Quantum Nanostructures and Nanofabrication

RLE Groups
Quantum Nanostructures and Nanofabrication Group, NanoStructures Laboratory

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The Quantum Nanostructures and Nanofabrication Group researches the application and fabrication of devices using the foundations of quantum mechanics with a focus on:
(1) superconductive devices and materials applied to quantum computing and single-photon detection; (2) nanofabrication methods; and (3) architectural and system-related issues surrounding quantum computing. Superconductive devices are among the most readily engineered examples of devices exhibiting quantum-mechanical effects. We therefore work with superconductive materials, materials processing and analysis. Also, because quantum-mechanical effects are primarily observable at microscopic length scale, we develop and implement novel methods of nanofabrication. Finally, our interests also include the architectural and system-related issues surrounding the application of quantum-mechanical devices to computation. We take a multi-disciplinary approach to these topics, using techniques from physics, electrical-engineering, computer science, chemistry, and biology.

1. Fabrication Methods for Adiabatic Quantum Computing Devices

Sponsors:
QuaCGR Fellowship, AFOSR

Project Staff:
B. Cord, W. Kaminsky, T. Orlando, K. K. Berggren

Quantum-computing devices have been successfully implemented in several types of systems including ion traps, nuclear spins, photon cavities, and superconductive circuits. Of these systems, the last offers several key advantages, the first and foremost being that superconductor-based qubits can be fabricated in large numbers in CMOS-compatible materials using standard techniques adapted from the semiconductor industry [1]. Adiabatic quantum computing (AQC) with superconductors has been recently proposed as an innovative approach to quantum computing [2].

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 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.

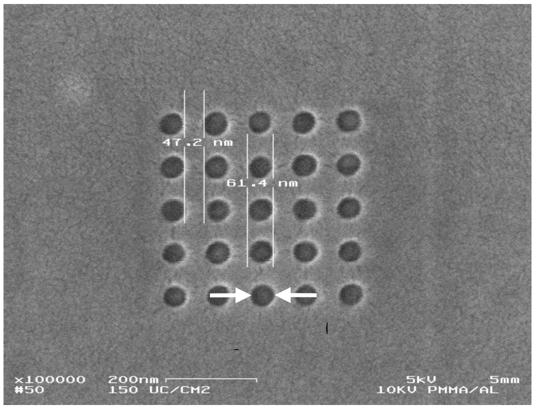

Figure 1: *Scanning electron micrograph of an array of 60-nm-diameter features in photoresist*

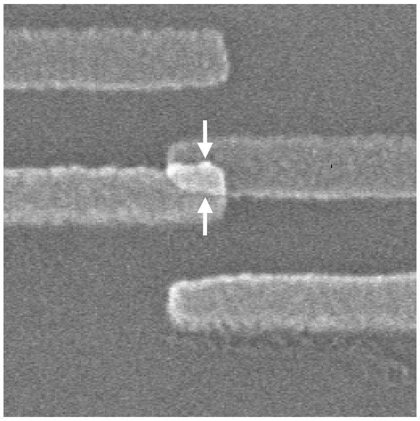

Figure 2: *Scanning electron micrograph of an 0.007 μm^2 Al/AlO$_x$/Al Josephson junction fabricated via shadow-mask evaporation*

References:

[1] K.K. Berggren, “Quantum Computing with Superconductors,” *Proceedings of the IEEE,* vol. 134, no. 10, pp. 1630-1638, Oct. 2004.

[2] W. M. Kaminky, S. Lloyd, and T. P. Orlando, “Scalable superconducting architecture for adiabatic quantum computation”.

2. Sub-resolution Lithography Using Quantum State Quenching

Sponsors:
MIT

Project Staff:
M. Rådmark, K. K. Berggren

Past work has demonstrated deep-sub-resolution spot-size and resolution in nanolithography in atomic beams using quantum state quenching near the node of an optical field [1]. Recently an extension of this technique has been proposed to directly control the patterning of molecules [2]. We envisage an implementation strategy consisting of three steps. In the first step, a diffraction-limited spot of the photo-resist would be excited. Immediately thereafter, a second incident pulse containing a node at its center would quench the outer parts of this spot, decreasing the spot size below the diffraction limit. In the third step, the remaining excited molecules would react to expose the resist.

A standing wave is one possible field distribution that can be used for this application. A key property of this standing wave is that its maximum intensity should be much higher than the saturation intensity for de-excitation. The region where the intensity of the standing wave is too low to effectively quench excited molecules will then be very narrow and the remaining excited spot will be much smaller than the diffraction limit. The distribution of excited molecules, after quenching by the second pulse, will depend on the intensity of this pulse. Figure 1 shows calculations of point-spread functions (PSFs) given by a quenching pulse with a standing wave of different intensities. With a wavelength of the standing wave on the order of 400 nm and a maximum intensity of ~ 10 W/μm^2, the PSF of excited molecules could be made very narrow and spot sizes on the order of tens of nanometers could be achieved. Such a narrow PSF could then be scanned across the substrate to achieve continued scaling of optical lithography into the sub-50-nm regime.

Future work in this project will focus on devising an appropriate chemical system in which to realize this phenomenon.

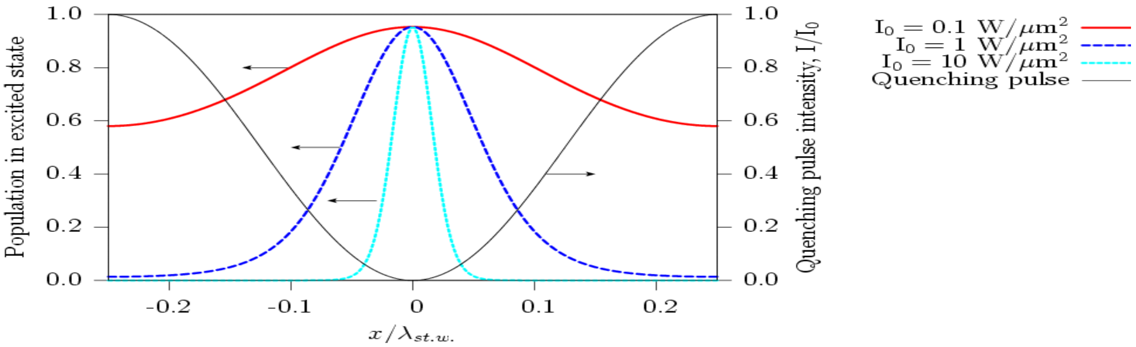

Figure 1: *Distribution of molecules in the excited state, after the effects of a quenching pulse. I_0 is the maximum intensity of the quenching pulse and $\lambda_{st.w.}$ is the wavelength of the standing wave. The molecular cross section for stimulated emission is assumed to be 10^{-16} cm^2. The higher the intensity of the quenching pulse is, the more effectively it will quench excited molecules around the node, leading to a narrower PSF.*

References:

[1] A P Chu, K K Berggren, K S Johnson and M G Prentiss. "A virtual slit for atom optics and nanolithography". Quantum Semiclass. Opt. 8 (1996) 521-529.

[2] Stefan W Hell. "Strategy for far-field optical imaging and writing without diffraction limit". Physics Letters A 326 (2004) 140-145.

3. Evolvable Hardware

Sponsors:
MIT Lincoln Laboratory

Project Staff:
D. Sanchez, K. K. Berggren

Harnessing *all* of the intrinsic data-processing power of electronic devices is impossible through traditional circuit design. While complex physical processes involving electronic, thermal, and even quantum phenomena underlie the operation of the devices, standard circuit design methodology appropriately mandates a level of abstraction where most of these phenomena are safely ignored. In this work, we investigate the possibility that enhanced data processing capabilities exist in previously neglected classical degrees of freedom of a circuit [1].

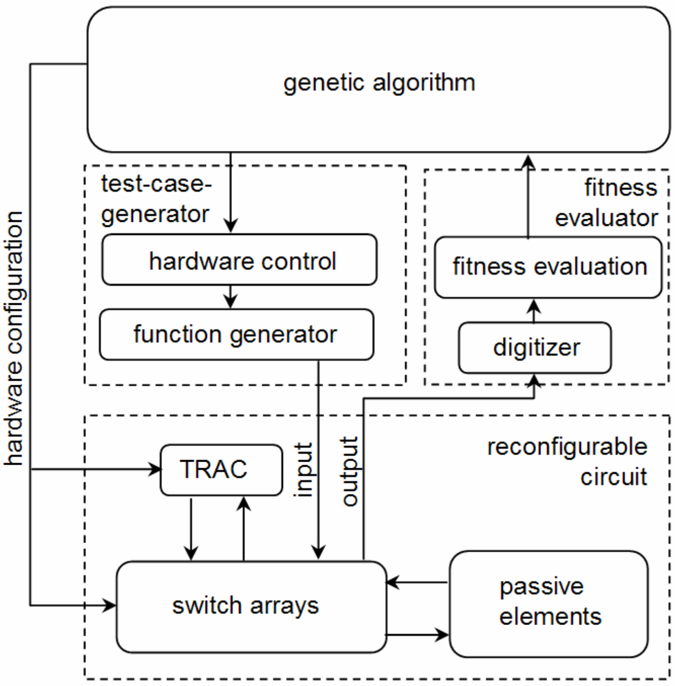

Figure 1: *System representation for automated circuit design using an evolvable hardware approach. TRAC and switch configurations are generated by the genetic algorithm. These configurations are then tested using a sequence of test cases and a fitness assigned to each particular configuration. The fitness is used to select appropriate configurations for ensuing generations of the algorithm.*

Design that explicitly incorporates the full phase space of electronic devices into the standard design methodology is fraught with problems: noise, fabrication margins, and poorly understood interactions between the various physical degrees of freedom of the system, conspire to make a conventional approach difficult. Our approach instead uses reconfigurable hardware, in conjunction with a genetic algorithm (GA) to search for an optimal circuit configuration based on performance evaluated in hardware. In this approach, many of the limitations of traditional design are removed as the algorithm search is based on the input-output performance and can use all degrees of freedom in the system. Our specific goal is to test these ideas by generating an analog-to-digital converter using hardware evolution of a reconfigurable circuit controlled by a GA. The reconfigurable circuit consists of “Totally-Reconfigurable Analog Circuit” chips from Zetex, interfaced with passive circuit elements and each other through switch arrays. Our use of switch arrays in this way is a departure from past work [2], and provides a way to scale the device to much larger levels of complexity. We have been able to demonstrate the operation of our system by realizing an evolved frequency doubler on a standalone TRAC. We are currently working on incorporating switch arrays and digitally programmable passive elements into the system to exploit the larger phase space of the complete reconfigurable circuit.

References:

[1] A. Thompson, “An Evolved Circuit, Intrinsic in Silicon, Entwined with Physics,” in T. Higuch, M. Iwata, W. Liu (eds.) *Proc. Of the 1st Int. Conf. on Evolvable Systems: from Biology to Hardware,* LNCS, vol. 1259, Springer-Verlag, pp. 390-405, 1997.

[2] I. Ozsvald, "Short-Circuiting the Design Process: Evolutionary Algorithms for Circuit Design using Reconfigurable Analogue Hardware," *Masters Thesis*, 1998.

4. Fabrication of Superconducting Nanowire, Single-Photon Detectors

Sponsors:
MIT Lincoln Laboratory

Project Staff:
Joel K.W. Yang, R. Hadfield, G. Gol’tsman, B. Voronov, K.K. Berggren

Sponsorship:
MIT Lincoln Laboratory

Several novel applications have recently emerged that rely on high-speed single-photon detectors (SPDs), for example quantum cryptography. The nanowire SPD consists of a 4-nm-thick, ~ 100-nm-wide, superconducting NbN wire operating at 4.2 K or below. This device detects single photons at 1550-nm wavelength with a detection efficiency (DE) of ~ 5%, which is too low to be of use for most applications. Its proposed GHz-counting rate is several orders of magnitudes faster than has been demonstrated by other types of SPDs to date [1]. The aim of our research is to improve the detection efficiency (DE) of the nanowire SPDs and to make devices capable of GHz-counting rates. Figure 1 shows a scanning electron micrograph (SEM) of a nanowire SPD that consists of closely spaced nanowires in a large-area meander. We are working to improve DE by (1) using thicker and more optically absorptive NbN films; (2) defining even narrower nanowires; (3) improving the linewidth uniformity; (4) increasing the length of the nanowire (and thus the total area of the meander); and (5) identifying and minimizing sources of material damage (such as electro-static discharge, plasma-damage, and thermal damage). We have recently developed a fabrication process using electron-beam lithography and hydrogen-silsesquioxane (HSQ) resist followed by a reactive-ion etch (RIE). This process, combined with an electron-beam proximity-effect correction technique, allows us to fabricate wires 150-μm long and less than 100-nanometer wide with line-width non-uniformity of ~ 5%, covering an area of ~ 25 μm^2 [2]. Figure 2 shows an SEM image of one of the devices we have made using this process that was 25-nm-wide: the narrowest superconducting nanowire ever fabricated for this type of detector.

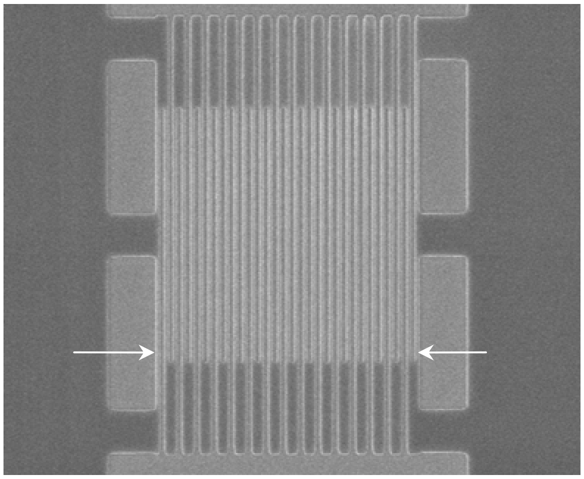

Figure 1: *SEM image showing a superconducting nanowire meander structure with uniform 100-nm-wide linewidths, fabricated using electron-beam lithography.*

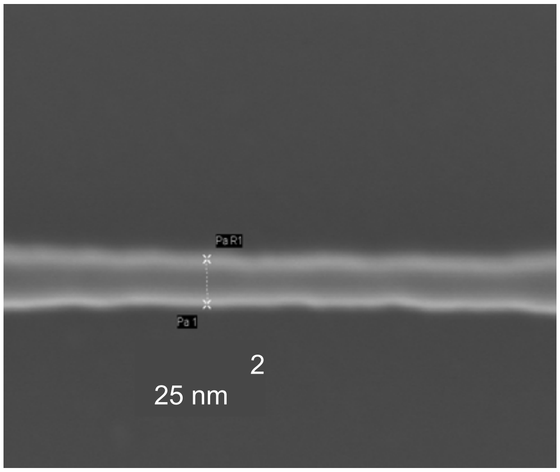

Figure 2: *SEM image of the narrowest superconducting wire that we have fabricated. Narrower wires will have higher detection efficiencies.*

References:

[1] A. Verevkin, A. Pearlman, W. Slysz, J. Zhang, M. Currie, A. Korneev, G. Chulkova, O. Okunev, P. Kouminov, K. Smirnov, B. Voronov, G.N. Gol'tsman, and R. Sobolewski, “Ultrafast superconducting single-photon detectors for near-infrared-wavelength quantum communications,” *Journal of Modern Optics*, v 51, n 9-10, pp. 1447-58, 2004.

[2] Joel.K.W. Yang, E. Dauler, A. Ferri, A. Pearlman, A. Verevkin, G. Gol’tsman, B. Voronov, R. Sobolewski, W.E. Keicher, and K.K. Berggren, “Fabrication development for nanowire GHz-counting-rate, single-photon detectors,” to be published in *IEEE Transactions on Applied Superconductivity*, 2005.

5. An Approach to Realizing Index Enhancement without Absorption for Immersion Lithography

Sponsors:
AFOSR

Project Staff:
V. Anant, M. Rådmark, T. C. Killian, K. K. Berggren

We propose and evaluate a scheme for refractive-index enhancement that achieves the following objectives: (1) an index of refraction much greater than unity in an atomic vapor (~6); and (2) optical amplification rather than absorption of the propagating probe beam. The scheme achieves the first of these objectives by tuning the probe beam close to an atomic resonance, and the second by using an additional incoherent optical pump beam that inverts population between the two levels with which the near-resonant probe beam interacts. This scheme is simple and is shown to be tolerant to temperature-related broadening effects. However, it is susceptible to intensity-related broadening effects, and background noise due to amplified spontaneous emission. Extensions of such a scheme may find applications in the fields of immersion microscopy and immersion photolithography, where the high-index material could replace lower-index immersion-liquids, and also in applications such as all-optical switching, where an optically-controlled refractive index is desirable.

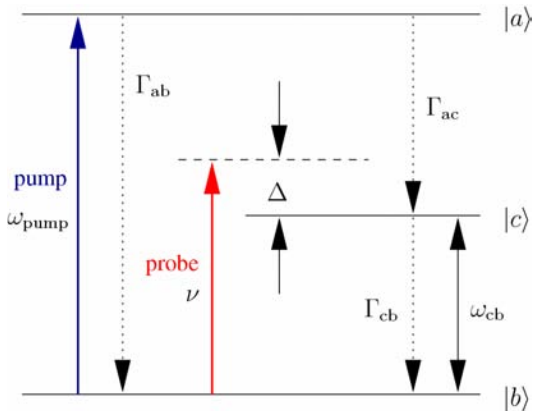

Figure 1: *Energy-level diagram showing incoherent decay rates and driving fields for the index-enhanced medium. A two-level system with ground state Ib> and excited state Ic> interacts with a coherent oscillating electromagnetic probe field at frequency v detuned by Δ from the energy difference (ω_{cb}) between Ic> and Ib>. An incoherent oscillating electromagnetic pump field at frequency ω_{pump}= ω_{ab} promotes population from Ib>to upper lying level Ia>. Ia> is an upper level that decays at rate Γ_{ac} to level Ic>.*

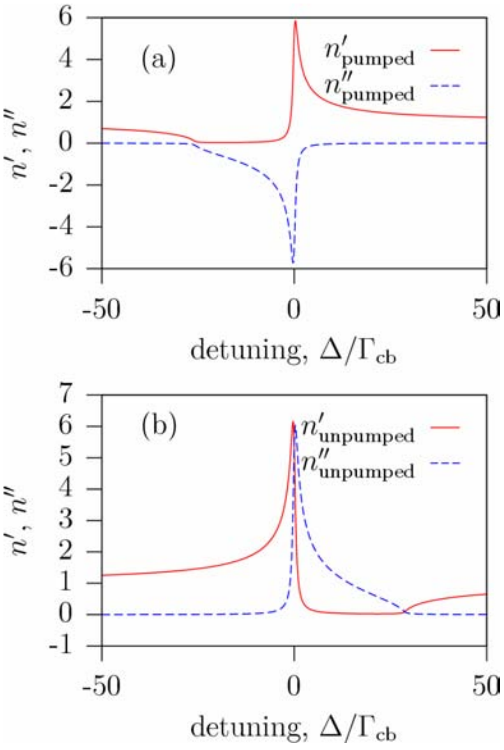

Figure 2: *Plot of the refractive index n' and absorption coefficient n" as a function of Δ for the 4^1S_0 to 4^1P_1 transition in Ca: (a) pumped case, and (b) unpumped case. For the pumped case, we see that n" < 0, resulting in amplification (rather than absorption) of the probe laser. The maximum value of n' occurs slightly off resonance ($n'_{max} \approx 6$ at $\Delta \approx 0.3\ \Gamma_{cb}$).*

References:

[1] V. Anant, M. Rådmark, T. C. Killian, and K. K. Berggren, “Refractive-index enhancement with gain in an atomic vapor.” (Submitted to Journal of Vacuum Science & Technology B.).

Publications

Journal Articles, Published

1. J. K. W. Yang, E. Dauler, A. Ferri, A. Pearlman, A. Verevkin, G. Gol'tsman, B. Voronov, R. Sobolewski, W. E. Keicher, K. K. Berggren, "Fabrication Development for Nanowire GHz-Counting-Rate Single-Photon Detectors,", *IEEE Transactions on Applied Superconductivity* 15: 626-630 (2005).

2. 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: 841-844, (2005).

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4. K. K. Berggren , "Quantum Computing with Superconductors," *Proceedings of the IEEE*, 92: 1630 (2004). Invited Paper.

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