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Charge-based quantum computing using single donors in semiconductors

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Solid-state quantum computer architectures with qubits encoded using single atoms are now feasible given recent advances in the atomic doping of semiconductors. Here we present a charge qubit consisting of two dopant atoms in a semiconductor crystal, one of which is singly ionized. Surface electrodes control the qubit and a radio-frequency single-electron transistor provides fast readout. The calculated single gate times, of order 50 ps or less, are much shorter than the expected decoherence time. We propose universal one- and two-qubit gate operations for this system and discuss prospects for fabrication and scale up.

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In the search for an inherently scalable quantum computer (QC) technology solid-state systems are of great interest. One of the most advanced proposals is based on superconducting qubits,¹ where coherent control of qubits has been demonstrated and decoherence times measured.² The Kane scheme,³ in which qubits are defined by nuclear spin states of buried phosphorus dopants in a silicon crystal, has also attracted considerable attention due to its promise of very long (ms or longer) decoherence times below 1 K. Recent advances in single-dopant fabrication,⁴⁻⁶ together with the demonstration of fast single-electron transistor (SET) charge detection,^{7,8} bring the Kane Si:P architecture closer to reality. These important results notwithstanding, the demonstration of single-spin readout remains a major challenge. Here we consider a Si:P dopant-based qubit in which the logical information is encoded on the charge degrees of freedom. This system, which is complementary to the Kane concept, is not dependent on single-spin readout and, given the present availability of fabrication⁴⁻⁶ and readout^{7,8} technologies, can now be built. A two-qubit gate based on the charge qubit scheme we describe will enable an experimental determination to be made of the key sources of decoherence and error in a nanoscale silicon QC architecture. Such devices therefore provide an important and necessary pathway towards the longer term goal of real-spin Si:P devices.

Semiconductor quantum-dot charge-based qubits were first considered in 1995 by Barenco *et al.*,⁹ where quantum information was encoded in excitation levels, and later by Fedichkin *et al.*¹⁰ for position-based charge qubits in GaAs. Very recently, coherent oscillations have been observed¹¹ in a GaAs double quantum dot providing realization of a charge-based qubit with coherence times above 1 ns, accessible by existing fast pulse technology. In this paper we assess the potential of Si:P donor-based charge qubits by calculating the energetics and gate operation times for realistic device configurations and gate potentials and find that both one- and two-qubit operations times are well within the relevant decoherence times for the system.

The buried donor charge qubit is shown in Fig. 1 for the case of P dopants in Si, although a number of other dopant-substrate systems could also be considered, such as GaAs:Si. The lowest two states of a single electron localized by the

double well formed by two donor P^+ ions give rise to a natural identification of the quantum logic states. External control over the barrier height and potential offset (or symmetry) is facilitated by B and S gates, respectively, placed above the buried P-P⁺ system, as in Fig. 1(b). With appropriate negative bias we can identify localized qubit states with high precision: $|0\rangle = |L\rangle$ and $|1\rangle = |R\rangle$, as shown in Fig. 1(c). Finally, a SET facilitates initialization and readout of the qubit.

The Si:P charge qubit will decohere faster than the Kane nuclear spin qubit—however, as analysis of the qubit dynamics will show, the typical gate operation times τ_{op} of order 50 ps are also commensurately faster than the μs time scale¹² of the spin qubit. In what follows we estimate the decoherence time τ_{ϕ} associated with phonons and gate fluctuations, finding $\tau_{\text{op}} < \tau_{\phi}$ for these mechanisms, and conclude that fluctu-

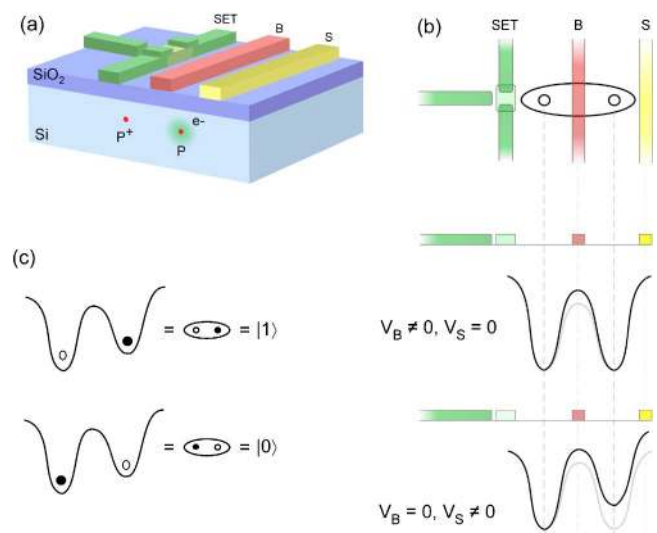


FIG. 1. (Color online) Buried charge qubit. (a) The solid-state charge qubit based on buried dopants D , forming a $D-D^+$ system with one electron, shown explicitly for the case for Si:P. (b) The gated charge qubit showing barrier (B gate) and symmetry (S gate) control, together with a single electron transistor (SET) for charge-based readout. (c) One possible choice of logical states $|0\rangle$ and $|1\rangle$, defined as shown in terms of left- and right-localized states.

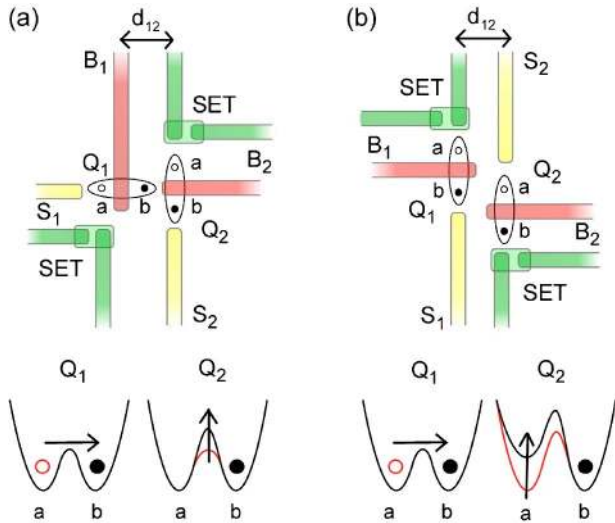


FIG. 3. (Color online) Qubit coupling schemes based on the Coulomb interaction. (a) CNOT configuration and (b) CPHASE configuration.

to the system having collapsed into the left or right state with probabilities $|c_0|^2$ and $|c_1|^2$, respectively.

In Fig. 3 we present two distinct arrangements for qubit coupling, complete with gate structures and SET readout. For the case of the CNOT arrangement [Fig. 3(a)] proposed by Landauer¹⁸ for quantum dot coupling and by Fedichkin *et al.*¹⁰ for GaAs qubits, the horizontal qubit Q_1 acts on the effective barrier height of the vertical qubit Q_2 , and the coupling is primarily $\Gamma_{zx}\sigma_z^{(1)}\sigma_x^{(2)}$. We also consider here a CPHASE arrangement [Fig. 3(b)] which is easily extended to a linear array of coupled qubits (Fig. 4). Since the two qubits Q_1 and Q_2 act on each other symmetrically, quantum information can be transmitted to either the left or right in a qubit array. The effective coupling for the CPHASE gate is $\Gamma_{zz}\sigma_z^{(1)}\sigma_z^{(2)}$. An in-depth investigation of the coupled qubit dynamics, controlled by such relatively complex gate structures, is beyond the scope of this paper; however, we have performed a preliminary semiclassical calculation to obtain an order-of-magnitude estimate. By moving a charge of $1.0e$ between the a and b positions of Q_1 for both coupling schemes (shown in Fig. 3, with Q_1 chosen to be 30–60 nm from Q_2) the effective dynamics of Q_2 were determined with corresponding coupled qubit operation times of $0.1 \rightarrow 1$ ns.

Successful operation of quantum devices is contingent on coherence times remaining longer than the time required for arbitrary rotations. Primary sources of decoherence include phonons, Johnson noise on the gates, and materials-related charge noise. At mK temperatures the thermal phonon population is very small, but spontaneous phonon emission can still occur. A calculation of LA phonon decoherence for the P-P⁺ system¹⁹ at 100 mK concluded that for donor separations of 25 nm and greater, τ^{phonon} is of order μs . The corresponding phonon-induced error for a one-qubit NOT gate (operating on σ_x) has recently been shown to be very low,²⁰ while for σ_x rotations an error of 3×10^{-3} was obtained.²⁰ This error rate is, however, very sensitive to the phonon wavelength cutoff used in the calculation (in relation to the

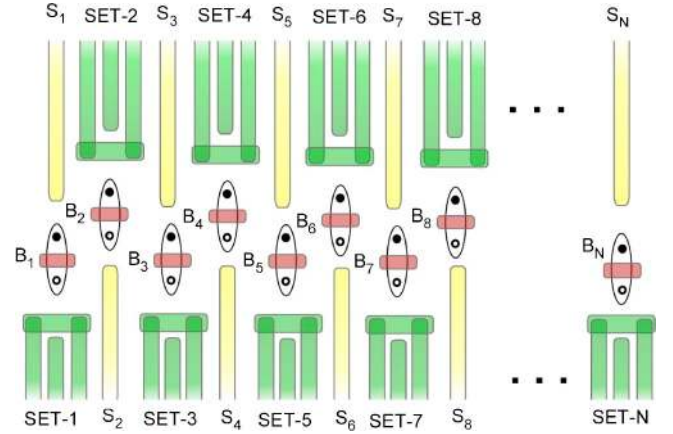


FIG. 4. (Color online) Schematic of a scaled-up architecture based on the staggered CPHASE configuration.

qubit length scale) and can be lower than 10^{-5} for a wide range of parameters.²¹ Irrespective of whether the error rate is below the 10^{-4} level required for fault-tolerant QC's, it appears that a significant number of gate operations will be possible, enabling proof-of-principle operation. An analysis of decoherence due to noise fluctuations on the S and B gates was carried out using a master equation approach.²² While the qubit is in a quiescent state, the dominant off-diagonal (od) contribution to the density matrix is $\rho_{\text{od}}(t) \approx \exp[-(C_S^{(z)})^2 \lambda_S t / 2\hbar^2]$, where λ_S scales the fluctuations and is given by the Johnson formula $\lambda_S = Rk_B T / \pi$. Using low-temperature electronics at $T \sim 10$ K and $R \sim 50 \Omega$, we obtain $\tau_{\phi}^{\text{Johnson}} \approx 2\pi\hbar^2 / Rk_B T (C_S^{(z)})^2 \sim 720$ ns.

A serious source of decoherence for all charge-based qubits is due to charge fluctuations in the surrounding environment.²³ In particular, individual charge traps can produce sudden and large changes in the noise signal at random times (random telegraph signals). In superconducting charge qubits^{2,24} the experimental coherence times of ~ 1 ns are predicted to be limited by this charge noise,²³ while the $\tau_{\phi} \sim 1$ ns observed in quantum dot qubits^{11,13} may be similarly determined. We note that the nanosecond coherence times observed in GaAs qubits^{11,13} are for quantum dots with ~ 25 electrons. The corresponding P-P⁺ qubit coherence time might well be longer since it may be more difficult to isolate the qubit space from other states in GaAs quantum dots than for the single-electron qubit system. The use of high-quality materials with low trap densities and refocusing pulse techniques may further extend the decoherence time. Furthermore, operation of the two-donor system in the delocalized basis where the qubit logic is less vulnerable to environmental charge fluctuations should lead to a significant suppression of the dephasing effects of charge noise, as is the case for Josephson “phase” qubits where the coherence time has been extended to 500 ns.²⁵

Realization of the devices shown in Figs. 1 and 3 requires an ability to dope a semiconductor at the single-donor level with interdonor spacings in the range 20–100 nm. Due to the long-range nature of the Coulomb coupling and the ability to tune the intraqubit tunneling rate using the B gate, constraints on the donor spacings are significantly relaxed in comparison with previous spin-based donor schemes.³

Single-atom doping of a semiconductor with the required positional accuracy has recently been demonstrated by two contrasting approaches. In the first, scanning-probe lithography of a hydrogenated silicon surface together with epitaxial Si overgrowth are used to construct a buried P array with precision <1 nm using atomic assembly.^{4,5} In the second, the donors are implanted through an array of nanoscale apertures and on-chip ion impact detectors are used to ensure that just one P ion passes through each aperture.⁶ The positional accuracy of the second approach is limited by the straggle which occurs during implantation and will be comparable to the donor depth (10–20 nm). Both approaches, although currently developed for Si:P, can in principle be applied to other systems, such as GaAs:Si. When combined with appropriate control and measurement electronics such devices allow gate voltage pulses on time scales <50 ps and can perform single-shot projective measurements of electron position on time scales less than $1 \mu\text{s}$.^{26,27} It is therefore anticipated that one-qubit experiments on such structures will soon be possible.

With single-atom doping and SET readout schemes for Si:P now available⁶ it is expected that N -qubit architectures could be constructed in the near future. Figure 4 is a straightforward extension of the two-qubit CPHASE gate of Fig. 3(b), where each qubit has an associated readout SET as well as the required S and B gates. The SETs would most conveniently be located on alternating sides of the one-dimensional array of qubits in order to localize the readout to the target qubit. Vertical via-connections will be needed to

make contact to the central B gates, necessitating layered insulator and metal structures, which is standard in modern very large scale integrated (VLSI) circuits.

In conclusion, gate operation times and decoherence rates have been calculated for Si:P charge qubits based on individual buried dopants with realistic gate configurations and bias voltages. Two coupling configurations were considered, including a CPHASE arrangement which can be conveniently scaled to a linear array of qubits. We find that one- and two-qubit gate operation times are accessible using existing pulse generator technology and are well within the estimates of decoherence due to phonons and gate fluctuations. The effect of environmental charge fluctuations can be gauged by measurements of $\tau_\phi \sim 1$ ns for GaAs quantum dot charge qubits.^{11,13} While experimental measurement of decoherence times will be necessary to determine the viability of this scheme for fault-tolerant QC, proof-of-principle demonstrations of qubit control and entanglement should be possible and as such will provide essential information towards the longer-term goal of Si:P spin-based quantum computing.

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