

Fabrication of Far-Infrared Anti-reflective Metasurfaces and Sub-wavelength Mirrors for Fabry Perots

CNF Project Number: 2458-16, 3337-26

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Primary Source(s) of Research Funding: Fred Young, National Science Foundation, NASA Goddard Space Flight

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Primary CNF Tools Used: ASML PAS 5500, Heidelberg MLA 150 Maskless Aligner, Unaxis 770 Deep Silicon Etcher, Oxford 81/82 Etchers, General Material Anneal 1 Furnace, Odd Hour E-beam Evaporator

Abstract:

Here we fabricate high-performance cryogenic far-infrared silicon-based optics for use in astronomical telescopes. We deep-silicon etch anti-reflective metasurfaces which achieve transmission $>90\%$ at 300GHz. We also pattern gold metal meshes on silicon using a bilayer LoR & photoresist, achieving a wire width of $<2\mu\text{m}$ with high yield.

Summary of Research:

There are two primary projects covered in this report, both of which share a similar goal of creating far-infrared optics for use for astronomical spectroscopy. The first project is fabrication of etalons for a scanning Fabry Perot, being installed on the Fred Young Submillimeter Telescope (FYST) in early 2027. The second project is fabrication of virtually imaged phase arrays (VIPAs), which are a high resolving power spectrometer. The VIPAs fabricated at the CNF will be used as flight hardware on a balloon-based observatory launching in 2029.

Project 1: The scanning Fabry Perot being used on FYST is made up of two silicon wafers with a gold mirror surface on one side, and a deep silicon etched anti-reflective metasurface on the other, shown in Figure 1. The anti-reflective surfaces improve transmission, as vacuum-silicon interfaces result in $\sim 30\%$ of the optical power to be reflected. The anti-reflective metasurface allows for transmission up to $\sim 95\%$. Figure 3 shows the major

fabrication steps to create these two-layer deep-silicon etched structures.

The mirror surface forms a light resonator cavity. The Q-factor (known as finesse) can be tuned by changing the reflectivity of the mirrors. Since the mirrors also need to be low-loss, we choose gold, the lowest loss mirror surface for operation at 4K. Reflectivity is tuned by varying the geometry of sub-wavelength metal mesh structures on the surface of the silicon etalon, as seen in Figure 3.

Project 2: Scanning Fabry Perots can achieve high transmission and high resolving power, however they are prone to vibrations, and require careful mirror alignment at cryogenic temperatures. For these reasons, a solid-state spectrometer is appealing, particularly for air-borne and space observatories. The Planetary Origins and Evolution Multispectral Monochromator (POEMM) mission is a balloon-borne 1.8m telescope using state-of-the-art spectrometers developed here at Cornell and fabricated at the CNF. The VIPA spectrometers are comprised of a highly polished block of silicon, with metal mesh mirrors deposited on both sides of the block. Figure 4 shows an optical diagram of an integrated

VIPA. Side R1 is a solid gold coating for maximum reflectivity, while R2 is a tunable reflective metal mesh (similar to Figure 3). However, these VIPAs operate a shorter wavelength, making the sub-wavelength (generally $\lambda/3$) metal meshes more difficult. We therefore adopt a rounded metal mesh to reduce current density and improve fabrication yield.

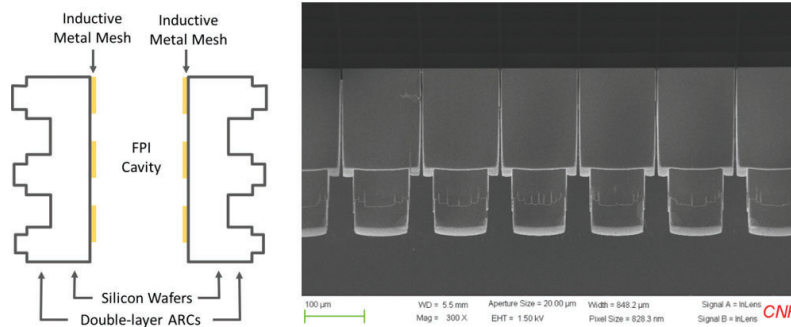


Figure 1: (left) Fabry Perot cavity design (right) cross-sectioned deep silicon etched anti-reflective 'coating' (ARC) metasurfaces.

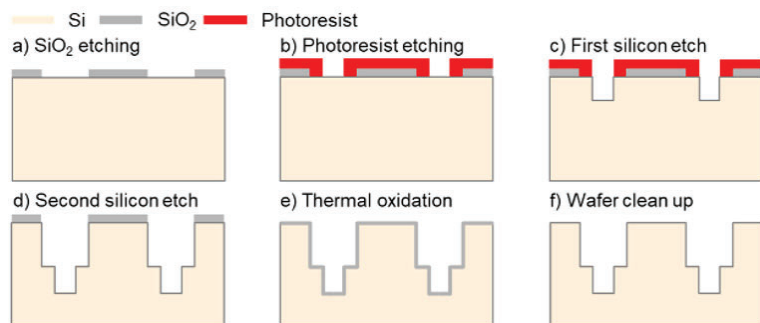


Figure 2: Anti-reflective metasurface fabrication overview.

Conclusions and Future Steps:

Through the end of 2026, we plan to finish fabrication of 150mm Fabry Perot etalons for use on the Fred Young Submillimeter Telescope, being deployed in January 2027. Significant development still needs to be done for fabrication of the VIPA spectrometers. VIPA is particularly difficult to fabricate on due to the substrate's abnormal thickness and shape. Custom fixturing is needed for every step of the fabrication process. This is also anticipated to be completed with flight-ready hardware by end of 2026.

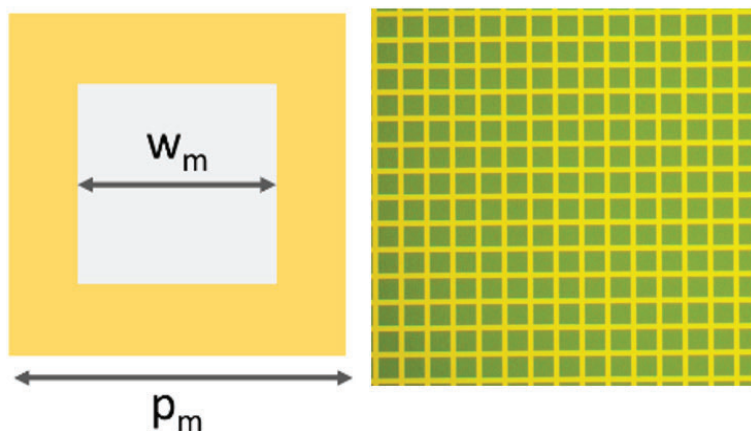


Figure 3: (left) metal mesh mirror surface unit cell (right) fabricated gold mesh on silicon.

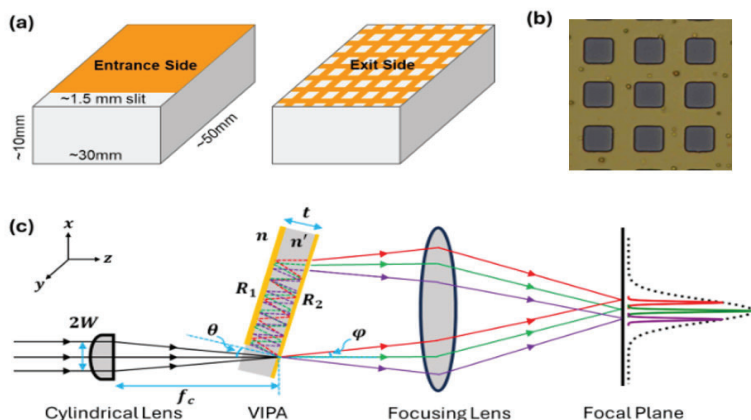


Figure 4: (a) VIPA silicon block (b) fabricated metal mesh pitch=10um (c) VIPA optical diagram.

On-chip Si₃N₄ Gyroscope Enhanced by Ultra-High Weak Value Amplification

CNF Project Number: 2524-17

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Primary CNF Tools Used: ASML stepper, Suss Gamma Resist Cluster, Oxford 100 Inductively coupled plasma reactive ion etching (ICP-RIE), Oxford 82, Oxford PECVD, Furnace B1, E4, AJA Sputter, SEM Gemini, Veeco Icon AFM, PT VLN Deep Silicon Etch

Abstract:

We demonstrated that the performance of on-chip optical gyroscope can be addressed by applying weak value amplification, which resolves an intrinsic trade-off in the optical gyroscope that the sensitivity increases with the size of the gyro.

Summary of Research:

From everyday navigation using smartphones to controlling the attitude of satellites, modern society increasingly relies on gyroscopes that can precisely track motion in real time while being compact enough to minimize device size. Although optical gyroscopes have demonstrated superior motion detection sensitivity compared to traditional MEMS gyroscopes, they typically face a fundamental tradeoff: increased sensitivity with larger size 1–5. We address this trade-off by employing the weak value amplification (WVA) method, enabling the development of small yet highly sensitive on-chip optical gyroscopes.

We integrate the weak value device, which has demonstrated a signal amplification of 30 dB₆, with a Sagnac interferometer coupled to a ring resonator (Fig 1). The rotating ring resonator generates an optical phase difference between the counter-propagating light due to the Sagnac effect. The weak value device (the left half of the device) can “concentrate” the phase difference information into the dark port (D1, D2) of the Sagnac interferometer, so that the amount of detected light and the resulting shot noise are both reduced, while the detected signal intensity is maintained. Therefore, the weak value amplified interferometer can allow more light participating in the phase sensing up to a point that the detector is saturated, which effectively increases the signal-to-noise ratio. With the phase signal amplified by the 30 dB WVA, a compact optical gyroscope can obtain

a resolution comparable to that of a 35 times bigger gyro without WVA. This enhancement thus resolves the trade-off between the footprint and the resolution intrinsic to any optical gyro based on Sagnac effect. Moreover, different from the regular interferometric gyroscope 3,5,7, the weak value amplified gyroscope naturally has a maximized response to the Sagnac phase without any phase bias used to operate at the interferometer quadrature. Therefore, the weak value enhanced gyro can be operated with a lower cost and in a more compact space by removing the modulation and demodulation electronics, which are required by the regular gyroscopes to produce a quadrature bias.

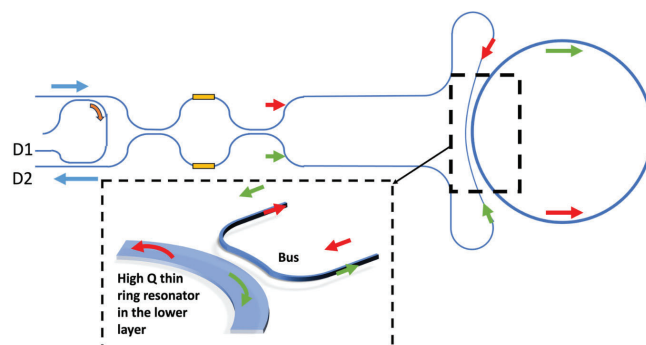


Figure 1: A schematic of the weak value enhanced gyroscope. Inset shows the two-layer structure of the ring-bus coupling.

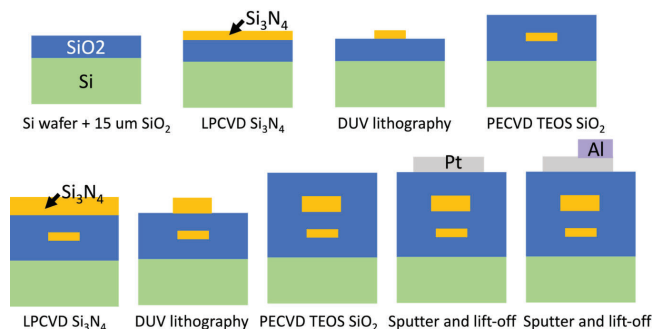


Figure 2: Main fabrication steps.

We fabricate the on-chip optical gyroscope on a CMOS compatible silicon nitride platform. The fabrication process (Fig.2) begins by depositing a ~ 60 nm Si_3N_4 layer using the low-pressure chemical vapor deposition (LPCVD) on top of a 15-um thermal-grown SiO_2 layer as shown in Figure 2. We pattern 5-um ring resonator waveguides with the ASML DUV lithography and etch with OXFORD 100 (inductively coupled plasma reactive ion etcher). The high-aspect-ratio waveguide structure lowers the light propagation loss and thus makes a high-Q ring. The cladding is a 1.5 um SiO_2 layer deposited by OXFORD PECVD with the TEOS recipe. Next, we deposit another 300 nm Si_3N_4 layer using LPCVD to pattern the rest waveguides, including the bus and the interferometer supporting weak value amplification, which requires more confinement and are less sensitive to loss. The cladding is a 3-um TEOS PECVD silicon oxide layer. The PECVD oxide layers are annealed in B1 furnace to outgas the Hydrogen-related impurities. Then, we pattern the microheaters with ASML DUV photolithography. Then, we sputter 10 nm Titanium as an adhesion layer and another 100 nm Pt with AJA sputter. The metal residues remaining on the photoresist are then removed using acetone under sonication to finalize the formation of microheaters on the chip. In order to make pads compatible with wire bonding, we further pattern with the ASML and sputter 1um Al pads at the end of the Pt circuits with 10nm Ti adhesive layer underneath. The liftoff is again done by resist removal in the acetone with sonication. We etch SiO_2 next to the waveguide input tapers with OXFORD 100 to create vertical facets for fiber-to-chip-edge coupling. Si is etched by Bosch process with VLN Si deep etcher to further deepen the facet trench to accommodate fibers.

Conclusions and Future Steps:

We have successfully integrated the weak value amplification with the on-chip optical gyroscope devices. Our future research aims to demonstrate the enhancement in gyroscope performance by weak value amplification.

References:

- [1] Lefevre, H. C. The Fiber-Optic Gyroscope, Second Edition. (Artech House, 2014).
- [2] Dell'Olio, F., Natale, T., Wang, Y.-C. & Hung, Y.-J. Miniaturization of Interferometric Optical Gyroscopes: A Review. *IEEE Sensors Journal* 23, 29948–29968 (2023).
- [3] Feng, C. et al. Interferometric Integrated Optical Gyroscope Based on Silicon Nitride Waveguide Ring. *IEEE Sensors Journal* 24, 23781–23788 (2024).
- [4] Huffman, T., Davenport, M., Belt, M., Bowers, J. E. & Blumenthal, D. J. Ultra-Low Loss Large Area Waveguide Coils for Integrated Optical Gyroscopes. *IEEE Photonics Technology Letters* 29, 185–188 (2017).
- [5] Gundavarapu, S. et al. Interferometric Optical Gyroscope Based on an Integrated Si_3N_4 Low-Loss Waveguide Coil. *Journal of Lightwave Technology* 36, 1185–1191 (2018).
- [6] Mei, Y., Song, M., Jordan, A. N. & Cardenas, J. 30 dB on-chip ultra-high inverse weak value amplification. *Opt. Lett.*, OL 51, 3293–3296 (2026).
- [7] Ma, H., He, Z. & Hotate, K. Reduction of Backscattering Induced Noise by Carrier Suppression in Waveguide-Type Optical Ring Resonator Gyro. *Journal of Lightwave Technology* 29, 85–90 (2011).
- [8] Bauters, J. F. et al. Ultra-low-loss high-aspect-ratio Si_3N_4 waveguides. *Opt. Express*, OE 19, 3163–3174 (2011).

Waveguide vs Quantum Well Emission in AlGa_N-Based Deep-Ultraviolet LEDs on Bulk AlN Substrate

CNF Project Number: 2801-19

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Primary CNF Tools Used: PT770 ICP-RIE, Oxford PE-ALD, E-beam evaporator, AS 200 I-line stepper, Heidelberg MLA, Ultra SEM, PE-CVD, Woollam RC2 ellipsometer.

Abstract:

Deep-ultraviolet (DUV) laser diodes (LDs) emitting in the UV-C wavelengths of 100–280 nm have the potential to enable applications such as bio/chemical sensing, disinfection, and medical treatment. While electrically injected AlGa_N UVC laser diodes have been recently reported with a quantum well active region grown by metal-organic chemical vapor deposition (MOCVD) [1] and nanowires by molecular beam epitaxy (MBE) [2], laser diodes with AlGa_N quantum wells grown by MBE on bulk AlN substrates in the wavelength range below 280 nm have not yet been reported. Here, we report an MBE-grown AlGa_N laser-diode heterostructure on bulk AlN that sustains continuous-wave current densities exceeding 4 kA/cm² and exhibits a transition of spontaneous emission from the waveguide (~265 nm) to the quantum well (~281 nm). We also investigate the mechanism responsible for QW population and radiative recombination transition using simulation. This study is a step towards realizing low-threshold current density AlGa_N-based DUV laser diodes by MBE.

Summary of Research:

Fig. 1(a) shows the device heterostructure grown by nitrogen plasma-assisted MBE. The AlGa_N epilayers on the bulk AlN substrate along the (0001) direction. Fig. 1 (b)-(c) summarize the characterization of the as-grown MBE films including X-ray diffraction symmetric and asymmetric scans. Quasi-vertical circular diodes from the heterostructure were fabricated on the sample, with a schematic shown in Fig. 2(a). The devices sustain continuous-wave current densities up to 3 kA/cm² at ~15 V without observable degradation, as shown in Fig. 2(b).

The room temperature electroluminescence spectra show that at low current density, the emission is dominated

by a waveguide peak near 265 nm. With increasing injection, a longer-wavelength quantum well emission near 281 nm emerges and progressively dominates. Spectral deconvolution in Fig. 3(b) shows that the quantum well peak wavelength remains nearly constant with current, while the waveguide peak exhibits only a small redshift, indicating minimal self-heating. The integrated intensities in Fig. 3(c) reveal a clear crossover from waveguide to quantum well-dominated emission at ~3.1 kA/cm², indicating current-driven carrier redistribution into the quantum well. The corresponding light–current–voltage characteristics in Fig. 3(d) show a monotonic increase in optical output without rollover up to 4.2 kA/cm², confirming stable high-current operation required for UVC laser diodes [1,3].

To identify the mechanism limiting waveguide-quantum well carrier redistribution, self-consistent drift diffusion simulations using SiLENSe were performed. The radiative recombination profile in Fig. 4(a) shows that in the low-injection regime for 4.4–4.8 V bias voltages, the dominant recombination region shifts from the waveguide to the quantum well with increasing bias. The corresponding hole distribution in Fig. 4(b) reveals that this transition is driven by increased hole population in the quantum well, enabled by carrier pile-up near the polarization-induced barriers and gradual quantum well filling. In contrast, the electron concentration in Fig. 4(c) is already high and weakly bias dependent. This identifies hole-limited transport as the bottleneck for efficient quantum well recombination.

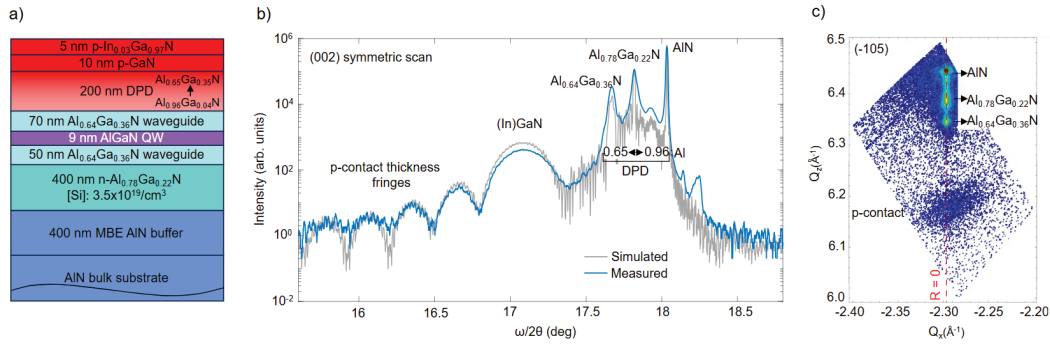


Figure 1: a) Layer structure of the AlGaIn heterostructure grown by MBE on metal polar bulk AlN substrate. b) Symmetric X-ray diffraction scan used to determine the AlGaIn composition in the structure. c) Asymmetric reciprocal space map (RSM) to confirm the AlGaIn layers are pseudomorphically grown on the substrate.

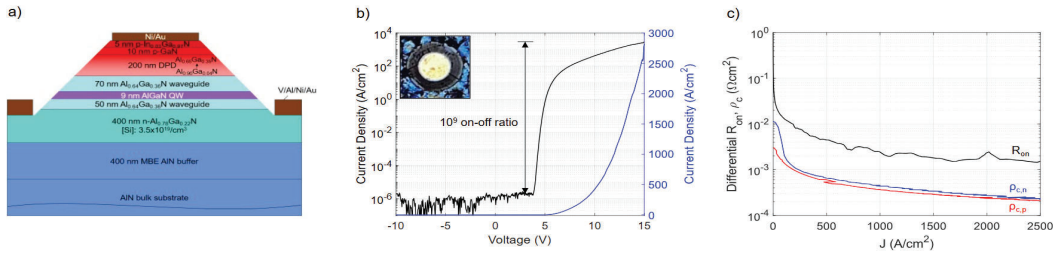


Figure 2: a) Schematic of the cross section of the fabricated circular LED. b) Linear and log-scale current density vs voltage of a 30 μm anode LED, shown in the inset. c) Differential ON-resistance of the same diode from (b), and p- and n-type specific contact resistances from rectangular TLM measurements.

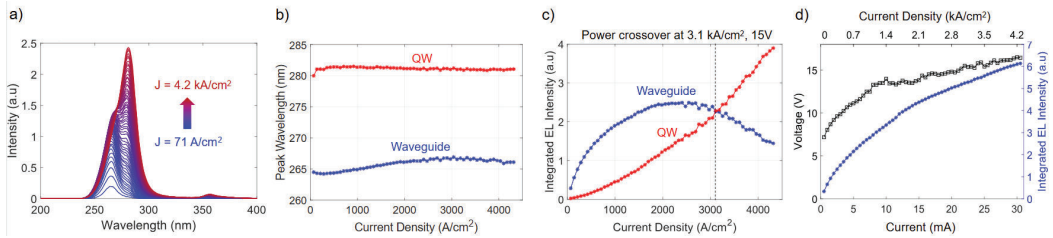


Figure 3: (a) CTLM-IV curves comparison of p-contact without undergoing n contact anneal, after undergoing n-contact anneal with SiO₂ cap, and after undergoing n-contact anneal without SiO₂ cap. IVs are plotted for 2 μm spacing. (b) Resistance vs metal electrode spacings for the data shown in (a).

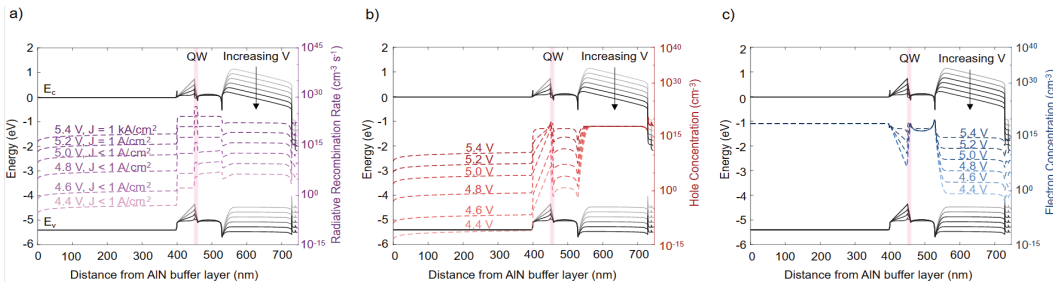


Figure 4: (a) Room temperature J-V characteristics of two LEDs, one with SiO₂ capping method and one without. The differential ON-resistance was extracted at 400 A/cm². (b) IV from batch test of LEDs with and without SiO₂ capping. (c) Room temperature electroluminescence of an LED with the SiO₂ capping method. Inset shows the microscopy image of a fabricated LED.

Conclusions and Future Steps:

To further reduce the current density needed to achieve population inversion and lasing in the device, further structure optimization to reduce the hole injection will be investigated.

References:

- [1] Z. Zhang et al., Appl. Phys. Expr. 12, 124003 (2019).
- [2] S. Zhao et al., Appl. Phys. Lett. 109, 191106 (2016).
- [3] Z. Zhang et al., Appl. Phys. Lett. 121, 222103 (2022).

Programmable Poling for Electric Field Induced Second Harmonic Generation

CNF Project Number: 2971-21

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Primary CNF Tools Used: Oxford PECVD, Oxford 100 ICP Dielectric, ASML DUV Stepper

Abstract:

Nonlinear photonics uses coherent interactions between optical waves to engineer functionality that is not possible with purely linear optics. Traditionally, the function of a nonlinear-optical device is determined during design and fixed during fabrication, which limits the scope and flexibility of its use. Here, we present a photonic device with an arbitrarily reconfigurable distribution of $\chi^{(2)}$ nonlinearity. To showcase the versatility of our device, we show mixing of different spectral, spatial, and polarization modes through three-wave mixing. Furthermore, we show that a programmable $\chi^{(2)}$ can adapt to nontrivial underlying waveguide geometries to synergize the linear and nonlinear behavior. Our work shows that we can transcend the conventional one-device-one-function paradigm, expanding the potential applications of nonlinear optics in situations where fast device reconfigurability is not merely practically convenient but essential—such as quantum light sources, all-optical signal processing, and optical computation.

Summary of Research:

Lithography-free photonics has attracted considerable attention in the field of programmable photonics because the large number of programmable parameters allows the device to move beyond the one-device-one-function paradigm. This means lithography-free devices can perform a large range of tasks and compensate for fabrication error [1]. Recent advances in lithography-free technology have enabled a device with real index of refraction modulation on-chip. This device relies on a lithium niobate waveguide and photoconductor electrically in series, which allows spatially patterned illumination to induce a refractive index pattern of the same shape. This device has enabled one of the largest purely optical on-chip matrix vector multiplications by

utilizing active optimization [2]. Using the same device concept, the core material can be replaced with silicon nitride, which possesses a large induced $\chi^{(2)}$ during an electric-field-induced second harmonic (E-Fish) process. This enables lithography-free programmable nonlinear photonics [3].

By engineering $\chi^{(2)}$ quasi-phase matching (QPM) gratings on a channel waveguide, we realized versatile functions on a single device, flexibly controlling nonlinear optical processes in the spectral, spatial, and polarization domains. The programmability of the device further enabled in-situ inverse designs and optimizations based on real-time experimental feedback, robustly achieving complex functions that are challenging on conventional non-programmable devices. Specifically, we demonstrated the advantage of real-time optimization by phase-matching nonlinear processes on waveguides that periodically change their width and long, spiral waveguides. These experiments show the scalability, versatility, and highly multi-mode capabilities of programmable nonlinear optics to expand the capabilities of future platforms all while maintaining high device yield.

Continuous-Wave Three-Wave Mixing:

To fabricate the nonlinear programmable slab waveguide, we started with a conductive P-type Si substrate with 1 μm of thermal SiO_2 and 2 μm of PECVD SiNx . We then deposit 1 μm of PECVD SiO_2 as a hard mask and pattern photoresist on top using an ASML stepper. We then etch the SiO_2 hard mask, followed by an etch of the SiNx waveguide. Afterwards, we deposit an additional 1 μm of PECVD SiO_2 , anneal at 1200 $^\circ\text{C}$ for 8 hours, and deposit Si-rich SiN as the photoconductor. The process is finished by sputtering an ITO electrode on the very top and cleaving the waveguide facets open. By applying high voltage to the device stack and selectively

activating the photoconductor with patterned illumination, we can control the electric field distribution (and through the E-FISH effect, the induced $\chi^{(2)}$ nonlinearity) in the SiNx waveguide. Figure 1 shows a diagram of the device's operating principle and potential tasks that a programmable $\chi^{(2)}$ enables.

Figure 2 shows some of the classical nonlinear processes that can all be accomplished on one device. Specifically, we show broadband second harmonic generation, sum frequency generation, difference frequency generation, and polarization mixing through Type-0, Type-I, and Type-II processes. Our experiments show a tunable fundamental harmonic bandwidth of 130 nm, which is limited by the laser implemented in these experiments.

Phase-Matching on Complex Underlying Waveguide Geometries:

While the previous demonstrations were presented on straight waveguide geometries, our approach to programmable $\chi^{(2)}$ can be extended to more complex geometries. As Figure 3 shows, we can use real-time experimental feedback to partition a waveguide structure into many pieces and actively scan the grating period and grating phase on each piece to achieve optimal performance. This technique requires minimal information about the underlying waveguide geometry and can be adapted to a broad bandwidth of pump wavelengths. We then extend this real-time optimization technique to 10.1 cm long spiral waveguides and demonstrate increased nonlinear conversion efficiency over longer phase-matching distances. Furthermore, we show that the phase-matching grating can be adapted to different wavelengths over a 130 nm bandwidth without sacrificing nonlinear performance. This shows that, despite the lower magnitude of the induced $\chi^{(2)}$ compared to existing platforms, real-time optimization shows a path to scale the performance of programmable devices over longer propagation lengths. Moreover, because the $\chi^{(2)}$ pattern can be adapted to waveguides with spatially varying width, linear optical properties can be augmented with complex nonlinear functionalities.

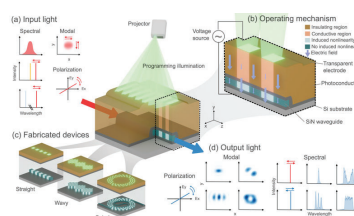


Figure 1: Overview of device operating principle and capabilities. (a) Possible types of fundamental harmonic inputs. (b) Schematic of how programmable illumination induces a programmable $\chi^{(2)}$ nonlinearity. (c) Different waveguide geometries presented in this work. (d) Possible output second-harmonic modes generated in the programmable nonlinear waveguide device.

Figure 2: Continuous-wave experiments. (a) Cartoon diagram of experiment used to show second harmonic generation (SHG), difference frequency generation (DFG), and sum frequency generation (SFG). Experimental results for SHG (b), DFG (c), and SFG (d). (e) Shows the cartoon diagram for polarization mixing experiments, with the results shown in (f).

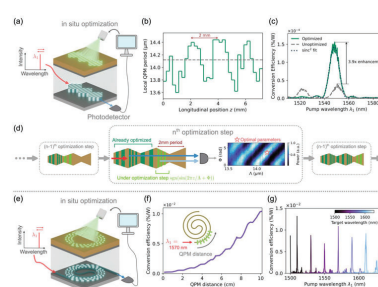
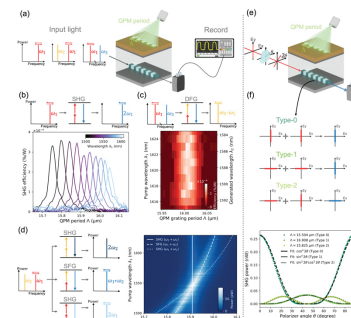


Figure 3: Phase-matching non-straight waveguide geometries. (a) Experimental diagram for phase-matching waveguides with periodically changing width. (b) Optimized phase-matching period at each partition and (c) nonlinear transfer function for optimized and un-optimized phase-matching gratings. (d) Shows the optimization routine that uses real-time experimental feedback to improve nonlinear performance. (e) Experimental diagram for phase-matching long, spiral waveguides. (f) and (g) show the scaling of SHG and broadband tunability capabilities of phase-matching a 10.1 cm long spiral.

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References:

- [1] P. L. McMahon, Nature Reviews Physics 5, 717 (2023).
- [2] T. Onodera, M.M. Stein, B.A. Ash, M.M. Sohoni, M. Bosch, R. Yanagimoto, M. Jankowski, T. P. McKenna, T. Wang, G. Shvets, M. R. Shcherbakov, L.G. Wright, and P.L. McMahon, Arbitrary control over multimode wave propagation for machine learning. Nat. Phys. 22, 164–171 (2026).
- [3] R. Yanagimoto, B.A. Ash, M.M. Sohoni, M.M. Stein, Y. Zhao, F. Presutti, M. Jankowski, L.G. Wright, T. Onodera, P.L. McMahon, Programmable on-chip nonlinear photonics. Nature 649, 330–337 (2026).

Programmable Inverse-designed Devices

CNF Project Number: 2971-21

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Primary Source(s) of Research Funding: National Science Foundation (award CCF-1918549)

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Primary CNF Tools Used: Oxford PECVD, PVD75 Sputter, Disco Dicing Saw

Abstract:

Inverse design has emerged as a powerful approach in nanophotonics, enabling compact devices with complex functionalities that are difficult to realize using conventional hand-designed layouts. Yet its practical scale remains limited by discrepancies between simulated and real-world devices, long and costly fabrication iterations, and the inflexibility of static lithographic devices. Here we demonstrate an in situ inverse-design platform based on a two-dimensionally programmable thin-film lithium niobate slab waveguide. Patterned illumination of a photoconductive layer redistributes the electric field across the chip, producing optically controlled electro-optic modulation that sculpts the refractive-index distribution over $\sim 10,000$ programmable regions. This architecture removes the need to fabricate a new nanostructure for each function and enables reconfiguration in 1.5 s with no known rewriting limit. Using the same physical device, we realized diverse photonic functions without the need to modify existing device or optical setup, including 4×4 mode permutations with -28 dB crosstalk, 4×4 Hermite–Gaussian mode demultiplexing with -15 dB crosstalk, 8×8 mode permutations, and matrix–vector multiplication. We also demonstrated in situ trained broadband operation from 1500 nm to 1600 nm and wavelength demultiplexing of 1310 nm and 1550 nm signals. Such a programmable platform could also enable applications for reconfigurable and on-chip spatial modulation in optical telecommunications. Our in situ way of inverse design can also extend to conventional inverse design to improve performance.

Summary of Research:

Integrated photonics enables compact, scalable, and energy-efficient systems for communications, sensing, signal processing, and computing. However, conventional photonic devices are typically assembled

from hand-designed components whose footprints, fabrication sensitivity, and performance constraints limit their scalability. Inverse design addresses these limitations by using computational optimization to explore large design spaces and discover compact, non-intuitive structures[1]. Nevertheless, conventional inverse design still depends on accurate numerical simulation followed by sophisticated cleanroom fabrication and experimental characterization. As device complexity increases, computational costs grow rapidly, simulation–experiment gaps become more significant, and repeated fabrication cycles become increasingly expensive[2]. Moreover, lithographically defined devices are fixed after fabrication, preventing post-fabrication correction and limiting their ability to perform multiple or changing functions.

Programmable photonics offers a route to overcome these constraints by allowing device behavior to be modified and optimized after fabrication. Here, this capability is realized using a two-dimensionally programmable thin-film lithium-niobate slab waveguide whose refractive-index distribution is controlled by patterned illumination of a photoconductive layer[3], as shown in Figure 1. Experimental measurements are incorporated directly into the optimization loop through physics-aware training, enabling the programmed index pattern to adapt to the actual device rather than relying solely on simulation. The platform can be reconfigured in approximately 1.5 seconds and supports repeated programming without a known rewriting limit. Using a single chip, it implements 4×4 and 8×8 mode permutations, Hermite–Gaussian mode demultiplexing, matrix–vector multiplication, wavelength-independent operation from 1500 to 1600 nm, and wavelength demultiplexing between 1310 and 1550 nm. These demonstrations establish in situ inverse design as a promising approach for rapidly creating diverse photonic functions while reducing fabrication iterations and the simulation–reality gap.

Inverse-designed Single-wavelength Devices

At an operating wavelength of 1550 nm, the programmable waveguide was in situ inverse-designed to implement several representative spatial transformations, including 4×4 and 8×8 Gaussian-mode permutations, 4×4 Hermite–Gaussian mode demultiplexing, and 4×4 matrix–vector multiplication. The results are shown in Figure 2. During training, each input mode was generated sequentially, the corresponding output intensity was measured, and the illumination pattern was optimized using a loss function that promoted coupling to the desired output while suppressing the largest crosstalk channel. The optimization converged within approximately 7–20 minutes, achieving maximum crosstalk values of -27 dB for the 4×4 permutation, -15 dB for Hermite–Gaussian demultiplexing, and -13 dB for the 8×8 permutation. The platform also reproduced ten independently trained random matrices, demonstrating that the same physical device can be reprogrammed to perform general linear transformations.

Inverse-designed Broadband Devices

The same in situ inverse-design approach was extended to produce wavelength-independent operation across the 1500–1600 nm telecommunications band. Rather than optimizing the device at only one wavelength, the training loss combined experimental performance measured at 1500 and 1600 nm, encouraging a single illumination pattern to satisfy the target transformation at both spectral endpoints. This method was applied to random matrix generation, 4×4 and 8×8 mode permutations, and Hermite–Gaussian mode demultiplexing, with performance characterized across the full 100 nm range at 1 nm resolution. The results are shown in Figure 3. The 4×4 permutation maintained crosstalk below -20 dB, while the Hermite–Gaussian demultiplexer and 8×8 permutation remained below approximately -10 dB, demonstrating that in situ optimization can suppress wavelength-dependent dispersion and preserve device functionality over a broad optical bandwidth.

Inverse-designed Wavelength Demultiplexer

In contrast to the broadband devices, which were optimized to behave similarly across wavelength, the wavelength demultiplexer was designed to deliberately exploit dispersion and route 1310 nm and 1550 nm signals to different output channels. A task-specific digital model was trained using illumination patterns and experimental measurements collected at 1550 nm, with augmented patterns introduced to capture device distortions and improve model robustness. During physics-aware training, the two laser wavelengths were

injected sequentially through a shared optical path, and the measured losses at both wavelengths were combined so that the programmed pattern simultaneously directed each wavelength toward its designated output. The results are shown in Figure 4. The resulting two-channel wavelength demultiplexer achieved a maximum crosstalk of approximately -9 dB.

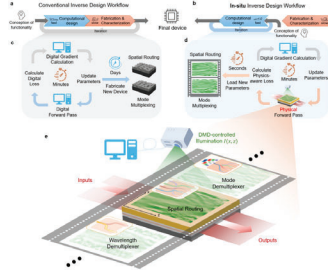


Figure 1.

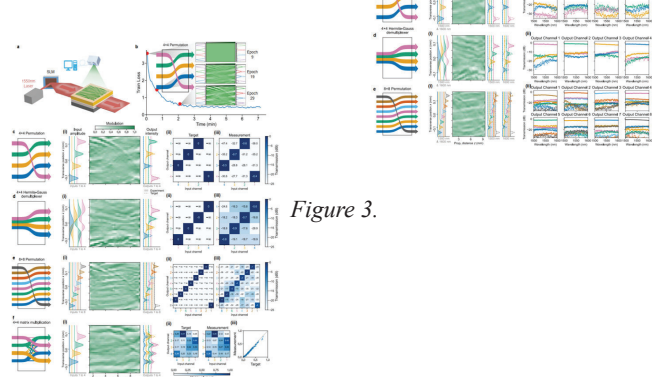


Figure 2.

Figure 3.

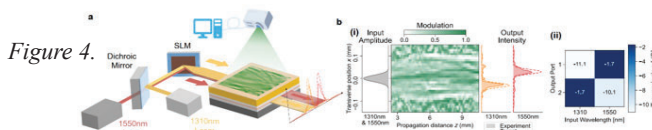


Figure 4.

Acknowledgements:

PLM gratefully acknowledges financial support from a David and Lucile Packard Foundation Fellowship.

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References:

- [1] P. L. McMahon, *Nature Reviews Physics* 5, 717 (2023).
- [2] T. Onodera, M.M. Stein, B.A. Ash, M.M. Sohoni, M. Bosch, R. Yanagimoto, M. Jankowski, T. P. McKenna, T. Wang, G. Shvets, M. R. Shcherbakov, L.G. Wright, and P.L. McMahon, Arbitrary control over multimode wave propagation for machine learning. *Nat. Phys.* 22, 164–171 (2026).
- [3] R. Yanagimoto, B.A. Ash, M.M. Sohoni, M.M. Stein, Y. Zhao, F. Presutti, M. Jankowski, L.G. Wright, T. Onodera, P.L. McMahon, Programmable on-chip nonlinear photonics. *Nature* 649, 330–337 (2026).

Suspension Free Acousto-optic Modulator for Near Ultraviolet and Visible Wavelength

CNF Project Number: 2985-21

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User(s): Oscar Jaramillo (1, 2), Hamim Mahmud Rivy (1)

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Primary Source(s) of Research Funding: NSF

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Research Group Website: <https://sites.coecis.cornell.edu/mehta/>

Primary CNF Tools Used: Heidelberg Mask Writer - DWL2000, Heidelberg MLA 150 Maskless Aligner, ASML PAS 5500/300C DUV Wafer Stepper, Metticon, Zeiss Ultra SEM, PT770 Etcher, Woollam RC2 Spectroscopic Ellipsometer, AFM, Furnaces, Oxford PECVD, Keyence VHX-7100 Digital Microscope and Oxford FlexAL.

Abstract:

In this work, we fabricate and characterize suspension-free inter-modal acousto-optic modulator for light modulation near $\lambda = 397$ nm, by taking advantage of a surface acoustic wave mode confinement that is co-localized with the optical mode in a buried optical waveguide. Optical confinement is achieved using waveguides fabricated from the $(\text{HfO}_2)_{0.67}(\text{Al}_2\text{O}_3)_{0.33}$ composite, while surface acoustic waves are confined vertically by SiO_2 and laterally by AlN trenches.

Summary of Research:

Acousto-optic modulators (AOMs) are widely used for frequency, phase, and amplitude modulation in a broad range applications including microwave to optical signal processing [1], quantum information control [2] and atomic physics. Their ability to modulate light with a high extinction ratio (~ 70 dB), fast switching times (tens of nanoseconds), high optical power handling (tens of milliwatts), and wide frequency tunability (tens of megahertz) has made them an inseparable component in atomic physics laboratories. However, conventional bulk AOMs have a relatively large footprint because the acoustic field is not tightly confined to the optical mode. In addition, they typically require 1-10 W of RF drive power, limiting their scalability and compatibility with photonic integrated circuits. To address these limitations, several on-chip AOM platforms have been demonstrated but most of them rely on suspended optomechanical waveguides and limited at telecommunications wavelengths ($\lambda \approx 1550$ nm), which limits power handling, makes them possibly incompatible with low temperature operation and limits integration with a cryogenic ion trap chip [3-6]. In addition, the use of non-standard CMOS materials

and fabrication processes, presents challenges for large-scale integration in commercial foundries. Moreover, the material platforms explored to date generally exhibit significant optical loss at ultraviolet (UV) and visible wavelengths, which are essential for a wide range of applications, including biochemical spectroscopy and quantum control of trapped ions, neutral atoms, and solid-state quantum systems [7,8]. Here, we design and fabricate a material platform which aims to maximize the overlap coupling coefficient by engineering co-propagating acoustic an optical waveguide leveraging surface and lateral acoustic guiding.

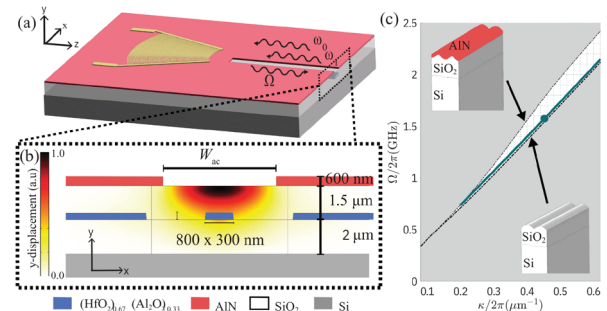


Figure 1: a) Schematic of a release-free AOM with co-confined acoustic and optical modes. b) Cross section showing the dominant (y) displacement of a confined acoustic mode. c) Dispersion of guided mode with top (bottom) light-cone of a $\text{AlN}+\text{SiO}_2$ (SiO_2) RM.

The AOM (shown in Fig.1) is composed of a $(\text{HfO}_2)_{0.67}(\text{Al}_2\text{O}_3)_{0.33}$ multi-mode optical waveguide buried in 1.5 μm of SiO_2 and a 600 nm thick film of sputtered AlN used to launch a counter-propagating acoustic wave via a focusing inter-digitated transducer (Fig. 1a). The film stack-up supports a surface acoustic wave Rayleigh mode (top inset of Fig. 1c), which together with an etched trench of width W_{ac} on AlN , creates a confined acoustic mode that overlaps with the buried optical waveguide (Fig. 1b). This dominant

displacement of the Rayleigh mode along the y-direction, which shifts the top and bottom boundaries of the optical mode, couples the TE₀₀ and the TE₀₁ modes at $\lambda = 397$ nm (optical modes are shown in Fig.2).

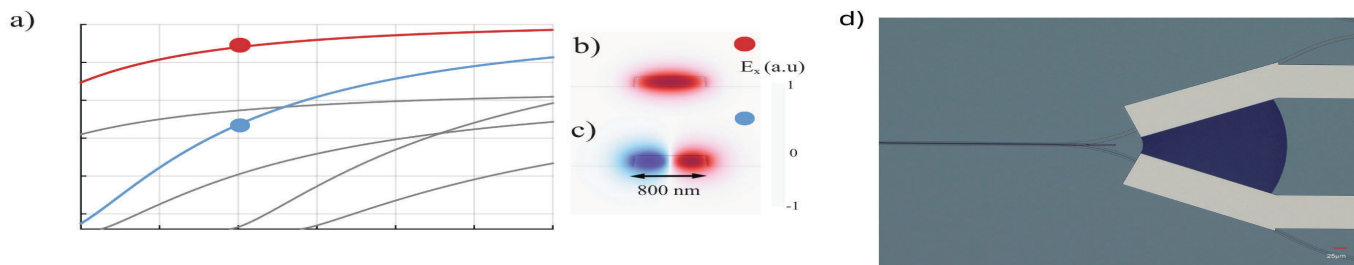


Figure 2: Figure 7.2: a) Effective index of a 300 nm thick waveguide and varying width. b) TE₀₀ mode and c) TE₀₁ mode. d) Micrograph of the fabricated device.

We fabricated the device in CNF. To fabricate the device (shown in Fig. 1) in, we deposit 300 nm thin layer of thermal $(\text{HfO}_2)_{0.67}(\text{Al}_2\text{O}_3)_{0.33}$ composite on a silicon substrate $2 \mu\text{m}$ of thermal SiO_2 by atomic layer deposition (ALD). The optical waveguides are photolithographically patterned by using an ASML 248 nm DUV photolithography system. After that, we deposit a thin layer of thermal Alumina via thermal ALD followed by an approximately $1.5 \mu\text{m}$ of TEOS SiO_2 deposition. The TEOS SiO_2 is planarized to remove the surface morphology by chemical-mechanical polishing (CMP). Next, we deposit 600 nm of AlN as active piezo-electric layer and pattern the electrodes via photolithography followed by 200 nm Aluminum evaporation and lift-off. Finally, the acoustic waveguides are patterned via direct-write lithography. The micrograph of the fabricated device is shown in Fig. 2d.

The preliminary measurements of these fully fabricated devices demonstrate transducer-waveguide coupling efficiency $|\eta| = 17.5 \pm 0.23$ dB and waveguide loss $\alpha_{\text{wg}} = -16.8 \pm 0.8$ dB/mm. In addition, we measured acousto-optic modulation efficiency -35 dB (our best measured devices) for RF drive power of 63 mW, for devices with 400 μm interaction length. The measured modulation efficiency is significantly lower than the theoretical prediction, possibly due to phase mismatch between the optical and acoustic waves. Theoretical calculations predict complete mode conversion at an RF drive power below 3 mW under ideal phase-matched conditions.

In future, we will focus on improving the acousto-optic modulation efficiency by optimizing phase matching between the optical wave and acoustic wave by accurately characterizing the material properties of TEOS, reducing the acoustic and optical waveguide loss and by incorporating new device geometry and acoustic transducer design.

Conclusions and Future Steps:

We have successfully integrated the weak value amplification with the on-chip optical gyroscope devices. Our future research aims to demonstrate the enhancement in gyroscope performance by weak value amplification.

References:

- [1] Andrews, R. W. et al. Bidirectional and efficient conversion between microwave and optical light. *Nat. Phys.* 10, 321–326 (2014).
- [2] Verhagen, E., Deléglise, S., Weis, S., Schliesser, A. & Kippenberg, T. J. Quantum-coherent coupling of a mechanical oscillator to an optical cavity mode. *Nature* 482, 63–67 (2012).
- [3] C. J. Sarabalis, R. Van Laer, R. N. Patel, Y. D. Dahmani, W. Jiang, F. M. Mayor, and A. H. Safavi-Naeini, “Acousto-optic modulation of a wavelength-scale waveguide,” *Optica* 8, 477–483 (2021).
- [4] L. Zhang, C. Cui, P.-K. Chen, and L. Fan, “Integrated-waveguide-based acousto-optic modulation with complete optical conversion,” *Optica* 11, 184–189 (2024).
- [5] E. A. Kittlaus, W. M. Jones, P. T. Rakich, N. T. Otterstrom, R. E. Muller, and M. Rais-Zadeh, “Electrically driven acousto-optics and broadband non-reciprocity in silicon photonics,” *Nat. Photonics* 15, 43–52 (2021).
- [6] Q. Lin, S. Fang, Y. Yu, Z. Xi, L. Shao, B. Li, and M. Li, “Optical multi-beam steering and communication using integrated acousto-optics arrays,” *Nat. Commun.* 16, 1–7 (2025).
- [7] D. J. Blumenthal, “Photonic integration for UV to IR applications,” *APL Photonics* 5 (2020).
- [8] G. Moody, V. J. Sorger, D. J. Blumenthal, P. W. Juodawlakis, W. Loh, C. Sorace-Agaskar, A. E. Jones, K. C. Balram, J. C. Matthews, A. Laing et al., “2022 roadmap on integrated quantum photonics,” *J. Physics: Photonics* 4, 012501 (2022).

Direct Growth of Crack-free Stoichiometric Silicon Nitride on Sapphire for Wide-band Photonics

CNF Project Number: 3190-24

Principal Investigator(s): Xiyuan Lu

Affiliation: University of Maryland College Park

Primary Source(s) of Research Funding: National Institute of Standards and Technology

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Primary CNF Tools Used: LPCVD and Anneal Furnaces, Ellipsometry (WOOLLAM), Electron Beam Lithography (JEOL, Stepper (ASML), Reactive Ion Etcher (OXF80), Scanning Electron Microscope

Abstract:

This report summarizes the technical achievements of our research on the growth of silicon nitride (Si_3N_4) films on sapphire substrates. We successfully demonstrated the deposition of crack-free stoichiometric Si_3N_4 films up to 2 μm thick using low-pressure chemical vapor deposition (LPCVD). The residual stress in these films was measured to be only 200 MPa, in contrast to the typically higher stresses observed in Si_3N_4 grown on silicon. This advancement enables the effective fabrication of photonic devices with low optical losses of 0.25-0.37 dB/cm across a wide spectrum, enhancing the viability of Si_3N_4 for broad photonic applications.

Summary of Research:

Silicon nitride on insulator structures has been a pivotal component in the development of photonic integrated circuits, mainly due to its advantageous optical properties. However, the residual tensile stress associated with Si_3N_4 films grown on silicon can lead to cracking, especially at thicknesses above 400 nm. This study focuses on the use of sapphire substrates, which possess a higher coefficient of thermal expansion (CTE) than silicon, to alleviate this stress.

Figure 1 summarizes the growth and stress data. Stress characterization of LPCVD silicon nitride (Si_3N_4) on a sapphire substrate (SiNoSa) shows significantly lower stress levels compared to Si_3N_4 on a silicon substrate (SiNoSi). SiNoSa can be grown crack-free up to at least 2 μm thickness without substrate modification. In contrast, SiNoSi easily cracks for films between 350 nm to 400 nm thick, with cracking occurring beyond 600 nm and making growth challenging without modification at thicknesses over 1000 nm. Various approaches

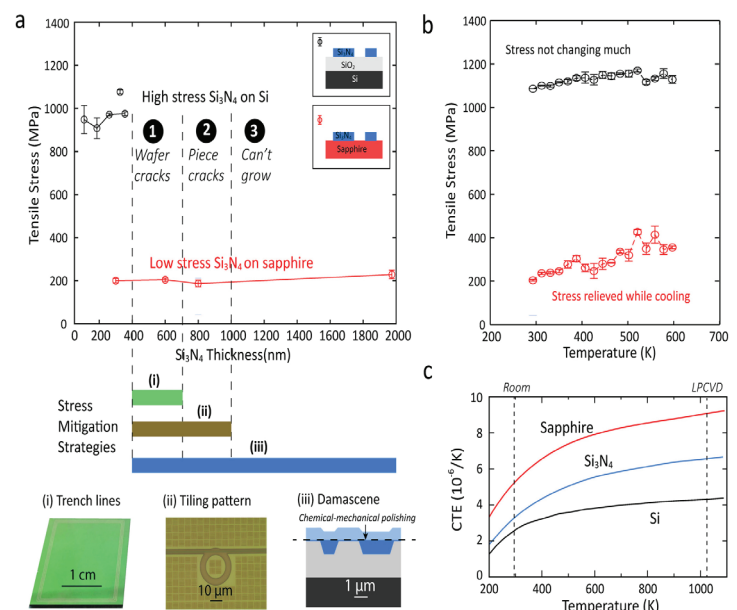


Figure 1.

have been employed for stress mitigation in SiNoSi:

1. Trench lines are effective for film thickness from 400 nm to 700 nm.
2. Tiling patterns incorporating features of 10 μm to 100 μm help reduce stress accumulation in unpatterned areas and facilitate thickness up to 1000 nm with better reproducibility across wafers.
3. Damascene processing allows for the growth of thicker films, reaching levels up to 2 μm , typically followed by chemical mechanical polishing and often used in conjunction with tiling patterns for crack termination.

Temperature-dependent stress measurements for both SiNoSa and SiNoSi indicate notable differences in behavior between the two substrates, confirming that the Sa help to relax the tensile stress and therefore prevent the cracks.

We conducted comprehensive experiments using LPCVD techniques to deposit Si_3N_4 on sapphire. Our results confirmed the ability to grow crack-free films up to 2 μm in thickness. Stress analysis revealed significantly lower residual stress levels when sapphire was utilized as a substrate.

References:

- [1] Z. Ma, X Lu, D. Westly, and K. Srinivasan, "Direct growth of crack-free thick stoichiometric silicon nitride films on sapphire for wide-band photonics" CLEO: Science and Innovations, SM4B. 3 (2026).

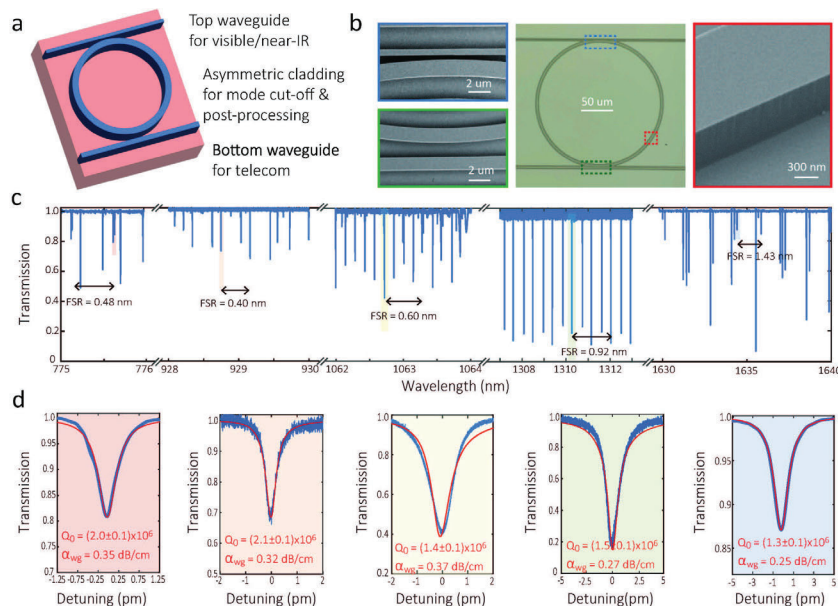


Figure 2.

Figure 2 summarizes the optical characterization of the devices we fabricated. Notably, our findings demonstrate propagation losses of 0.35 dB/cm at 780 nm, 0.37 dB/cm at 1064 nm, and 0.25 dB/cm at 1630 nm, matching or surpassing those of Si_3N_4 on silicon substrates.

Utilizing advanced techniques such as ellipsometry and prism coupling measurements, we characterized the optical properties and confirmed low optical losses across various wavelengths. Device fabrication through microring resonators illustrated the practicality of this growth method, showcasing high intrinsic optical quality factors.

Far UVC LED Project

CNF Project Number: 3281-25

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User(s): Madhav Ramesh, Jay VanDelden

Affiliation: Visium

Primary Source(s) of Research Funding: Company funds

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Research Group Website: <https://visium.one/>

Primary CNF Tools Used: Heidelberg MLA, Angstrom e-beam evaporator, PT770 etcher, GCA i-line stepper

Abstract:

Far UVC light (~ 222 nm or ~ 5.6 eV) is excellent at disinfecting the air and surfaces indoors, while being relatively harmless to humans. Light emitting diodes (LEDs) are efficient devices with a small footprint; they can be made to be $\sim 10\times$ to $100\times$ smaller than the width of a human hair. There are several challenges in realizing far UVC LEDs requiring. Thus, developing and researching these devices has far reaching implications and relevance for disinfection technology. At the CNF, we are developing a process for AlGaIn based p-n diodes on bulk AlN substrates towards far UVC LEDs for commercial disinfection applications.

Summary of Research:

LEDs are p-n diodes which involve direct bandgap semiconductors, typically crystalline in nature. To emit in the ~ 5 eV to 6 eV range, aluminum gallium nitride (AlGaIn) is an excellent material candidate with widespread research already existing particularly in the UV A,B,C regimes (235 to 400 nm) [1-3]. In this project, we developed a process to turn crystalline material epitaxially grown at Visium Ultralabs into fully functional LEDs at the CNF, starting with wavelengths in the far UV-C (200 nm - 235 nm) regime. The cross section of the epitaxially grown structure is shown in Figure 1.

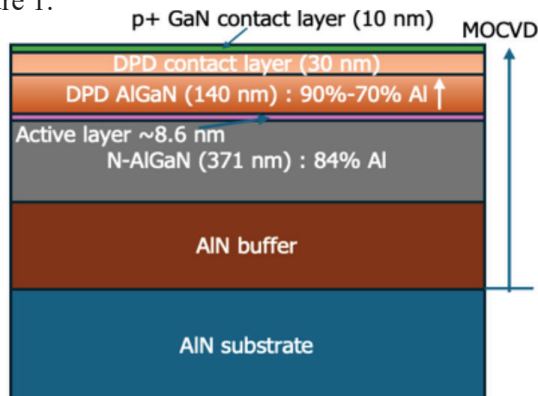


Figure 2: Cross section of epitaxially grown LED heterostructure based on aluminum gallium nitride (AlGaIn).

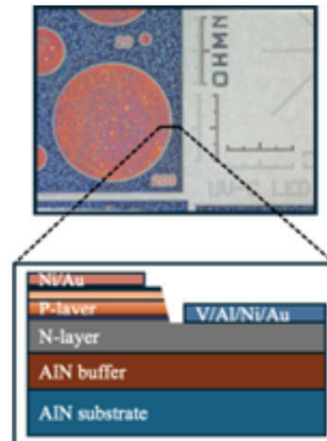


Figure 2: Top view optical image of LEDs and cross section schematic.

The structure essentially comprises p-type and n-type AlGaIn layers with high Al composition ($>70\%$ on average across the thickness) grown on an AlN substrate. These substrates provide a wide range of advantages including low dislocation density, superior thermal management, and high crystal quality. The structure was then processed in the cleanroom by dry etching, metal deposition by electron beam evaporation and rapid thermal annealing to form LEDs as indicated in Figure 2. Here, a top view optical image along with a cross section is shown. Subsequently, these LEDs were tested by electrical probing and the current-voltage (I-V) characteristics are shown in Figure 3. The diode seems to exhibit a turn ON voltage between 5-6 V, characteristic of high-quality high AlGaIn p-n diodes. The reverse leakage is also exceptionally low, with the current close to the noise floor of the instrument over a wide range of voltages. Subsequently, these diodes were tested for electroluminescence by flowing different currents and observing the light emission spectrum which is shown in Figure 4. These LEDs made at the CNF are a great initial demonstration of functionality and are the first of many more to come.

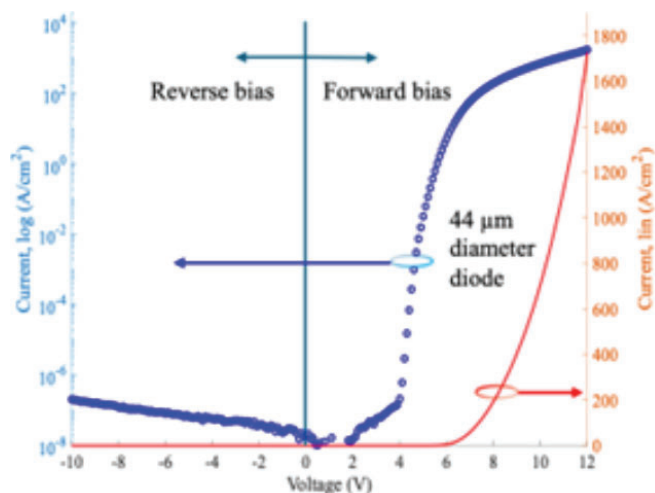


Figure 3: Current-voltage (I - V) characteristics in the log (left) and linear (right) scales, showing low reverse leakage and high on current.

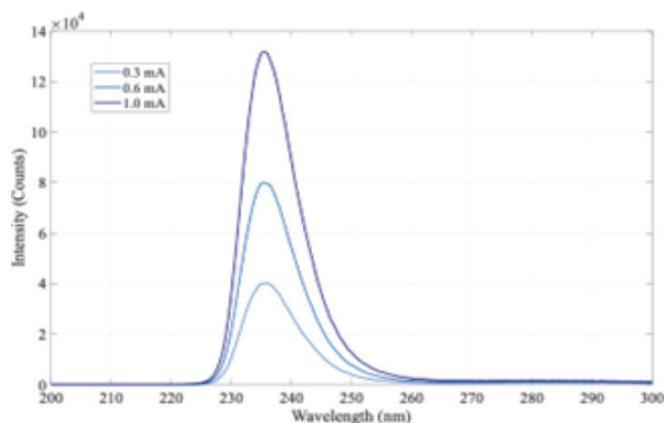


Figure 4: Electroluminescence spectra at different current injection for the processed LEDs.

Conclusions and Future Steps:

We have demonstrated functional LEDs emitting in the UV-C regime, a significant step towards developing efficient ~ 222 nm emitting devices for disinfection. Ongoing effort and future work involve wafer-scale processing of LEDs on AlN substrates, optimization of n-type and p-type contacts, and packaging.

References:

- [1] Dabing, et al. Adv. Opt. Photonics. 10.1 (2018): 43-110.
- [2] Kneissl et al. Nat. Photonics. 13.4 (2019): 233-244.
- [3] Jing, et al. Adv. Electron. Mater. 11.1 (2025): 2300840.

Lithographic Phase Masks for Spatial Control of Squeezed Light

CNF Project Number: 3309-25

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User(s): Dong Beom Kim

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Primary Source(s) of Research Funding: Startup funding

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Primary CNF Tools Used: Heidelberg MLA150 maskless aligner, Oxford 81 reactive ion etcher, AJA sputtering deposition system

Abstract:

We have fabricated low-loss silica-based phase plates to induce coherent phase control onto light. This is a preliminary step towards broader spatial-mode control of squeezed light.

Summary of Research:

In this project, we are developing a coherent control scheme for shaping quantum light. Recent work from our group points to the possibility that, by sending spatially phase-modulated light into a nonlinear medium such as a fiber, quantum statistical properties such as squeezing can be steered into different transverse modes supported by the fiber [1]. These modes can be filtered out by means of a phase plate at the output of the fiber. In particular, one wants to reflect the light exiting the fiber off a phase plate which imparts a phase profile corresponding to a higher-order mode, and then pass it through a lens and pinhole to filter out higher-order modes. A phase plate is created by etching variable thicknesses into silica to introduce position-dependent phases, hence the need for nanofabrication. The use of phase plates is important because it enables filtering out a particular higher-order mode with very little loss, as low as 5 or 10%. In contrast, if an SLM is used to do output filtering, although one has greater control over the output beam profile, the combined reflection and diffraction losses would be at best 15% but are often larger in practice. By keeping loss confined to 10%, it enables observing levels of squeezing up to 10 dB below the shot noise level.

The phase plates are created in house at Cornell NanoFacility by photolithographic etching of silica wafers. An example of phase plates that we have produced in order to isolate the first two higher-order modes of a GRIN fiber, and their superpositions, are shown in Fig. 1. In particular, by making SiO₂-Cr-photoresist trim-layer structures and wet/dry etching with Cr-etchant photolithography.

The next steps are now to perform the quantum light measurements: our new lab now has demonstrated capabilities to send spatially-phase-modulated femtosecond pulses through nonlinear fibers, and perform the needed mode-filtering with the phase plates. We are now working to demonstrate squeezing of controllable spatial modes.

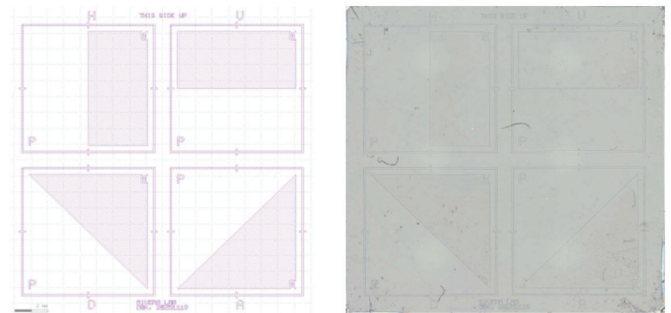


Figure 1: Preliminary results on phase plate nanofabrication. (Right) layout and (Left) microscope images of phase plates we have produced based on photolithography. The plates are designed such that the one half of the phase plate imparts a phase shift of π relative to the other for light with a wavelength of 1550 nm. The two plates on the top are designed for high efficiency filtering of the first two higher-order "dipolar" modes of a graded index multimode fiber with orientations in the x and y (top-bottom) directions respectively. The plates on the bottom isolate superpositions of the x- and y- oriented higher-order modes.

References:

- [1] Sloan, Jamison, et al. "Programmable control of the spatiotemporal quantum noise of light." arXiv preprint arXiv:2509.03482 (2025).

End-to-end Design of a Diffractive Optical Element

CNF Project Number: 3319-25

Principal Investigator(s): Kristina Monakhova

User(s): Hasindu Kanaththage

Affiliation: Ann S. Bowers College of Computing and Information Science, Cornell University

Primary Source(s) of Research Funding: Startup funds

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Research Group Website: <https://kristinamonakhova.com/>

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, Zygo Optical Profilometer, Hamatech HMx900

Abstract:

Diffractive optical elements (DOEs) designed through end-to-end optimization of optics and a reconstruction network can encode task-specific features during imaging, improving downstream performance of the task. However, fabricating DOEs with high precision is a challenging task. This work addresses the fabrication of a DOE ($6.9 \text{ mm} \times 6.9 \text{ mm}$) designed for a depth-from-defocus task, with $1 \text{ } \mu\text{m} \times 1 \text{ } \mu\text{m}$ lateral resolution, and a maximum feature height of $1.19 \text{ } \mu\text{m}$. The DOE is fabricated via grayscale lithography using an MLA150 maskless aligner on S1813 photoresist spin-coated onto fused silica. A 256-step test pattern is used to calibrate the contrast curve relating gray level to feature height, correcting for the nonlinear response of the photoresist. However, grayscale exposure with the MLA150 introduces periodic stitching artifacts ($\sim 50 \text{ nm}$, $\sim 4\%$ of maximum feature height), degrading height accuracy even after calibration. To mitigate this, an n-over exposure method is applied, in which the pattern is exposed multiple times with small lateral shifts to average out stitching error. Using this method, artifact height is reduced to $5\text{--}10 \text{ nm}$ ($0.4\text{--}0.8\%$ of maximum feature height), yielding significantly improved height fidelity across gray levels.

Summary of Research:

The goal of the research is to fabricate a diffractive optical element (DOE) which is designed using end-to-end optimization of optics and reconstruction network for a specific task (e.g., depth estimation). The designed DOE is able to encode task-specific features during the imaging process which allows the reconstruction network to perform better on the task. However, fabricating the designed DOE with a high precision remains a challenging task.

This work focuses on fabrication of a DOE designed for a depth-from-defocus task. The imaging setup consists of a single lens, a DOE, and a sensor. During

the imaging, two images of the same scene are captured by defocusing the lens. These two images are used to estimate the scene depth using a bio-inspired depth estimation network [1]. In the design phase, the captured images are rendered using differentiable ray tracing and wave propagation through the imaging optics. The rendered images are fed to the depth estimation network and the result is compared with a ground truth depth map to compute the error. A gradient based optimizer is used to optimize the phase map of the DOE and the parameters of the depth estimation network to minimize the error.

The designed DOE is $6.9 \text{ mm} \times 6.9 \text{ mm}$ in size with a lateral resolution of $1 \text{ } \mu\text{m} \times 1 \text{ } \mu\text{m}$ and a maximum feature height of $1.19 \text{ } \mu\text{m}$. The fabrication process starts with spin coating a fused silica wafer with S1813 photoresist at 4500 rpm . The coated wafer is baked at 115°C for 60 seconds. Then the photoresist is exposed using the MLA150 maskless aligner. Grayscale lithography is used as the exposure method with 256 gray levels.

Prior to the fabrication of the actual DOE, a test pattern is used to calibrate the contrast curve for grayscale lithography. The test pattern is a step structure with 256 steps, each corresponding to one gray level. Initially, the wafer is exposed with multiple copies of the test pattern, each using a different base laser dosage. The exposed wafer is developed using AZ 726MIF developer in the Hamatech HMx900. Developed test patterns are measured using the Zygo optical profilometer. Using the measurements, an appropriate base laser dose is selected which covers a wide range of gray levels without saturating the height response. The measurements showed a noisy, nonlinear relationship between the gray level and feature height. By fitting a curve to the measurements, the contrast curve is calibrated to obtain a linear height variation with gray level.

However, despite the calibration, the height variation remained noisy due to severe stitching artifacts introduced by the MLA150 during the exposure. These

artifacts appeared every 40 μm with a height of ~ 50 nm ($\sim 4\%$ of the max height). To reduce this, we used the n-over method, in which the photoresist is exposed n times with lateral shifts to average out stitching artifacts. We currently use a recipe with a base dose of 2200 mJ/cm², maximum power of 19%, and 4 exposures (each shifted by 10 μm). This reduced the stitching artifact height to a range within 5-10 nm ($\sim 0.4\%$ - 0.8% of the max height), resulting in a less noisy height variation with gray level.

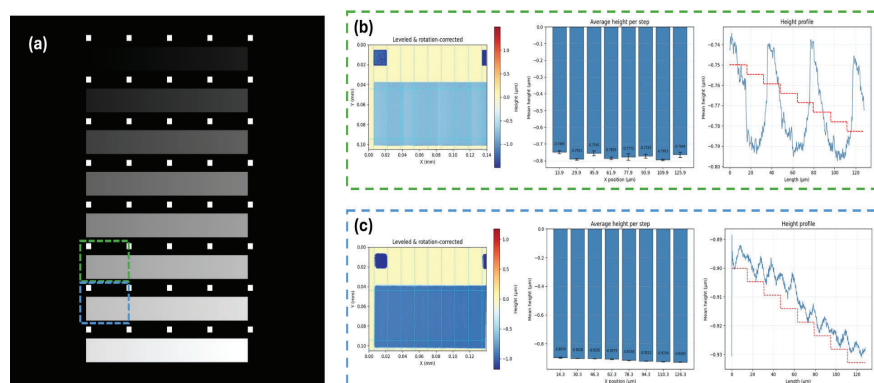


Figure 1: (a) Test pattern used for the contrast curve calibration. (b) and (c) show the profilometer measurements from sections of the (b) single exposure, and (c) 4-over exposure test patterns. Each subfigure shows the 2D height profile (left), mean step heights for the shown sections (middle), and the variation of mean height along the shown sections (right).

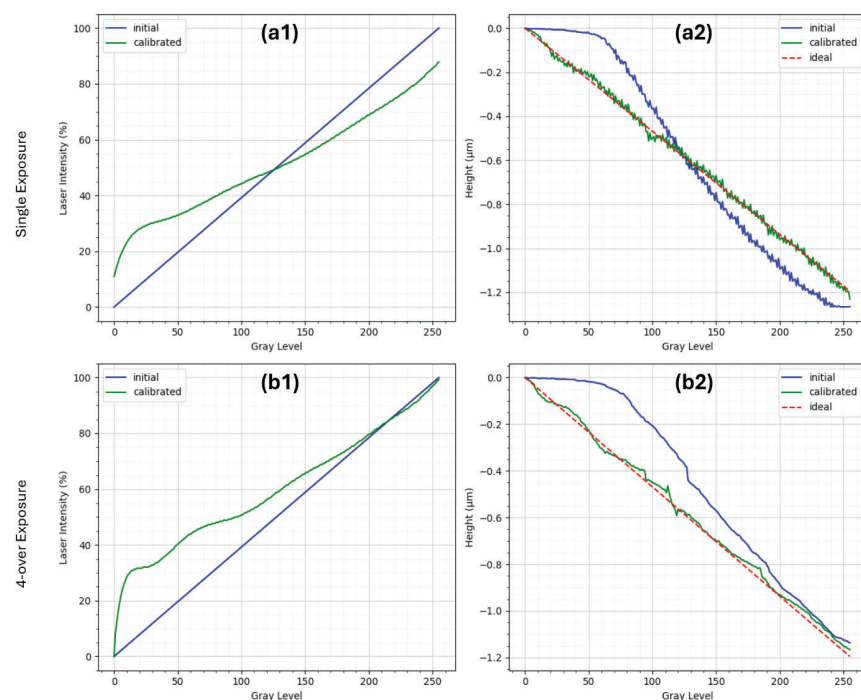


Figure 2: Contrast curve calibration and height response for the test pattern with single exposure (top row) and 4-over exposure (bottom row). (a1) and (b1) show initial and calibrated contrast curves. (a2) and (b2) show the initial and calibrated height response curves for the two exposure settings. The single exposure is performed with a base dose of 1334 mJ/cm² and 100% maximum power. For the 4-over exposure, a base dose of 2200 mJ/cm² and 19% maximum power is used.

Conclusions and Future Steps:

Grayscale lithography provides a faster method of fabricating diffractive optical elements with high precision. MLA150 allows grayscale lithography with 256 gray levels, but introduces severe stitching artifacts during the exposure. We use the n-over method to expose the wafer with shifted versions of the same pattern to reduce these artifacts. Through this method, our process brings down the stitching artifact height more than 5 times leading to much smoother feature height variations. The future work includes transferring the test pattern to the wafer using the Oxford 100 ICP-RIE etcher, calibrating the etching recipe, and fabricating the final diffractive optical element.

References:

- [1] Ferreira, Marcos A., et al. "SpiderCam: Low-Power Snapshot Depth from Differential Defocus." Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. 2026.

Cathodoluminescent Evaluation: Validating a Broadband Cathodoluminescent Technology for 193 Nanometer Photoresist Processing

CNF Project Number: 3350-26

Principal Investigator(s): Tom Dunbar

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Primary Source(s) of Research Funding: United States Economic Development Administration, with New York State matching support, through Syracuse University's New York Smart I-Corridor Tech Hub Collaboration and Commercialization Center New York Tech Hub Resources and Innovation Vouchers Program

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Primary CNF Tools Used: ABM Mask Aligner

Abstract:

Work at the Cornell NanoScale Science and Technology Facility evaluated whether a broadband cathodoluminescent source emitting near 190 nanometers could produce an actinic response in photoresist intended for 193 nanometer processing. A four-inch wafer carrying a 36–39 nanometer resist film was exposed through a rotating mechanical sector mask containing repeated resolution targets. The clearest patterned response occurred after a 45 second exposure at 10 percent pulsed duty, equivalent to approximately 4.5 seconds of cumulative full-on operation. After post-exposure bake and development, patterned regions remained. The present interpretation is negative-tone behavior. This result establishes preliminary actinic feasibility, while dose optimization, repeatability, quantitative resolution, and full-field uniformity remain to be demonstrated.

Summary of Research:

The project is developing a cleanroom-operable, large-area cathodoluminescent flood source for photoresist processing near 193 nanometers. The initial facility experiment addressed the most basic feasibility question: whether the lamp emission could create a developed resist response. The lamp was positioned over the wafer stage in the ABM Mask Aligner exposure area, as shown in Figure 1. The exposure fixture used a lower plate with six evenly spaced sector openings and a rotatable upper plate with one matching opening. Repeated line-and-space targets were distributed around the mask, including fields identified as 550 nanometers and 500 nanometers.

Two wafer runs were completed at 10 percent pulsed duty. The first used exposure times from less than one second through eight seconds. The second used times from 10 seconds through two minutes. The



Figure 1: Cathodoluminescent lamp and temporary support fixture positioned over the ABM Mask Aligner wafer stage for the initial exposure experiment.

clearest interpretable feature response was observed in the 45 second sector. This condition corresponds to approximately 4.5 seconds of cumulative full-on exposure. The wafer received a post-exposure bake at 110 degrees Celsius for 60 seconds and was developed in fresh 2.38 percent tetramethylammonium hydroxide for 45 seconds, followed by a deionized-water rinse and nitrogen dry.

Post-development optical inspection showed visible line-and-space response and adjacent mask-label features in the 45 second region. Figure 2 shows the close view, and Figure 3 shows the wider view with the 550 and 500 nanometer labels. The one-minute and two-minute sectors showed mainly sector outlines without visible fine features. The current working interpretation is overexposure within an observed negative-tone response: exposed material became less soluble or chemically hardened and remained after development. The images are qualitative microscope-monitor photographs and do not support a final claim for resolution, optimized dose, process repeatability, or uniform exposure.

The first test was enabled by coated wafers provided through Professor Greg Denbeaux at the University at Albany. Garry Bordonaro at the Cornell NanoScale Science and Technology Facility, with assistance from Erin Lavigne at NY CREATES, helped establish a practical path toward future resist preparation and testing at Cornell. This coordination removed an immediate material-access barrier and supports the next controlled process sequence.

The next phase will be scaled to the available source rather than framed as a full-wafer demonstration. The present 50 millimeter lamp is expected to support a reproducibly illuminated raster-scan region of approximately 40 millimeters in diameter. Initial work will therefore evaluate uniformity only within the illuminated area of a selected mask sector, with the goal of covering that sector completely. Depending on available funding, hardware, and authorization, uniformity may first be established by direct measurement scanning rather than by another photoresist exposure. Development of additional 190 nanometer lamp assemblies and a broader photoresist-uniformity study remain possible later steps, but are not assumed in the current plan.

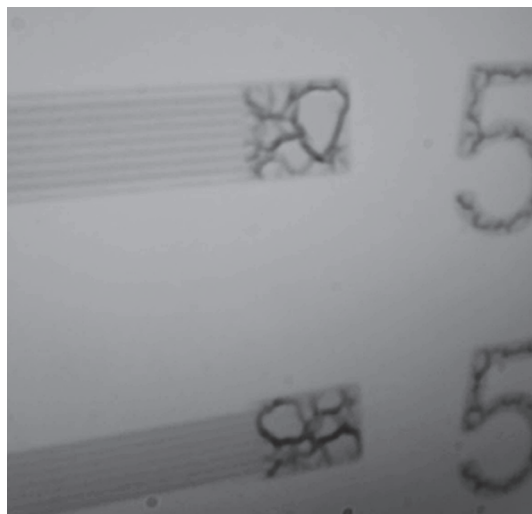


Figure 2: Close microscope-monitor photograph from the 45 second exposure region showing visible patterned response near the line-and-space fields.

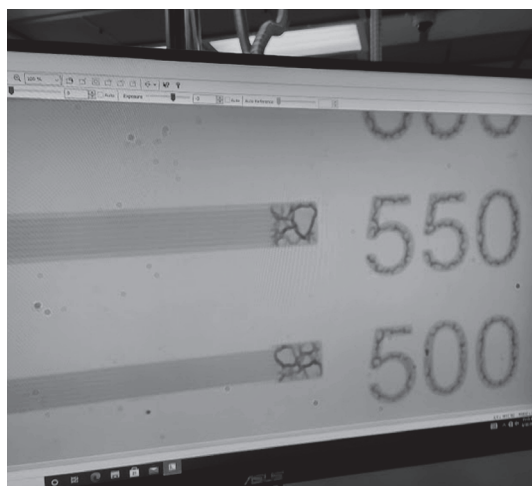


Figure 3: Wider microscope-monitor photograph from the same region showing line-and-space structures and the 550 nanometer and 500 nanometer mask labels.

Conclusions and Future Steps:

The facility work established preliminary proof that the cathodoluminescent lamp can generate a developed actinic response in 193 nanometer-type photoresist. The strongest evidence occurred at the 45 second, 10 percent duty condition. Near-term work will concentrate on characterizing the usable illuminated region of the existing 50 millimeter source and assessing uniformity over a selected sector, potentially by direct measurement scanning. Additional resist exposures, specialized lamp assemblies, and broader spatial studies will proceed only as resources and authorization permit. Claims will remain limited until calibrated measurements and repeat runs are available.

References:

- [1] ABM Mask Aligner