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| 14. ABSTRACT We have developed two experimental schemes that can be used to implement the Factorized Quantum Lattice-Gas Algorithm for the 1D Diffusion Equation with Persistent-Current Qubits. One scheme involves biasing the PC Qubit at multiple flux bias points throughout the course of the algorithm. An implementation analogous to that done in Nuclear Magnetic Resonance Quantum Computing is also developed. Errors due to a few key approximations utilized and differences between the PC Qubit and NMR systems were studied. Adiabatic quantum computation (AQC) is an approach to universal quantum computation in which the entire computation is performed in the ground state of a suitably chosen Hamiltonian. To make feasible a large-scale AQC experiment, we have proposed a scalable architecture for AQC based on the superconducting qubits. We have developed a set of processes that address the theoretically predicted need for extremely well-matched Josephson junction qubits in quantum computers. The work has focused on novel fabrication approaches such as nanoimprint lithography, which is able to replicate patterns with an extremely high degree of uniformity, and on methods of electron-beam lithography that achieve exceptional resist contrast, and thus high resolution, low line-edge roughness, and a correspondingly high degree of dimensional control in the resulting figures. We have accomplished this feat using two complimentary methods, one for negative-tone resist using cold development, the other for positive-tone resist using salt in the development solution. We have also demonstrated a method of Al/AIO _x /Al junction fabrication that uses lithographically-defined reentrant resist profiles. | | | | | |
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**Small-Qubit-Number Methods for
Superconductive Quantum Computation**

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1. Abstract

We have developed two experimental schemes that can be used to implement the Factorized Quantum Lattice-Gas Algorithm for the 1D Diffusion Equation with Persistent-Current Qubits. One scheme involves biasing the PC Qubit at multiple flux bias points throughout the course of the algorithm. An implementation analogous to that done in Nuclear Magnetic Resonance Quantum Computing is also developed. Errors due to a few key approximations utilized and differences between the PC Qubit and NMR systems were studied. Adiabatic quantum computation (AQC) is an approach to universal quantum computation in which the entire computation is performed in the ground state of a suitably chosen Hamiltonian. To make feasible a large-scale AQC experiment, we have proposed a scalable architecture for AQC based on the superconducting qubits.

We have developed a set of processes that address the theoretically predicted need for extremely well-matched Josephson junction qubits in quantum computers. The work has focused on novel fabrication approaches such as nanoimprint lithography, which is able to replicate patterns with an extremely high degree of uniformity, and on methods of electron-beam lithography that achieve exceptional resist contrast, and thus high resolution, low line-edge roughness, and a correspondingly high degree of dimensional control in the resulting figures. We have accomplished this feat using two complimentary methods, one for negative-tone resist using cold development, the other for positive-tone resist using salt in the development solution. We have also demonstrated a method of Al/AlO_x/Al junction fabrication that uses lithographically-defined reentrant resist profiles.

2. Accomplishments/New Findings

2.1 Implementation Schemes for the Factorized Quantum Lattice-Gas Algorithm for the One-dimensional Diffusion Equation using persistent-current qubits.

Most algorithms designed for quantum computers will not best their classical counterparts until they are implemented with thousands of qubits. For example, the factoring of binary numbers with a quantum computer is estimated to be faster than a classical computer only when the length of the number is greater than about 500 digits [1]. In contrast, the Factorized Quantum Lattice-Gas Algorithm (FQLGA) [2] for fluid dynamics simulation, even when run on a quantum computer significantly smaller than the one just discussed, has significant advantages over its classical counterparts.

The FQLGA is the quantum version of classical lattice-gases (CLG)[3]. CLG are an extension of classical cellular automata with the goal of simulating fluid dynamics without reference to specific microscopic interactions. The binary nature of the CLG lattice variables is replaced for the FQLGA by the Hilbert space of a two-level quantum system. The results of this replacement are similar to that of the lattice-Boltzmann model, but with a few significant differences [4]. The first is the exponential decrease in required memory. The second is the ability to simulate arbitrarily small viscosities.

We have developed two implementations of the algorithm for the 1D diffusion equation using the PC Qubit. The first consists of initializing the qubits while keeping them in their ground state, and then performing the collision by quickly changing their flux bias points and then performing a single $\pi/2$ pulse (Fig.1). This initialization technique could prove quite useful, since relaxation effects are avoided, but the way we have implemented the collision is not easily generalized to other collisions. A more general collision implementation was then developed by decomposing the unitary collision matrix into a sequence of single qubit rotations and coupled free evolution. The single qubit rotations then also serve to initialize the fluid's mass density.

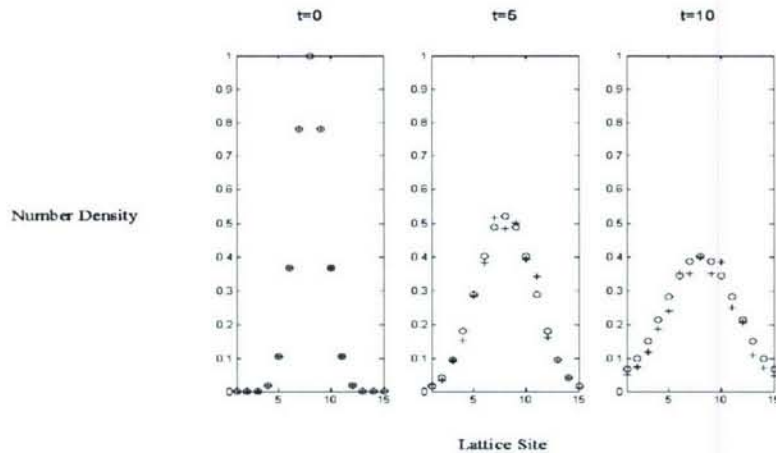


Fig.1. Simulation of the FQLGA for 1D diffusion is pictured (o) alongside simulation of the first proposed implementation (+). The expected diffusion of a Gaussian is observed.

The details of this work were recently published [5]. In this publication, we presented two experimental schemes that can be used to implement the Factorized Quantum Lattice-Gas

Algorithm for the 1D Diffusion Equation with Persistent-Current Qubits. One scheme involves biasing the PC Qubit at multiple flux bias points throughout the course of the algorithm. An implementation analogous to that done in Nuclear Magnetic Resonance Quantum Computing is also developed. Errors due to a few key approximations utilized were discussed and differences between the PC Qubit and NMR systems were highlighted.

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4. J. Yepez, An efficient quantum algorithm for the one-dimensional Burgers equation, quant-ph/0210092.
5. David M. Berns and T. P. Orlando, "Implementation Schemes for the Factorized Quantum Lattice-Gas Algorithm for the One-dimensional Diffusion Equation using persistent-current qubits," *Quantum Information Processing*, **4**, pp. 265-282, (2005).

2.2 Scalable Superconducting Architecture for Adiabatic Quantum Computation

Adiabatic quantum computation (AQC) is an approach to universal quantum computation in which the entire computation is performed in the ground state of a suitably chosen Hamiltonian [1]. As such, AQC offers intrinsic protection against dephasing and dissipation. Moreover, AQC naturally suggests a novel quantum approach to the classically intractable constrained minimization problems of the complexity class NP. Namely, by exploiting the ability of coherent quantum systems to follow adiabatically the ground state of a slowly changing Hamiltonian, AQC promises to bypass automatically the many separated local minima occurring in difficult constrained minimization problems that are responsible for the inefficiency of classical minimization algorithms. To date, most research on AQC has focused on determining the precise extent to which it could outperform classical minimization algorithms. The tantalizing possibility remains that---at least for all practical purposes---AQC offers at least a large polynomial, and often an exponential, speedup over classical algorithms. However, it may be the case that in the same way the efficiency of many practical classical algorithms for NP problems can only be established empirically, the efficiency of AQC on large instances of classically intractable problems can only be established by building a large-scale AQC experiment.

To make feasible such a large-scale AQC experiment, we have proposed a scalable architecture for AQC based on the superconducting persistent-current (PC) qubits already under development here at MIT. As first proposed in [2], the architecture naturally incorporates the terms present in the PC qubit Hamiltonian by exploiting the

isomorphism between antiferromagnetic Ising models in applied magnetic fields and the canonical NP-complete graph theory problem Max Independent Set. Such a design notably removes any need for the interqubit couplings to be varied during the computation. Moreover, since Max Independent Set remains NP-complete even when restricted to planar graphs where each vertex is connected to no more than 3 others by edges, a scalable programmable architecture capable of posing any problem in the class NP may simply take the form of a 2D, hexagonal, square, or triangular lattice of qubits.

Our latest version of the architecture [3] permits interqubit couplings to be limited to nearest-neighbors and qubit measurements to be inefficient. We have extended the practical interest of AQC by exhibiting a simple, scalable architecture that can handle any class NP problem. Moreover, we have specifically shown how to implement this architecture with present-day superconducting persistent-current (PC) qubits, which constitute a promising approach to lithographable solidstate qubits. The architecture addresses all the major technological obstacles to implementation by being able to tolerate manufacturing imprecision, imperfect measurements, and interqubit couplings that cannot vary during the course of the computation. Moreover, the architecture also highlights two special benefits previously unappreciated about PC qubits and AQC, respectively. First, it shows that it is possible to design inductively coupled flux qubits that can switch from ferromagnetic to antiferromagnetic couplings simply by adjusting the bias fluxes in their loops. Second, it demonstrates that AQC should be able to turn to advantage the classically troublesome fact that frustrated spin systems encoding NP-complete energy minimization problems generically freeze out of equilibrium by turning this endemic fact from something that for all previous algorithms promoted errors into something that prevents them.

[1] D. Aharonov, *et al.* (v1: 2004, May; v2: 2005, Mar.) Adiabatic quantum computation is equivalent to standard quantum computation. (<http://arxiv.org/abs/quant-ph/0405098>).

[2] W.M. Kaminsky and S. Lloyd, "Scalable architecture for adiabatic quantum computing of NP-hard problems," in *Quantum Computing and Quantum Bits in Mesoscopic Systems*, A.J. Leggett, B. Ruggiero, and P. Silvestrini, Eds. New York: Kluwer Academic, 2004, pp. 229-236.

[3] W.M. Kaminsky, S. Lloyd, and T.P. Orlando, (2004, Mar.) Scalable superconducting architecture for adiabatic quantum computation. (<http://arxiv.org/abs/quant-ph/0403090>.)

2.3 A Robust Shadow-Mask Evaporation Process for sub-50nm Josephson Junctions

Suspended shadow-mask evaporation is a widely-used process for fabricating Al/AlO_x/Al Josephson junctions. Its minimal processing overhead and compatibility with high-resolution scanning electron-beam lithography (SEBL) make it ideal for rapidly generating simple superconducting circuits for quantum computing applications. The primary challenge in designing a shadow-mask evaporation process is the patterning of a suspended membrane, or shadow mask, in a two-layer photoresist structure. A junction is then created under the shadow mask via two aluminum angle-evaporation steps, with a brief oxidation to produce the tunnel barrier in between.

The resist bilayer in a shadow-mask process is typically composed of a thick support layer underlying a thin, high-resolution imaging layer. Previous shadow-mask processes have generally used poly(methyl)methacrylate (PMMA) as the imaging resist and PMMA/PMAA copolymer or low-molecular-weight PMMA as the support layer. The difference in the sensitivities of the support and imaging layers was usually enough to produce sufficient undercut for a clean evaporation and liftoff after a single exposure step. However, the fact that the imaging and support layers were developed simultaneously led to a degradation in resolution, as the additional development time required to create a sufficient undercut in the support layer caused an unwanted increase in linewidths in the imaging layer. In addition, the reliance on development to produce the necessary undercut made the process very sensitive to poorly-controlled factors in the development process; implementing this type of process in our lab showed very inconsistent results and spotty device yields.

By using poly(dimethylglutarimide) (PMGI) as the support layer and extensively characterizing its unique properties, many of these problems have been eliminated[1]. As the support layer in a suspended shadow-mask process, Poly(dimethylglutarimide) (PMGI) has several desirable properties. It is not affected by the organic solvents used to develop PMMA, while the bases that develop PMGI do not affect PMMA. As a result, the two layers in a PMMA/PMGI bilayer can be developed independently; the resolution of the PMMA layer will not be affected by the development of the undercut layer. The decoupling of the two development processes means that the resolution of the process is limited only by the resolution of the imaging layer.

Since the primary factor limiting process resolution is now the PMMA imaging layer, considerable work has been done to push the resolution of PMMA past previously-established limits. Recently, developing PMMA below room temperature has been shown to increase the contrast of the resist, which in turn increases its final resolution[2][3][4]. The benefits of this effect appeared to increase as the development temperature was reduced, but no temperatures lower than -17°C had been investigated in published work, leading us to hypothesize that it may be possible to reach even higher resolutions by further reducing the temperature, possibly close to the freezing point of the developer at approximately -80°C [5]. Our experiments showed that this was not the case, however; below a certain temperature, the exposure process causes significant crosslinking of the exposed PMMA molecules, altering their dissolution behavior and degrading the contrast significantly (figure 2). Fortunately, we were able to identify an optimum development temperature; when PMMA is developed at this temperature, feature sizes of 10 nm and below are readily achievable even on a relatively low-cost 30 KeV electron-beam lithography tool (figure 3).

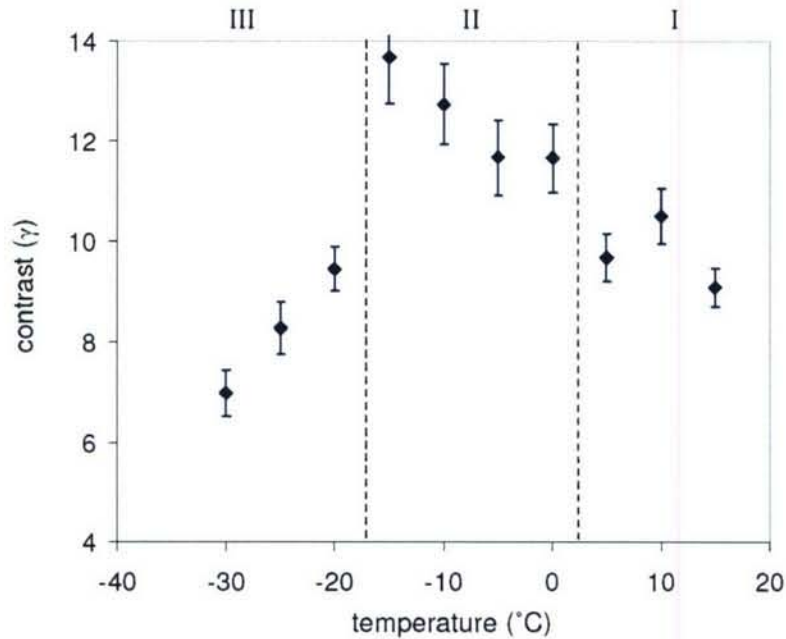


Figure 2: Resist contrast function γ as a function of temperature; to the first order, a higher γ value corresponds to higher lithographic resolution. Three temperature regimes are visible in the plot; in region I, contrast is degraded by development of partially-exposed resist at the edges of the exposure area. In region II these partially-exposed polymer chains are frozen in place, enhancing contrast, and in region III the presence of increasing amounts of crosslinked PMMA hinders the development process of highly-dosed resist and sharply degrades the contrast. From this chart, the optimal range of development temperatures appears to fall between 0°C and -15°C, with optimum contrast occurring at -15°C.

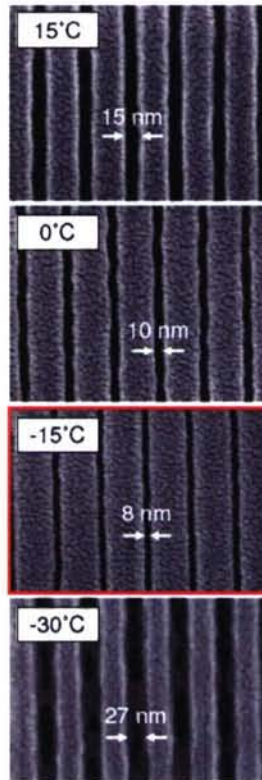


Figure 3: SEM images of 60-nm-pitch gratings developed at 15°C, 0°C, -15°C, and -30°C and etched into a Si substrate, showing the minimum achievable linewidth at each development temperature. As the contrast data in figure 2 predicts, the resolution improves as the temperature is reduced, peaks at -15°C, then drops sharply at -30°C. The poor line-edge definition and bridging in the -30°C micrograph are characteristic of sloped resist sidewalls, a symptom of poor resist contrast.

2.4 Using High-Contrast Salty Development of Hydrogen Silsesquioxane for Sub-10-nm-Half-Pitch Lithography

Currently, flux-based qubits require Josephson junctions in order to provide a potential surface whose eigenstates can approximate those of a two-level quantum system. But Josephson junctions are complex to fabricate, requiring multilevel patterning; and can introduce noise through the presence of impurity states in the tunneling barrier. Additionally, Josephson junctions are primarily fabricated using polycrystalline metals for electrodes, where unpassivated chemical bonds in the grain boundaries of the superconductors could potentially cause further noise. On the other hand, quantum-phase-slip (QPS) qubits promise the same parametric characteristics as Josephson-junction-based qubits, but require patterning of fewer material layers, and no barrier oxide (and thus contain fewer potential sources of noise)[6]. These qubits also require patterning at exquisitely fine feature dimensions, which is difficult to achieve using

conventional electron-beam technology.

Hydrogen silsesquioxane (HSQ) is a negative-tone electron resist that allows direct writing of etch-resistant silicon-oxide nanostructures with low line-edge roughness. However, due to its low contrast, patterning high-resolution, densely packed nanostructures in HSQ has been a challenge. In this work, we increased the contrast of HSQ by adding NaCl salt to an aqueous NaOH alkali developer. Remarkably, this salty developer resulted in contrast enhancement without significant decrease in resist sensitivity. The improved contrast of HSQ enabled the fabrication of 7-nm-half-pitch nested-“L” structures in a 35-nm-thick resist using a 30 kV electron-beam acceleration voltage as shown in Fig. 4.

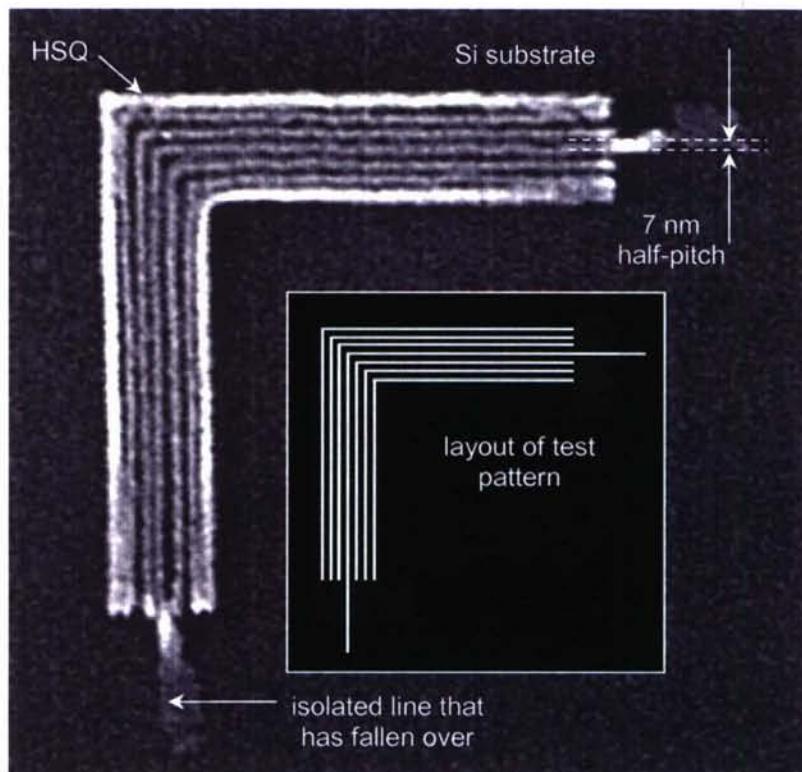


Fig. 4. SEM of 7-nm-half-pitch nested-“L” structures exposed in 35-nm-thick HSQ using a Raith 150 electron-beam lithography system operated at 30 kV beam acceleration voltage. Development was done in 1% wt. NaOH with 4% wt. NaCl.

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6. J. E. Mooij and C. J. P. M. Harmans, "Phase-slip flux qubits," *New J. Phys.*, vol. 7, pp. 219, (2005).

3. Personnel Supported

The following were supported in part by this contract:

PI's: Terry Orlando and Karl Berggren. Graduate students: David Berns and Vikas Anant

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Bryan Cord is supported in part by ARO through the QuACGR fellowship program

4. Publications

This is a cumulative list of publications:

1. David M. Berns and T. P. Orlando, "Implementation Schemes for the Factorized Quantum Lattice-Gas Algorithm for the One-dimensional Diffusion Equation using persistent-current qubits," *Quantum Information Processing*, **4**, pp. 265-282, (2005).
2. W.M. Kaminsky, S. Lloyd, and T.P. Orlando, "Scalable superconducting architecture for adiabatic quantum computation," submitted for publication (see <http://arxiv.org/abs/quant-ph/0403090>).
3. W.M. Kaminsky and S. Lloyd, "Scalable architecture for adiabatic quantum computing of NP-hard problems," in *Quantum Computing and Quantum Bits in*

Mesoscopic Systems, A.J. Leggett, B. Ruggiero, and P. Silvestrini, Eds. New York: Kluwer Academic, 2004, pp. 229-236.

4. K. Segall, D. S. Crankshaw, D. Nakada, B. Singh, J. Lee, T. P. Orlando, K. K. Berggren, N. Markovic, M. Tinkham, "Experimental characterization of the two current states in a Nb persistent-current qubit," *IEEE Trans. Appl. Supercon.* 13. 1009-1012, (2003).
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8. J. K. W. Yang, V. Anant, and K. K. Berggren, "Enhancing etch resistance of hydrogen silsesquioxane via postdevelop electron curing," "Robust Shadow-Mask Evaporation via Lithographically-Controlled Undercut." *Journal of Vacuum Science & and Technology B*, vol. 24(6), pp. 3157-3161, 20063139-3144 (2006).
9. B. Cord, J. Lutkenhaus, K. W. Yang, A. J. Kerman, E. A. Dauler, V. Anant, K. M. Rosfjord, and K. K. Berggren, "Modeling the Electrical and Thermal Response of Superconducting Nanowire Single-Photon Detectors," *IEEE Transactions on Applied Superconductivity*, submitted for publication (in review) (2007).
10. J. K. W. Yang and K. K. Berggren, "Using High-Contrast Salty. "Optimal Development of Hydrogen Silsesquioxane for Sub-10-nm-Half-Pitch Lithography," "Temperature for PMMA," *Journal of Vacuum Science & and Technology B*, submitted for publication (in review) (2007).

5. Interactions/Transitions

1. Participation in EIPBN conference by Cord and Yang.
2. Participation in the 2006 March APS meeting by Berns and Kaminsky.
3. Participation in the 2006 March APS meeting by Berns and Kaminsky.

6. Inventions, patents

Provisional patent application, MIT Ref. No. 12539L, “Resist Developer for Enhanced Contrast,” submitted May 2007. Joel K. Yang, Karl K. Berggren.