Nanostructures Technology, Research and Applications

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1. Nanostructures Laboratory

The Nanostructures Laboratory (NSL) at MIT develops techniques for fabricating surface structures with feature sizes in the range from nanometers to micrometers, and uses these structures in a variety of research projects. The NSL is closely coupled to the Space Nanotechnology Laboratory (SNL) with which it shares facilities and a variety of joint programs. The NSL and SNL include facilities for lithography (photo, interferometric, electron-beam, and x-ray), etching (chemical, plasma and reactive-ion), liftoff, electroplating, sputter deposition, and e-beam evaporation. Much of the equipment, and nearly all of the methods, utilized in the NSL/SNL are developed in house. Generally, commercial processing equipment, designed for the semiconductor industry, cannot achieve the resolution needed for nanofabrication, is inordinately expensive, and lacks the required flexibility for our research. The research projects within the NSL/SNL fall into three major categories: (1) development of nanostructure fabrication technology; (2) short-channel semiconductor devices, nanomagnetics and microphotonics; (3) periodic structures for x-ray optics, spectroscopy, atomic interferometry and nanometer metrology.

2. Scanning-Electron-Beam Lithography

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Figure 1 is a photograph of the scanning-electron-beam lithography system (VS-2A) located in the scanning-electron-beam lithography (SEBL) facility, Room 38-165. This instrument was obtained as a donation from IBM in 1993. Its digital pattern generator is based on a commercial high-performance array processor, which uses dual RISC processors. The system is capable of creating large-area patterns composed of multiple stitched fields. Conversion software has been
developed which allows a CAD data file to be fractured and translated prior to exposure by the electron-beam tool.

The VS-2A can expose substrates up to 20 cm diameter, at linewidths down to 70 nm. The goals of the SEBL facility are to: (1) provide the MIT research community with an in-house SEBL capability for writing directly on experimental device substrates; (2) advance the state-of-the-art in SEBL, particularly with regards to pattern placement accuracy and long-range spatial-phase coherence; and (3) pattern x-ray nanolithography masks for in-house use. In order to write concentric circular patterns, such as Fresnel zone plates, software was developed to generate arbitrary arcs of an annulus with user-specified start and finish radii and angles.

The VS2A is heavily used in a variety of projects, both mask making and direct write. These have included: 3-D, 2-D, and 1-D photonic bandgap structures; optical-communication filters; arrays of Fresnel zone plates; electrical contacts to bismuth nanowires; high-density magnetic nanodots for information storage; distributed-feedback lasers; sub-100 nm electronic devices; dual-gate sub-100nm MOSFETs; diffractive optical elements; and magnetic random access memory devices. Masks have been made for x-ray nanolithography and intimate-contact photolithography.

VS-2A is also used extensively in experiments on spatial-phase-locked e-beam lithography, in a program aimed at achieving nanometer-level pattern placement accuracy. A new method for high-precision measurement of interfield stitching errors was also developed based on a modified moiré technique.

The scanning-electron-beam lithography facilities of the NSL has been augmented with the acquisition of a Raith Turnkey 150. This system features a beam diameter as fine as 5nm. Feature sizes down to 17nm have been achieved. The primary utilization of the Raith system will be in a program to develop spatial-phase-locked e-beam lithography (SPLEBL).

Figure 1. Photograph of the VS-2A scanning-electron-beam lithography system. The operator is Research Specialist Mark Mondol.
3. **Spatial-Phase-Locked Electron-Beam Lithography**

**Sponsors**

U.S. Army Research Office  
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**Project Staff**

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Spatial-phase-locked electron-beam lithography (SPLEBL) promises to reduce pattern-placement errors in electron-beam-lithography systems to the nanometer level. Such high precision is essential for a variety of future lithographic applications. SPLEBL is currently the only approach capable of achieving such accuracy. In SPLEBL, a low-level, periodic signal, derived from the interaction of the scanning e-beam with a fiducial grid on the substrate, is used to continuously track the position of the e-beam while patterns are being written. Any deviation of the beam from its intended location on the substrate is sensed, and corrections are fed back to the beam-control electronics to cancel errors in the beam’s position. In this manner, the locations of patterns are directly registered to the fiducial grid on the substrate.

Considerable effort has been devoted to the installation and testing of a Raith-150 electron-beam lithography (EBL) system, a new tool which provides sub-20-nm patterning resolution. A systematic study of fluorescent polymers has been carried out to identify suitable polymers for patterning a scintillating fiducial grid. Also, a bench-top electron-beam test column has been operated with electrostatic lenses, and is undergoing further modifications for the installation of a high-speed electron-beam dose modulator.

Figure 2 shows a Raith-150 EBL system, a sub-20-nm-resolution, nanometer-placement-accuracy tool which was purchased for the SPLEBL research. This system has been used to pattern 18-nm holes, 17-nm gates, and 42-nm-pitch gratings. After installation at MIT, the field-stitching accuracy and pattern overlay accuracy were measured to be 21 nm and 27 nm respectively, where both values are mean plus 2σ. Subsequent experiments have been carried out to measure the tool’s intrafield distortion, and initial results indicated systematic distortion, about 20 nm in magnitude, near two field boundaries. We are currently evaluating methods to eliminate this distortion. Software for the sparse-sampling mode of SPLEBL (details reported last year) has been transferred to the Raith system. This software will be tested on the system once a sensitive photodetection system is installed in the tool’s vacuum chamber. The photodetector consists of an optical light-collection assembly and an external photomultiplier tube. This will be used to detect a faint optical signal from the scintillating fiducial grid. With SPLEBL, the patterning accuracy and resolution of the Raith tool will be unmatched.

Significant work has also been carried out to improve the quality of the scintillating fiducial grid. Drawing on the extensive literature concerning scintillating detectors used in particle physics, and through our collaboration with Professor Swager of the Chemistry Department, we have identified and tested over thirty different scintillating systems. The best of these with regard to brightness, process compatibility, high contrast patternability (quenchability) via UV interference lithography, and resistance to damage by the electron beam, have been retained for further testing and modification. In general the systems contain a methyl or dimethyl styrene polymer as the base, along with a strong scintillator (anthracene with naphthalene, or p-terphenyl) for the primary
emission source, and an efficient secondary scintillator (POPOP) to act as a wavelength shifter to match to the SPLEBL detector. An example system, along with the energy pathway, is illustrated in Figure 3. The scintillator and polymer are dissolved in chlorobenzene and spun onto the wafer, and patterned with UV interference lithography. Future scintillation work will investigate the use of additives and additional bleaching layers to improve the scintillator’s UV-quenching contrast.

Initial electron-emission tests were carried out in the bench-top electron-beam column. A tungsten filament was used as the electron source, and an electrostatic lens was incorporated into the column. The electron beam was colimated with the electrostatic lens and two beam-line apertures. The e-beam was viewed on a phosphor screen, and the current was measured to be over 100 nA at maximum voltage settings. The acceleration voltage used was 5 kV. After introducing the quadra-deflector plates into the beam line, the e-beam was severely perturbed. This was due to charging of insulators supporting the deflectors. The deflector is currently being modified, and a numerical simulation is being developed to trace the electron paths through the deflection apparatus. The simulation will provide information about beam-shape distortions, deflection magnitude, and chromatic aberrations introduced by the deflection apparatus.

In the next phase of this program, the sparse-sampling SPLEBL algorithm will be fully integrated into the Raith-150 system, and tested using our most recently developed scintillating polymer and photomultiplier detector. We expect pattern-placement errors to be reduced to less than 5 nm, mean plus sigma, in this demonstration of SPLEBL. We will also begin to investigate real-time modes of SPLEBL on the Raith system.

Figure 2. The Raith-150 electron-beam lithography system. This tool provides sub-20-nm patterning resolution, and will be used to demonstrate nanometer pattern-placement accuracy via spatial phase locking.
Polystyrene Base (87%wt) absorbs most of the energy from the incident electrons

Naphthalene (8%wt) enhances the non-radiative energy transfer from the Polystyrene to the Anthracene

POPOP (2.5%wt) absorbs light from Anthracene and emits light at the wavelength of our detector

Anthracene (2.5%wt) is the primary scintillator

Figure 3. Example scintillating system with polystyrene as the base, anthracene as the primary scintillator, and POPOP as the wavelength shifter. Naphthalene is an energy-transfer-enhancing additive. The polystyrene absorbs most of the energy from the incident electrons, and the energy is passed along as indicated.

4. X-Ray Nanolithography

Sponsors


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For several years, we have been developing the tools and methods of x-ray nanolithography. We have explored the theoretical and practical limitations, and endeavored to make its various components (e.g. mask-making, resists, electroplating, sources, alignment, etc.) reliable and “user-friendly.” Because of the critical importance of x-ray mask technology, we discuss this in a separate section.

Our sources for x-ray nanolithography are simple, low-cost electron-bombardment targets. We utilize the L line of copper at $\lambda = 1.32$ nm. The sources are separated by a 1.5 $\mu$m-thick SiNx vacuum window from a helium-filled exposure chamber. In the future, we hope to replace the CuL sources with a higher-flux plasma-focus source.

In earlier research, we showed that for wavelengths longer than 0.8 nm, the important limit on resolution is diffraction in the gap between mask and substrate. With a CuL source, a 50 nm feature must be exposed at a mask-to-substrate gap of less than about 4 $\mu$m in order to maintain good process latitude. A 25 nm feature would require a gap of 1 $\mu$m. For very small features, we eliminate the gap and use contact between the substrate and the flexible membrane mask. This
technique has enabled us to replicate features as small as 20 nm in a practical, reproducible way. Figure 4 shows scanning electron micrographs of device patterns with feature sizes less than 40 nm.

To create the x-ray masks, the pattern is first written by electron-beam lithography onto an x-ray “mother” mask, using either one of our two in-house e-beam system. The e-beam written pattern is developed, and gold is electroplated into the resist mold. A negative replica, or “daughter” mask is created by exposing with the mother mask using soft-contact x-ray nanolithography. Finally, the daughter mask is exposed onto the device substrate.

We have investigated process latitude at these extremely fine feature sizes. Figure 5 shows how developed linewidth changes for up to 50% overdevelopment (i.e. developing for 50% longer than it takes for the feature to clear) as a function of linewidth. As can be seen from the plot, the measured feature on the substrate remains within a +/- 10% process window (within the accuracy of the measurement) for isolated features as small as 30 nm and for dense features (greater than 1:3 line:space ratio) as small as 45 nm. This data indicates that soft-contact x-ray lithography is extremely robust and offers very wide process latitude.

Figure 4. Scanning electron micrographs of device patterns with feature sizes less than 40 nm achieved by x-ray nanolithography followed by liftoff. The x-ray mask is shown on top and the lifted-off pattern is on the bottom.
Figure 5. Plot of linewidth variation from nominal (i.e. developed for the time required to clear features) for up to 50% overdevelopment. Isolated features stay within a +/-10% process window for features as small as 30 nm. Dense (line:space ratio of 1:3 or greater) features remain in the process window for features as small as 45 nm.

5. Improved Mask Technology for X-Ray Lithography

Sponsors

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Project Staff

Michael H. Lim, James M. Daley, Ken-ichi Murooka, Shingo Uchiyama, M. Feldman (LSU) and Professor Henry I. Smith.

At feature sizes of 100 nm and below the mask-to-substrate gap in x-ray lithography, G, must be less than ~10 µm. Thus, for nanolithography the mask membrane should be considerably flatter than 1 µm, preferably ~100 nm. Our mask technology is based on low-stress, Si-rich silicon nitride, SiNx. This material is produced in a vertical LPCVD reactor. Membranes of SiNx can be cleaned and processed in conventional ways. For absorber patterns we electroplate gold onto the membrane, using a specially designed apparatus, after resist exposure and development. A Ti/Au plating base is deposited on the membrane prior to resist coating. To pattern periodic structures on the x-ray masks, we use interferometric lithography (IL), and for patterns of arbitrary geometry we use e-beam lithography. A high-resolution Leo SEM and a Digital Instruments STM/AFM are used to inspect x-ray masks for defects. Radiation hardness for SiNx membranes remains a problem at dose levels corresponding to production (i.e., millions of exposures). For research purposes, however, the material is entirely acceptable. Currently we are investigating the problem of x-ray mask distortion, which is a potential problem in x-ray lithography.

X-ray mask distortion is rooted in the flexibility of its membrane. The membrane responds to stress in the absorber patterns by flexing both in-plane and out-of plane. Distortion caused by this
motion, especially in-plane, must be overcome if x-ray lithography is to meet the overlay requirements of future electronic and optical devices. Thus far, the x-ray lithography community has attacked this problem by trying to achieve very low-stress absorbers and, when necessary, compensating for absorber induced stress by modifying the pattern written by the electron beam. We are pursuing a new approach in which we first measure the membrane distortion and then correct it.

To measure distortion, we have developed a broadly applicable, nondestructive, global, membrane-distortion measurement technique called Holographic-Phase-Shifting Interferometry (HPSI). The HPSI system is based on the interferometric lithography (IL) system we use to generate large-area, highly-coherent gratings. Figure 6 is a schematic of the IL apparatus, configured as a HPSI system. The IL system splits a laser beam ($\lambda=351$nm) and forms two mutually coherent spherical waves, which interfere at the substrate at a half-angle $\theta$. The standing wave created at the substrate surface is used to expose photoresist. After development, the grating is present on the substrate surface or can be etched into it. The IL system is used as a holographic interferometer by mounting the IL-generated grating on the substrate platform, and placing a fluorescent screen in front of one or both of the spatial filters, as depicted in Figure 6. A fringe pattern appears on the screen, which is due to the superposition of two wave fronts: one reflected from the substrate surface and the other back-diffracted from the grating. If the grating has suffered no distortion between exposure and reinsertion, the reflected and back-diffracted beams will be identical and no fringes will be observed on the screen. Any in-plane distortion of the grating will result in a fringe pattern. A CCD camera is used to capture the fringes. To increase the precision, a phase-shifting measurement is implemented, by changing the phase of one of the arms and acquiring several images, Fig. 7. In order to use this apparatus to measure the in-plane distortion, we etch shallow IL-generated gratings into the membrane.

We have developed an analytical technique that predicts both in-plane distortion (IPD) and out-of-plane distortion (OPD) arising from arbitrary stress distributions in 2D. Moreover, we can also solve the inverse problem; i.e., we can predict the stress distribution which, when applied to any existing distortion, eliminates it. The calculational techniques are based on the variational method. It is relatively straightforward to formulate the total energy due to membrane distortion, even for a very complicated stress distribution. We calculate the true distortion by minimizing the total membrane energy due to the placement of the stressed absorber; the total energy is straightforward to formulate for even complicated absorber distributions. Figure 8 shows the results of a calculation where half the SiN$x$ membrane is covered with an absorber under tensile stress.

A correcting stress distribution can be introduced by means of local heating. Figure 9 shows the analytical result of a 7.5 mm spot, with a 1°C elevation in temperature, centered on a 50 mm square SiN$x$ membrane that is 1 µm thick. There is a peak displacement of 6.3 nm that occurs around the edges of the spot. This is equivalent to a circularly shaped absorber with 1.3 MPa of stress. The analysis indicates the time constant of the heating is less than one second. Moreover the calculational process also requires less than one second to complete.

Figure 10 shows a comparison of a self-consistent calculation of the distortion from a locally heated spot and the measured distortion.

We hope to build on this work by developing a system that can actively introduce a heat distribution into the x-ray mask in order to correct for membrane distortion in real-time. If successful, this should enable x-ray nanolithography to be used in applications such as integrated optics which demand the highest accuracy, precision and coherence in the placement of pattern elements.
Figure 6: A schematic of the Holographic Phase-Shifting Interferometer (HPSI) based on the interferometric lithography system that we use to generate highly-coherent gratings.

Figure 7: The HPSI uses diffractive metrology to make a rapid, global measurement of the distortion of a membrane. (a) Contour plot of phase distortion (nonlinear component) obtained by the HPSI. Successive contours are separated by $\pi/2$ radians., (b) conversion of the phase map of (a) into a distortion map.
Figure 8: Our calculational technique can solve both in-plane and out-of-plane membrane distortions in 2-dimensions. For example, covering half-plane of a 10 mm square SiNx membrane with an absorber results in both IPD and OPD displacements. (a) shows a 2-dimensional map of the IPD, which clearly indicates that a 1-D approximation would be inadequate. This is more clearly shown in (b), as the cross-sectional slices of the x component of the distortion along the x-axis vary as one moves closer to the boundary of the membrane. (c) and (d) show that the OPD also has a significant 2-D component.
Figure 9: The calculated distortion of a 50 mm square SiN membrane, with a thickness of 1 µm, in the presence of a 7.5 mm spot with 1°C rise in temperature. (a) The vector map showing the 2D distortion; (b) the cross-section of the x-component along the x-axis.

Figure 10: A comparison of the calculated distortion and the measured distortion.

Sponsors

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Project Staff

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An experimental high-precision, x-ray exposure system has been constructed that employs Interferometric Broad-Band Imaging (IBBI) for alignment (Fig. 11(a)). The IBBI scheme utilizes grating and checkerboard type alignment marks on mask and substrate, respectively, which are viewed through the mask from outside the x-ray beam at a Littrow angle of 20 degrees with f/10 optics and a 110 mm working distance (Fig. 11(b)). Each mark consists of two gratings (or checkerboards) of slightly different periods, \( p_1 \) and \( p_2 \), arranged so that \( p_1 \) is superimposed over \( p_2 \) and \( p_2 \) over \( p_1 \) during alignment. Alignment is measured from two identical sets of moiré fringes, imaged onto a CCD, that move in opposite directions as the mask is moved relative to the substrate. Alignment is determined from the relative spatial phase of the two fringe sets, measured with a high-sensitivity frequency-domain algorithm.

When a point x-ray source is employed, image placement errors can be significantly larger than the feature dimension if the position of the source is unknown. Specifically, the requirements for nanometer overlay are: (1) the gap must be known and controlled to < 0.1 \( \mu \text{m} \) and (2) the source axis (i.e., the perpendicular from the source to the mask) must be known to about 100 \( \mu \text{m} \).

The gap can be determined and controlled with a previously described Transverse Chirp Gapping (TCG) scheme, which permits interferometric sensitivity to gap using a single mark on the mask. The gap information is encoded into the spatial phase of a pair of fringes, which are observed with the same microscope as IBBI fringes.

A straightforward means of determining the source axis is to directly observe the x-rays from the point source passing through an array of circularly symmetric, tubular absorbers. As shown in Fig. 12(a), the source axis detection apparatus consists of an x-ray-sensitive CCD camera and a close-packed bundle of micropipettes (inner diameter=700 \( \mu \text{m} \), length=33 mm). The divergence of the x-ray point source results in obscuration of the x-ray flux by the micropipettes, in proportion to the distance away from the system axis. This radially-dependent obscuration yields a pattern detected by the CCD, shown in Fig. 12(b), in which the source axis intercepts the image in its upper left corner. In the source alignment procedure: (1) the micropipette bundle is translated to the point of maximum pattern symmetry (Fig. 12(c)), (2) the center of the bundle is observed with an optical microscope and denoted with crosshairs (Fig. 12(d)), and (3) a point on the x-ray mask, observed with the microscope, is aligned to the crosshairs. This scheme enables alignment of the mask to the source axis within 100 \( \mu \text{m} \), corresponding to overlay runout <1 nm (using a 3 \( \mu \text{m} \) gap and a source-mask separation of 250 mm.).

Prior to finding the source axis, the axis of the micropipette bundle is adjusted such that it is parallel to the wafer normal. For this purpose a 3x normal-incidence microscope images a laser beam which passes through one of the micropipettes, retroreflects from a surface parallel to the CCD camera and the wafer, and returns through the micropipette. The micropipette angles are adjusted (Fig. 13(a), (b)) until a single optical mode is observed within the micropipette (Fig. 13(c)), indicating alignment of the micropipette to the wafer normal within a few microradians.
Conventional metrological methods are inadequate for measuring the overlay accuracy of IBBI. For this purpose we employ the moiré fringes formed by the superposition of the exposed resist pattern (250 nm thick) on top of the IBBI alignment mark (etched 200 nm into the wafer). The relative spatial phase of these fringes is examined with a normal incidence optical microscope and analyzed with the IBBI algorithm.

A normal-incidence optical micrograph of such fringes is shown in Fig. 14(a) and a closer view of aligned dual-gate transistors is shown in Fig. 14(b). The phase analysis was performed on a Y alignment mark directly underneath the x-ray point source. The data for three sequential exposures on the same mark indicates misalignment of 2.5, -3.1 and 6.0 nm. Each exposure was performed several days apart, without realigning the source-mask axis. The variation in overlay is attributed to mechanical drift of the x-ray source position, since in each exposure the feedback system recorded a mean misalignment of <1 nm, such as in Fig. 14(c). In normal operation the source axis alignment will be ascertained before each exposure.

The unique collection of capabilities of IBBI alignment, TCG gapping, and x-ray axis alignment are being employed in the fabrication of a variety of electronic and optical devices, including 25 nm effective-channel-length n-MOS transistors.

Figure 11: (a) X-ray exposure and alignment system. Mask and wafer are located in a helium ambient and exposed to x-rays. (b) Schematic of IBBI scheme which enables an alignment beam to enter at a 20 deg. angle through a viewport before and during exposure. Fringes result from interference between mask gratings and wafer checkerboards of similar periods. The fringes are imaged onto a CCD camera and analyzed in the frequency domain. The relative mask-wafer position is controlled by piezos with integral capacitive sensors.
**Figure 12**: (a) Schematic of point source alignment apparatus. Divergent x-rays are radially obscured by the micropipette bundle and observed with an x-ray-sensitive CCD camera. (b) Image from the CCD with the perpendicular to the source misaligned and (c) aligned to the center of the micropipette bundle. (d) Image of the micropipette bundle with a normal-incidence optical microscope illuminated with white light and the center denoted with crosshairs. A point on an x-ray mask is aligned to the crosshairs to complete the mask-source alignment.

**Figure 13**: Images of laser light retroreflected from a wafer passing through a micropipette adjusted to three different angles: (a) misaligned with wafer normal, (b) approaching wafer normal, and (c) aligned with wafer normal (within a few microradians), as indicated by a single optical mode within the micropipette.
7. Interference Lithography

Sponsors

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Project Staff

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Interference lithography (IL) is the preferred method for fabricating periodic and quasi-periodic patterns that must be spatially coherent over large areas. For spatial periods down to 200 nm, an argon ion laser is used in a Mach-Zehnder configuration, with a fringe-locking feedback system, as illustrated in Figure 15. This scheme produces large area (10-cm-diameter) gratings with long-range spatial-phase coherence. Fringe locking ensures reproducibility of exposure.

In the past year, two additional tools were constructed that use the 325 nm line of a HeCd laser. One is a Lloyds-mirror interferometer designed for printing gratings or grids on substrates up to 10 cm in diameter, shown in Figure 16. The primary advantages of this system are its simplicity and the fact that the period of exposure can be varied from many microns down to ~170 nm without realignment of the optical path. Another system similar to the one shown in Figure 15 is being built with collimating lenses donated by Ultratech Corporation. This system will have the dual functions of interference lithography and holographic phase-shifting interferometry (HPSI). In the HPSI, the grating pattern formed by the interference of the two arms of the HPSI is superimposed over a pre-existing grating on the substrate. By analyzing the moiré pattern formed between the two gratings, spatial phase distortions on the order of parts per million in the substrate grating can be accurately measured and mapped. In many applications, spatial-phase distortions even as small as ppm can be problematic. We are currently investigating innovative methods for reducing spatial-phase distortions in gratings printed using interference lithography.
The gratings and grids produced by interference lithography have found a wide range of applications. The Chandra x-ray astronomy satellite launched in August of 1999 included hundreds of matched, high-precision gratings. Other applications being pursued include: ultra-high-density magnetic information storage, alignment templates for organic crystals and co-polymers, atom-beam interferometry, and the use of interferometrically-produced grids as fiducials in spatial-phase-locked electron-beam lithography and in a new approach to metrology for the sub-100 nm domain.

For spatial periods of the order of 100 nm, a source wavelength below 200 nm must be used. Since such sources have limited temporal coherence, one is forced to employ an achromatic scheme, as shown in Figure 17. The source is an ArF laser (193 nm wavelength). A collimating lens, polarizer and scanning system are interposed between the source and the interferometer in order to achieve reasonable depth-of-focus and large exposure areas. Using this system, gratings and grids of 100 nm period (50 nm features and 50 nm spaces) are obtained in PMMA on top of an antireflection coating. Figure 18 shows a 100 nm-period grid etched into Si produced achromatic interferometric lithography and a sequence of etching steps. Grids of Si posts are being used to investigate photo-and eletroluminescence which may result from charge-carrier quantum confinement.

A new generation of interference lithography tools is being developed, based on the achromatic principle in which gratings are used rather than mirrors to split and recombine beams. These new tools will produce gratings and grids of 50 nm period (25 nm lines and spaces), and will, of necessity, utilize wavelengths below 100 nm. One such achromatic interferometer will be installed on the 13 nm undulator line at the University of Wisconsin. Another will be set up here at MIT and utilize the 58 nm wavelength from a neon discharge.

![Figure 15. Schematic of the MIT interferometric lithography system. The system occupies a 2x3m optical bench in a class 100 clean environment. The beamsplitter directs portions of the two interfering spherical beams to photodiodes. A feedback locking is achieved by differentially amplifying the photodiode signals and applying a correction to the Pockels cell which phase shifts one of the beams.](image-url)
Figure 16. Schematic of a Lloyds-mirror interferometer. The substrate and mirror are fixed at a 90° angle to one another, and centered in a single incident beam. The spatial-period of the exposed grating is varied by rotating the substrate/mirror assembly about its center point.

Figure 17. Achromatic interferometric lithography (AIL) configuration employed to produce 100 nm-period gratings and grids.
8. Zone-Plate-Array Lithography (ZPAL)

Sponsors

Defense Advanced Research Projects Agency; MDA972-97-1-000
MIT Lincoln Laboratory under Air Force contract F19628-00-C-0002.

Project Staff

Dr. David J. D. Carter, Dario Gil, Rajesh Menon, and Professor Henry I. Smith

In semiconductor lithography, glass masks are illuminated with deep UV laser light and their image is reduced through a lens onto the substrate to define circuitry. As feature sizes are pushed toward 100 nm, lithography is becoming increasingly costly and difficult, and may soon limit the industry juggernaut.

At the MIT Nanostructures Laboratory, a considerably simpler approach is showing great promise. The new scheme, called zone-plate-array lithography (ZPAL) is made possible by inexpensive, high-speed computation and micromechanics. ZPAL replaces the “printing press” of traditional lithography with a technology more akin to that of a laser printer.

Instead of a single, massive lens, an array of hundreds of microfabricated Fresnel-zone-plate lenses is used, each focusing a beam of light onto the substrate. A computer-controlled array of micromechanical mirrors turns the light to each lens on or off as the stage is scanned under the

00nm-period posts in Si

Figure 18: Scanning electron micrograph of a 100 nm-period grid, exposed in PMMA on top of an antireflection coating, and transferred into Si by reactive ion etching.
array, thereby printing the desired pattern in a dot-matrix fashion. No mask is required, enabling designers to rapidly change circuit designs. A schematic of ZPAL is shown in Figure 19.

ZPAL leverages advances in nanofabrication, micromechanics, laser-controlled stages, and high-speed, low-cost computation to create a new form of lithography. We are developing ZPAL at UV, deep UV (DUV), EUV and x-ray wavelengths. Our experimental UV ZPAL system is currently operated at a wavelength of 442 nm. The system presently prints with an array of zone plates, fabricated at MIT, in conjunction with a micromirror array made by Texas Instruments.

Lithography Results

Figure 20 shows an array of nine pattern exposed in parallel with this system. Figure 21 shows a closer view of a nested L pattern. The image quality is very good, showing dense 350 nm lines and spaces. Future research will push to shorter wavelength and therefore finer feature size. For a DUV ZPAL system operating at $\lambda=157$ nm, we expect to be able to produce 90 nm feature sizes.

For most applications of lithography, it is desirable to control the linewidth to a fraction of the minimum feature size. Figure 22 shows how this is done with grayscaling in ZPAL exposures. In this case, 330 nm-wide pixels were exposed on a 110 nm grid. In the left-most micrograph, a single column of pixels was exposed. To widen the line, a second column was exposed at increasing doses. Then a third column was exposed (as shown in subsequent micrographs).

Because zone plates are diffractive optical elements, ZPAL can operate at EUV wavelengths (13.4 nm) or even in the soft x-ray regime ($\lambda\sim1-5$ nm). EUV or soft x-ray ZPAL should enable us to achieve feature sizes of about 20 nanometers at relatively low cost. We are developing a soft x-ray ZPAL system ($\lambda=4.5$ nm) to demonstrate the extendibility of ZPAL. Figure 23 shows a simulated pattern produced with such a system.

Microscopy Results

An array of zone plates can also be used as a massively parallel confocal microscope, allowing imaging over a large field of view. In addition, since zone plates can be inexpensively fabricated to work at deep-UV wavelengths, low-cost, high-resolution imaging is possible with zone-plate-array scanning-confocal microscopy (ZPAM).

ZPAM is similar to conventional scanning confocal microscopy (SCM), but with a few differences, as shown in Figure 24. First, the objective lens in the traditional SCM is replaced by an array of zone-plate objective lenses. Second, the detector (in this case a CCD array) is placed at the image plane of the zone-plate array, allowing the reflected light from each zone plate to be analyzed independently. In order to accomplish this, the confocal aperture must be somewhat larger than in conventional SCM, to pass enough diffracted orders to properly reconstruct the zone-plate array.

Figure 25 shows an image obtained with ZPAM. The sample is a silicon substrate with etched grating lines. The rough patterns in the center of the image were present in the sample. A close-up of the ZPAM image of a region of the sample is compared with a conventional optical micrograph of the same region. Note the large field-of-view at very high (~620 nm) resolution. Higher-NA zone plates and deep-UV illumination should allow sub-100 nm resolution, while a larger zone-plate array would allow a much larger field of view. This technology can be used for level-to-level alignment and placing the substrate at proper focus in ZPAL. ZPAM may also be suitable as a stand-alone technology for mask or wafer inspection.
Figure 19: Schematic of zone-plate-array lithography (ZPAL). An array of Fresnel zone plates focuses radiation beamlets onto a substrate. The individual beamlets are turned on and off by upstream micromechanics as the substrate is scanned under the array. In this way, patterns of arbitrary geometry can be created in a dot-matrix fashion. The minimum linewidth is equal to the minimum width of the outermost zone of the zone plates.

Figure 20: Scanning-electron micrograph of nine different patterns exposed in parallel with a UV ZPAL system. A micromirror array, manufactured by Texas Instruments, was used to multiplex the laser light to each zone plate. As the wafer stage was scanned, the zone-plate illumination pattern was changed to write the patterns in a dot-matrix fashion.
The minimum feature size of an optical projection system can be described as \( w_{\text{min}} = \frac{k_1 \lambda}{NA} \).

In this case the linewidth is 350 nm, the numerical aperture (NA) of the zone plates was 0.67, corresponding to a \( k_1 \) factor of 0.55. With modest improvements to NA and \( k_1 \), and using DUV radiation \( \lambda = 157 \text{nm} \), we expect to be able to print sub-100 nm features.

Figure 21: Scanning-electron micrograph of nested-L patterns produced at \( \lambda = 422 \text{nm} \) ZPAL. The minimum feature size of an optical projection system can be described as \( w_{\text{min}} = \frac{k_1 \lambda}{NA} \). In this case the linewidth is 350 nm, the numerical aperture (NA) of the zone plates was 0.67, corresponding to a \( k_1 \) factor of 0.55. With modest improvements to NA and \( k_1 \), and using DUV radiation \( \lambda = 157 \text{nm} \), we expect to be able to print sub-100 nm features.
Figure 22: Lines of varying width printed with grayscaling. Pixels (~330 nm in size) were exposed on a 110 nm grid. To widen the lines, a second column of pixels was exposed at increasing doses, then a third line was added. TOP: Scanning-electron micrographs of lines. CENTER: Schematic of exposure conditions for each line. BOTTOM: Plot of linewidth vs. line number.

Figure 23: Simulated patterns assuming λ=4.5 nm and an outer zone width of 25 nm. The slight proximity effect shown could be eliminated with a narrower-bandwidth source and/or by using an order-sorting aperture.
Figure 24: Schematic of zone-plate-array scanning-confocal microscopy (ZPAM). The zone plates are used as an array of objective lenses. The CCD detector is placed at the image plane of the zone-plate array, after the confocal aperture, allowing the reflected light from each zone plate to be analyzed independently. ZPAM can be used for placing the substrate at the zone-plate focal plane and for imaging the substrate.
Figure 25: Images obtained with ZPAM. Such images could be used for level-to-level lithographic alignment in ZPAL. TOP LEFT: Image of etched silicon sample. Rough patterns in center were present on the sample. Dark lines indicate zone-plate unit cells ~0.5 x 0.5 mm field-of-view, taken at ~620 nm resolution. TOP RIGHT: Close-up of ZPAM image of a scratch in the sample. BOTTOM RIGHT: Conventional optical micrograph of the same region for comparison.
9. Deep-Ultraviolet Contact Photolithography

Sponsor

Defense Advanced Research Projects Agency/NCCOSC Navy Grant N66001-98-1-8921

Project Staff

Dr. James G. Goodberlet, James M. Daley, Hamide Kavak, Mark K. Mondol and Professor Henry I. Smith

Deep-ultraviolet contact photolithography, now called conformable-contact photolithography (CCP), offers low-cost replication of sub-100-nm patterns at modest printing rates. For this technique, a patterned light-absorbing mask, less than 200 µm thick, is brought into intimate contact with a resist-coated substrate and then exposed with deep ultraviolet radiation, e.g. 220-nm wavelength from an arc lamp in our experiments. Because the mask is thin, intimate contact can be achieved over the entire substrate. In this manner, the substrate can be patterned with a single exposure, without the use of expensive relaying optics or laser radiation.

Multilevel alignment was demonstrated on a custom contact nano-aligner. The mask size was increased from one-inch diameter to three inches, and high-speed photoresists were used to reduce exposure times. Additionally, a numerical simulation of in-plane pattern displacements resulting from printing on spherical surfaces was completed.

Figure 26 shows the contact nano-aligner designed for conformable-contact photolithography. The aligner handles three-inch-diameter masks and wafers, and has nanometer-precision positioning actuators for X, Y, θ movement of the wafer. It also has electronic sensors and differential micrometers to adjust mask-to-wafer parallelism. A dual-field optical microscope is used to view fine alignment marks on the mask and wafer, while bringing the mask into intimate contact with the wafer. After alignment and contact are made, the assembly is moved under an exposure lamp. This contact nano-aligner has been used recently in two multi-level alignment experiments. These are the first of a series of multi-level patterning experiments that will be used to evaluate overlay accuracy in CCP.

The best result from the first two multi-level alignment trials is summarized in Figure 27. This vector graph represents overlay errors at different locations on the printed wafer. The length of the arrow corresponds to the magnitude of the displacement, i.e. compare with the 1 µm scale marker. For a 40mm x 40mm patterned area, the mean alignment error was below 175 nm, and the standard deviation was less than 150 nm. For a quarter of the area, enclosed by the dashed box, the mean alignment error reduced to about 50 nm. Much of the overlay error is attributed to the mask holder and intimate-contact process. The errors are expected to reduce with further modifications to the aligner.

To increase the patterning rate for CCP, several resists were investigated and compared to poly(methylmethacrylate) (PMMA), and the mask size was increased from one-inch diameter to three-inch diameter. Sub-100-nm patterning resolution was demonstrated with the larger mask and PMMA resist, although exposure times were several minutes for our lamp source. For high-speed photoresists such as Shipley Company’s 1813, UV-5 and UV-113, the exposure time was reduced to a few seconds. However, the patterning fidelity was not as good as with the slower PMMA resist. We are currently attempting to understand and improve the patterning fidelity with these fast resists.

Conformable-contact photolithography was originally proposed as a low-cost, high-resolution method for patterning on non-conventional surfaces such as cylinders and spheres. Previously
we demonstrated that CCP could be used to pattern on spheres, since the mask is thin and flexible. A numerical code was written to estimate the magnitude of in-plane pattern displacements that would result when a thin conformable mask is brought into intimate contact with a sphere. The radius of curvature of the spherical substrate was 10 mm, determined by a specific application, and the mask diameter was taken as 75mm. The estimated in-plane displacements were determined to be greater than 100 \( \mu \)m. This amount of displacement will likely require pattern pre-biasing and careful metrology to determine overlay accuracy of the printed pattern.

Under renewed sponsorship, this research program will be extended to evaluate overlay accuracy, and to fabricate micro devices using conformable-contact photolithography.

Figure 26. The contact nano-aligner. This apparatus was designed and built to achieve sub-50-nm mask-to-substrate multi-level alignment for conformable-contact photolithography.

Figure 27. Multi-level alignment results. The vectors represent the magnitude and direction of overlay errors measured after a second-level patterning step with conformable-contact
photolithography. The contact nano-aligner, shown in Figure 1, was used to align the first and second levels.

10. Nanomagnets

Sponsors

National Science Foundation DMR9871539; IBM Graduate Fellowship

Project Staff


We are using interferometric lithography (IL) to produce large-area arrays of ‘nanomagnets’ with spatial of 100 - 200nm. These particles have been made by electrodeposition, by evaporation and liftoff, or by etching of a sputtered film. We are exploring the switching mechanisms of the particles, the thermal stability of their magnetization, interparticle interactions, and assessing their suitability for various data-storage schemes. The collective behavior of the arrays can be measured using magnetometry and compared with the behavior of individual particles using magnetic-force microscopy in order to understand how the behavior of one magnet is affected by its neighbors. From such data, the intrinsic variability between particles can be determined, and related to the microstructure. For instance, we found that the reversal in 30 nm-diameter polycrystalline Ni particles is governed by the grain structure.

We have also performed micromagnetic simulations to explore the remanent magnetic states, and mechanisms for magnetization reversal in these structures. Small particles have near-uniform magnetization states, while larger ones develop more complex structures such as magnetization vortices or domain walls. Good agreement between model and observed remanent states is obtained, taking the shape and crystal orientation into account.

These particle arrays have potential uses in ‘patterned media’, in which each particle stores one bit of data according to its magnetization direction.

Figure 28: An array of electrodeposited Ni pillars, with diameter 90 nm and height 220 nm. The magnetic image shows that each pillar is magnetized ‘up’ (light) or ‘down’ (dark).
Figure 29: An array of conical Ni particles made by evaporation. These have diameter 30 nm and period 100 nm. The magnetic properties are governed by the grain size, leading to superparamagnetic behavior at room temperature. At low temperatures the coercivity increases in agreement with a computational model.

11. Magnetic Random Access Memories (MRAMs)

Sponsors:
TDK Corp., DARPA MDA972-97-1-003 through U. of New Orleans

Project Staff:
C.A. Ross, H.I. Smith, B. Vogeli, F. Castano, M. Walsh, Y. Hao, S. Haratani, in collaboration with J.Q. Wang

Sponsorship:
MRAMs are solid-state non-volatile magnetic storage devices in which each bit of data is stored an a small, elongated magnetoresistive sandwich element. A typical magnetoresistive (MR) sandwich consists of two magnetic layers of different coercivity, one hard and one soft.
The direction of magnetization of the hard layer is used to represent the data bit. To write data, a magnetic field is applied by passing a current through a conductor line (word line) adjacent to the element, such that the field is large enough to change the magnetization of the hard layer. To read, a smaller current is passed, which can change the magnetization of the soft layer only. The resistance of the element depends on whether the hard and soft layers are magnetized parallel or antiparallel, hence changes in the resistance resulting from the reversal of the soft layer can be used to probe the magnetic state of the hard layer. Elements are arranged in a rectangular array and connected with conductor lines, allowing individual elements to be selected.

We have used interference lithography combined with reactive ion etching and ion-milling to produce arrays of Co/Cu/NiFe spin-valve elements and prototype MRAM structures. The aim of this research is to investigate the behavior of sub-100 nm elements, much smaller than those used in present-day MRAM devices.

To tailor the properties of the pseudo spin valve (PSV) elements for MRAM devices, we analyzed the hysteretic behavior of large-area arrays of rectangular and elliptical PSV dots. Rectangular dots of sub-100nm width with aspect ratios ranging from 1:1 to 1:10 were fabricated by exposing and etching a first grating into an SiO2-layer, and then spin-coating the sample with new resist and exposing a second grating of different period perpendicular to the first one. The hysteresis obtained from an array of 80x140nm PSV dots exhibits two distinct steps, as shown in the Figure 30, corresponding to the separate switching of the Co and NiFe layers. The switching of the two magnetic layers and their antiparallel alignment at remanence leads to the conclusion that the layered PSV-structure is preserved through the pattern transfer process. Upon increasing the aspect ratio of the PSV-dots, the magnetic field at which the soft layer switches to antiparallel alignment decreases and eventually the two magnetic layers align parallel at remanence, as required for MRAM devices.
Fig. 31. Hysteresis loop of an array of 80 nm x 140 nm elliptical particles made of a Co/Cu/NiFe film. The steps in the loop correspond to the separate switching of the NiFe and Co layers, which are coupled antiparallel at remanence.

In Fig. 31, an MRAM structure is shown. The PSV elements are located where the horizontal word lines and the nearly vertical sense lines intersect, sandwiched between the sense lines and a 30nm SiO$_2$-insulation layer. The buried PSV elements form a large-area array of 80x180nm PSV dots, as indicated by magnetic measurements. Their magnetic behavior is similar to that of large-area PSV-dot arrays of the same dimensions. Both word and sense lines were found to be conductive.

Figure 32: Scanning electron micrograph of an array of PSV elements located at the intersection of the horizontal word lines and vertical sense lines.
12. Magnetic Nanostructures made by Block Copolymer Lithography

Sponsors:

National Science Foundation through a Seed Grant from the MIT Center for Materials Science and Engineering

Project Staff:

C.A. Ross, J. Cheng, H. I. Smith, collaboration with E.L. Thomas

Block copolymers consist of polymer chains made from two chemically distinct polymer materials. These can separate to form small scale domains whose size and geometry depend on the molecular weight of the two types of polymer and their concentration. The domains have a very uniform distribution of sizes and shapes. We have been using block copolymers as templates for the formation of magnetic particles, by selectively removing one type of domain and using the resulting template to form a nanostructured magnetic film. This can lead to hexagonally close packed arrays of magnetic dots or columns with diameters on the order of 20 nm and periodicities of order 50 nm. As an example, a block-copolymer has been used as a lithography template to ion-mill a thin magnetic film into a close-packed array of magnetic dots. Such materials are useful for studying the thermal stability, switching behavior, and interactions between magnetic particles that are smaller than can be obtained using conventional lithography techniques. They may also be useful in future generations of storage materials such as flexible media.

Figure 33: An array of Co dots, 8 nm thick and 20 nm in diameter, made by block-copolymer lithography. The array has a coercivity of about 100 Oe at room temperature.
13. **Development of Fabrication Techniques for Building Integrated-Optical Grating-Based Filters**

**Sponsors**

Air Force Office of Scientific Research  
Contract: F49620-96-1-0126

**Project Staff**

J. Todd Hastings, M. Jalal Khan, Michael H. Lim, Thomas E. Murphy, Professor Hermann Haus, and Professor Henry I. Smith.

Bragg gratings have widespread application in the rapidly growing field of optical telecommunications. A Bragg grating is formed by creating a periodic corrugation or refractive index modulation in an optical waveguide. Such a structure behaves as a wavelength-selective filter, reflecting a narrow band of wavelengths while transmitting all other wavelengths. Fiber Bragg gratings, in which a periodic index modulation is induced in the core of a photosensitive optical fiber, are now manufactured and used for a variety of applications, including dispersion compensation and wavelength add/drop filters. As optical networks spread deeper into the consumer market, it will become important to have low-cost, manufacturable Bragg grating devices that can be integrated on a chip with other electrical and optical components. The transition from fiber-optic devices to integrated-optical devices may be likened to the development of integrated circuits as a replacement for discrete components. This project seeks to develop the technology for building Bragg grating devices in planar optical waveguides.

Figure 34 illustrates the general structure of an integrated Bragg grating. Integrated Bragg gratings offer several advantages over fiber Bragg gratings. First, the integrated Bragg grating is formed by physically corrugating a waveguide, therefore it does not rely upon a photorefractive index change. This enables one to build Bragg gratings in materials that are not photorefractive (e.g. Si or InP), and allows stronger gratings to be constructed since the grating strength is not limited by the photorefractive effect. Second, integrated Bragg gratings can be made smaller, and packed closer together than fiber-optic devices. Third, the planar fabrication process gives better control over the device dimensions. For example, the beginning and end of the Bragg grating can be sharply delineated rather than continuously tapered. Abrupt phase shifts can be introduced at any point in a grating, and precise period control can be achieved. In essence, the integrated Bragg grating can be engineered on a tooth-by-tooth basis. Fourth, multiple levels of lithography can be combined, with precise nano-alignment between them, allowing the Bragg gratings to be integrated with couplers, splitters, and other electronic or photonic components. For this reason, relatively sophisticated optical filters can be constructed using integrated Bragg gratings.

Despite the flexibility afforded by Bragg gratings, their application in integrated-optical devices has been limited to relatively simple components, largely because the required fabrication techniques have not been adequately developed.

The fabrication of integrated Bragg gratings involves two lithography steps: one defines the relatively coarse waveguide features, and one that defines the fine-period grating features. While the waveguides can be patterned using conventional optical photolithography, high-resolution nanolithography must be used to print the Bragg gratings. Moreover, these two lithography levels must be precisely aligned relative to one another.
We use a combination of several different types of lithographies to generate the Bragg grating patterns for our devices. Interference lithography is the cornerstone of our Bragg grating work. In interference lithography, two coherent laser beams are crossed, generating a standing wave interference pattern. This standing wave pattern is used to expose photoresist, yielding a coherent deep-submicron-period grating, which serves as a fiducial reference for subsequent steps.

For devices that require long Bragg gratings with engineered phase shifts, we use a technique called spatially-phase-locked e-beam lithography (SPLEBL), which combines the long-range spatial coherence of interference lithography with the flexibility of e-beam lithography. Using an interferometrically-generated grating as a guide, we are able to write long grating patterns with our e-beam tool, avoiding the inter-field stitching errors which would otherwise spoil the device.

In order to allow precise alignment between the gratings and the waveguides, we have developed a technique of adding alignment marks to interferometrically-generated patterns. In this technique, we use our e-beam lithography system to place alignment marks on an interferometrically-generated pattern. Before writing the alignment marks, the e-beam system samples the existing grating in order to ensure that the marks are precisely aligned to the submicron gratings.

In most cases, the techniques mentioned above are not applied directly to a device, but instead to an x-ray mask. Once the mask is generated, with the appropriate gratings and alignment marks, the patterns can be repeatedly transferred to optical substrates using x-ray lithography.

One of the critical challenges faced by integrated Bragg gratings is that they require submicron grating structures patterned over relatively tall optical waveguides. In order to address this topography problem, we have developed a novel dual-hardmask process, depicted in Figure 35. This allows both lithography steps to be performed over essentially planar surfaces. The process is quite general, in that it can be applied to almost any waveguide structure. For example, Figure 36 illustrates how we have used this approach to pattern a quarter-wave-shifted Bragg grating on top of a 1.1 micron-high InGaAsP waveguide. This micrograph illustrates the power and flexibility of our fabrication scheme: we can engineer complex submicron-period Bragg-grating structures with precisely positioned, abrupt phase shifts, placed atop relatively tall waveguide structures. Figure 37 illustrates the results of our collaboration with Lucent Technologies, where these complex structures were epitaxially overgrown to complete the optical structure. Figure 38 shows the performance of the fabricated in-line Bragg grating structures.
**Figure 34:** Schematic of an integrated Bragg grating. A shallow corrugation is etched into the top surface of a waveguide. Depending on the index of refraction, the Bragg grating period should be between 215 nm and 540 nm.

**Figure 35:** Dual layer hardmask process used to pattern fine-period Bragg gratings atop relatively tall waveguide structures. The process is designed such that all lithography steps are performed over essentially planar topography.
Figure 36: Scanning electron micrograph depicting a quarter wave shifted 244.4 nm period Bragg grating etched into the top surface of an InGaAsP waveguide.

Figure 37: Scanning electron showing the profile of the overgrown structure; the square tooth grating shows very little degradation. Chuck Joyner, of Lucent Technologies, performed the overgrowth.
Figure 38: Performance of the in-line filters shows that our fabrication sequence results in good devices.

14. Design of Integrated Bragg Grating-Based Filters for Optical Communications

Sponsors

Air Force Office of Scientific Research

Contract F49620-96-1-0126

Project Staff

Thomas Murphy, J. Todd Hastings, M. Jalal Khan, Michael H. Lim, Joseph Huang, Professor Hermann Haus, and Professor Henry I. Smith.

We have developed a set of new lithographic techniques specifically tailored to meet the needs of integrated Bragg gratings. As a vehicle for demonstrating these techniques, we are in the process of developing two novel devices which could play an important role in future optical networks.

The first device we are developing, depicted in Figure 39, is based upon quarter-wave-shifted Bragg gratings. When a quarter-wave shift is introduced in an otherwise uniform Bragg grating, the resultant structure behaves as an optical resonator, similar to a Fabry-Perot cavity or a ring resonator. The structure is designed such that only one wavelength channel from a multi-wavelength system will excite the resonator. The device therefore acts as an add/drop filter, enabling the addition or extraction of a channel from the bus waveguide, while leaving all other
channels unaffected. The second resonator, located below the bus, ensures that there is no appreciable reflection of the resonant channel into the input port of the device.

The device depicted in Figure 39 is a first-order filter, which has the characteristic Lorentzian bandpass response expected for a single-pole resonator. By cascading multiple resonators, it is possible to achieve more complicated higher-order filters. To address the complex design challenges of these filters, we have developed an equivalent-circuit model that maps the Bragg-grating-based waveguides onto equivalent electrical circuits consisting of resistors, inductors, and capacitors. Once this association has been made, the spectral response of the filter may be engineered using standard circuit tables. For example, we have used the equivalent circuit technique to design third-order Butterworth filters. Once we have mapped the electrical parameters to their corresponding optical parameters, we use computer simulations to calculate the physical dimensions of the waveguides and gratings that yield the desired values for these optical parameters. This dual approach of using analytic techniques and computer simulations to design devices enables us to generate detailed design tables which take into account, and allow for, unpredictable variations in the manufacturing sequence.

The second device that we are developing, depicted in Figure 40, is a simpler Bragg-grating filter. The gratings in this device are long, structures without quarter-wave shifts. In this implementation, each of the Bragg gratings acts like a wavelength-selective reflector. The two identical Bragg gratings are integrated in a Mach-Zehnder interferometer, which separates the signals reflected from the gratings from the input signal. Light is launched in the upper left port of the device, and split equally by the coupler. A portion of the light is reflected by the identical Bragg gratings located in the arms of the interferometer. Provided the arm lengths are matched, these reflected signals recombine and emerge in the lower left port of the device.

Depending upon the characteristics of the Bragg grating, the filter can be configured to perform many different functions. For example, by appropriately selecting the length and depth of the Bragg grating, the reflection spectral response can be made to have a bandpass shape. The spectral response is typically apodized by slowly varying the strength of the grating along its length. With this configuration, the device performs as an add/drop filter: one wavelength channel is reflected by the gratings, while all other channels pass-through unaffected. The same channel may be simultaneously added by launching it in the upper right port.

We are also investigating the integration of Bragg gratings with Silicon-On-Insulator (SOI) ridge waveguides. These waveguides are clad by SiO₂ below and by air above. By carefully selecting the silicon thickness, ridge height, and ridge width, one can maintain single-mode operation while providing a large waveguide cross-section for efficient fiber coupling. A typical waveguide cross-section is shown in Figure 40a. Figure 40b shows the experimentally measured filter response of a long uniform grating etched into the waveguide ridge. SOI is commercially available and can be processed with standard Si fabrication techniques. In addition, no cladding overgrowth is required. Despite these advantages, the difficulties of minimizing loss and optimizing fiber coupling while maintaining adequate grating-strengths make SOI a challenging material system.

The devices described here illustrate the rich variety of optical filters that can be constructed using integrated Bragg gratings in various materials systems. We are currently in the process of building and testing these devices.
Figure 39: A schematic diagram of the resonator-based add/drop filter. Several independent data channels, each at a different wavelength, travel along the bus waveguide. One channel excites the quarter-wave-shifted Bragg resonator, and is tapped off in the upper port of the device. This device may be operated in reverse, allowing one to selectively add a channel to the bus.

Figure 40: A schematic diagram of Bragg gratings integrated in a Mach-Zehnder interferometer. The identical gratings located in the opposite arms are designed to reflect a portion of the incident light. The filtered signal emerges in the lower left port.
15. Fabrication of Optical Sources in III-V Materials Using Photonic Crystals

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Project Staff:
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Enhanced Extraction from a Light-Emitting Diode Modified by a Photonic Crystal

Semiconductor LEDs have the potential to be low-cost and long lifetime solid-state lighting sources for applications as varied as room lighting and flat-panel displays. LEDs are also used in short-range telecommunication systems and may be desirable for optical interconnects in computers. Unfortunately, most of the light emitted from a semiconductor LED is lost to planar guided modes propagating within the high dielectric material resulting in a low extraction efficiency. In this work, a 2D photonic crystal is used to cause strong Bragg scattering of the emitted light into radiation modes improving the extraction efficiency. By adjusting the dimensions of the photonic crystal, enhanced extraction of particular wavelengths of light into the vertical direction is achieved.

The structure studied here consists of a triangular lattice of air holes that create the 2D photonic crystal. The exact parameters of the 2D photonic crystal, such as the lattice constant, hole diameter, and hole depth, depend on the desired wavelength of operation and the material system. The structure [Figure 42(a)] consists of an In_{0.51}Ga_{0.49}P/In_{0.20}Ga_{0.80}As active region on top of a low dielectric Al_{2}O_{3} spacer layer and an Al_{2}O_{3}/GaAs distributed Bragg reflector (DBR). The asymmetric active region consists of an 8 nm In_{0.20}Ga_{0.80}As quantum well (QW) sandwiched between an upper In_{0.51}Ga_{0.49}P layer of thickness either 95 nm or 158 nm and a lower
In$_{0.51}$Ga$_{0.49}$P layer of thickness 32 nm. The photoluminescence (PL) spectrum exhibits a peak wavelength of 980 nm and a full-width at half-maximum (FWHM) of 65 nm for the QW at room temperature. To minimize nonradiative carrier recombination at the air hole surfaces, and to retain all of the active material in the QW, the holes do not penetrate the In$_{0.20}$Ga$_{0.80}$As QW. The asymmetry of the active region, however, allows the etched holes of the photonic crystal to be deep enough to cause strong Bragg scattering of the index-guided light. The DBR stop band ranges from 800-1300 nm and reflects the QW emission. The 0.5 µm low-dielectric Al$_x$O$_y$ layer minimizes the coupling to the lateral guided modes in the high-dielectric layers of the DBR. A 30 x 30 µm$^2$ photonic crystal region is centered within a 50 or a 100 µm square LED mesa.

The device structure is grown using gas-source molecular beam epitaxy. The separation layer is initially grown as Al$_{0.98}$Ga$_{0.02}$As and the DBR consists of AlAs and GaAs layers. A SiO$_2$ layer is deposited on the grown structure using plasma enhanced chemical vapor deposition. The holes are defined in PMMA by direct-write electron-beam lithography. The electron beam writes a square pattern in the PMMA to represent each hole. The beam size, however, is larger than the step size for translating the electron beam. This leads to the desired circular pattern following development.

The PMMA is used as a mask in transferring the hexagonal pattern to the SiO$_2$ layer using RIE. This is accomplished by RIE with a CHF$_3$ plasma using 15 second steps in between 1 minute cool-down steps, during which the electrode is back-cooled with He gas flow. The purpose of the cool-down step is to prevent flowing of the PMMA mask. The SiO$_2$ mask is subsequently used in the RIE of the holes into the upper InGaP cladding layer using RIE with a CH$_4$/H$_2$/O$_2$ plasma in a 20:20:2.5 gas flow ratio. The mesas are next defined using photolithography followed by RIE with the CH$_4$/H$_2$/O$_2$ plasma to penetrate the active region. RIE with a He:BCl$_3$:Cl$_2$ plasma in a 25:10:5 gas ratio is used to expose the mesa sidewalls. The final step in the device fabrication is the wet thermal oxidation of the Al$_{0.98}$Ga$_{0.02}$As separation layer and the AlAs DBR layers.

Each sample consists of an array of LEDs where each mesa contains a different lattice constant and hole diameter for the photonic crystal. The LED mesas are pumped optically using a Ti:Al$_2$O$_3$ laser emitting at 810 nm. The pump light may be focused to a < 5 µm diameter spot on the sample allowing for localized excitation of the QW. The pump beam is reflected by the underlying DBR. The focusing lens has a numerical aperture of .25. Light collected from each LED mesa is imaged onto a coupled charge device (CCD) camera or directed into an optical spectrum analyzer (OSA). By placing various chromatic filters in front of the CCD camera, a qualitative understanding of the LED enhancement is obtained. Spectrally-resolved PL is obtained with the OSA.

Figure 43 shows an example of improved extraction from an LED mesa containing a photonic crystal designed to cause strong Bragg scattering of 925 nm light emitted from the quantum well. Various chromatic filters are placed in front of the CCD camera and the PL observed using localized excitation of the QW is shown in Figure 43(a). Each filter transmits a spectral range of 10 nm FWHM centered about 925 nm, 950 nm, 975 nm, and 1000 nm. The pump light is focused down to a < 5 the CCD camera and the PL observed using localized excitation of the QW is shown in Figure 43(a). Each filter transmits a spectral range of 10 nm FWHM centered about 925 nm, 950 nm, 975 nm, and 1000 nm. The pump light is focused down to a < 5 the CCD camera and the PL observed using localized excitation of the QW is shown in Figure 43(a). Each filter transmits a spectral range of 10 nm FWHM centered about 925 nm, 950 nm, 975 nm, and 1000 nm. The pump light is focused down to a < 5 µm diameter spot just outside the edge of the photonic crystal region on the LED mesa. By optically pumping a region outside the photonic crystal, light that is emitted from the QW is index-guided in all lateral directions, with some of the light coupling to modes in the photonic crystal. Only wavelengths of the QW emission near the calculated wavelength of 925 nm are efficiently extracted in the vertical direction. Therefore, the image taken at 925 nm shows the most light being extracted from the device. Figure 43(b) is a plot of the spectrally-resolved PL obtained using the OSA. There is a dramatic difference in the PL spectrum for the photonic crystal LED mesa as compared to a reference mesa containing no
photonic crystal. By taking the ratio of the two spectra in Figure 43(b), a 100-fold enhancement in
the intensity of light in the vertical direction is obtained at 925 nm.

Figure 42 (a) Schematic of the 2D photonic crystal LED mesa structure. (b) Cross-sectional
SEM.

Figure 43 (a) PL with various chromatic filters. (b) PL spectrum from photonic crystal LED mesa
featured in (a) and reference LED mesa.

Alexei A. Erchak, D. J. Ripin, S. Fan, G. S. Petrich, L. A. Kolodziejski, E. P. Ippen, and J. D.
Joannopoulos, "Increased light extraction from a light-emitting diode using a two-dimensional
photonic crystal", Quantum Electronics and Laser Science Conference, San Francisco, California,
May 7-12, 2000.

Alexei A. Erchak, D. J. Ripin, S. Fan, G. S. Petrich, L. A. Kolodziejski, E. P. Ippen, and J. D.
Joannopoulos, "Increased light extraction from a light-emitting diode using a two-dimensional
photonic crystal", NATO Advanced Study Institute: Photonic Crystals and Light Localization,

Alexei A. Erchak, D. J. Ripin, S. Fan, Peter Rakich, G. S. Petrich, L. A. Kolodziejski, E. P. Ippen,
and J. D. Joannopoulos, "Enhanced emission from a light-emitting diode modified by a photonic
crystal", Symposium on Microphotonics-Materials, Physics, and Applications, Materials Research
Society Fall Meeting, Boston, Massachusetts, November 27-December 1, 2000. Materials
16. Fabrication of 3-D Photonic Bandgap Structures

Sponsors

National Science Foundation
Contract DMR-9808941

Project Staff

Minghao Qi, Professor John Joannopoulos, Professor Henry I. Smith

Photonic Bandgap Structures (PBG) offer opportunities for miniaturizing a variety of conventional optical devices. 3-D PBG structures have advantage over 2-D structures in that they eliminate the loss of light through substrates or air. Figure 44 illustrates the improved 3D structure we are now attempting to fabricate using planar fabrication techniques. Modeling indicates that it has a large, complete bandgap. Our fabrication process allows defects to be introduced in a controlled manner.

Despite the structural difference from the structure under investigation last year, the new photonic crystal is similar from the fabrication point-of-view. The processes we have developed so far can be applied to the new structure with only minor tuning.

To take advantage of the fact that the PBG patterns are identical at each layer, a new lithography scheme using X-ray lithography and IBBI alignment, illustrated in Figure 45 will be used. The process is to be carried out with a single X-ray mask to reduce registration errors. A set of complimentary IBBI marks are first transferred to the wafer while the device area and IBBI marks are blocked. The extremely high detectivity of IBBI scheme and active feedback stabilized X-ray exposure system ensure the accurate alignment. We believe that the simplified design and lithography scheme will enable us to succeed in fabricating the 4-layer structure, suitable for optical testing.
Figure 44. Depiction of a 3D photonic-bandgap (PBG) crystal to be fabricated at a 630 nm period in x-direction. The photonic crystal is made of Si, with a refractive index of 3.4 at 1.53 micrometer (the midpoint of the bandgap). An ideal bandgap of 21% of the midgap frequency can be achieved. For an attenuation of more than 98% in the normal direction, only four deposition/planarization cycles are required.

Figure 45. Schematic of IBBI alignment using only one X-ray mask. The mask contains device area, a set of IBBI marks (minimum 3 as shown in the figure) and a set of complimentary IBBI marks (not shown in the figure). Shown at the bottom are the illustrative images of Moiré patterns formed by overlaid IBBI alignment marks.
17. Guiding Light Through Sharp Bends Using Two Dimensional Photonic Crystals

Project Staff:

Solomon Assefa, Alexei A. Erchak, D. J. Ripin, S. G. Johnson, M. Mondol, Dr. Gale S. Petrich, Professor Erich P. Ippen, Professor John D. Joannopoulos, Professor Leslie A. Kolodziejski, and Professor Henry I Smith

Sponsors:

Small scale optical signal processing requires waveguiding an optical signal around sharp bends with a radius of curvature on the order of an optical wavelength. Conventional waveguiding is the result of total internal reflection at the interface between the high-refractive index guiding layer and its low-index surroundings. However, waveguide bends in the conventional index-contrast waveguides may cause large optical losses depending on the radius of curvature of the bend. These optical losses due to radiation can be avoided by using a two-dimensional (2D) photonic crystal.

The 2D photonic crystal consists of an array of cylindrical rods of high dielectric material above a low dielectric material (Figure 46a). Waveguides are created by introducing a line defect of smaller radius cylinders into the 2D photonic crystal (Figure 46b,c). The forest of periodic dielectric rods, which surrounds the line defect, creates a photonic band gap (PBG) or a range of frequencies in which light cannot propagate. Thus, an optical signal with a frequency inside the PBG has its energy confined inside the line defect. The radius of the cylinders in the line defect remains large enough to provide index guiding in the third dimension (normal to the plane of periodicity of the photonic crystal). Localization of the mode inside the line defect allows guiding around sharp corners including even a 90 degree bend with low optical loss.

The cylindrical rods of the photonic crystal consist of a high-index 860 nm thick GaAs layer sandwiched between a 100 nm SiO₂ cap layer and a 640 nm low-index AlₓOᵧ layer. An additional 860 nm thick AlₓOᵧ layer is below the cylindrical rods in order to isolate the GaAs guiding layer from the GaAs substrate. The heterostructure is grown using gas source molecular beam epitaxy on a (100) GaAs substrate. The AlₓOᵧ is initially grown epitaxially as AlGaAs and this oxidized... The fabrication process commences by evaporating 100 nm of SiO₂ using chemical vapor deposition. Next, the waveguide and photonic crystal are defined by using direct-write electron-beam lithography. Each sample is coated with polymethyl methacrylate (PMMA). Each cylinder is defined by exposing a square pattern; the finite beam width rounds-off the corners of each square yielding a circular hole upon development. From simulation, the largest PBG is obtained for a rod diameter of 300 nm. To observe a shift in the frequency range of the PBG, patterns with cylinder diameters ranging from 270 nm to 330 nm are fabricated. Experiments covering a range of doses are done to find the optimal parameters for the exposures. As shown in Figure 47, a dose of 375 µC/cm², current of 50pA, and clock frequency of 0.09MHz gave hole diameters close to the desired values. The input and output coupling waveguides and different sized arrays of holes are written by stitching 250 m fields.

A 30 nm thick nickel film is evaporated on the sample after the PMMA is developed, and a liftoff process is performed. The pattern is transferred to the SiO₂ by reactive-ion etching (RIE) in a CHF₃ plasma after which the nickel mask is removed. This etch is done at 10 mT pressure and 300V DC bias, yielding an etch rate of 16 nm/min. Using the SiO₂ mask, the cylindrical rods are created by etching the GaAs and the AlGaAs to a total depth of 1.5 µm using a BCl₃ plasma. The power and the DC bias are carefully monitored to avoid sputtering of the SiO₂ mask. Also, the etching is done at low pressure and low flow to minimize the formation and deposition of polymers on the mask, on the sidewalls, and inside the trenches. This helps to eliminate
micromasking of the etching surfaces. Next, the AlGaAs is transformed into Al$_x$O$_y$ using a wet thermal oxidation process. Finally, each sample is lapped and cleaved in order to create a smooth input facet to promote the efficient coupling of a test signal of 1.55 µm wavelength.

In the near future, transmission through the various structures shall be investigated. Of particular interest is the size of the photonic bandgap and the transmission through a straight line-defect waveguide. Coupling losses at the input and output of the 2D photonic crystal waveguide shall be investigated. Finally, the transmission through a sharp 90 degree bend shall be measured and compared to theoretical simulations.

![Photonic Crystal Waveguides](image)

**Figure 46:** (a) photonic crystal (b) linear waveguide (c) 90 degree bend waveguide.

![SEM of Holes in PMMA](image)

**Figure 47:** SEM of e-beam-written array of holes in PMMA
18. Development of High Speed DFB and DBR Semiconductor Lasers

Sponsors

MIT Lincoln Laboratory, Contract BX-6558

Project Staff

Farhan Rana, Michael H. Lim, Elisabeth Koontz, Professor Rajeev Ram, Professor Leslie Kolodsiejski and Professor Henry I. Smith.

High-speed semiconductor DFB and DBR lasers are crucial for high-speed optical communication links. These lasers can be directly modulated at frequencies reaching 20 to 30 GHz. They have important applications in optical links based upon WDM (wavelength division multiplexing) technology. Direct laser modulation schemes are much simpler to implement and integrate than modulation schemes based upon external modulators. However, modulation bandwidth of external modulators can easily go beyond 60 GHz. Thus, it is technologically important to have DFB/DBR lasers whose modulation bandwidths compete with those of external modulators. The goal of this project is to develop DFB and DBR lasers capable of being modulated at high speeds with low distortion and chirp.

High performance DFB and DBR lasers demand that careful attention be paid to the design of the grating, which provides the optical feedback. Spatial hole burning, side mode suppression, radiation loss, laser linewidth, spontaneous emission in non-lasing modes, lasing wavelength selection and tunability, laser relaxation oscillation frequency etc. are all features that are very sensitive to the grating design. Improved grating design can significantly enhance laser performance, especially at higher modulation frequencies. In the last few years various techniques have been developed in Nanostructures Laboratory that allow fabrication of gratings with spatially varying characteristics and with long-range spatial-phase coherence. Chirped optical gratings with spatially varying coupling parameter can be made using a combination of Interferometric lithography, spatially phase-locked electron beam lithography and X-ray lithography. This provides us a unique opportunity for exploring a wide variety of grating designs for semiconductor DFB and DBR lasers. We plan to explore laser devices suited for high speed as well as for low noise operation.

We have developed techniques for fabricating high-speed polyimide-planarized ridge waveguide laser structures that have low capacitance and are therefore ideally suited for high frequency operation. Figure 48 shows the cross section of a polyimide-planarized InP DFB laser. The active region consists of strain compensated InGaAsP multiple quantum wells. The grating and the ridge are dry etched in RIE using a mixture of hydrogen and methane. Planarization is achieved by spinning multiple coatings of polyimide followed by a high temperature cure. Cured polyimide is dry etched in RIE using a mixture of oxygen and carbon tetrafluoride until the top of the ridge gets exposed. Ohmic contact to the ridge is made by lift-off on top of the polyimide layer. The thick layer of polyimide significantly reduces the capacitance between the top metal contact and the substrate. A large value of this capacitance can short out the active region at high frequencies. Figure 49 shows an SEM micrograph of a laser structure fabricated using this process. Figure 50
shows the measured output power from a DFB laser fabricated using the polyimide process. Figure 51 shows the measured spectrum of the DFB laser. Laser characteristics show reasonably high single-mode output power with a side mode suppression ratio of 40 dB.

We are also developing techniques to fabricate co-planar stripline structures for high-speed DFB/DBR lasers. Co-planar striplines offer improved microwave performance compared to microstrip structures. Figure 52 shows a polyimide based co-planar stripline laser structure. Fabrication of this structure requires etching polyimide such that the sidewalls do not become too steep so that metal interconnects can be run over them. We have successfully developed etching techniques for polyimide that allows us to control the sidewall angle. Figure 53 shows an SEM of a metal interconnect running over the sidewall of a polyimide layer.

![Polyimide planarized DFB ridge waveguide laser](image)

**Figure 48:** Polyimide planarized DFB ridge waveguide laser.

![SEM of a polyimide planarized DFB laser](image)

**Figure 49:** SEM of a polyimide planarized DFB laser.
Figure 50: Measured output power from a DFB laser. Maximum single-mode output power is more than 6 mW.

Figure 51: Measured spectrum of a DFB laser. Side mode suppression ratio is 40 dB.
The double-gate (DG) MOSFET (Figure 54) is considered a promising device for CMOS scaling to deep sub-100 nm gate lengths. However, realization of the ideal DG-MOS structure involves significant technological challenges: formation and alignment of gates above and below a thin single-crystalline silicon layer, and achieving low source/drain resistance for this thin layer. We are addressing these issues through integration of three primary technologies: wafer bonding with pre-patterned features, interferometric alignment, and selective epitaxy.
Monte-Carlo modeling predicts that double-gated devices that are scaled to $L_{\text{eff}} = 25$ nm will have transconductances $G_m$ in excess of 2000 mS/um, while maintaining almost perfect sub-threshold slope. However, models also predict that the tolerance in aligning front and back gates has to be within $L_g/4$ in order to avoid performance deterioration due to overlap capacitance. The $L_g/4$ requirement translates into 6 nm alignment tolerance for a 25 nm channel. In order to meet this alignment challenge we will use the IBBI (Interferometric Broad-Band Imaging) alignment technique which achieves sub-nanometer misalignment detectivity. The planar double-gate devices will be fabricated starting with a SIMOX wafer. First the gate stack for the back-gate will be deposited and patterned by x-ray lithography. The structure will then be covered by a layer of CVD oxide, planarized, and bonded to a “handle wafer”. The bulk of the SIMOX wafer will then be chemically etched using the back-oxide of the SIMOX wafer as the etch-stop. The fabrication will then follow a conventional SOI (Silicon on Insulator) process, with front gate precisely aligned to back-gate layer using the IBBI alignment scheme. The final structure is depicted in Figure 54.

We employ a direct alignment approach to form top-gates with correct relative placement to the bottom-gates. We have demonstrated the functionality of this alignment system. Figure 55 shows a DG-MOS device after top-gate x-ray lithography, with buried n+ poly gate visible beneath a 25 nm silicon layer. Although we have attained alignment detectivity of the order of several nanometers, final alignment results are equally a function of precise pattern placement between the upper- and lower-gate x-ray masks. We have been developing a process to obtain this precision through close proximity x-ray mask replication. In this scheme, gate patterns from the upper-gate mask are transferred to the lower-gate mask using x-ray lithography. This is done while the alignment marks of the two masks are aligned. Lithography of this sort is challenging primarily for two reasons: 1) the pattern on the replicated mask must be of the same polarity as that on the source mask, 2) it is necessary to maintain sub-100 nm resolution. Maintaining pattern polarity is a subtle yet crucial aspect of this process. Recently we have succeeded in developing a mask replication process compatible with these constraints. The process that takes place on the duplicate mask involves the following four steps: X-ray patterning positive resist, liftoff (yielding a pattern reversal), etch down (forming trenches) and finally, Au electroplating within those trenches. Once these steps are accomplished, mother and daughter masks have precisely matching patterns when the two masks are compared face-to-face. This is a key result for this project.

We are also investigating performance of deeply scaled DG vs. bulk MOS. It has been projected that with aggressive channel dopant profile engineering, bulk may scale down to ~25 nm $L_{\text{eff}}$ which may be near the practical DG-MOS limit. However, to achieve this the bulk MOSFET must have very heavy ($\sim 1 \times 10^{19}$ cm$^{-3}$) peak body doping to suppress punch-through, which results in a very high transverse electric field ($E_{\text{eff}}$) at the inversion layer. According to the well-verified universal mobility relationship, this can be expected to result in severely degraded mobility in bulk MOSFETs. In SOI devices with undoped channels, short channel effects are suppressed by limiting silicon and oxide film thicknesses. Body charge can be essentially zero, resulting in low $E_{\text{eff}}$ and correspondingly superior mobility. Using 2D numerical simulations (Avant! Medic$^\text{TM}$) we have determined the doping required for electrostatically sound bulk uniform-doped n-MOSFETs (at the $L_{\text{eff}} = 50$ and 25 nm generations), as well as the resulting $E_{\text{eff}}$ seen by electrons in the inversion layer. In Figure 56 we show the corresponding range of mobility expected, based on the universal dependence of mobility on $E_{\text{eff}}$. Also shown are results for one additional bulk, and three SOI, MOSFET architectures. Our results suggest that single-gate SOI is an attractive alternative down to 50 nm $L_{\text{eff}}$. For deeper scaling, double-gate SOI should have a 3-4X mobility advantage over aggressively designed bulk NMOS.
Fig. 54: Double-gate (DG) NMOS transistor with 25 nm effective channel length. Gate-to-gate alignment is via IBBI.

Fig. 55: DG-NMOS device after top-gate x-ray lithography. Alignment of gates is via IBBI.
Fig. 56: Universal effective MOSFET mobility curves from [2], with regions of operation delineated for five different bulk and SOI device architectures. Figure 56a corresponds to the 50 nm $L_{eff}$ generation, and Figure 56b to the 25 nm generation. “DG $\Phi_{mg}$” refers to double-gate SOI with midgap gate workfunctions. “DG-n+p+” refers to double-gate SOI with asymmetrical n+ / p+ poly gates. For each device architecture the range of $E_{eff}$ is determined from 2D simulation, and corresponds to a range of inversion layer densities ($Q_{inv}$) from $2.4 \times 10^{12}$ to $2.4 \times 10^{13}$ cm$^{-3}$. In the case of DG $\Phi_{mg}$, $Q_{inv}$ is the sum of inversion charge in both inversion layers, except for special case noted in Figure 4b.

20. Optimal MOSFET Design for Low Temperature Operation

Personnel
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(R. Dennard – IBM, D. Antoniadis, H. Smith)

Sponsorship
IBM, Intel (Intel Fellowship)

Low temperature operation of MOSFETs improves their performance by increasing the mobility and by allowing lower threshold voltages. The goals of this project are to understand how to achieve an optimal device design at low temperature and how much performance gain occurs at low temperature.

A set of devices from IBM which have two different threshold voltage designs (a “low-$V_{th}$” design and a “high-$V_{th}$” design) were used to examine two design options. Since a device’s switching speed depends on both current and capacitance, the two designs were compared at the same channel length (approximately the same gate capacitance) allowing the on-current of the devices to give a direct measure of device switching speed. Also, in order to make a fair comparison, a forward substrate bias was used to adjust the off-current of all devices to the same value ($10^{-9}$ cm$^{-2}$ V$^{-1}$ s$^{-1}$).
A(µm). A large forward bias can be used, with no impact on the off-current, because the source and drain p-n junction current is significantly reduced at low temperature. Plotting each device’s on-current versus each devices’ channel length (L_{eff}) clearly shows that the low-V_{th} design consistently yields a higher on-current for a given L_{eff} (Figure 57) and same off-current (Figure 57).

![On-current vs. L_{eff} at I_{off}=10^{-9} A/µm](image)

Figure 57: On-current vs. L_{eff} at I_{off}=10^{-9} A/µm

Examining device characteristics (again, at the substrate bias needed to set the off-current), the low-V_{th} devices have a steeper subthreshold slope than the high-V_{th} devices (Figure 58 middle) which, given the fixed off-current, results in a lower V_{th} (Figure 58 top) and thus a higher on-current. The low-V_{th} designs also have less short channel effects as evidenced by their lower drain induced barrier lowering (DIBL) at a given L_{eff} (Figure 58 bottom).
The differences in subthreshold slope and short channel effects are directly related to the maximum depletion depth in the channel ($x_{d,max}$). For instance, a small $x_{d,max}$ gives a larger (shallower) subthreshold slope, but better short channel effects. In this case, although the two device designs (at a given $L_{eff}$) have the same off-current, the high-$V_{th}$ design has a smaller $x_{d,max}$ than the low-$V_{th}$ design. This results in the worse subthreshold slope which gives a higher $V_{th}$ and thus a lower on-current. What this suggests is that designing for a low threshold voltage requires both reaching the maximum off-current allowed, as well as minimizing the subthreshold slope by having as large a $x_{d,max}$ as allowed by short channel effects limits.

In summary, the optimal design of a MOSFET at low temperatures requires the use of a low threshold voltage. A low $V_{th}$ with the proper $x_{d,max}$ (balancing the subthreshold slope and short channel effects) is best achieved by using a lower channel doping, than a room temperature device, coupled with a forward substrate bias. The experimental results above for 80 nm N-MOSFETs at 200 K show the low-$V_{th}$ design achieving a 5% higher on-current (for the same off-current) than the high-$V_{th}$ design.

Continuing work is focusing on quantifying the origins of the performance gains across designs and versus temperature.
21. High-Dispersion X-ray Transmission Gratings for Space Research

Project Staff

J. Carter, R. C. Fleming, E. Murphy
(Dr. Mark L. Schattenburg, Profs. Claude R. Canizares and Professor Henry I. Smith)

Sponsors

NASA (Contract NAS8-38249), NOAA (through XOPT Inc.)

High-dispersion x-ray and EUV transmission gratings are fabricated for space missions including the Solar EUV Monitor (SEM) on the NASA Solar and Heliospheric Observatory (SOHO) mission, launched December 2, 1995, the NASA Chandra x-ray telescope, launched July 23, 1999, and the NOAA Geostationary Operational Environmental Satellites (GOES N, O, P, Q) missions. The Chandra telescope provides high-resolution imaging and spectroscopy of x-ray-emitting astrophysical objects, with unprecedented power and clarity, which is significantly widening our view of the Universe. The SOHO and GOES satellite series perform solar extreme ultraviolet (EUV) monitoring which provides early warning of solar flare events that could imperil satellite and astronaut operations.

Many hundreds of large-area, gold transmission gratings, with 200 nm and 400 nm periods, were required for the High-Energy-Transmission-Grating Spectrometer (HETGS) on Chandra, which provides high-resolution x-ray spectroscopy in the 100 eV to 10 keV band (see Fig. 59). In order to achieve spectrometer performance goals, the gratings need to have very low distortion (<200 ppm) and high-aspect-ratio structures, significantly pushing the state-of-the-art of nanofabrication (see Fig. 60). While the Chandra gratings were fabricated on thin (<1.0 µm) polymer membranes, the SOHO and GOES gratings need to be freestanding to transmit the softer solar spectrum, and are supported instead by a lithographically-patterned nickel mesh.

The need for high grating quality, and tight production deadlines, demand a robust, high-yield manufacturing process. Gratings are fabricated by interference lithography with tri-level resist, followed by cryogenic reactive-ion etching and gold electroplating. Additional masking steps followed by nickel plating fabricate the mesh support structure, and a chemical etching step yields mesh- or membrane-supported gratings suitable for space use. Additional processing is required to align and bond the gratings to frames. A simplified depiction of the process for fabricating membrane-supported gratings is shown in Fig. 61. The Space Nanotechnology Laboratory (SNL) has extensive facilities for high-yield volume production of transmission gratings. Gratings undergo extensive testing before assembly into space instrumentation.
Figure 59. Photograph of the HETGS flight instrument on the Chandra x-ray telescope, which consists a 1.0 meter-diameter aluminum wheel populated with hundreds of 200 nm and 400 nm-period gold x-ray transmission gratings (340 total).

Figure 60. Scanning-electron micrograph of a 200 nm-period HETGS gold x-ray transmission grating, cleaved to show line sidewalls.
Figure 61. Simplified depiction of HETGS grating fabrication process.
22 Super-smooth X-ray Reflection Gratings

Project Staff
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Sponsors
NASA (Grant NAG5-5105), Columbia University (NASA Contract NAS5-98037)

Grazing-incidence x-ray reflection gratings are an important component of modern high-resolution spectrometers and related x-ray optics. These have traditionally been fabricated by diamond scribing with a ruling engine, or more recently, by interference lithography followed by ion etching. These methods result in gratings which suffer from a number of deficiencies, including high surface roughness and poor groove profile control, leading to poor diffraction efficiency and large amounts of scattered light.

We are developing improved methods for fabricating blazed x-ray reflection gratings which utilize special (111) silicon wafers, cut ~1 degree off the (111) plane. Silicon anisotropic etching solutions, such as potassium hydroxide (KOH), etch (111) planes extremely slowly compared to other crystallographic planes, resulting in the desired super-smooth blaze surface. Previous work used similar off-cut (111) silicon substrates to fabricate blazed diffraction gratings. However, that method utilized a second KOH etch step that compromised the grating facet flatness and is unsuitable for small grazing-angle x-ray diffraction.

Our gratings are patterned using interference lithography with the $\lambda=351.1$ nm wavelength, and transferred into the substrate using tri-level resist processing, reactive-ion etching (RIE), and silicon-nitride masking during the KOH etch. The narrow (~100 nm) ridge of silicon which supports the nitride mask is removed using a novel chromium lift-off step followed by a CF$_4$ RIE trench etch. The result is extremely-smooth sawtooth patterns, which, after applying a thin evaporative coating of Cr/Au, are suitable for x-ray reflection (see Figure 62). Gratings have been tested with special x-ray spectrometers in the laboratories of our collaborators at Columbia University and the Lawrence Berkeley Laboratory. Peak gratings efficiencies achieved are ~35% greater than those of the best available ruled masters of comparable design (see Figure 63).

Potential applications of these improved gratings are for synchrotron studies and satellite-based high-resolution x-ray spectroscopy for planned NASA missions such as Constellation X. The current phase of the work involves patterning gratings on super-flat wafers, and trimming the substrates into the desired rectangular format.
Figure 62. (a) An AFM image of a traditional mechanically-ruled and replicated x-ray reflection grating (Bixler et al., Proc. SPIE 1549, 420-428 [1991]). Note the rough, wavy grating surfaces that lead to poor diffraction performance. (b) An AFM image of a blazed x-ray reflection grating fabricated by anisotropic etching of special off-cut (111) silicon wafers. Note the improvement of grating surface flatness and smoothness, leading to significantly improved performance.
Figure 63. Comparison of x-ray diffraction efficiency measured at Lawrence Berkeley Laboratory and electromagnetic finite element calculations performed at Columbia University. Peak gratings efficiencies achieved are ~35% greater than those of the best available ruled masters of comparable design.

23 UV-blocking Transmission Gratings Filters for Neutral Atom Imaging

Project Staff
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Sponsors
LANL (Contract G3630019-97), SwRI (Contract 83832)

Neutral-atom-beam imaging detectors are used to study dilute plasmas in astrophysical environments such as the magnetospheric regions of the Earth and other planets, and laboratory systems such as Tokamaks. Neutral atom emission can be a particularly useful probe of plasmas since neutrals travel in straight lines-of-sight, unperturbed by electromagnetic fields.

Charge-exchange interactions between Solar-wind particles and atoms in the Earth’s tenuous outer atmosphere are predicted to form strong currents of neutral atoms (mostly oxygen and helium) emanating from the Earth, which, if they could be imaged, would provide unprecedented real-time mapping of this complicated magnetohydrodynamic environment. This information would be valuable in order to safeguard the health of orbiting satellites, and ensure the stability of our nation’s electric power grid.
Unfortunately, sensitive orbiting neutral-beam detectors are easily overwhelmed by the bright flux of UV photons typically emitted from astrophysical plasmas (mostly the $\lambda=121.6$ nm emission from hydrogen and the 58.4 nm emission from helium). Filters that allow the passage of low-energy neutral atoms but block UV light are essential for the performance of this instrumentation (see Figure 64). Through several years of collaboration with the Los Alamos National Laboratory (LANL), the University of West Virginia, the University of Southern California, and the Southwest Research Institute (SwRI), we have developed neutral beam filters which consist of mesh-supported, 200 nm-period, gold transmission gratings with 30-60 nm wide slots (Figure 65). The tall, narrow slots in the gratings behave as lossy waveguides at or below cutoff, providing UV discrimination to particles on the order of millions.

The SNL was awarded contracts by SwRI and LANL to deliver a quantity of flight grating filters for the Medium Energy Neutral Atom (MENA) instrument on the NASA Magnetospheric Imaging Medium-Class Explorer (IMAGE) mission, launched March 25, 2000, and improved gratings for the NASA Two Wide-Angle Imaging Neutral-atom Spectrometers (TWINS A, B) Missions.

Gratings are fabricated by interference lithography with tri-level resist, followed by cryogenic reactive-ion etching and gold electroplating. Additional masking steps followed by nickel plating fabricate the mesh support structure, and a chemical etching step yields mesh-supported gratings suitable for space use. Additional processing is required to align and bond the gratings to frames.

*Figure 64.* Concept of UV filtering by means of a metal freestanding grating. As a result of polarization and waveguide effects, UV is blocked while allowing the passage of atoms. In this way, UV background counts on the atom detector are avoided.
Figure 65. Scanning-electron micrograph image of a UV blocking grating. Due to the narrow slot width of 30-35 nm, as shown in the picture, and the large slot depth (~500 nm), the UV transmission is extremely low ($10^{-6}$ to $10^{-7}$ at $\lambda = 121.6$ nm), while decreasing the transmitted atomic flux by only a factor of 10.

24 Transmission Gratings for X-ray and Atom-Beam Spectroscopy and Interferometry.

Sponsors
X-OPT, Inc.

Project Staff:
Timothy A. Savas, James M. Carter, Edward Murphy, Dr. Mark L. Schattenburg, and Professor Henry I. Smith

Transmission gratings with periods of 100 to 1000 nm are finding increasing utility in applications such as x-ray, vacuum-ultraviolet, and atom-beam spectroscopy and interferometry. Over 30 laboratories around the world depend on MIT-supplied gratings in their work. For x-ray and VUV spectroscopy, gratings are made of gold and have periods of 100 to 1000 nm, and thicknesses ranging from 100 to 1000 nm. The gratings are most commonly used for spectroscopy of the x-ray emission from high-temperature plasmas. Transmission gratings are supported on thin (1 micron) polyimide membranes, or made self supporting (“free standing”) by the addition of crossing struts (mesh). (For short x-ray wavelengths, membrane support is desired, while for the long wavelengths, a mesh support is preferred in order to increase efficiency.) Fabrication is performed by interference lithography combined with reactive-ion etching and electroplating. Progress in this area tends to focus on improving the yield and flexibility of the fabrication procedures.

Another application is the diffraction of neutral-atom and molecular beams by mesh supported gratings. Lithographic and etching procedures have been developed for fabrication of free-standing gratings and grids in thin silicon nitride (SiNx) membranes supported in a Si frame. Figure 66 shows a free-standing 100 nm period grating in 100 nm-thick silicon nitride. Figure 67
shows a 100 nm-period grid in a 100 nm-thick SiNx membrane. Such a grid is used in experiments as a "molecular sieve."

We have established a collaboration with the Max-Planck Institute in Göttingen, Germany, in which they utilize our gratings of 100 nm period in diffraction experiments using atomic, molecular, and helium-cluster beams. As shown in Figure 68 the diffraction of atomic and molecular beams reveals striking deviations from Kirchhoff’s optical diffraction theory. The analysis of the diffraction intensities allowed for a quantitative determination of the attractive atom(molecule)-surface van der Waals interaction at the silicon nitride surface for various atomic and molecular species including He, Ne, Ar, Kr, He*, Ne*, D2, and CH3F. The diffraction of cluster beams by a transmission grating has been established as a unique technique for the non-destructive mass selection and detection of small and weakly bound van der Waals clusters. Recently, the Göttingen group discovered bound states in mixed-isotope helium clusters, e.g. 3He4He2, 4He4He3, etc., by diffraction from one of our 100-nm-period gratings as shown in Figure 69. In addition, they employed the grating to measure the bond length of the helium dimer, 4He2, which is assumed to be the weakest molecular bond. Further experiments based on the transmission gratings include the study of cluster formation dynamics and the search for the Efimov effect in the helium trimer.

Data obtained by helium-atom-beam diffraction at large incident angles showed Lyman ghosts in the spectrum. This data led to the development of new fabrication techniques to improve the quality of the free-standing gratings in silicon nitride. Diffraction spectra from gratings made with the improved process show no Lyman ghosts, illustrating the important synergy between applications and nanofabrication.

Highly successful diffraction experiments with beams of buckyballs (C60) have been carried out with our 100 nm-period, free-standing SiNx gratings by Dr. Markus Arndt of the University of Vienna.

Our 100 nm-period free-standing SiNx gratings are also used for atom interferometry by two groups: those of Prof. David Pritchard of MIT and Prof. Bruce Doak of the State University of Arizona. Pritchard’s group interferes neutral beams of sodium atoms while Doak’s group interferes helium beams (performed at the Max Planck Institute in Göttingen, Germany in collaboration with P. Toennies).
Figure 66. Scanning electron micrograph of a free-standing 100 nm-period grating (50 nm-wide bars) in a silicon nitride membrane of area 500 microns by 5 mm.

Figure 67. Scanning electron micrograph of a free-standing 100 nm period grid in a silicon nitride membrane of area 500 micron by 5 mm. Such grids are used in experiments to separate out Helium trimers from other clusters.
Mixed $^4$He-$^3$He-isotope clusters discovered by diffraction from 100 nm-period-grating at $T_0 = 5$ K, $P_0 = 1$ bar.

Figure 68. Rare-gas atom-beam diffraction patterns. These results were obtained by Wieland Schöllkopf and Peter Toennies at the Max-Planck Institute in Göttingen, Germany, using a free-standing, 100nm-period grating.
Figure 69. Non-destructive mass separation of small mixed-isotope helium clusters. These results were obtained by Wieland Schöllkopf and Peter Toennies at the Max-Planck Institute in Göttingen, Germany, using a free-standing, 100nm-period grating.

25 Sub-100 nm Metrology Using Interferometrically Produced Fiducial Grids

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The ability to see and measure the results of a process is critical to advancing fabrication technology. Historically, the development of improved microscopy techniques led to rapid progress in microfabrication. Thus, the scanning-electron microscope was essential to the microelectronics revolution. Similarly, the scanning-tunnelling microscope is creating a revolution in the study of interfaces and nanostructures.

In the past, metrology of microstructures and the measurement of workpiece distortion (e.g., a photolithographic reticle or x-ray mask) has been based on point-by-point measurement through an optical microscope using an X-Y table monitored by a laser interferometer. Although this approach enables relative distances in a plane to be measured with 1 nm-level detectivity, it is
expensive, tedious, and subject to a number of shortcomings, including the necessity of placing rather perturbative marks on a workpiece. We have initiated a new approach to metrology for the sub-100 nm domain that is based on large-area fiducial grids produced by interference lithography. This new approach is complementary to the point-by-point approach in much the same way that aerial photogrammetry is complementary to ground-based land surveying for the mapping of terrain.

A key element in this new initiative is the holographic-phase-shifting interferometer (HPSI) interferometer, illustrated in Figure 70. This system, once it is fully developed, will enable us to measure in a global manner the in-plane distortion of a workpiece, provided one of its surfaces contains a shallow fiducial grid. Ideally, the grid on the workpiece will be created by interference lithography or a derivative thereof, such as near-field holography.

The Semiconductor Industry Association (SIA) roadmap calls for minimum features to shrink below 35 nm over the next 15 years, implying that planar metrology tools with errors below 1.0 nm will be required in the next decade (see Figure 71). We propose that interferometrically patterned grids are nearly ideal vehicles to this end. As part of this new initiative in sub-100 nm metrology, we are pursuing a variety of approaches to eliminate the distortion in interferometrically produced grids, decreasing the coefficient of the hyperbolic phase progression (a consequence of creating a grid by interfering spherical wavefronts), and increasing the useful area of fiducial grids.

One such approach is scanning-beam-interference lithography (SBIL), depicted schematically in Figure 72. The concept here is to combine the sub-1 nm displacement measuring capability of laser interferometry with the interference of narrow coherent beams to produce coherent, large-area, linear gratings and grids. Our ultimate goal is to produce gratings over areas many tens of centimeters in diameter with sub-nm distortion. These would be used to calibrate lithography tools or used directly as optical encoder scales, eliminating the laser interferometer and significantly improving performance while reducing cost.

SBIL requires sophisticated environmental controls to mitigate the effects of disturbances such as acoustics, vibration, and air turbulence, and variations of temperature, pressure, and humidity. The system also features real-time measurement and control of image phase using heterodyne fringe detection, acousto-optic modulator phase locking (see Figure 73), and a high-speed digital signal processor (DSP) controller (see Figure 74).
Figure 70. Schematic of the holographic phase-shifting interferometer (HPSI). A spherical wave back-diffracted from a shallow substrate grid, and a second wave specularly reflected, interfere on a fluorescent screen at the spatial filter. The fringes are imaged onto a CCD. By shifting the beam splitter with a piezo, a computer generates an X-Y map of phase error.
Figure 71. Semiconductor Industry Association (SIA) roadmap tracking critical dimension (CD) or minimum feature size, overlay error, mask image placement error, and metrology tool error. The MIT effort seeks to produce grating metrology standards with sub-nm errors, which would be used as planar metrology length scales or optical encoders in lithographic equipment, eliminating the laser interferometer.

Figure 72. Schematic of the scanning beam interference lithography (SBIL) system. A pair of narrow, distortion-free beams overlap and interfere at the substrate, producing a small grating “image.” The substrate is moved under the beams, writing a large area grating. Tightly overlapped scans ensure a uniform dose.
Figure 73. Schematic of SBIL acousto-optic (AO) modulator phase locking system. The phase of the grating image is measured by the small inner interferometer close to the writing surface. This information is processed by a digital signal processor and used to control RF frequency synthesizers which drive the AO modulators, thus locking the image phase to the moving substrate.

Figure 74. Schematic of SBIL system architecture. The system utilizes a frequency stabilized HeNe laser ($\lambda=632$ nm) and heterodyne interferometry to measure substrate position, and argon ion ($\lambda=351.1$) heterodyne interferometry to measure image fringe phase. Phase error signals are processed by an IXTHOS 4x167 MHz DSP board, which then drives the stage DC motors and the RF frequency synthesizer that controls the fringe-locking AO modulators.
26. Field Emitter Array Flat Panel Displays for Head-Mounted Applications

Sponsorship
Lincoln Laboratory - #BX-5956

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Advances in nanostructure technology have made feasible small, high-resolution, high-brightness and high-luminous-efficiency field-emitter-array sources for Head-Mounted Displays (HMDs). HMDs are expected to have a variety of applications in military, medical, commercial and entertainment fields. The technology most commonly used in deployed HMD systems is the CRT which is bulky, because of the use of a single electron gun to generate images on a cathodoluminescent screen, but has the most desirable attributes of high luminous efficiency, high brightness and easy image rendition. However, the relay optics required for see-through HMDs become complicated because of the bulky nature of the CRT. For other applications, such as entertainment virtual reality, the most commonly used image source is the backlit Active-Matrix-Liquid-Crystal Display (AMLCD), which is thin and has high resolution. Furthermore, the addressing electronics are integrated on the same substrate as the image source. However, the backlit AMLCD image source does not have sufficient brightness nor luminous efficiency to make it suitable for application to see-through HMDs.

Our approach to demonstrating a small, high-resolution, high-luminous-efficiency and high-brightness display is the field-emitter-array Flat-Panel Display (FED) which incorporates a high-density, high-performance array of low-voltage field emitters, as shown in Figure 75. CMOS-controlled electron emission from the tips impinges on a cathodoluminescent screen. It is thus possible to integrate the addressing and signal conditioning electronics on the same substrate as the Field Emitter Arrays (FEAs). The main advantage of this approach is the reduction of the number of wires and bond pads from about 2,000 to about 50. For example, it will be difficult to attach > 2,000 wires to bond pads in an area of 1.5” x 1.5” and obtain ultra-high vacuum in the display envelope. High resolution (>1000 dpi) FEDs are only possible if the addressing/driver and other signal conditioning electronics are integrated on the same substrate as the field emitter arrays.

Our initial objective is to demonstrate low-voltage field-emitter arrays fabricated using interferometric lithography for future integration with Si CMOS technology. Interferometric lithography is used to define the emitter cone arrays that are spaced 200 nm tip-to-tip and have <50 nm gate-to-emitter separation. Fabricated cone-field-emitter arrays with a 320-nm period have demonstrated emission currents of 1 mA at a gate voltage of 20V from 900 cones in a 10 µm x 10 µm area. This current is more than adequate for a brightness of 1000 fL at a screen voltage of 500V.

Our initial efforts focused on modeling the scaling behavior of FEA devices. Numerical simulation and computer models to predict FEA performance have been developed and continue to be refined. These models allow us to explore the effects of device scaling on the emitter’s output characteristics. The results of this study have directed our fabrication efforts toward devices whose performance will not only be better, but more dependent on geometries that can be well controlled in the manufacturing process. Simulation results indicate that we will be able to increase the current density and reduce the operating voltage, by decreasing the tip-to-tip separation to 200 nm.

FEAs of 200 nm period have been fabricated by using interferometric lithography and standard processing techniques. Additional metallization layers and conventional lithography were used to create discrete Molybdenum Spindt arrays for electrical characterization. The fabricated cones have similar size and structure to those simulated, Figure 76. Standard CMOS processing
techniques have been also been combined with the interferometric lithography to form 200 nm-period arrays of Si etched cones, Figure 77. TEM analysis of the oxidation sharpened emitter tips showed tips with radii as small as 2.5 nm, Figure 78.

A semi-automated Ultra High Vacuum (UHV) probe chamber has been developed for the electrical characterization of FEA s. This test bed allows the performance of the arrays to be evaluated without the lengthy overhead of vacuum packaging devices. Device performance has been shown to be not only dependent on the device physical structure, but also on surface contamination that may have resulted during fabrication and MEMS processing. The UHV probe chamber has the capability to do device conditioning including plasma surface cleans and wafer bake-out. The system is combine with a UHV Scanning Maxwell Microscope, and allows the future expansion to include other surface analysis chambers including a Kelvin Probe and Auger.

Electrical characterization of the 100 nm-aperture Molybdenum arrays and silicon arrays, (both 200 nm tip-to-tip spacing), has shown that arrays can operate at voltages as low as 16 volts and 13 volts respectively. We have demonstrated initial testing of low-gate-voltage FEA s with discrete solid state devices. We replace the resistor that previous approaches have used to limit and control emission current with a MOSFET. Current control is critical to the uniformity of brightness across the display. It was possible to control the emitted current density and increase temporal stability using the gate voltage of the transistor load. This may enable analog voltage gray scale or temporal gray scale, Figure 79.

The above demonstration has gone a long way to show the feasibility of high brightness, high-resolution FEA image sources for head-mounted displays.

Figure 75: Concept of a field emission display pixel. The display would use a 2D matrix addressable electron source allowing temporal and spatial modulation.
Figure 76: 100 nm gate aperture molybdenum field-emitter cones with chromium gate formed using a vertical evaporation.

Figure 77: 200 nm-period, 70 nm-aperture Silicon arrays with polysilicon gate. Array was formed by a rough cone formation, oxidation sharpening and CMP planarization.
$\sim 2.5 \text{ nm radius circle for comparison to tip}$

epoxy filler

$\sim$ uncertainty of edge $\sim 0.6 \text{ nm}$

Figure 78: TEM of sharpened silicon tip.

Figure 79: Silicon array anode current vs. MOSFET gate voltage showing control of over 3 orders of magnitude of the anode current with small variations in the MOSFET gate voltage. The temporal stability improves when in the MOSFET controlled regime.
27. Journal Articles, Published


27.1 Journal Articles, Submitted for Publication


27.2 Meeting Papers, Published


27.3 Meeting Papers, to be published:


27.4 Conference Presentations:

27.5 Theses:

