Superconducting Circuits and Quantum Computation

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Here we use superconducting circuits as components for quantum computing and as model systems for non-linear dynamics. Quantum computation holds the potential to solve problems currently intractable with today's computers. Information in a quantum computer is stored on quantum variables, and that information is processed by making those variables interact in a way that preserves quantum coherence. Typically, these variables consist of two quantum states, and the quantum device is called a quantum bit or qubit. Superconducting quantum circuits have been proposed as qubits, in which circulating currents of opposite polarity characterize the two quantum states. The goal of the present research is to use superconducting quantum circuits to realize a fully functional qubit, to perform measurement of these qubits, to model the sources of decoherence, and to develop scalable algorithms. A particularly promising feature of using superconducting technology is the potential of developing high-speed, on-chip control circuitry with classical, high-speed superconducting electronics. The picosecond time scales of this electronics means that the superconducting qubits can be controlled rapidly enough that the qubits remain phase-coherent over the lifetime of the computation.

Superconducting circuits are also model systems for collections of coupled classical non-linear oscillators. Recently we have demonstrated a ratchet potential using arrays of Josephson junctions as well as the existence of a novel non-linear mode, known as a discrete breather. In addition to their classical behavior, as the circuits are made smaller and with less damping, these non-linear circuits will go from the classical to the quantum regime. In this way, we can study the classical-to-quantum transition of non-linear systems.

1. Niobium Superconducting Persistent-Current Qubits with Deep Submicron Josephson Junctions

Project Staff
David M. Berns, William D. Oliver (MIT Lincoln Laboratory), Sergio O. Valenzuela, Terry P. Orlando, Vladimir Bolkhovsky (MIT Lincoln Laboratory), Earle Macedo (MIT Lincoln Laboratory)

The basic component of a quantum computer is the qubit, the quantum analog to today's bits. Any two-level quantum system could serve as a qubit; however, the qubit must satisfy two major criteria for practical quantum computing: long coherence times and the ability to scale to thousands of qubits. Persistent-current (PC) qubits are promising candidates for realizing such a large-scale quantum computer. The PC qubit is a superconducting circuit with Josephson Junction elements, which can be effectively operated as a two-level quantum system [1].

With a tri-layer process using optical lithography, we can create the deep-submicron Josephson Junctions required to realize large qubit tunnel-couplings, which allow improved immunity to dielectric-induced decoherence, and there is no foreseeable barrier to large-scale integration. We have recently begun measuring and characterizing the PC qubits designed with these deep-submicron Josephson Junctions fabricated with the Nb-Al/AlOx-Nb trilayers. Initial testing of the Josephson Junctions shows excellent performance down to sizes necessary for long decoherence times (Figure 1), and first studies of how the ground state of the new qubits changes as you sweep the applied DC flux show the large tunnel-couplings we were aiming for (Figure 2).

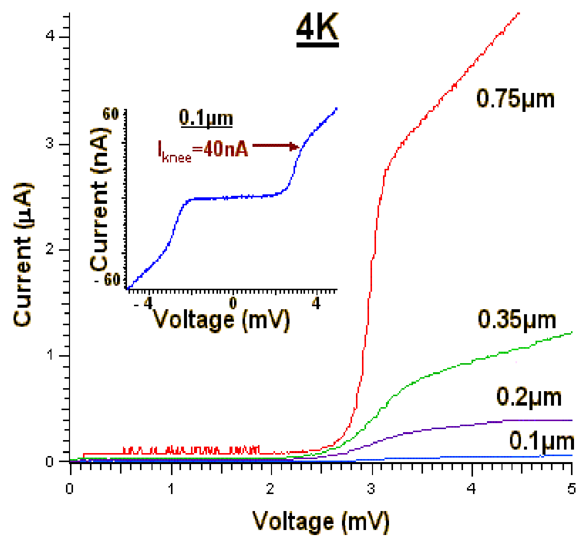


Figure 1 : IV traces taken at 4K for a few different test junctions, from 0.75 μm down to 0.1μm. Blown up in the inset is the 0.1 μm junction IV and we see a knee current of 40nA and a very large subgap resistance.

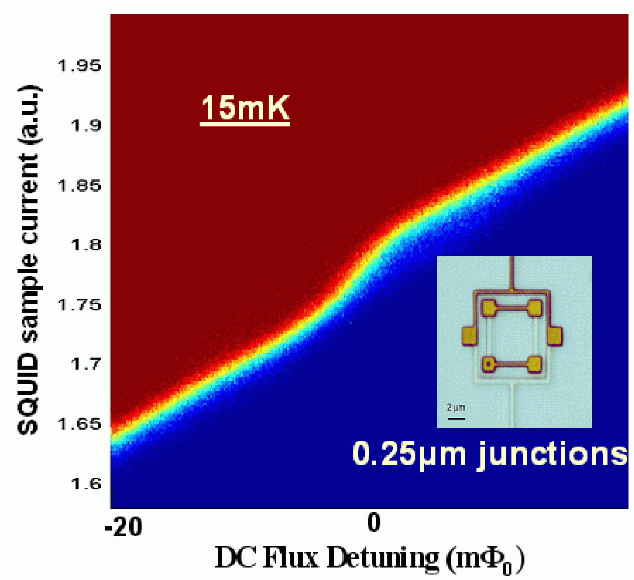


Figure 2 : Qubit step taken at dilution refrigerator temperatures with the device seen in the inset, where the larger junctions are 250nm on a side . One can clearly see that as you change the applied dc magnetic flux one sees the transition of the ground state from one circulating current state to the other.

References

[1] T.P. Orlando, J.E. Mooij, L. Tian, C.H. van der Wal, L.S. Levitov, S. Lloyd, J.J. Mazo, "Superconducting Persistent-Current Qubit," *Physical Review B: Condensed Matter and Materials Physics* 60(22): 15398-15413 (December 1999).

2. Mach-Zehnder Interferometry in a Persistent-Current Qubit

Project Staff

William D. Oliver (MIT Lincoln Laboratory), Yang Yu, Janice C. Lee, Karl K. Berggren, Leonid S. Levitov, Terry P. Orlando

We have demonstrated Mach-Zehnder (MZ)-type interferometry with a niobium superconducting persistent-current qubit. These experiments exhibit remarkable agreement with theory, and they will find application to non-adiabatic qubit control methods. The qubit is an artificial atom, the ground and first-excited states of which exhibit an avoided crossing. Driving the qubit with a large-amplitude harmonic excitation sweeps it through this avoided crossing two times per period. The induced Landau-Zener (LZ) transitions at the avoided crossing cause coherent population transfer between the eigenstates, and the accumulated phase between LZ transitions varies with the driving amplitude. This is analogous to a Mach-Zehnder interferometer, where the LZ transition is the beasmplitter and the relative phase accumulated between LZ transitions is the optical path length difference between the arms of the interferometer. Over the entire length of the microwave driving pulse we have a sequence of Mach-Zehnder interferometers. We have observed MZ quantum interference fringes as a function of the driving amplitude for single- and multi-photon excitations.

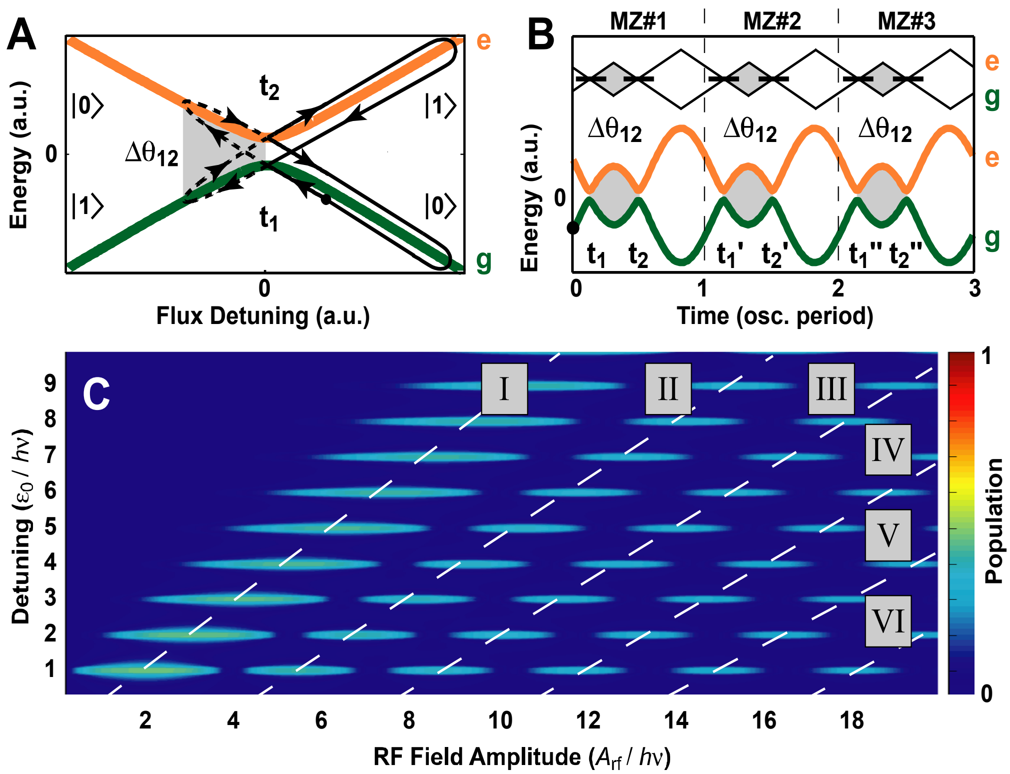


Figure 1: (a) Energy of the two-level system. Starting at the marker, the qubit state is swept through the avoided crossing twice, accumulating a phase between the LZ transitions that occur. (b) The corresponding energy variation over a few pulse periods. The sequence of LZ transitions and phase accumulation are analogous to a sequence of Mach-Zehnder interferometers. (c) Qubit population as a function of driving amplitude. We see the Bessel dependence to the Mach-Zehnder-like quantum interference for n-photon transitions.

References

[1] W.D. Oliver, Y. Yu, J.C. Lee, K.K. Berggren, L.S. Levitov, T.P. Orlando, "Mach-Zehnder Interferometry in a Strong Driven Superconducting Qubit," *Science* 310(9): 1653-1657 (December 2005)

3. Coherent Quasi-classical Dynamics of a Niobium Persistent-Current Qubit

Project Staff

David M. Berns, Sergio O. Valenzuela, William D. Oliver, Leonid S. Levitov, Terry P. Orlando

We have recently demonstrated Mach-Zehnder (MZ)-type interferometry in the persistent-current (PC) qubit, in the strong driving limit [1]. We have now extended this work to much lower driving frequencies. By driving our system at frequencies smaller than our linewidth we have observed a new regime of quasi-classical dynamics within the strong driving limit. Now a transition at a DC flux detuning resonant with n photons is assisted by neighboring resonances. In this regime we find remarkable agreement to theory by assuming the population transfer rate for the nth photon resonance is the sum of rates from all other resonances.

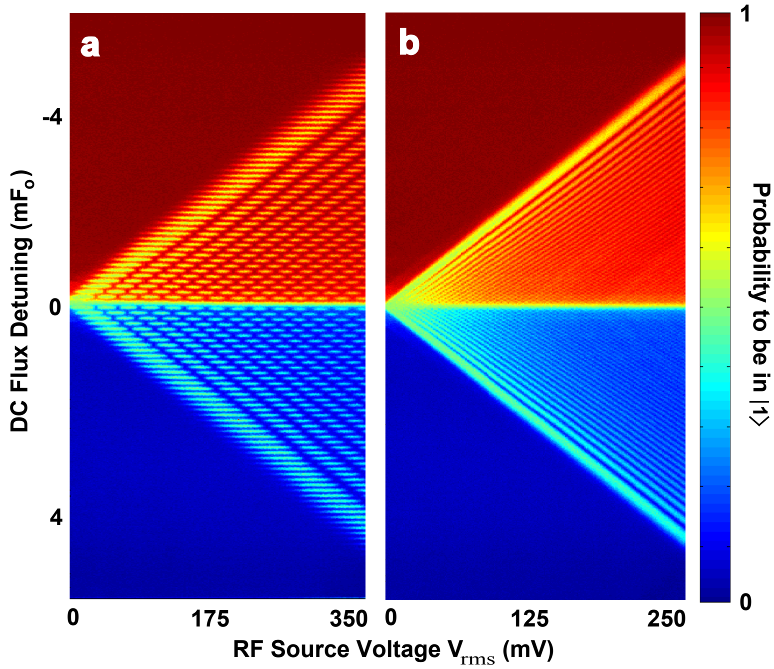


Figure 1: Qubit population as a function of driving amplitude. (a) Driving frequency = 270MHz. We see the Bessel dependence to the Mach-Zehnder-like quantum interference for n-photon transitions. (b) Driving frequency = 90MHz. Individual resonances are no longer distinguishable but we still see coherent quantum interference.

References

[1] W.D. Oliver, Y. Yu, J.C. Lee, K.K. Berggren, L.S. Levitov, T.P. Orlando, "Mach-Zehnder Interferometry in a Strong Driven Superconducting Qubit," *Science* 310(9): 1653-1657 (December 2005)

4. Microwave-Induced Cooling of a Superconducting Qubit

Project Staff

Sergio O. Valenzuela, William D. Oliver, David M. Berns, Karl K. Berggren, Leonid S. Levitov, Terry P. Orlando

We have recently demonstrated microwave-induced cooling in a superconducting flux qubit [1]. The thermal population in the first-excited state of the qubit is driven to a higher-excited state by way of a sideband transition. Subsequent relaxation into the ground state results in cooling. Effective temperatures as low as 3 millikelvin are achieved for bath temperatures from 30 - 400 millikelvin, a cooling factor between 10 and 100. This demonstration provides an analog to optical cooling of trapped ions and atoms and is generalizable to other solid-state quantum systems. Active cooling of qubits, applied to quantum information science, provides a means for qubit-state preparation with improved fidelity and for suppressing decoherence in multi-qubit systems.

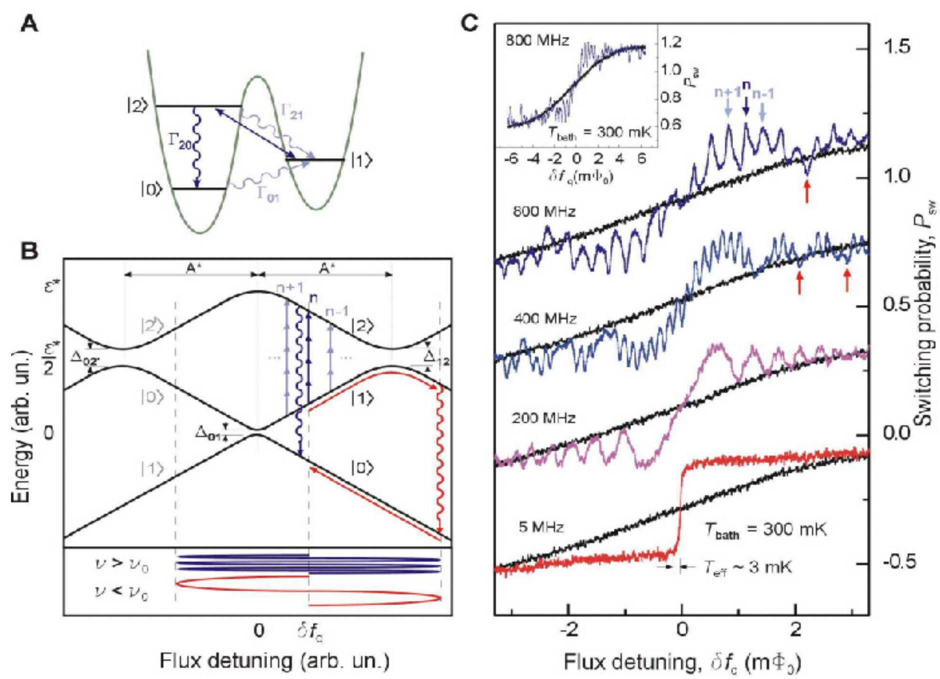


Figure 1: Sideband cooling in a flux qubit. (a) Double well illustration of cooling. External excitation transfers thermal population from state 1 to state 2, from which it decays to the ground state 0. (b) Band diagram illustion of cooling. 1 to 2 transitions are driven resonantly at high driving frequencies and occurr adiabatically at low driving frequency. (c) Thermal population cooled at different frequencies. Cooling from 300mK to as low as 3mK is shown.

REFERENCES:

[1] S.O. Valenzuela, W.D. Oliver, D.M. Berns, K.K. Berggren, L.S. Levitov, and T.P. Orlando, “Microwave-Induced Cooling of a Superconducting Qubit,” *Science* 314: 1589 (2006).

5. Resonant Readout of a Persistent Current Qubit

Sponsors

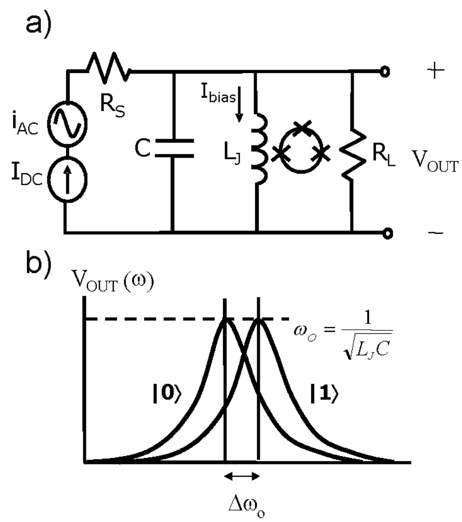
AFOSR Grant F49620-01-1-0457 under the DOD University Research Initiative on Nanotechnology (DURINT) program, and by ARDA, and LPS.

Project Staff

Janice C. Lee, William D. Oliver (MIT Lincoln Laboratory), Terry P. Orlando

The two logical states of a persistent current (PC) qubit correspond to oppositely circulating currents in the qubit loop. The induced magnetic flux associated with the current either adds to or subtracts from the background flux. The state of the qubit can thus be detected by a DC SQUID magnetometer inductively coupled to the qubit.

We have implemented a resonant technique that uses a SQUID as a flux-sensitive Josephson inductor for qubit readout. This approach keeps the readout SQUID biased at low currents along the supercurrent branch. The low bias reduces the level of decoherence on the qubit, and is more desirable for quantum computing applications. We incorporated the SQUID inductor in a high-Q on-chip resonant circuit, and were able to distinguish the two flux states of a niobium PC qubit by observing a shift in the resonant frequency of the readout circuit. The nonlinear nature of the SQUID Josephson inductance as well as its effect on the resonant spectra of the readout circuit was also characterized.



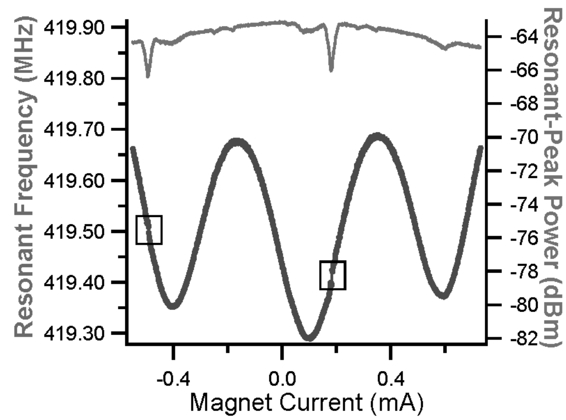


Figure 1a: The SQUID inductor is incorporated in a resonant readout circuit. It is inductively coupled to a PC qubit to detect its state. Figure 1b: A transition of the qubit state changes the Josephson inductance of the SQUID, and can be sensed as a shift in the resonant frequency of the readout circuit.

Figure 2: Experimental results at 300mK: the lower plot (left axis) shows the modulation of the resonant frequency with external magnetic field. Qubit steps corresponding to transitions between opposite flux states were observed at every 1.3 periods of the SQUID lobe. The upper plot (right axis) shows the corresponding peak amplitude of the resonant spectrum. The dip in peak power coincides with the qubit step.

REFERENCES:

[1] J.C. Lee, W.D. Oliver, and T.P. Orlando, "Resonant Readout of a Persistent Current Qubit," *IEEE Transactions on Applied Superconductivity* 15(2): 841 - 844 (June 2005)

[2] J.C. Lee, "Magnetic Flux Measurement of Superconducting Qubits with Josephson Inductors," Master of Science thesis, MIT, 2002

6. Type-II Quantum Computing Using Superconducting Qubits

Sponsors:

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Project Staff:

David Berns, William M. Kaminsky, Bryan Cord, Karl Berggren, Dr. William Oliver (MIT Lincoln Laboratory), Terry P. Orlando

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 recently 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 □/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.

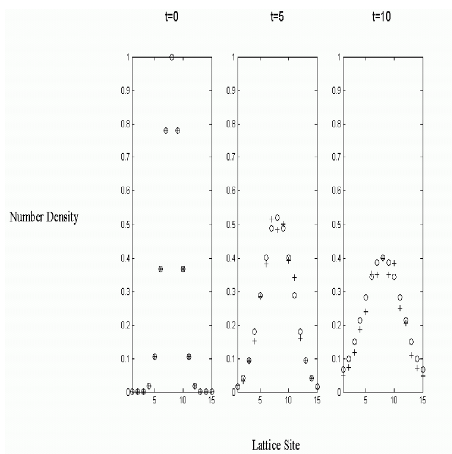

Fig.1. Simulation of the FQLGA for 1D diffusion is pictured(o) alongside simulation of the first proposed implementation(+). The expected diffusion of a gaussian is observed.

References:

[1] K. Berggren, "Quantum Computing with Superconductors," *Proceedings of the IEEE* 92(10): 1630 (2004).

[2] J. Yepez, "Quantum Computation and Quantum Communication," *Lecture Notes in Computer Science* 1509, Springer-Verlag 35 (1999).

[3] D. A. Wolf-Gladrow, "Lattice-Gas Cellular Automata and Lattice Boltzmann Models," Edited by A. Dold et al., Springer (2000).

[4] J. Yepez, "An Efficient Quantum Algorithm for the One-Dimensional Burgers Equation," quant-ph/0210092.

7. Scalable Superconducting Architecture for Adiabatic Quantum Computation

Sponsors
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Project Staff
William M. Kaminsky, Seth Lloyd, Terry P. Orlando

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 [2,3]. 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 [4-8] 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 [9, 10] already under development here at MIT. As first proposed in [11], the architecture naturally incorporates the terms present in the PC qubit Hamiltonian by exploiting the isomorphism [12] 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. Finally, the latest version of the architecture [13] permits interqubit couplings to be limited to nearest-neighbors and qubit measurements to be inefficient.

REFERENCES:

[1] D. Aharonov, W. van Dam, J. Kempe, Z. Landau, S. Lloyd, O. Regev, “Adiabatic Quantum Computation is Equivalent to Standard Quantum Computation,” The Quantum Physics E-Print Archive, no. 0405098, March 2005; available: http://arxiv.org/abs/quant-ph/0405098.

[2] A.M. Childs, E. Farhi, J. Preskill, “Robustness of Adiabatic Quantum Computation,” Physical Review A: Atomic, Molecular, and Optical Physics 65(1) 012322: 1-10 (January 2002).

[3] J. Roland, N.J. Cerf, “Noise Resistance of Adiabatic Quantum Computation Using Random Matrix Theory,” Physical Review A: Atomic, Molecular, and Optical Physics 71(3) 032330: 1-9 (March 2005).

[4] E. Farhi, J. Goldstone, S. Gutmann, J. Lapan, A. Lundgren, D. Preda, “A Quantum Adiabatic Evolution Algorithm Applied to Random Instances of an NP Complete Problem,” *Science* 292: 472-475 (April 2001).

[5] A.M. Childs, E. Farhi, J. Goldstone, S. Gutmann, “Finding Cliques by Quantum Adiabatic Evolution,” *Quantum Information and Computation* 2(3): 181-191 (May 2002).

[6] W. van Dam, M. Mosca, U. Vazirani, “How Powerful is Adiabatic Quantum Computation?” presented at the 42nd Annual Symposium on Foundations of Computer Science, Las Vegas, Nevada, pages 279–287, October 2001.

[7] E. Farhi, J. Goldstone, S. Gutmann, “Quantum Adiabatic Evolution Algorithms versus Simulated Annealing,” *The Quantum Physics E-Print Archive*, 0201031 (January 2002); available: http://arxiv.org/abs/quant-ph/0201031.

[8] G.E. Santoro, R. Martonak, E. Tosatti, R. Car, “Theory of Quantum Annealing of an Ising Spin Glass,” *Science*, 295: 2427-2430 (March 2002).

[9] J. E. Mooij, T. P. Orlando, L. Levitov, Lin Tian, Caspar H. van der Wal, and Seth Lloyd, “Josephson Persistent-Current Qubit,” *Science* 285: 1036-1039 (August 1999).

[10] T.P. Orlando, J.E. Mooij, L. Tian, C.H. van der Wal, L.S. Levitov, S. Lloyd, J.J. Mazo, “Superconducting Persistent-current Qubit,” *Physical Review B: Condensed Matter and Materials Physics*, 60(22): 15398-15413 (December 1999).

[11] W.M. Kaminsky, S. Lloyd, “Scalable Architecture for Adiabatic Quantum Computing of NP-hard Problems,” in *Quantum Computing and Quantum Bits in Mesoscopic Systems*, ed. A.J. Leggett, B. Ruggiero, P. Silvestrini, (New York: Kluwer Academic, 2004), 229-236.

[12] F. Barahona, “On the Computational Complexity of Ising Spin Glass Models,” *Journal of Physics A: Mathematical and General*, 15(10): 3241-3253 (October 1982).

[13] W.M. Kaminsky, S. Lloyd, T.P. Orlando, “Scalable Superconducting Architecture for Adiabatic Quantum Computation,” *The Quantum Physics E-Print Archive* no. 0403090 (March 2004); available: http://arxiv.org/abs/quant-ph/0403090.

8. Fabrication Methods for Adiabatic Quantum Computing Devices

Sponsors
Quantum Computing Graduate Research Fellowship, AFOSR grant F49620-01-1-0461

Project Staff
Bryan M. Cord, William M. Kaminsky, Terry P. Orlando, Karl K. Berggren

Adiabatic quantum computing devices (AQCs) have been implemented successfully in several types of systems, including ion traps, nuclear spins, and photon cavities. However, we find implementing AQCs in superconductive circuits offers several key advantages. Primarily, using standard techniques adapted from the semiconductor industry, we can fabricate very large numbers of superconductor-based qubits in CMOS-compatible materials, [1].

The stringent resolution and uniformity requirements for AQC devices present an interesting fabrication challenge. In order to perform certain AQC experiments, Josephson junctions with diameters of ~ 50 nm are useful. While previous quantum computing experiments at MIT used devices fabricated using optical projection lithography, sub-100 nm dimensions require alternate techniques, such as electron-beam lithography and suspended shadow-mask evaporation. Additionally, the uniformity of these nanoscale junctions must be high and the areas of the Josephson junctions within a single device must exhibit very low variation.

No readily-available lithographic technology meets these requirements, so research is being conducted on methods of defining arbitrary features as small as 50 nm with the precision required for adiabatic quantum computing. Current experiments have focused on improving the resolution and uniformity of the scanning electron-beam lithography (SEBL) system in the Nanostructures Laboratory, particularly in investigating the effects of different pattern geometries on the uniformity of very small features. Parallel work is also being done on a reliable, automated method of measuring the dimensions of very small structures for the purposes of determining uniformity, using scanning electron microscope (SEM) images and image-processing software.

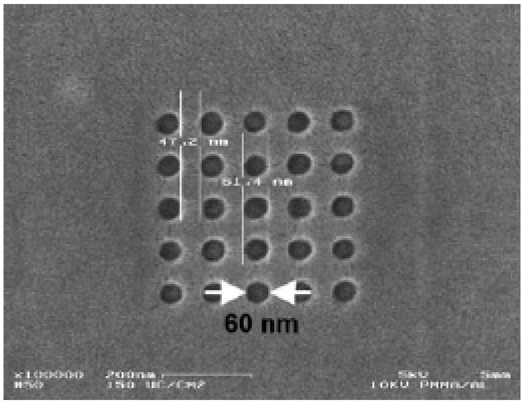

Figure 1: SEM of an array of 60nm diameter features in photoresist.

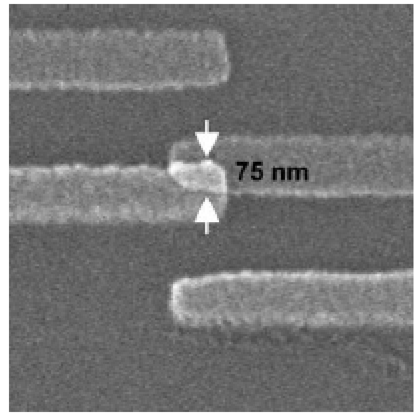

Figure 2: SEM of an 0.007μm2 Al/AlOx/Al Josephson junction fabricated via shadow-mask evaporation.

REFERENCES:

[1] K.K. Berggren, "Quantum Computing with Superconductors," *Proceedings of the IEEE*, 92(10): 1630-1638 (October 2004).

Publications

Journal Articles

W.D. Oliver, Y. Yu, J.C. Lee, K.K. Berggren, L.S. Levitov, T.P. Orlando, "Mach-Zehnder Interferometry in a Strong Driven Superconducting Qubit," *Science* 310(9): 1653-1657 (December 2005)

J.C. Lee, W.D. Oliver, T.P. Orlando, and K.K. Berggren, "Resonant Readout of a Persistent Current Qubit," *IEEE Transactions on Applied Superconductivity* 15(2): 841-844 (June 2005).

D.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(4): 265 (2005).

K. Segall, J.J. Mazo, and T.P. Orlando, "Multiple Junction Biasing of Superconducting Tunnel Junction Detectors," *Applied Physics Letters* 86: 153507:1-3 (Apr. 2005).

K.V.R.M. Murali, Z. Dutton, W.D. Oliver, D.S. Crankshaw, and T.P. Orlando, "Probing Decoherence with Electromagnetically Induced Transparency in Superconductive Quantum Circuits," *Physical Review Letters* 93(8): 087003 (August 2004).

Y. Yu, D. Nakada, J.C. Lee, B. Singh, D.S. Crankshaw, T.P. Orlando, W.D. Oliver, and K.K. Berggren, "Energy Relaxation Time between Macroscopic Quantum Levels in a Superconducting Persistent-Current Qubit," *Physical Review Letters* 92(11): 117904:1-4 (2004).

D.S. Crankshaw, K. Segall, D. Nakada, T.P. Orlando, L.S. Levitov, S. Lloyd, S.O. Valenzuela, N. Markovic, M. Tinkham, and K.K. Berggren, "DC Measurements of Macroscopic Quantum Levels in a Superconducting Qubit Structure with a Time-Ordered Meter," *Physical Review B* 69(14): 144518:1-9 (April 2004).

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," *Kluwer Academic* (2003)

Books/Chapters in Books

P. Hagelstein, S.D. Senturia, T.P. Orlando, *Introductory Applied Quantum and Statistical Mechanics* (Hoboken, New Jersey: John Wiley and Sons, 2004).

Theses

K. Murali, *Electromagnetically Induced Transparency and Electron Spin Dynamics using Superconducting Quantum Circuits*, Ph.D. Dissertation, Department of Electrical Engineering and Computer Science, MIT, February 2006

J. Lee, *Resonant Readout of a Superconducting Persistent Current Qubit*, Ph.D. Dissertation, Department of Electrical Engineering and Computer Science, MIT, June 2006

K. Brown, *Cryogenic Characterization of Josephson Junctions*, B.S., Department of Physics, MIT, May 2006