Development of Single and Double Layer Anti-Reflective Coatings for Astronomical Instruments

CNF Project Number: 2458-16

Principal Investigator: Gordon Stacey[1]

Users: Nicholas Cothard[2], Kenny Vetter[3], Mahiro Abe[3]

Affiliation(s): 1. Department of Astronomy, 2. Department of Applied and Engineering Physics, 3. Department of Physics; Cornell University

Primary Source of Research Funding: NASA Grant NNX16AC72G

Contact: stacey@cornell.edu, nc467@cornell.edu, kjv35@cornell.edu, ma797@cornell.edu

Primary CNF Tools Used: FilMetrics F50-EXR, FleXus film stress measurement, Zygo optical profilometer, ABM contact aligner, ASML 300C DUV stepper, Heidelberg DWL2000, Oxford PECVD, Anatech resist strip, Oxford 82 etcher, Unaxis 770 deep Si etcher

Abstract:

We are developing wide-bandwidth silicon substrate-based metal mesh mirrors for use in millimeter and sub-millimeter astronomical instruments. These mirrors are comprised of silicon substrates that are lithographically patterned with metal mesh reflectors on one surface and metamaterial anti-reflection coatings on their other surface. In the past year, this project has made significant progress in the development of our fabrication methods. We use standard lift-off lithography and metal evaporation tools to deposit and pattern our metal mesh filters. Our two-layer metamaterial anti-reflection coating fabrication makes extensive use of CNF's deep reactive ion etching devices and metrology tools such as profilometry and scanning electron microscopes. We are currently fabricating our meshes and anti-reflection coatings on high-resistivity silicon wafers that are low-loss, optical quality substrates. We will test the optical performance of our samples this summer using a Fourier transform spectrometer and will use the results to iterate and improve on our fabrication processes in the coming year.

Summary of Research:

The goal for this project is to fabricate silicon-substrate based metal mesh filters for use in millimeter and submillimeter astronomical instruments. This involves lithographic patterning of evaporated gold meshes on silicon wafers and etching double-layer metamaterial anti-reflection coatings (ARC) on the silicon surfaces using deep reactive ion etching (DRIE). These frequency dependent filters will be used as mirrors for Fabry-Perot interferometers (FPIs) to spectroscopically observe early star and galaxy formation. The double-layer design is necessary to provide wide bandwidth transmission to span the wavelengths of interest for our instruments. The metamaterial design is necessary to match the thermal expansion coefficients of the substrate and ARC layers because warpage due to cryogenic thin film stresses would strongly affect the optical performance of our interferometry and refractive optical elements.

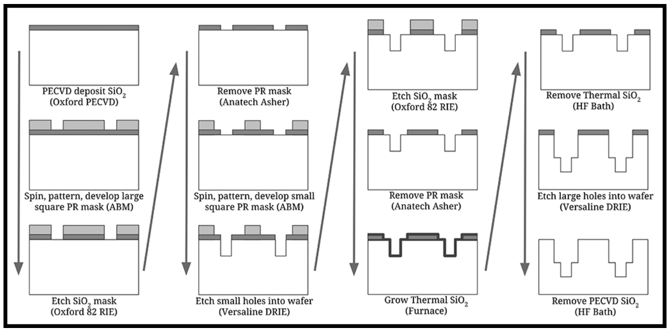

Figure 1: Process flow for fabricating a double-layer ARC on a silicon wafer. Dark grey represents thermal oxide. Light grey represents photoresist. White represents the silicon wafer.

The bulk of our work this year has been the development of our fabrication methods for high-throughput, wide-bandwidth double-layer metamaterial ARCs. This has involved many iterations of fabrication and metrology with a plethora of tools in the CNF cleanroom. We began investigating the methods to fabricate two-layer ARCs over a year ago and presented preliminary results in an Applied Optics paper last year [1]. Since this time, we have worked to improve our control of the etched geometry. Figure 1 shows our current fabrication recipe for two-layer ARCs.

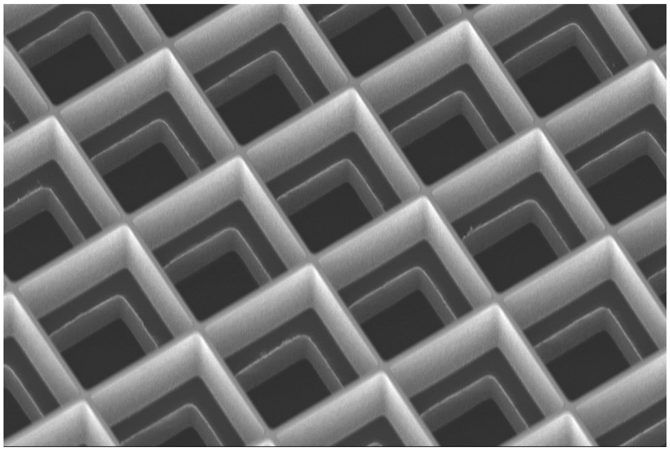

Figure 2: SEM image taken using CNF's Zeiss Ultra SEM showing successful fabrication of our two-layer metamaterial silicon ARC.

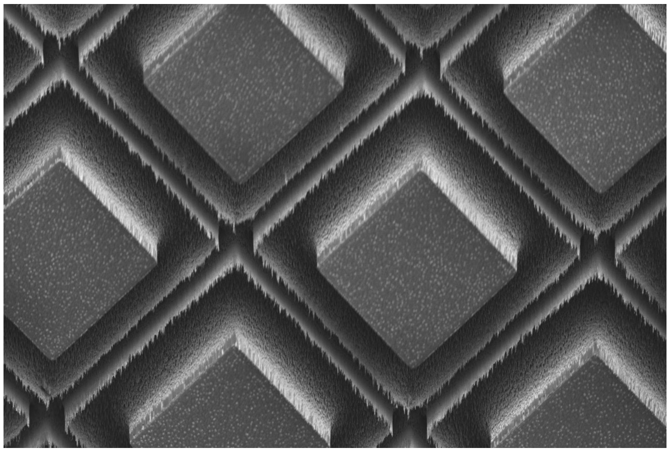

Figure 3: SEM image taken using CNF's Zeiss Ultra SEM showing a two-layer metamaterial silicon ARC with unwanted fence-like features between the upper and lower layers of the ARC.

We use stacked oxide and photoresist etch masks that are patterned on a silicon wafer before any silicon is etched. The oxide is deposited using CNF's Oxford plasma enhanced chemical vapor deposition (PECVD) and etched using the Oxford 82 etcher. Depending on the millimeter or sub-millimeter band that we are interested in, we pattern our photoresist etch masks using the ABM contact aligner or the ASML stepper with Gamma automatic coat-develop tool. With these etch masks patterned, we use either the Unaxis 770 deep silicon etcher or the Plasma-Therm deep silicon etcher. At intermediate steps inside our silicon etching, we measure the etch depth using the Zygo optical profilometer. Since last year, we have added a thermal oxide growth step and oxide removal step in between etching both silicon layers in order to clean-up the edge between both layers.

Figure 2 shows an SEM image (taken using CNF's Zeiss Ultra SEM) of a successful result of this fabrication procedure. Figure 3 shows an SEM image of the result of our old recipe, which did not include the thermal oxidation and HF bath in between the two etched layers. Notice the fence-like structure in between the upper and lower holes. Our new oxidation and removal steps can remove this unwanted structure. We are currently working to improve our control of this method and we are also looking for other methods to prevent the formation of this structure.

We are also currently fabricating these ARCs on optical quality, high-resistivity silicon wafers so that we can measure their transmittance using our lab's Fourier transform spectrometer (FTS) We have also been learning how to use negative lift-off photoresist techniques to pattern metal meshes onto silicon wafers. We have had success doing this using AZ nLOF 2020 photoresist with Microposit 1165 Remover with gold deposition using the CHA evaporator. We are beginning to fabricate these meshes on optical quality silicon so that we can measure their frequency dependent transmittance using our lab's FTS. This summer, we will fabricate meshes of various geometries and compare to our optical models.

These mesh filters and ARCs will be used to fabricate the mirrors of astronomical FPIs, which will be used for spectroscopic measurements in two major instruments. The first will be the HIRMES (high-resolution mid-infrared spectrometer) instrument, which will fly on NASA's airborne observatory Stratospheric Observatory for Infrared Astronomy (SOFIA) [2]. The second will be the CCAT-Prime telescope which Cornell is building on Cerro Chajnantor in the Chilean Atacama Desert [3]. HIRMES will observe in the far-IR, while CCAT-Prime will observe in the millimeter and sub-millimeter. Two wafers with ARC on one side and a metalized layer on the other side will form the resonant cavity of a FPI.

In the past year we have made great steps towards achieving our goals at CNF. We have demonstrated our ability to fabricate double-layer ARCs for different millimeter, sub-millimeter and far-IR wavelengths. We have used many of the fabrication and metrology tools at CNF. Our next steps are to better characterize our etched geometries and improve our metamaterial ARCs. We will be using Fourier transform spectrometers to measure our samples' optical performance and using the results to iterate on our fabrication design.

References:

[1] P.A. Gallardo, B.J. Koopman, N.F. Cothard, S.M.M. Bruno, G. Cortes-Medellin, G. Marchetti, K.H. Miller, B. Mockler, M.D. Niemack, G. Stacey, and E.J. Wollack, "Deep reactive ion etched anti-reflection coatings for sub-millimeter silicon optics," Appl. Opt. 56, 2796-2803 (2017)

[2] https://www.nasa.gov/feature/nasa-selects-next-generation-spectrometer-for-sofia-flying-observatory

[3] http://www.ccatobservatory.org/