Quantum Nanostructures and Nanofabrication

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

Optical Properties of Superconducting Nanowire Single-photon Detectors

Sponsors:
AFOSR, MIT Lincoln Laboratories, MIT

Project Staff:
V. Anant, A.J. Kerman, J.K.W. Yang, E.A. Dauler, K.M. Rosfjord, K.K. Berggren

High-efficiency single-photon detection requires careful design of the device optics. For superconducting-nanowire single-photon detectors (SNSPDs) [1-3], this challenge is amplified by the complexities of optical propagation in subwavelength structures. We have conducted an initial theoretical study of the optical design issues that must be addressed to achieve efficient absorption of infrared light by SNSPDs. We found that the absorption depends not only on geometrical parameters of the device, but also on the polarization of the incident photon. We are now testing our model by directly measuring the optical absorptance of SNSPDs fabricated at MIT. We will then feed back the testing results to the design process to realize high-efficiency SNSPDs that, by design, are either sensitive or insensitive to incident photon polarization. This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

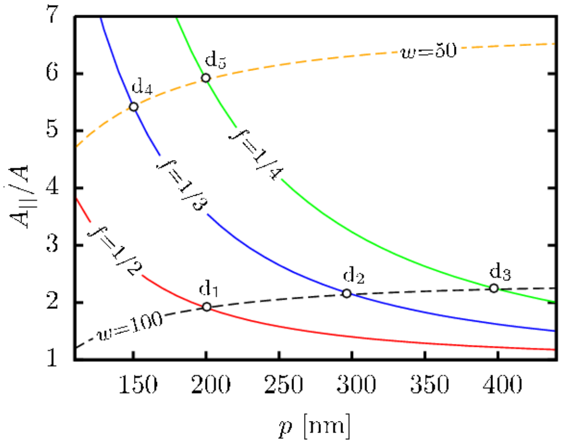

Figure 1: Plot of the predicted ratio of parallel to perpendicular absorptance by the SNSPD as a function of pitch, p, wire width w (given in nm), and fill factor, f=w/p. A maximum sensitivity to polarization occurs when the fill factor and wire width are both small. We fabricated devices that correspond to points d1-d5 shown on this plot in order to test our model.

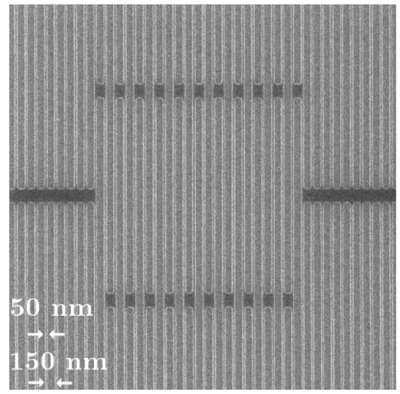

Figure 2: Scanning electron micrograph of device d4, where the wire width was 50 nm and pitch was 150 nm. This device was fabricated using processes described in [1] and tested using the apparatus described in [2] and [3].

References:

[1] J.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," IEEE Transactions on Applied Superconductivity, vol. 15, issue 2, part 1, pp. 626-630, June 2005.

[2] A.J. Kerman, E.A. Dauler, J.K.W. Yang, K.M. Rosfjord, V. Anant, G.N. Gol'tsman, B.M. Voronov, and K.K. Berggren, "Kinetic-inductance-limited reset time of superconducting nanowire photon counters," Appl. Phys. Lett., vol. 88, p. 111116, Mar. 2006.

[3] K.M. Rosfjord, J.K.W. Yang, E.A. Dauler, A.J. Kerman, V. Anant, B.M. Voronov, G.N. Gol'tsman, and K.K. Berggren, "Nanowire single-photon detector with an integrated optical cavity and anti-reflection coating," Optics Express, vol. 14, issue 2, pp. 527-534, Jan. 2006.

2. High-contrast Salty Development of Hydrogen Silsesquioxane

Sponsors:
MIT

Project Staff:
J.K.W. Yang, K.K. Berggren

In electron-beam lithography (EBL), the highest resolution one can achieve depends primarily on the electron-beam spot size and the resist contrast. As the electron-beam spot size is constrained by the type of EBL system used, which is not easily modified, the only practical route to improved patterning resolution is to use resists with better contrast. 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. Recent efforts to increase the contrast of hydrogen silsesquioxane (HSQ) have focused on developing with more concentrated bases [1], and elevating development temperatures [2]. While these strong developers improve contrast, they also can cause material damage and are thus unsuitable in certain situations: for instance, hot or concentrated bases etch Si and hence are not compatible with Si processing.

In this work, we instead increased the contrast of HSQ by adding salt (NaCl) to an aqueous NaOH developer. Figure 1 shows contrast curves of HSQ using different amounts of salt in an aqueous solution of 1% wt NaOH. We noticed that the resist contrast increased with increasing amount of salt. For 4% wt NaCl in 1% wt NaOH, we demonstrated a contrast value of 10 with a 30 kV beam acceleration voltage exposure of a 120-nm-thick resist. This achieved contrast was more than tripple those obtained from development in tetramethyl ammonium hydroxide (TMAH) [1,2]. We also notice that the addition of NaCl increased resist contrast without significant decrease in resist sensitivity. This effect allows one to achieve higher resolution without increasing electron-beam exposure times.

Finally, we studied the effect of development with salt on the fabrication of nanostructures. Figure 2 shows an SEM image of 13-nm-wide HSQ lines in a 30-nm-pitch grating. These gratings were formed by single-pass electron exposure of 50-nm-thick HSQ on Si at 30 kV acceleration voltage in a Raith 150 EBL system, followed by development in an aqueous solution of 1% wt NaOH with 4% wt NaCl for 4 mins. The addition of salt into the developer has enabled us to increase our resolution by roughly a factor of three. In addition to enhancing the contrast of HSQ, these experiments could provide an improved understanding of the developmental mechanism of HSQ.

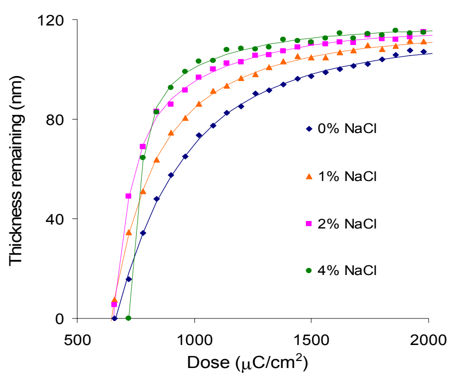

Figure 1: Plot of remaining HSQ thickness vs. area dose for varying amounts of NaCl to aqueous 1% wt NaOH developer. Filled markers are data points while solid lines are fitting curves of exponential functions.

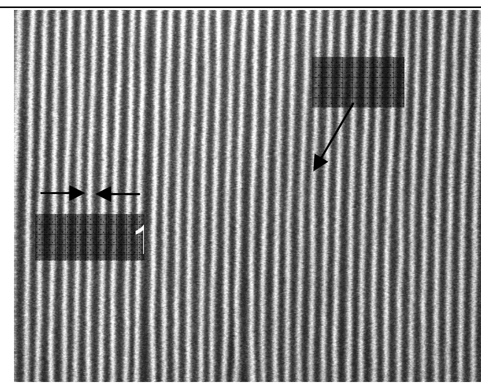

Figure 2: An SEM micrograph of 13-nm-wide HSQ lines in a 30-nm-pitch grating on Si. Lines were exposed at 30 kV acceleration voltage and developed in 4% wt NaCl in 1% wt NaOH.

References:

[1] W. Henschel, Y.M. Georgiev, and H. Kurz, "Study of a high-contrast process for hydrogen silsesquioxane as a negative-tone electron-beam resist," Journal of Vacuum Science & Technology B, vol. 21, pp. 2018-2025, 2003.

[2] Y.F. Chen, H.F. Yang, and Z. Cui, "Effects of developing conditions on the contrast and sensitivity of hydrogen silsesquioxane," Microelectronic Engineering, vol. 83, pp. 1119-1123, 2006.

3. Nodal Oprical Lithography: Breaking the Diffraction Limit

Sponsors:
AFOSR, MIT

Project Staff:
D. Winston, A. Chao, K. Rosfjord, S. Kooi, K.K. Berggren

We propose to use the quantum-optical properties of materials to achieve super-resolution in optical lithography. By using beams of light instead of electrons, we can avoid substrate damage, use more intense fields that can write faster, and write with multiple beams simultaneously. By optically gating the photochemistry in the resist, we can squeeze the point-spread function of the resist exposure caused by the patterning pulse and thereby achieve sub-diffraction nanopatterning.

Resolution improvement in lithographic systems using the optical field nodes has already been demonstrated using nonlinear optical processes in neutral atoms [1]. The process used atoms in excited states and then de-excited the atoms before they were able to use their absorbed energy to stimulate a reaction. In the case of a photoresist, as was recently proposed [2], the goal is to de-excite the photo-initiating species before it can generate free radicals (Figure 1) and facilitate polymerization/crosslinking (in the case of negative-tone resist) or chain scission (in the case of positive-tone resist).

Arbitrary, dense patterning may be achieved using two synchronized laser pulses, the second of which is patterned so that it has at least one point of zero intensity, and a negative-tone resist with an appropriate photo-initiating species (Figure 2). Because the nodes – the points of zero intensity – in the second pulse determine the pattern transferred to the resist, we call this technique "nodal lithography." Increasing the intensity of the second pulse will "squeeze" the resulting pattern because even as pulse intensity rises, nodes remain nodes; herein lies the potential for diffraction-unlimited patterning.

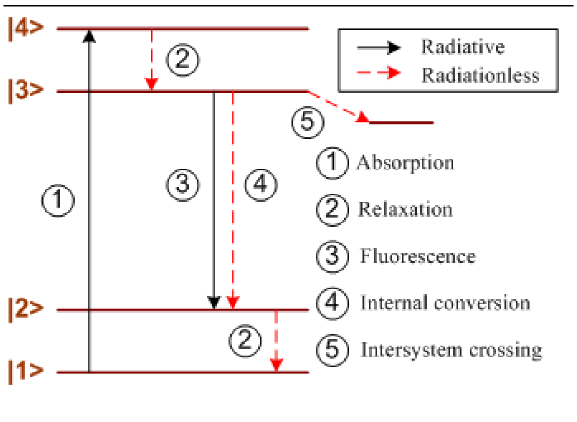

Figure 1: Energy-level diagram that models a few of the photophysical transitions, both radiative and radiationless, that a fluorescent molecule can undergo upon absorption of light. Following absorption, chemical reactions will occur after intersystem crossing. Optical de-excitation would induce fluorescence before intersystem crossing, thus deactivating the resist and enabling a tighter point spread function for higher-contrast features.

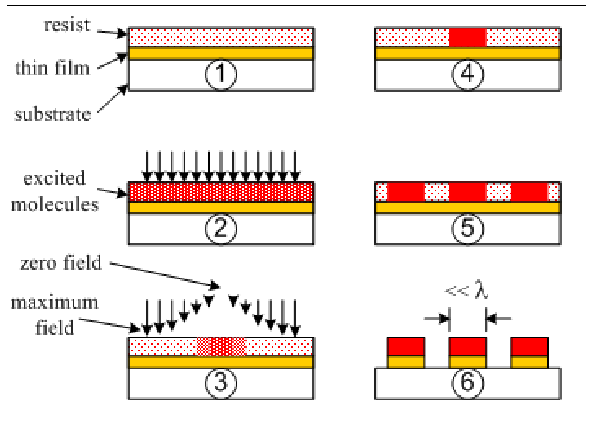

Figure 2: Exposure sequence for nodal lithography with a single node: (1) a photolabile (resist) material is put on top of a film to be patterned; (2) the resist is excited uniformly, rendering it reactive; (3) the resist is selectively quenched by a patterned light; (4) the molecules near the node, which were not quenched in step (3), react; (5) the substrate is translated relative to the radiation and steps (2)-(4) are repeated to form an arbitrary pattern; (6) the resulting pattern is developed and then transferred to the underlying film using a chemical or physical etching process.

References:

[1] K.S. Johnson, J.H. Thywissen, N.H. Dekker, K.K. Berggren, A.P. Chu, R. Younkin, and M. Prentiss, "Localization of metastable atom beams with optical standing waves: nanolithography at the Heisenberg limit," Science, vol. 280, no. 5369, pp. 1583-6, June 1998.

[2] S.W. Hell, "Strategy for far-field optical imaging and writing without diffraction limit," Physics Letters A, vol. 326, no. 1-2, pp. 140-5, May 2004

4. Characterization of Nondegenerate Spontaneous Parametric Downconversion Photon-pair Sources Using a Superconducting Nanowite Single-photon Detector

Sponsors:
DTO, DARPA, MIT, and AFOSR

Project Staff:
X. Hu, A.J. Kerman, E. Dauler, J.K.W. Yang, V. Anant, F.N.C. Wong, K.K. Berggren

As a basis of many quantum information processing applications, photon pairs can be generated efficiently by spontaneous parametric downconversion (SPDC) in a periodically poled lithium niobate (PPLN) crystal. For instance, pumped by a 532-nm laser source, the PPLN downconverter can efficiently yield nondegenerate photon pairs, a signal photon at ~800 nm and an idler photon at ~1600 nm [1]. To measure the efficiency of this process, we perform signal-idler coincidence measurements (Figure 1), which require high-efficiency, low dark-count-rate photon counters at those two wavelengths. To detect the signal photon at ~800 nm, a Si photon counter with efficiency about 50% is commercially available; however, to detect the idler photon at ~1600 nm, a commercial InGaAs avalanche photodiode (APD) can only achieve 20% detection efficiency.

We have instead fabricated a superconducting nanowire single-photon detector (SNSPD) to count the idler photons. Compared with the InGaAs APD, we have demonstrated that our SNSPD can achieve device detection efficiency as high as over 50% at near-infrared wavelengths [2]. Furthermore, to minimize the possible optical coupling loss from fiber to the SNSPD, we have designed an experimental setup to do optical coupling and helium-immersion SNSPD testing inside a dewar (Figure 2). We use a fiber focuser to shrink the mode size of the light down to 5-6 μm and a nanopositioner to further maximize the overlap of the optical mode and the SNSPD. Our preliminary calculation shows that our SNSPD can achieve ~50% system detection efficiency.

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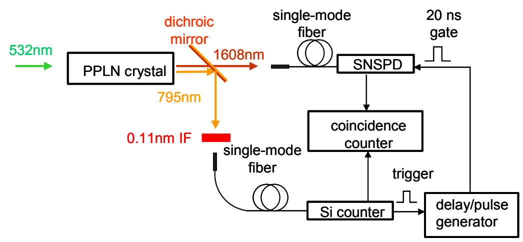

Figure 1: Schematic for photon-pair generation and the signal-idler coincidence measurements.

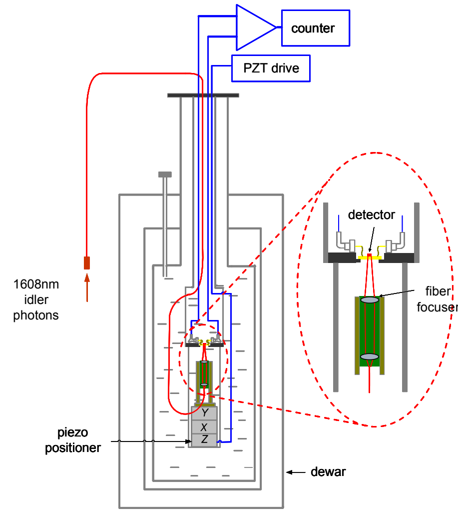

Figure 2: Schematic for helium-immersion testing of superconducting nanowire single-photon detectors.

References:

[1] E.J. Mason, M.A. Albota, F. König, and F.N.C. Wong, "Efficient generation of tunable photon pairs at 0.8 and 1.6 µm," Optics Letters, vol. 27, no. 23, pp. 2115-2117, Dec. 2002.

K.M. Rosfjord, J.K.W. Yang, E.A. Dauler, A.J. Kerman, V. Anant, B.M. Voronov, G.N. Gol'tsman, and K.K. Berggren, "Nanowire single-photon detector with an integrated optical cavity and anti-reflection coating," Optics Express, vol. 14, no. 2, pp. 527-534, Jan. 2006.

5. Templated Self-assembly of Sub- 10nm Quantum Dots

Sponsors:
MARCO MSD

Project Staff:
J. Leu, B. Cord, P. Anikeeya, M. Bawendi, V. Bulovic, K.K. Berggren

Suspended shadow-mask evaporation is a simple, robust technique for fabricating Josephson junctions using electron-beam lithography. The basic process entails the fabrication of an undercut structure in a resist bilayer to form a suspended “bridge,” followed by two angle-evaporations of superconducting material with a brief oxidation step in between, resulting in two overlapping wires separated by a thin oxide layer. Josephson junctions with sub-20-nm diameters are of particular interest in a variety of superconductive devices, including quantum bits. Unfortunately, standard shadow-mask fabrication techniques are unreliable at linewidths below 100 nm, requiring the development of a novel process for the fabrication of nanoscale Josephson junctions.

While most previous processes used PMMA for the top (imaging) layer and a PMMA/MAA copolymer for the bottom (support) layer, our process uses a PMMA/PMGI bilayer. This resist system allows the two layers to be developed separately, ensuring that the imaging layer is not biased during development of the undercut and allowing the process to achieve the full resolution of the PMMA layer (fig. 2). Additionally, the extent of the undercut in the support layer can be precisely controlled by defining it lithographically, making it possible to repeatably fabricate undercut regions as large as 600 nm.

Extensive modeling of both the exposure and development processes was used to verify our results. Using Monte Carlo and mass transfer simulations, we were able to produce a model that closely matches experimental data. With the process fully characterized, it is possible to produce a wide range of linewidth/undercut combinations. This robustness, combined with the high resolution of PMMA, will allow the reliable fabrication of sub-20-nm Josephson junctions.

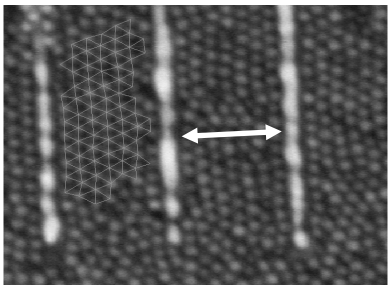

Figure 1: Scanning electron micrograph of a self-assembled quantum dot monolayer on a templated silicon substrate. The vertical lines are part of a template grating, with 10-nm-wide, 80-nm-tall Au lines at a pitch of 80 nm. The spheres are organically capped 8-nm CdZnS semiconducting quantum dots. Shown superimposed on the image is a wire grid indicating the adjacency relations of a well-ordered aggregate.

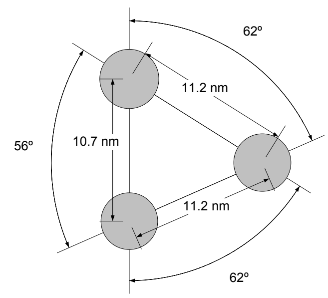

Figure 2: The averaged center-to-center distances and orientation of the quantum dot aggregate highlighted in Figure 1. The direction of tensile strain is perpendicular to the grating lines.

References:

[1] Y. Yin, Y. Lu, B. Gates, and Y. Xia, “Template-assisted self-assembly: A practical route to complex aggregates of mondispersed colloids with well-defined sizes, shapes, and structures,” J. Am. Chem. Soc., vol. 123, pp. 8718-8729, 2001.

[2] J.A. Liddle, Y. Cui, and P. Alivisatos, “Lithographically directed self-assembly of nanostructures,” J. Vac. Sci. Technol. B., vol. 22, no. 6, pp. 3409-3414, Nov./Dec. 2004.

6. Achieving Photon-number-resolution Using Multi-element Superconducting Photodetectors

Sponsors:
United States Air Force

Project Staff:
E. Dauler, A.J. Kerman, B. Robinson, V. Anant, K. Rosfjord, J.K.W. Yang, K.K. Berggren

We demonstrate an approach for combining multiple, independent, superconducting nanowire, single-photon detectors to create a high-speed, high-efficiency detector that can resolve photon number. Optical loss in distributing the light between the elements is eliminated by fabricating a detector array with an active area identical to a single device. The scanning-electron-microscope image shown in Figure 1 illustrates one approach for subdividing a ~10 μm × 10 μm active area into four independent elements. This interleaved arrangement ensures that the light will uniformly illuminate all four elements. The fabrication [2] consists of an optical lithography and liftoff process to fabricate metal contact pads and an electron-beam lithography and reactive-ion-etching process to pattern the superconducting nanowires. The additional grating features that are not electrically connected to the detector elements are used to eliminate proximity effects in the electron-beam exposure.

To achieve high-speed photon-number-resolution, the outputs from the independent elements would typically be combined digitally, but to better illustrate the detector's photon-number resolving capabilities, we have chosen to add the analog output signals. A two-element SNSPD was illuminated with attenuated, picosecond laser-pulses and the peak voltage of the summed output was measured. A representative histogram of the measured peak voltages is shown in the inset of Figure 2. It is clear that, even with the two output pulses summed, thresholds between zero, one, and two detection events can be easily selected. The probability of each of these cases can then be measured as a function of the light intensity; Figure 2 shows these probabilities, along with calculated probabilities for the 2-element detector and an ideal photon-number-resolving detector. This approach allows the number of photons to be measured over a wide range of attenuation with a factor of ≤ 2 error due to using only two elements.

This work is sponsored in part by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

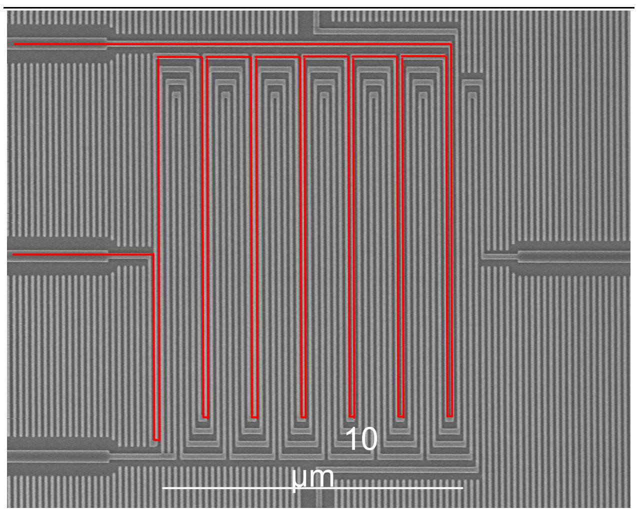

Figure 1: Scanning-electron-microscope micrograph of a 4-element device with an overlaid red curve highlighting one of the four independently biased and read-out detector elements.

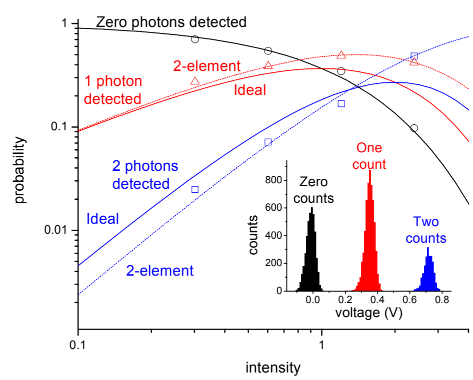

Figure 2: Measured and calculated probabilities of zero, one, and two counts with an inset showing the histogram of peak voltages, colored to indicate the regions contributing to the measured probabilities.

References:

[1] E.A. Dauler, B.S. Robinson, A.J. Kerman, J.K.W. Yang, K.M. Rosfjord, V. Anant, B. Voronov, G. Gol'tsman, and K.K. Berggren, IEEE Trans. Appl. Supercond., to be published.

[2] 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 Trans. Appl. Supercond., vol. 15, pp. 626-620, Jun. 2005.

7. Scanning Helium Ion Beam Lithography

Sponsors:
AFOSR, NRI

Project Staff:
B. Cord, M.K. Mondol, K.K. Berggren, L.A. Stern (Karl Zeiss SMT, Peabody, MA)

Scanning electron beam lithography (SEBL) has been the leading technology in low-volume, high-resolution nanofabrication for over three decades. Unfortunately inherent limitations of the technology, such as electron beam scattering, have made improvement in SEBL resolution past the 10-nanometer limit problematic. Recent advances in resist contrast enhancement have mitigated this somewhat, but reliable patterning of dense, sub-10-nm features remains nontrivial on even the most high-end SEBL tools.

One of the key advantages of patterning using a helium ion, rather than an electron beam, is the substantial reduction in beam scattering as it travels through the resist. Helium ions, with a comparatively higher mass, are affected much less by atomic collisions when traveling through a material and exhibit only minimal scattering in normal resist materials. Figure 1 shows the results of a Monte Carlo simulation of a 50 KeV helium ion beam traveling through a PMMA layer; at a depth of 50 nm (a typical resist thickness for many applications), the point-spread function of the beam is only 2 nm wide, narrower than even 100 KeV electron beams under similar conditions. This reduction in beam scattering should help reduce the proximity effect that makes patterning dense, high-resolution features difficult with SEBL.

Experimentation with helium ion beam lithography has recently been made possible by the development of a scanning helium ion beam microscope by Alis Corporation [1]. Their commercial-grade microscope has achieved imaging resolutions on the order of 1 nm, making it a promising candidate as a lithography tool. Basic experimentation with their lower-resolution "proof-of-concept" system has demonstrated that patterning and successful transfer of features is possible using standard SEBL processes. Figure 2 shows a field of Ti-Au dots patterned with the system using a film of PMMA on silicon and standard metallization and liftoff.

While issues such as vibration, pattern generation, and process control remain to be addressed, further experimentation with helium ion beam lithography may lead to a tool that meets or exceeds the performance of modern SEBL systems.

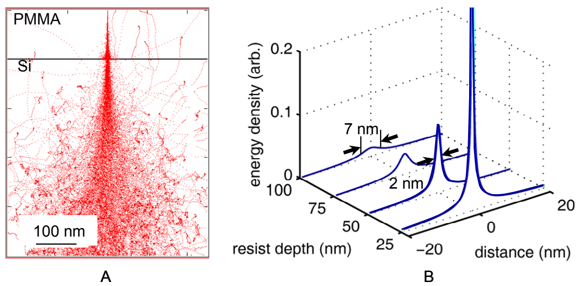

Figure 1: Simulation of He ion scattering in resist. (a) Result of SRIM-based Monte Carlo simulation of ion-scattering for 50 keV He ions traveling through 100 nm of PMMA into a Si substrate (b) Analysis of the data from (a) showing how the distribution of deposited energy widens as a function of resist depth. After 50 nm of resist (a practical thickness to work with), the beam width is only 2 nm. Note that this model does not take secondary electrons generated by the ion beam into account, as the details of the ion-secondary electron interactions are not yet fully understood.

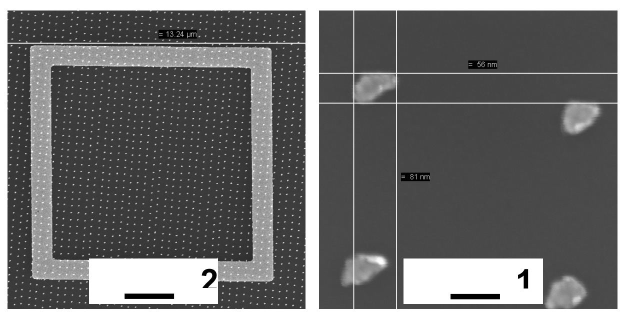

Figure 2: Scanning electron micrographs of a field of Ti-Au dots at two magnifications, fabricated by exposing 90 nm PMMA on a Si substrate to a single raster-scan of a helium ion beam and performing metal evaporation and liftoff on the resulting pattern. The consistently irregular dot shape in (b) is thought to be the result of vibrations in the system. The large square in (a) is a previously-fabricated fiducial mark.

References:

[1] B.W. Ward, J.A. Notte, N.P. Economou, “Helium ion microscope: A new tool for nanoscale microscopy and metrology,” J. Vac. Sci. Technology B, vol. 24, issue 6, pp. 2871-2874, Nov. 2006.

8. Scanning-Electron-Beam Lithography (SEBL) Facility

Sponsors:
MIT Institute facility under RLE

Project Staff:
Mark K. Mondol, Dr. Feng Zhang, Prof. Henry I. Smith, Prof. Karl Berggren

In 2004, the Nanostructures Lab converted its scanning-electron-beam-lithography (SEBL) facility in Room 38-165 into an Institute-wide service facility under the Research Laboratory of Electronics (RLE). This facility provides MIT and outside users with easily accessible e-beam lithography, coupled with resident expertise and advice. The facility is managed by Mark Mondol who provides training on the e-beam tools, direct patterning service, and advice on optimal nanofabrication techniques and strategies. The NanoStructures Laboratory (NSL) and the Microsystems Technology Laboratories (MTL) have service facilities for spin coating of resists, resist development and other forms of processing.

Projects that made use of the SEBL facility during the past year included: patterned nanotube growth; relief templates for self assembly of block copolymers; point-contact devices; 1-D and 2-D photonic crystals; ring-resonator add/drop filters; optical-polarization splitter-rotator devices; novel liquid-crystal devices; magnetic-memory devices; quantum photodetectors; templates for nanoimprint lithography; photomasks for interferometric-spatial-phase-imaging alignment and gapping; 4-point contacts for measurements on nanotubes and nanowires; III-V compound T-gate HEMTs and arrays of Fresnel zone plates. Research in lithographic processing included extreme cold development of PMMA and novel developer solutions for HSQ which demonstrated improved resolution and contrast. Use of the facility, by the MIT community, was widespread, there were: 25 Principal Investigators, 7 Departments, 8 Labs or Centers, 2 non-MIT entities and 45 distinct trained users over the last year.

Two SEBL tools are available. The Raith Turnkey 150 system is shown in Figure 1. Its electron-optical column is essentially identical to that of a Zeiss Gemini SEM, and provides a beam diameter as fine as 2 nm. Linewidths of ≤ 9 nm have been written with the system, as illustrated in Figure 2. The Raith 150 includes a pattern generator and laser-interferometer-controlled stage with an integrated software package which was upgraded to version 4.0 in the past year. This upgrade improved writing speed and system stability. Version 4.0 software now allows users to do automated field alignment to approximately ± 25nm. The system can operate from 1 to 30keV accelerating voltage. Wafers up to 150 mm can be loaded into the system. Typically, users are trained for 3 to 10 hours and then allowed to operate the tool on their own. The tool is available, for most users, 24 hours a day, 7 days a week.

Figure 3 is a photograph of the VS-26 system. This instrument was put together at MIT from two systems (VS-2A and VS-6) obtained as gifts from IBM in the mid 1990's. VS-26 has a minimum beam diameter of about 10 nm. It operates at a fixed accelerating voltage of 50keV. Conversion software has been developed which allows a CAD data file to be fractured and translated prior to exposure, additional software was developed to generate arbitrary arcs. Substrates up to 200 mm diameter can be exposed at linewidths down to ~30 nm. However, the area available for patterning is limited to 95x95 mm.

The Raith 150 is used in a program to develop spatial-phase-locked e-beam lithography, described elsewhere. The objectives of that program are to achieve sub-1 nm pattern-placement accuracy, and to reduce the cost and complexity of SEBL. In a conventional SEBL system costing several million dollars, pattern placement accuracy is typically much worse than 10 nm.

The SEBL facility encourages users with a variety of experience levels and requirements. Experienced users are able to carry out complex, multilevel aligned exposures on the Raith-150 tool. Less experienced users get hands-on instructions from facility staff, and guidance during the learning and initial fabrication stages.

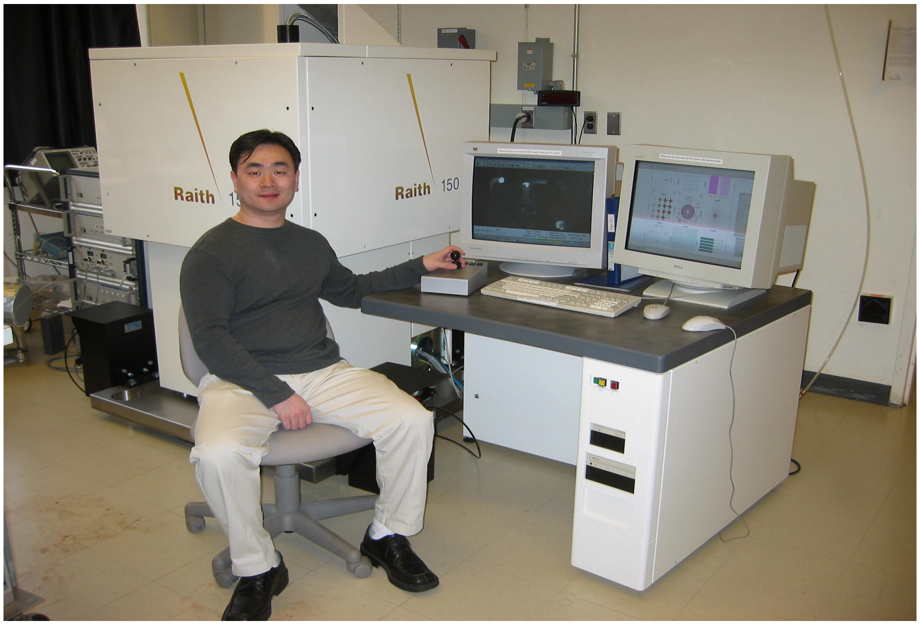

Figure 1. *The Raith-150 electron-beam lithography system. This tool provides sub-20-nm patterning resolution, and pattern-placement accuracy ~ 1nm via spatial phase locking. The operator is Dr. Feng Zhang.*

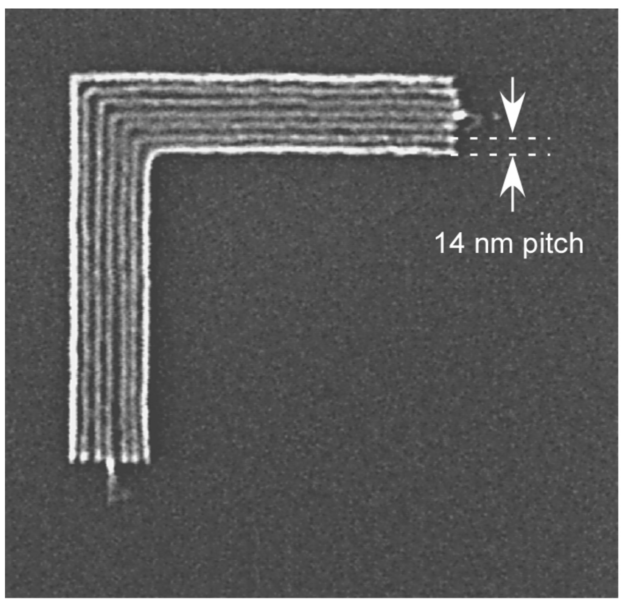

Figure 2: *Scanning-electron micrograph of exposed and developed HSQ illustrating the resolution of the Raith 150 SEBL system. (J. K. W. Yang and K. K. Berggren, "Using High-Contrast Salty Development of Hydrogen Silsesquioxane for Sub-10-nm-Half-Pitch Lithography," Journal of Vacuum Science & Technology B, submitted for publication (2007)*

Figure 3. *Photograph of the VS-26 scanning-electron-beam lithography system.*

Publications

Journal Articles, Published

1. S.O. Valenzuela, W.D. Oliver, D.M. Berns, K.K. Berggren, L.S. Levitov, T.P. Orlando, "Microwave-Induced Cooling of a Superconducting Qubit," *Science,* 314 (5805), 1589-1592, December 2006.

2. Joel K.W. Yang, Vikas Anant, K.K. Berggren, "Enhancing etch resistance of hydrogen silsesquioxane via postdevelop electron curing," *Journal of Vacuum Science and Technology B,* 24 (6), 3157-3161, November 2006.

3. B. Cord, C. Dames, K.K. Berggren, and J. Aumentado, "Robust shadow-mask evaporation via lithographically controlled undercut," *Journal of Vacuum Science and Technology B*, 24 (6), *3139*-3143, November *2006*.

4. Eric A. Dauler, Bryan S. Robinson, Andrew J. Kerman, Vikas Anant, Richard J. Barron, Karl K. Berggren, David O. Caplan, John J. Carney, Scott A. Hamilton, Kristine M. Rosfjord, Mark L. Stevens, Joel K. Yang, "1.25 Gbit/s photon-counting optical communications using a two-element superconducting nanowire single photon detector," *Proc. SPIE,* Vol. 6372*, Advanced Photon Counting Techniques;* Wolfgang Becker; Ed., Oct. 2006.

5. D. M. Berns, W. D. Oliver, S. O. Valenzuela, A. V. Shytov, K. K. Berggren, L. S. Levitov, and T. P. Orlando, "Coherent Quasiclassical Dynamics of a Persistent Current Qubit," *Physical Review Letters,* 97 (15), 150502, October 2006.

6. K.K. Berggren and A.J. Kerman, “Nanowires detect individual infrared photons,” *Laser Focus World,* 42 (9), 87-89, September 2006.

7. A.J. Kerman, E.A. Dauler, B.S. Robinson, R. Barron, D.O. Caplan, M.L. Stevens, J.J. Carney, S.A. Hamilton, W.E. Keicher, J.K.W. Yang, K. Rosfjord, V. Anant, and K.K. Berggren, “Superconducting Nanowire Photon-Counting Detectors for Optical Communications,” *Lincoln Laboratory Journal*, 16 (1), 217-224, 2006.

8. Andrew J. Kerman, Eric A. Dauler, William E. Keicher, Joel K. W. Yang, Karl K. Berggren, G. Gol'tsman, and B. Voronov, “Kinetic-inductance-limited reset time of superconducting nanowire photon counters,” *Applied Physics Letters*, 88 (11), 111116, March 2006.

9. Bryan S. Robinson, Andrew J. Kerman, Eric A. Dauler, Richard J. Barron, David O. Caplan, Mark L. Stevens, John J. Carney, and Scott A. Hamilton, Joel K. W. Yang, and Karl K. Berggren, “781-Mbit/s photon-counting optical communications using a superconducting nanowire detector,” *Optics Letters ,* 31 (4), 444-446, February 2006.

10. K. M. Rosfjord, J. K. W. Yang, E. A. Dauler, A. J. Kerman, V. Anant, B. Voronov, G. N. Gol’tsman, K. K. Berggren, “Nanowire Single-Photon Detector with an Integrated Optical Cavity and Anti-Reflection Coating” *Optics Express,*14 (2), 527-34, January 2006.