner[1,2], A. Marshall Stoneham[1,2], P. Thornton Greenland[1,2], Johan van Tol[3], Christopher W. M. Kay[1,4] and Gabriel Aeppli[1,2]

A prerequisite for exploiting spins for quantum data storage and processing is long spin coherence times. Phosphorus dopants in silicon (Si:P) have been favoured[1–10] as hosts for such spins because of measured electron spin coherence times (T_2) longer than any other electron spin in the solid state: 14 ms at 7 K with isotopically purified silicon[11]. Heavier impurities such as bismuth in silicon (Si:Bi) could be used in conjunction with Si:P for quantum information proposals that require two separately addressable spin species[12–15]. However, the question of whether the incorporation of the much less soluble Bi into Si leads to defect species that destroy coherence has not been addressed. Here we show that schemes involving Si:Bi are indeed feasible as the electron spin coherence time T_2 is at least as long as for Si:P with non-isotopically purified silicon. We polarized the Si:Bi electrons and hyperpolarized the $I = 9/2$ nuclear spin of ^{209}Bi, manipulating both with pulsed magnetic resonance. The larger nuclear spin means that a Si:Bi dopant provides a 20-dimensional Hilbert space rather than the four-dimensional Hilbert space of an $I = 1/2$ Si:P dopant.







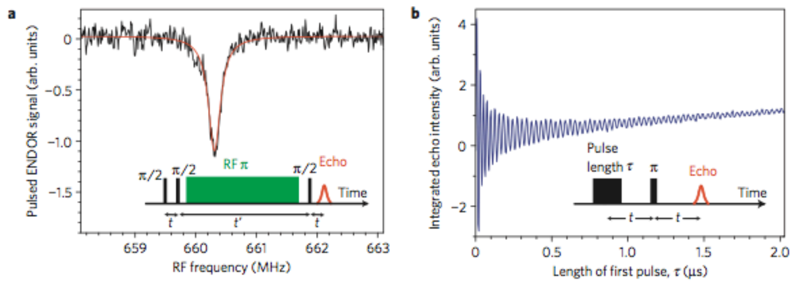


Figure 2 | Qubit manipulation. **a**, Pulsed ENDOR manipulates the Bi nuclear spin as well as the electron spin. A microwave frequency of 240 GHz (black rectangles in inset that control the electron spin) was used at a temperature of 3 K and the length of the radiofrequency (RF) pulse (green rectangle that controls the nuclear spin) was 150 μs. **b**, Rabi oscillations of the electron spin at 25 K with 9.7 GHz radiation. The spin is flipped using a pulse of τ = 13 ns duration.

LETTER

September 2010

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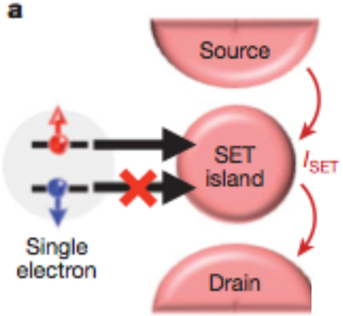
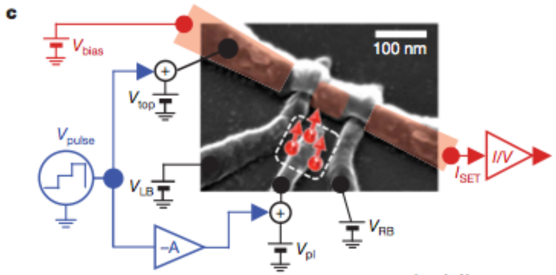
doi:10.1038/nature09392

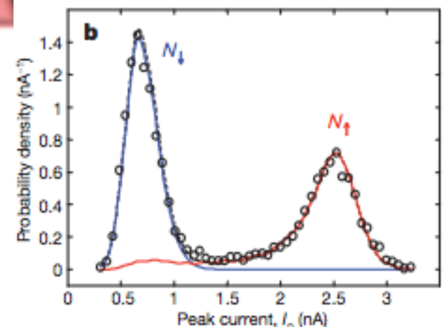
Single-shot readout of an electron spin in silicon

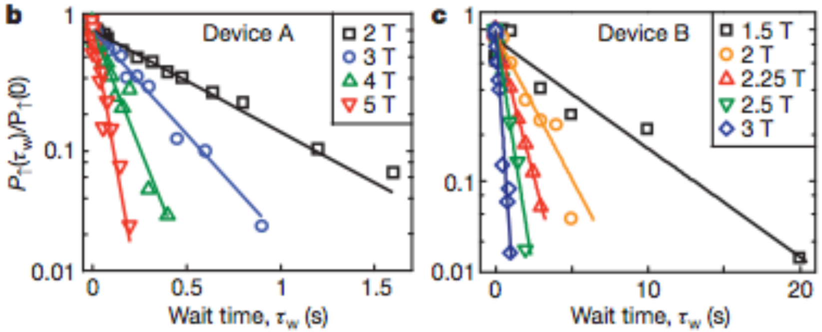
Andrea Morello[1], Jarryd J. Pla[1], Floris A. Zwanenburg[1], Kok W. Chan[1], Kuan Y. Tan[1], Hans Huebl[1]†, Mikko Möttönen[1,3,4], Christopher D. Nugroho[1]†, Changyi Yang[2], Jessica A. van Donkelaar[2], Andrew D. C. Alves[2], David N. Jamieson[2], Christopher C. Escott[1], Lloyd C. L. Hollenberg[2], Robert G. Clark[1]† & Andrew S. Dzurak[1]

The size of silicon transistors used in microelectronic devices is shrinking to the level at which quantum effects become important[1]. Although this presents a significant challenge for the further scaling of microprocessors, it provides the potential for radical innovations in the form of spin-based quantum computers[2–4] and spintronic devices[5]. An electron spin in silicon can represent a well-isolated quantum bit with long coherence times[6] because of the weak spin–orbit coupling[7] and the possibility of eliminating nuclear spins from the bulk crystal[8]. However, the control of single electrons in silicon has proved challenging, and so far the observation and manipulation of a single spin has been impossible. Here we report the demonstration of single-shot, time-resolved readout of an electron spin in silicon. This has been performed in a device consisting of implanted phosphorus donors[9] coupled to a metal-oxide-semiconductor single-electron transistor[10,11]—compatible with current microelectronic technology. We observed a spin lifetime of ~6 seconds at a magnetic field of 1.5 tesla, and achieved a spin readout fidelity better than 90 per cent. High-fidelity single-shot spin readout in silicon opens the way to the development of a new generation of quantum computing and spintronic devices, built using the most important material in the semiconductor industry.









Superconducting qubits

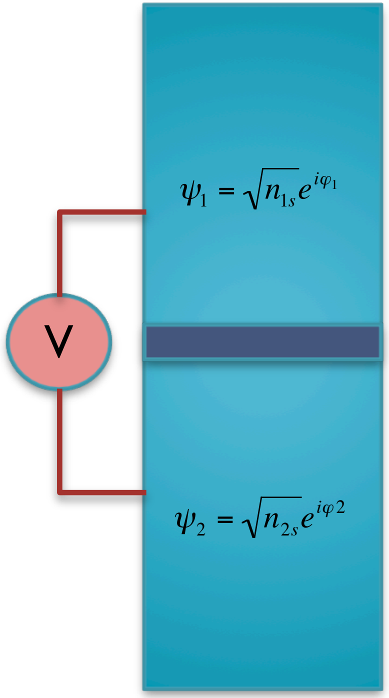
Josephson junction Hamiltonian:

$$H = E_C\left(-i\frac{\partial}{\partial\varphi} - N_g\right)^2 - E_J\cos(\varphi)$$

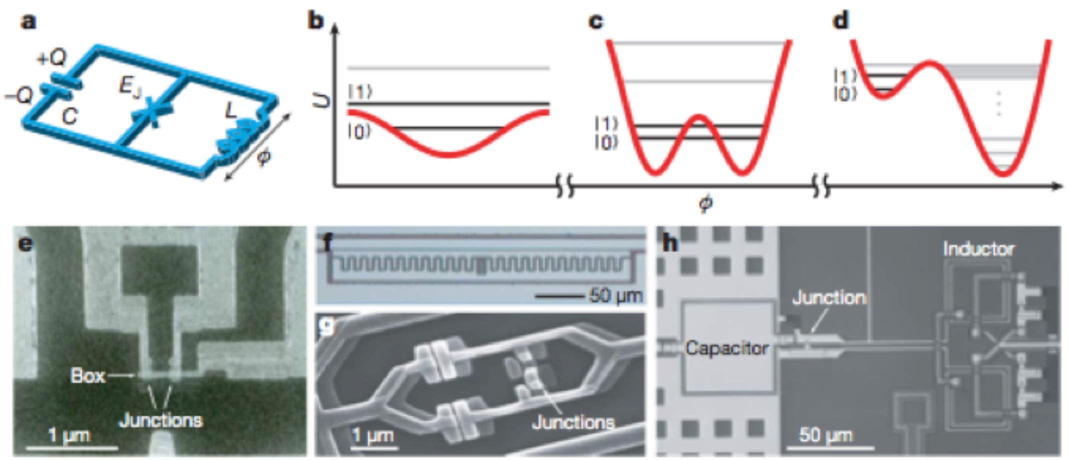
$$\varphi = \varphi_2 - \varphi_1$$

$$E_C = 4e^2/2C$$

$$E_J = I_C\Phi_0/2\pi$$



charge flux phase



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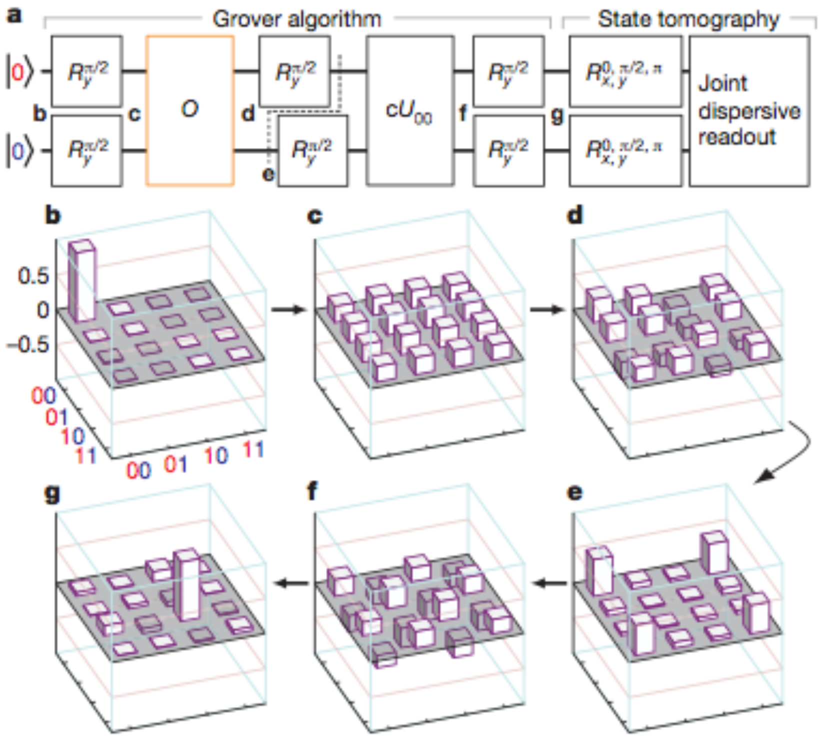
LETTERS

Demonstration of two-qubit algorithms with a superconducting quantum processor

L. DiCarlo[1], J. M. Chow[1], J. M. Gambetta[2], Lev S. Bishop[1], B. R. Johnson[1], D. I. Schuster[1], J. Majer[3], A. Blais[4], L. Frunzio[1], S. M. Girvin[1] & R. J. Schoelkopf[1]



QUANTUM PHYSICS

Tailor-made quantum states

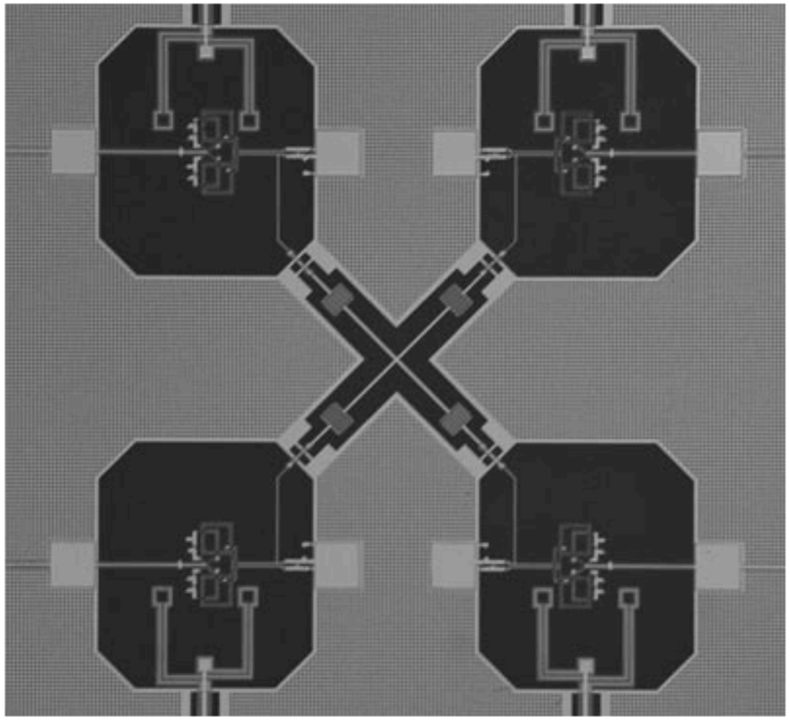
Yasunobu Nakamura

The ability to produce arbitrarily superposed quantum states is a prerequisite for creating a workable quantum computer. Such highly complex states can now be generated on demand in superconducting electronic circuitry.

As an innocent reductionist in elementary school, I dreamed of creating everything in the world by assembling atoms one by one, just like building with Lego blocks. Decades later, the dream has, to some extent, come true with the 'bottom-up' approach of nanotechnology in which, for example, single atoms can be manipulated and assembled using the tip of a scanning probe microscope. But physicists are now playing with even fancier — and often more fragile — 'quantum Lego blocks'. Using a bottom-up approach, Hofheinz *et al.*[1] (page 546 of this issue) report on-demand synthesis of arbitrary quantum states in a superconducting resonator circuit. Starting from a vacuum (zero-photon) state, the authors pile up physicsworld.com

Superconducting trio get entangled

Sep 29, 2010 5 comments



Entangling three qubits Santa Barbara style

Two independent teams of physicists in the US have entangled three superconducting quantum bits (qubits) for the first time. Entangled trios are of particular interest to those building quantum computers because three is the minimum number needed to do quantum error correction – which is needed to keep quantum computers running.

NMR/ESR in nano-stuff

PHYSICAL REVIEW B VOLUME 61, NUMBER 21 1 JUNE 2000-I

Solid-state nuclear-spin quantum computer based on magnetic resonance force microscopy

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(Received 13 September 1999)

We propose a nuclear-spin quantum computer based on magnetic resonance force microscopy (MRFM). It is shown that an MRFM single-electron spin measurement provides three essential requirements for quantum computation in solids: (a) preparation of the ground state, (b) one- and two-qubit quantum logic gates, and (c) a measurement of the final state. The proposed quantum computer can operate at temperatures up to 1 K.

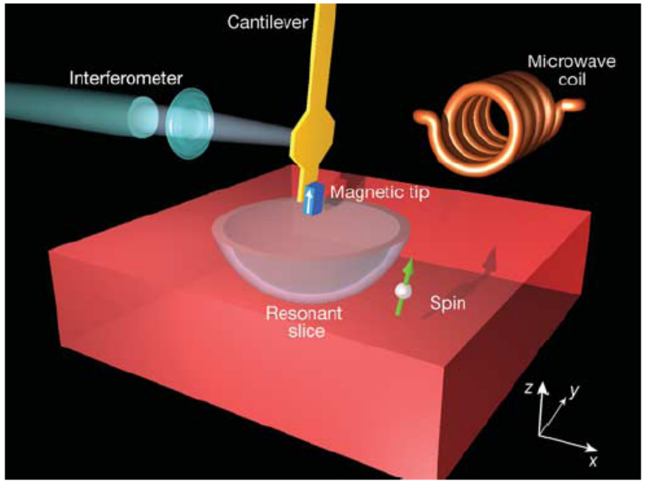

Figure 1 Configuration of the single-spin MRFM experiment. The magnetic tip at the end of an ultrasensitive silicon cantilever is positioned approximately 125 nm above a polished SiO_2 sample containing a low density of unpaired electron spins. The resonant slice represents those points in the sample where the field from the magnetic tip (plus an external field) matches the condition for magnetic resonance. As the cantilever vibrates, the resonant slice swings back and forth through the sample causing cyclic adiabatic inversion of the spin. The cyclic spin inversion causes a slight shift of the cantilever frequency owing to the magnetic force exerted by the spin on the tip. Spins as deep as 100 nm below the sample surface can be probed.

Single spin detection by magnetic resonance force microscopy

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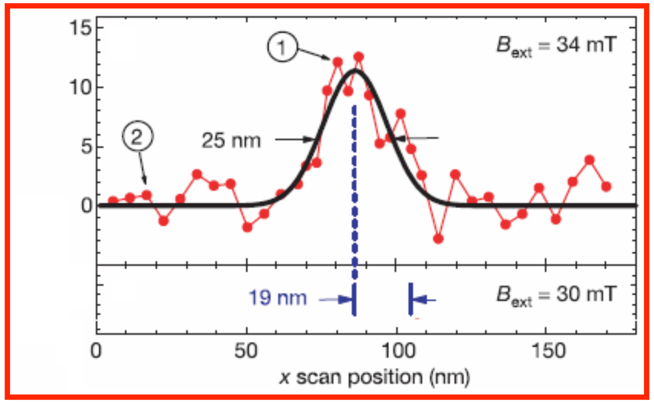
Magnetic resonance imaging (MRI) is well known as a powerful technique for visualizing subsurface structures with three-dimensional spatial resolution. Pushing the resolution below 1 μm remains a major challenge, however, owing to the sensitivity limitations of conventional inductive detection techniques. Currently, the smallest volume elements in an image must contain at least 10^{12} nuclear spins for MRI-based microscopy[1], or 10^7

NATURE | VOL 430 | 15 JULY 2004 | www.nature.com/nature



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Magnetic Systems

PHYSICAL REVIEW B 79, 054408 (2009)

Entanglement and Bell's inequality violation above room temperature in metal carboxylates

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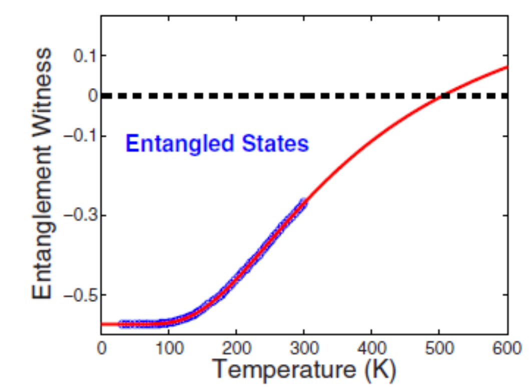
(Received 14 October 2008; revised manuscript received 15 December 2008; published 6 February 2009)



FEATURE ARTICLE www.rsc.org/materials | Journal of Materials Chemistry

Storing quantum information in chemically engineered nanoscale magnets†

A. Ardavan* and S. J. Blundell*

Received 5th June 2008, Accepted 11th September 2008
First published as an Advance Article on the web 17th November 2008
DOI: 10.1039/b809525f

We review the implementation of quantum information processing using quantum spins and pulsed spin resonance techniques. Molecular magnets, nanoscale clusters of coupled transition metal ions, offer various potential advantages over other spin systems as the building blocks of a quantum computer. We describe the strategies which must be employed in order to implement quantum algorithms in such nanoscale magnets and explain why, when evaluating the suitability of any physical system for embodying a qubit, it is essential to determine the phase relaxation time appropriate for an individual molecular spin. Experiments utilising pulsed spin resonance techniques show that the phase relaxation times in at least some molecular magnets are long enough to permit multiple qubit operations to be performed.

nature nanotechnology
ARTICLES
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PUBLISHED ONLINE: 1 FEBRUARY 2009 | DOI: 10.1038/NNANO.2008.404

Engineering the coupling between molecular spin qubits by coordination chemistry

Grigore A. Timco[1], Stefano Carretta[2], Filippo Troiani[3], Floriana Tuna[1], Robin J. Pritchard[1], Christopher A. Muryn[1], Eric J. L. McInnes[1], Alberto Ghirri[3,4], Andrea Candini[3], Paolo Santini[2], Giuseppe Amoretti[2], Marco Affronte[3,4]* and Richard E. P. Winpenny[1]*

The ability to assemble weakly interacting subsystems is a prerequisite for implementing quantum information processing and generating controlled entanglement. In recent years, molecular nanomagnets have been proposed as suitable candidates for qubit encoding and manipulation. In particular, antiferromagnetic Cr_7Ni rings behave as effective spin-1/2 systems at low temperature and show long decoherence times. Here, we show that these rings can be chemically linked to each other and that the coupling between their spins can be tuned by choosing the linker. We also present calculations that demonstrate how realistic microwave pulse sequences could be used to generate maximally entangled states in such molecules.

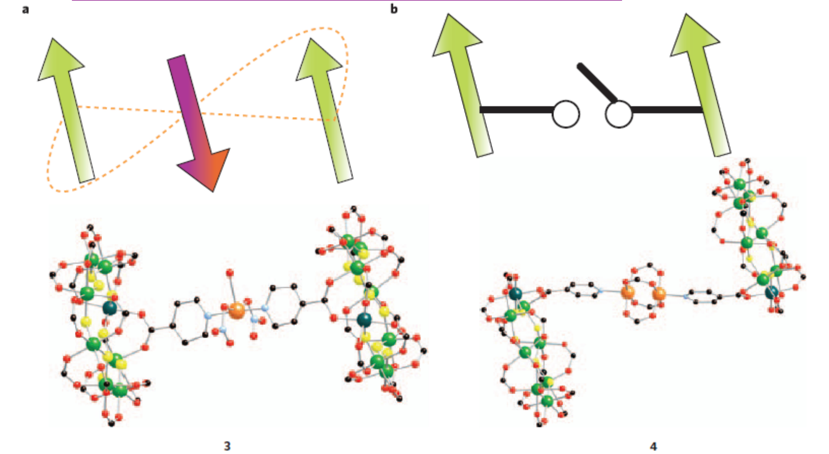

Figure 1 | Structures of the {Cr_7Ni}-link-{Cr_7Ni} molecules. a, Rings linked with a single Cu^{2+} centre (**3**) can be regarded as a three-qubit system. **b**, Rings coupled through a dimetallic link (**4**) implement two-qubit systems with switchable effective coupling. The coloured balls correspond to different atoms: Cr (light green), Ni (dark green), Cu (orange), O (red), N (blue), F (yellow) and C (black); tertiary butyl groups, NH_2Pr_2 and H atoms on H_2O are omitted for clarity.

Conclusions?

So is room-temperature quantum computing feasible?

Summing up, where do we stand? At liquid nitrogen temperatures, say 77 K, quantum computing is surely possible, if quantum computing is possible at all. At dry ice temperatures, say 195 K, quantum computing seems reasonably possible. At temperatures that can be reached by thermoelectric or thermomagnetic cooling, say 260 K, things are harder, but there is hope. Yet we know that small (say 2–3 qubit) quantum devices operate at room temperature. It seems likely, to me at least, that a quantum computer of say 20 qubits will operate at room temperature. I do not say it will be easy. Will such a QIP device be as portable as a laptop? I won't rule that out, but the answer is not obvious on present designs.

Audacious!

Cautious!

A large-scale quantum computer is certainly an extremely ambitious goal, appearing to us now as large, fully programmable classical computers must have seemed a century ago. However, as we approach this goal, we will grow accustomed to controlling the counterintuitive properties of quantum mechanics, and may reasonably expect side benefits such as new materials and new types of sensors. When we have mastered quantum technology enough to scale up a quantum computer, we will have tamed the quantum world and become inured to a new form of technological reality.