Development of Immersion Gratings to Enable a Compact Architecture for High Spectral and Spatial Resolution Imaging

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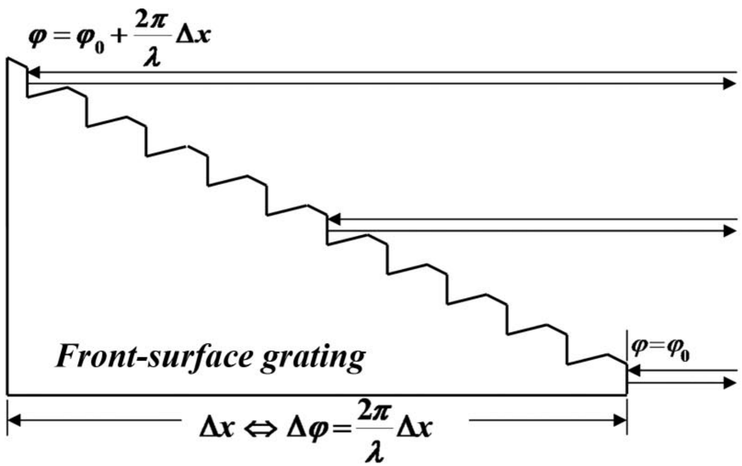
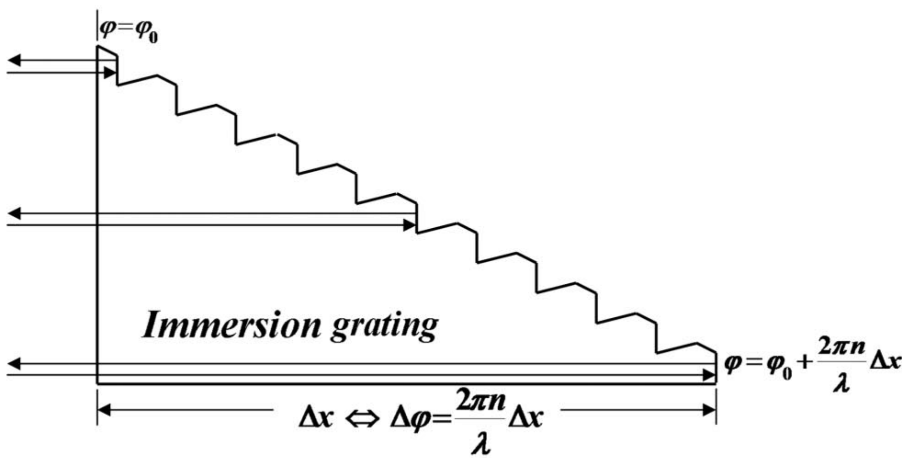
Science Overview

- Goal is to understand the time resolved behavior of CO, CO_2, and CH_4 in the Earth's atmosphere. This requires…
  - High cadence to understand temporal variations in sources and sinks
  - High spatial resolution to get accurate measurements against a ground background
  - High spectral resolution to get accurate abundances and vertical sounding information
- Infrared immersion gratings are an enabling technology because they can shrink instrument volumes by about an order of magnitude and can be less polarization sensitive.
  - Complete spectral coverage over a wide swath of wavelengths using a cross-disperser to get many orders on a detector with no spectral gaps.
  - Long-slit spectra in side-by side units to increase the field of view

Technology Overview



(a)



(b)

$n_{Si} \sim 3.4$

$$m\lambda = n_G \sigma(\sin\alpha + \sin\beta)$$

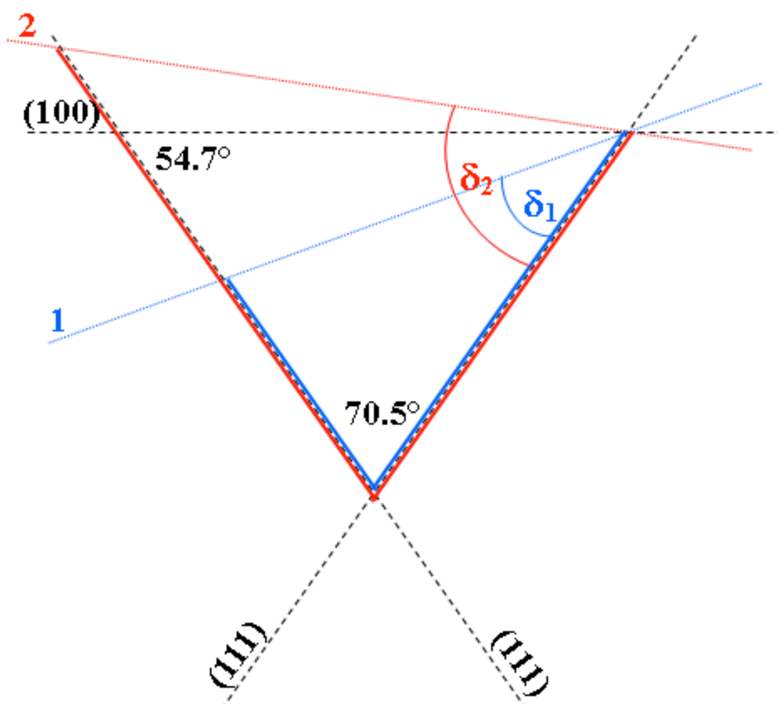
$$R_{\max} = \frac{2 n_G L \sin\delta}{\lambda}$$

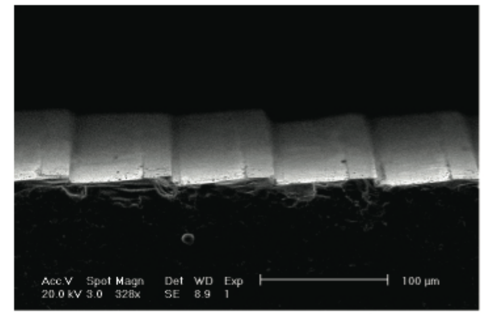
$$\frac{d\beta}{d\lambda} = \frac{2 n_G \tan\beta}{\lambda}$$

First described 200 years ago by Fraunhofer.

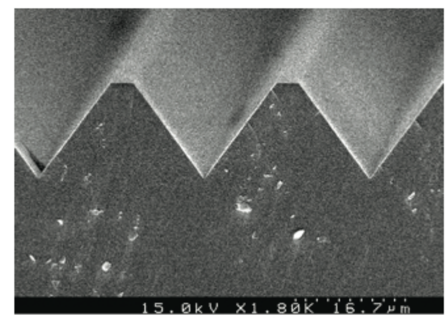
Technology Overview

By correctly orienting the disk surface with respect to the silicon crystal planes, we can produce a grating with any blaze angle.

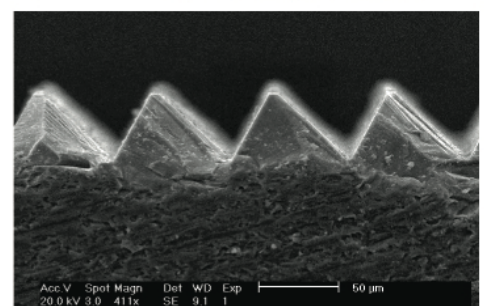




6.16°

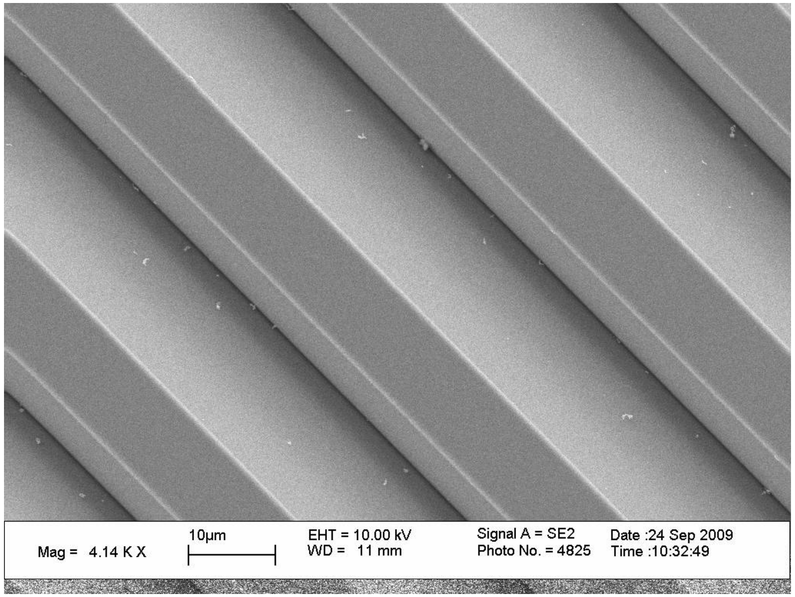


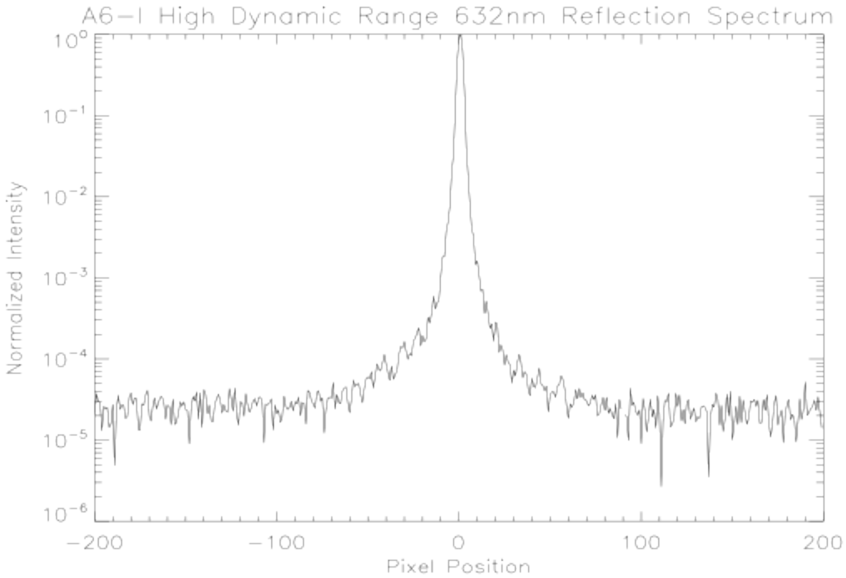
54.7°



63.4°

Technology Overview

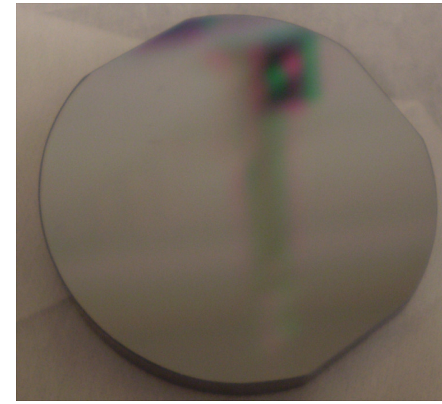




The perfect shape and low roughness of etched grooves means low scattered light levels.

The high placement precision leads to high efficiency and spectral purity.

Deployed Technology

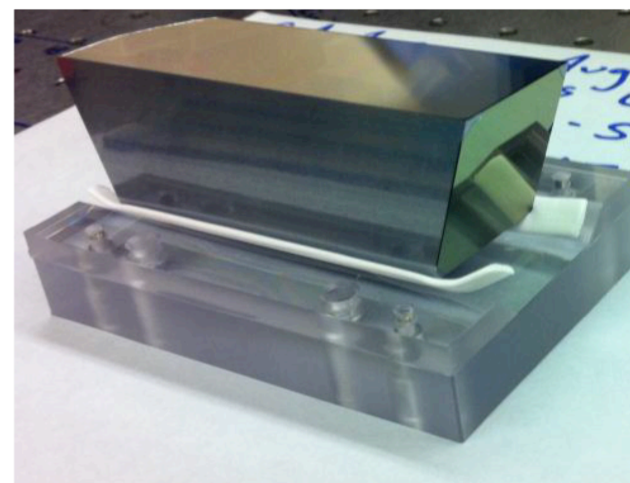


Silicon grism flight parts:

- James Webb Space Telescope NIRCam
- FORCAST on SOFIA Telescope

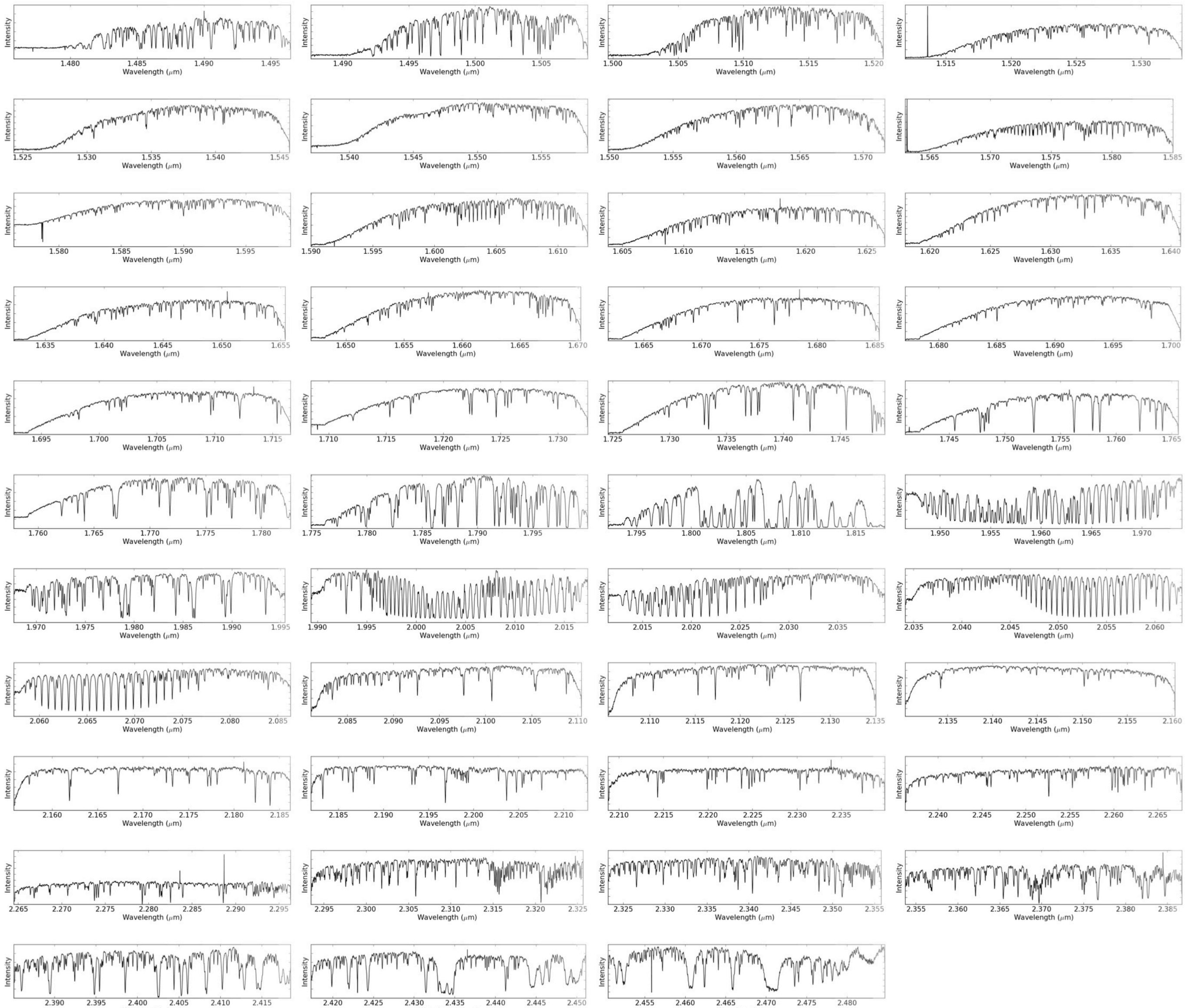
Echelle immersion gratings:

- Immersion GRating Infrared Spectrograph (IGRINS) installed at McDonald Observatory
- iShell for the NASA InfraRed Telescope Facility
- Planned GMT Near InfraRed Spectrograph (GMTNIRS) for the Giant Magellan Telescope.



Spectrum from the IGRINS instrument

IGRINS:
1.45-2.5 μm
R = 45,000



REVIEW OF JOINT UTEXAS/JPL ACT PROJECT

Summary of research goals

- To build and thoroughly test a set of silicon immersion gratings customized for the needs of Earth observation systems using a variety of patterning methods through a collaboration between The University of Texas at Austin and Jet Propulsion Laboratory

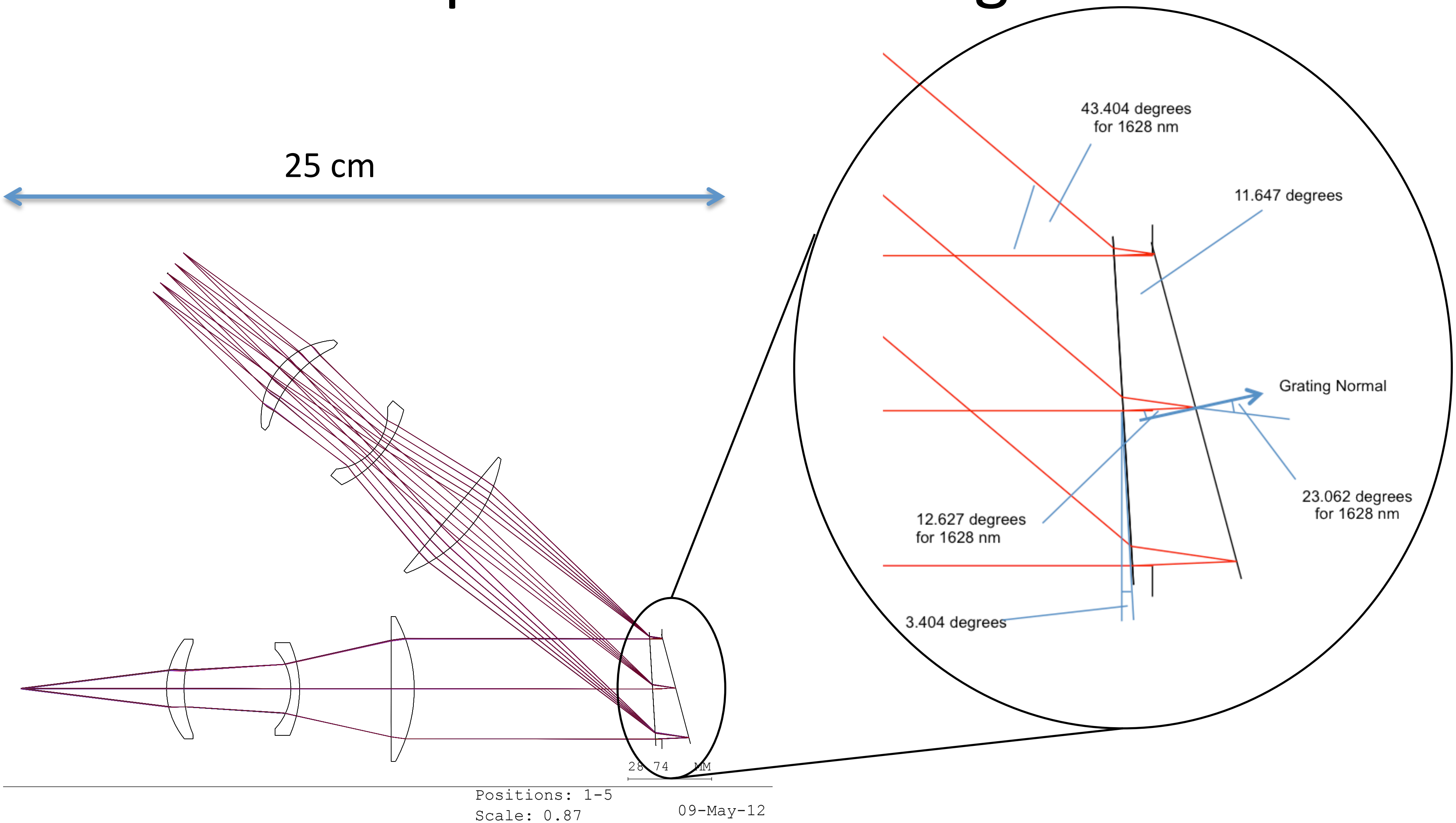
Overview

- Spectrometer conceptual design
- Process
  - Materials preparation
  - Manufacturing methods
  - Testing
- Lithography methods studied
  - Contact printing with wet etching
  - Binary e-beam lithography with wet etching
  - Grayscale lithography with plasma transfer etching
- Summary
- Instrument designs

Spectrometer design

- Conceptual design completed by JPL for three infrared channels:
  - 1.598-1.659 μm
  - 2.045-2.080 μm
  - 2.305-2.385 μm
- Grating parameters optimized for efficiency vs. blaze angle
  - Blaze angle defines the silicon material preparation
  - Grating constants (i.e., distance between grooves) defines the photomask or electron beam pattern

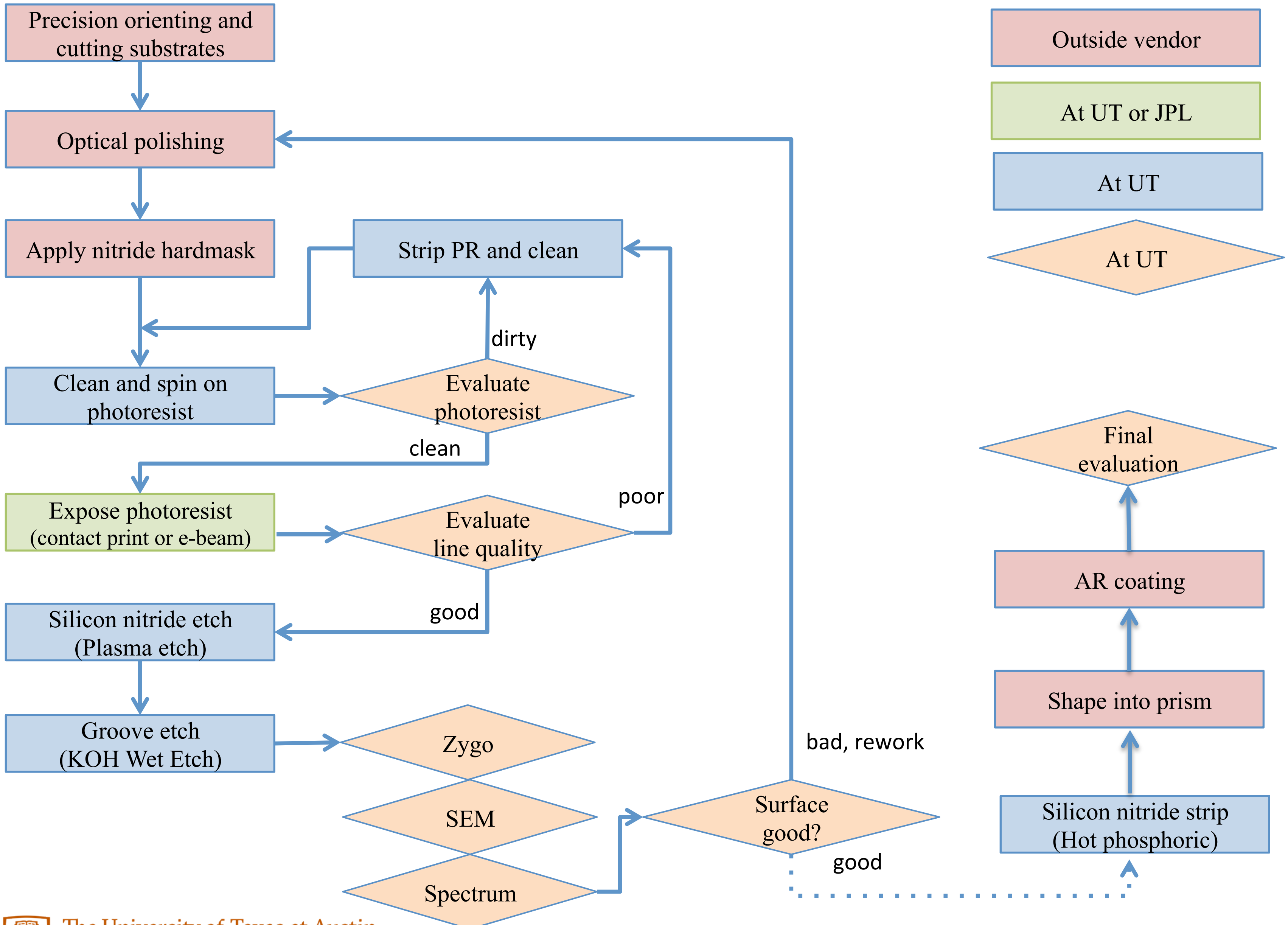
Spectrometer Design



Spectrometer layout

Detail of immersion grating

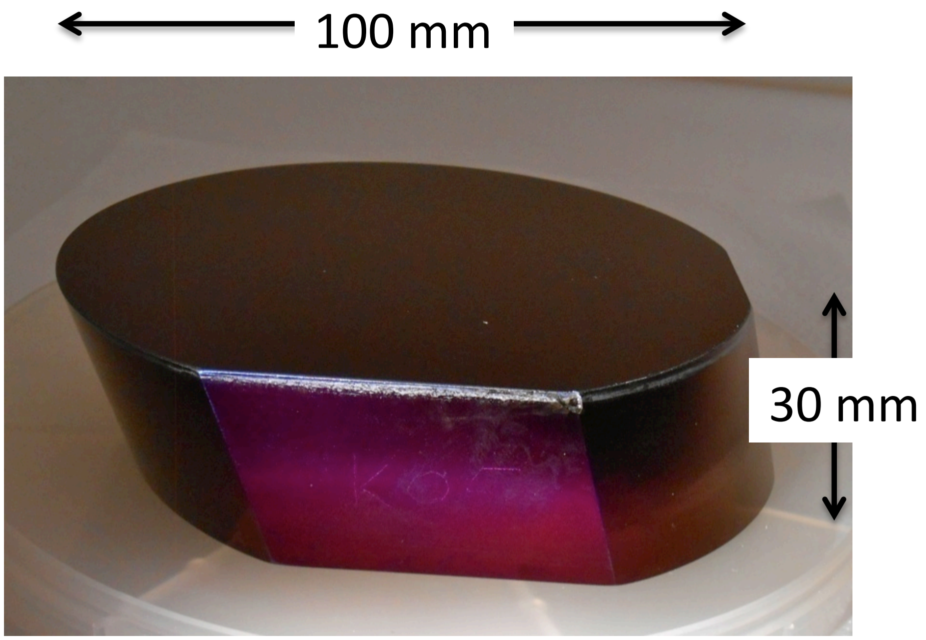
Background: process flow



Silicon substrate preparation

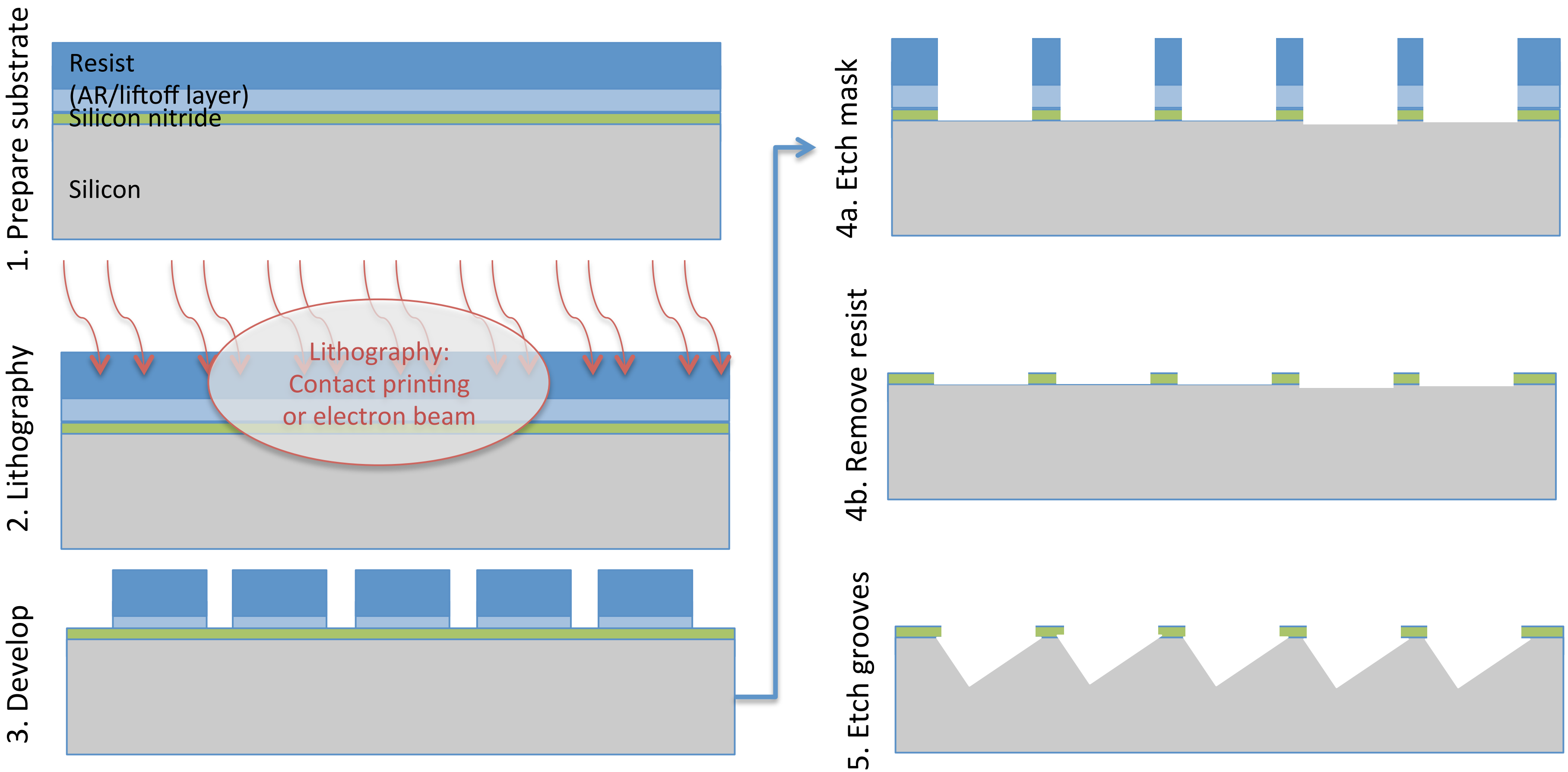
Material preparation requires coordination of:

1. Float-zone silicon boule, resistivity of >10,000 ohm-cm.
2. X-ray crystallography to orient to 0.04°. Tilt and slice boule.
3. Chemically mechanically polished to λ/10
4. LP-CVD silicon nitride 600 Å ± 5%



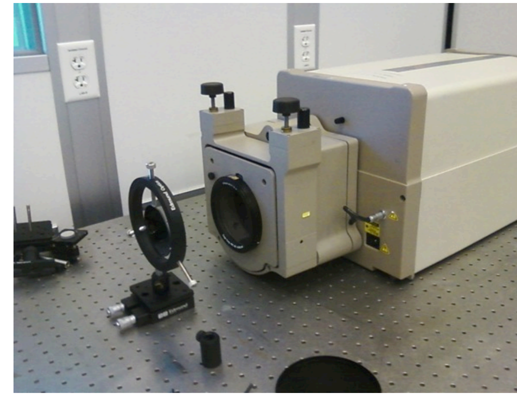
Completed substrate ready for manufacturing

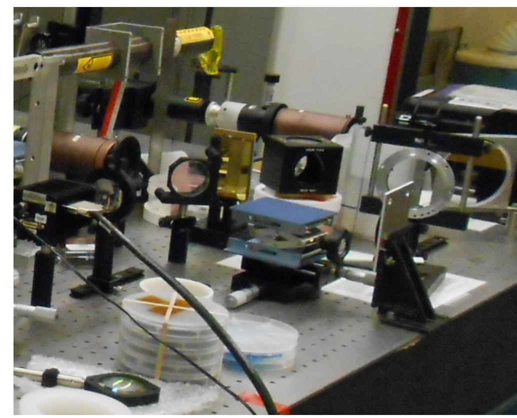
Manufacturing

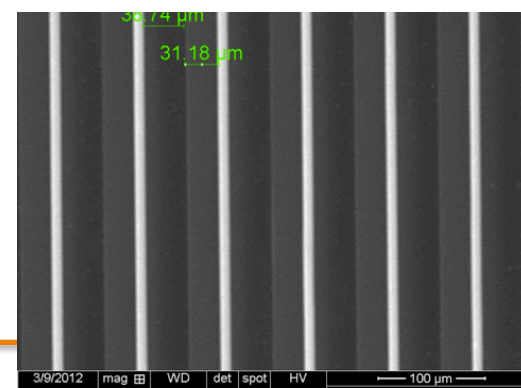


Testing and analyzing

Test	Specification
Front surface interferogram in Littrow at 633 nm (~2.15 µm in immersion)	λ/4 in immersion or ~120-180 nm peak-to-valley
Laser spectrum	Ghosts < 2 x 10^{-3}
Imaging with scanning electron microscope (SEM)	Smooth surface, <<1% defect area, confirm blaze



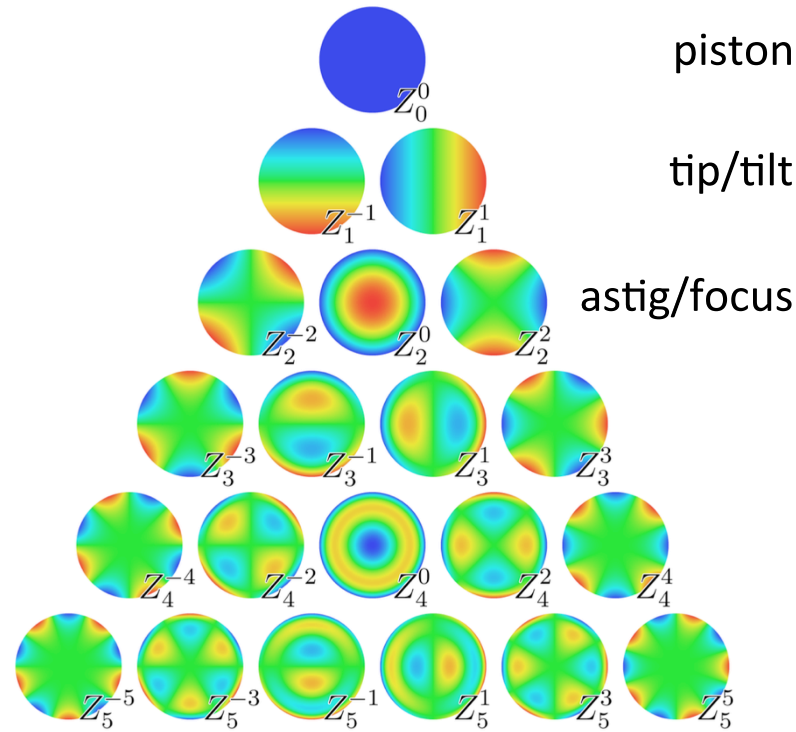




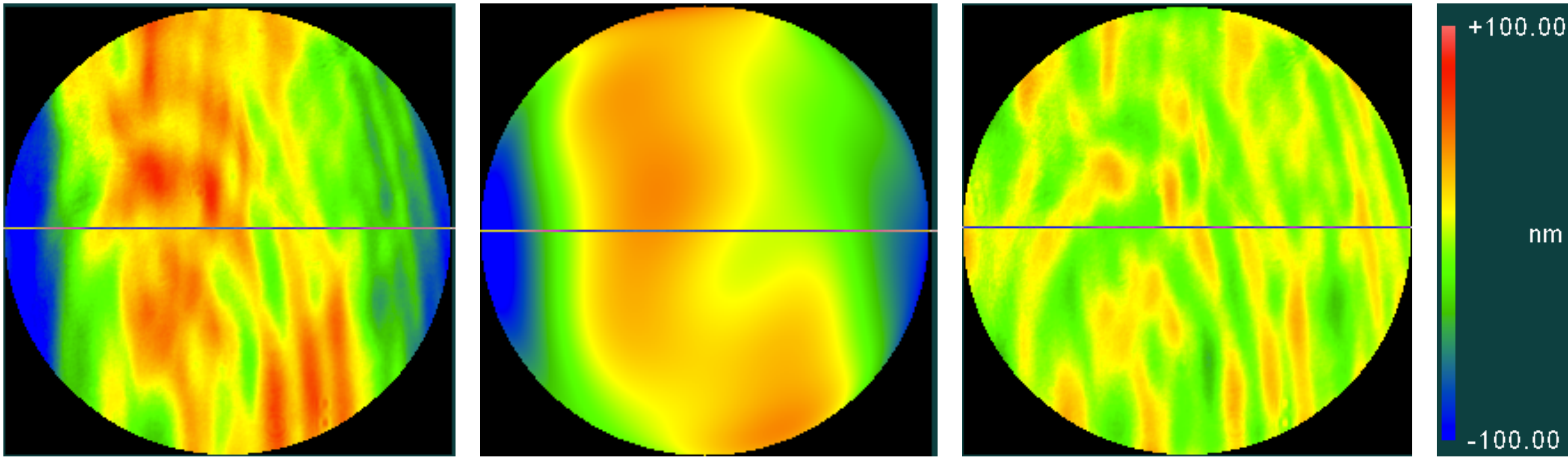
Modeling and interpreting the interferogram

Interpreting the interferogram

- We model the interferogram using the first few Zernike terms to model the *large scale aberrations*
- We subtract the large and medium scale aberrations from the full interferogram
- We call what it left the *residual error*



Modeling and interpreting the interferogram



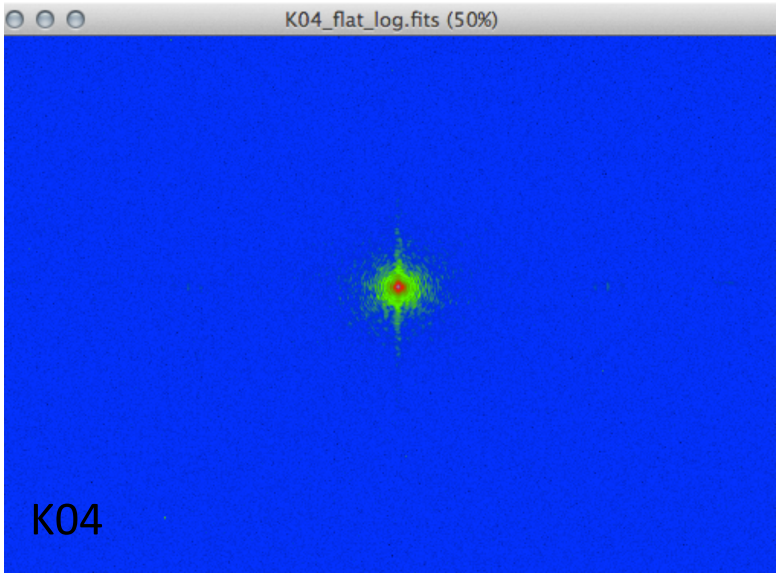
Full interferogram

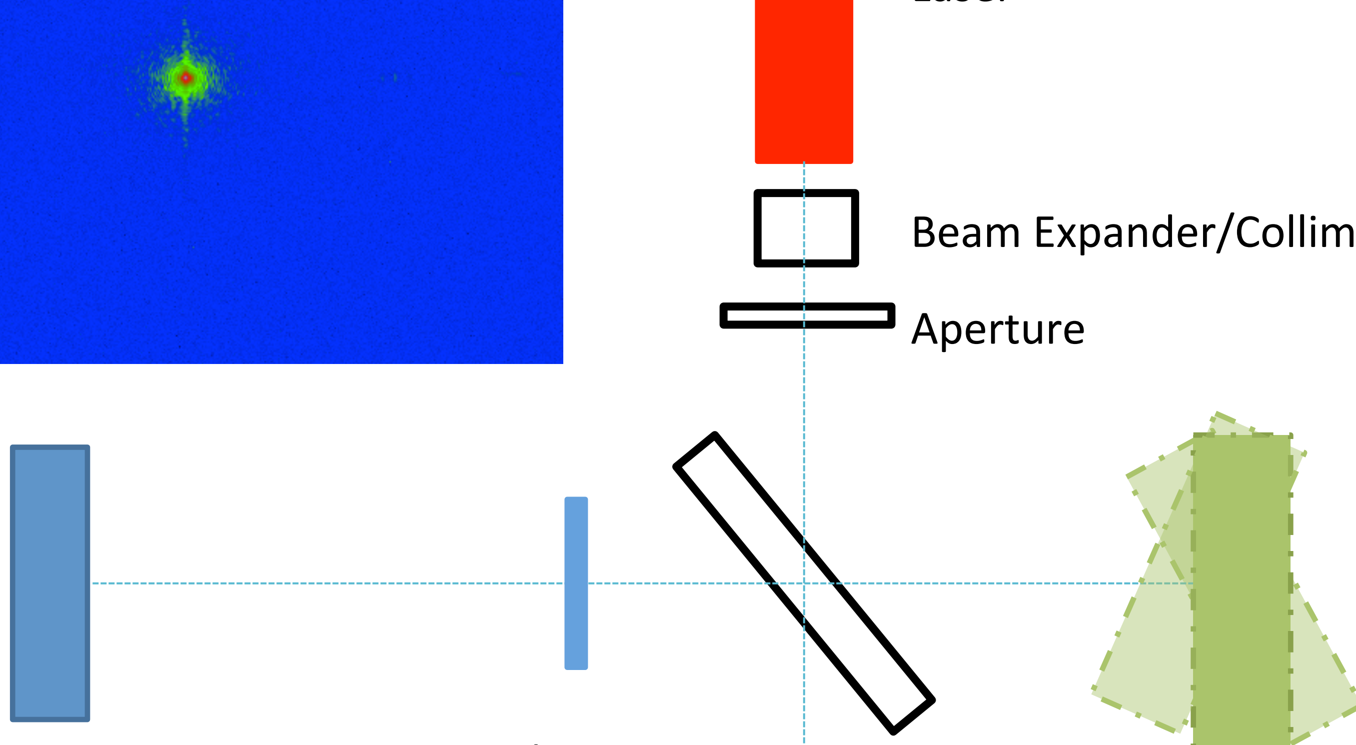
Zernike terms:
Large-scale error

Residual error

30mm beam
71° grating
PV = 187 nm (0.29 waves at 633 nm)

Laser spectrum





Focus of work

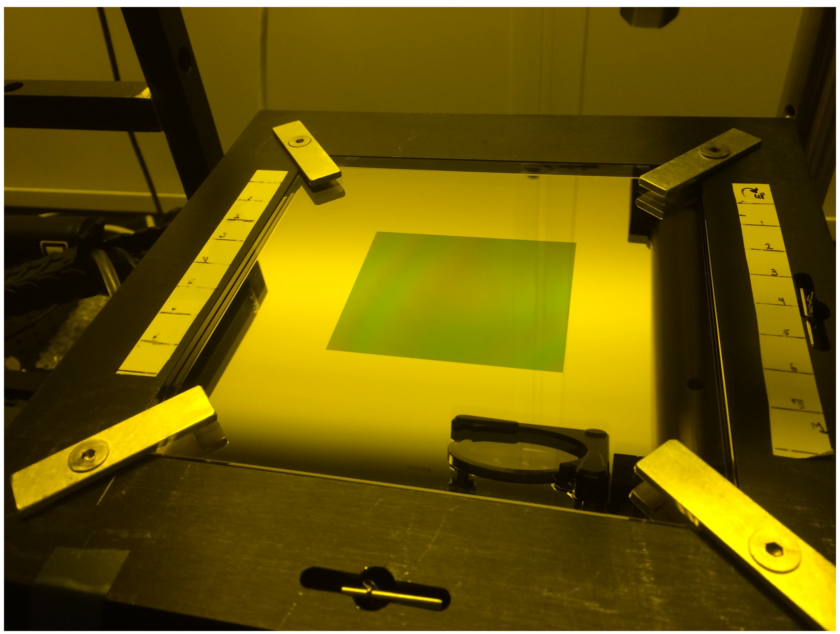
- Step-by-step process analysis.
  - Lithography: non-uniformities are directly patterned into the silicon
  - Plasma etching: optimized for uniformity
  - Wet etching: optimized for uniformity
- Largest contributor to the quality of the gratings is the lithography step
- Focus of work is improving and optimizing lithography

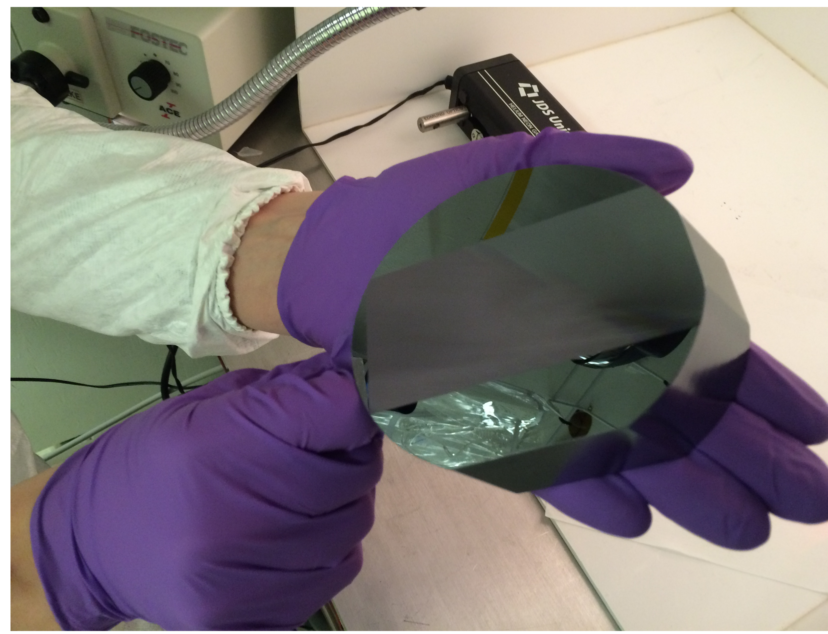
Lithography methods studied

Method	Advantage	Disadvantage
Contact printing (UTexas)	Established process	Larger grooves → higher order gratings
E-beam lithography with wet etching (JPL/UTexas)	Small grooves → low order gratings	Complex process Rowland ghosts
Grayscale lithography with transfer etch (JPL)	No pre-aligned silicon needed	Less precise blaze Lower efficiency

Method 1: Immersion grating built using contact lithography

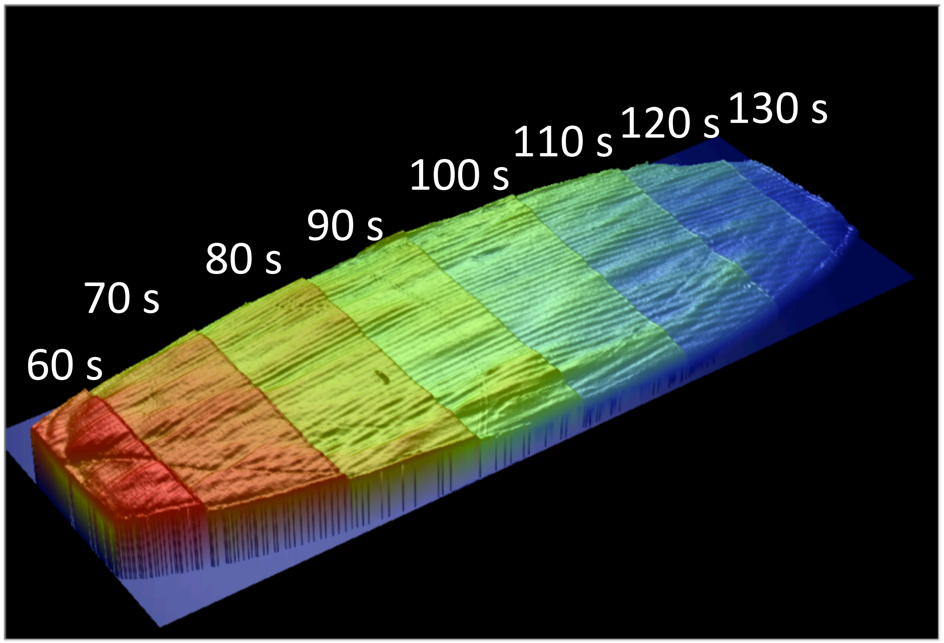
1. Process improvements in contact print lithography
2. Manufacture of contact printed grating
3. Shaping of grating into prism and testing

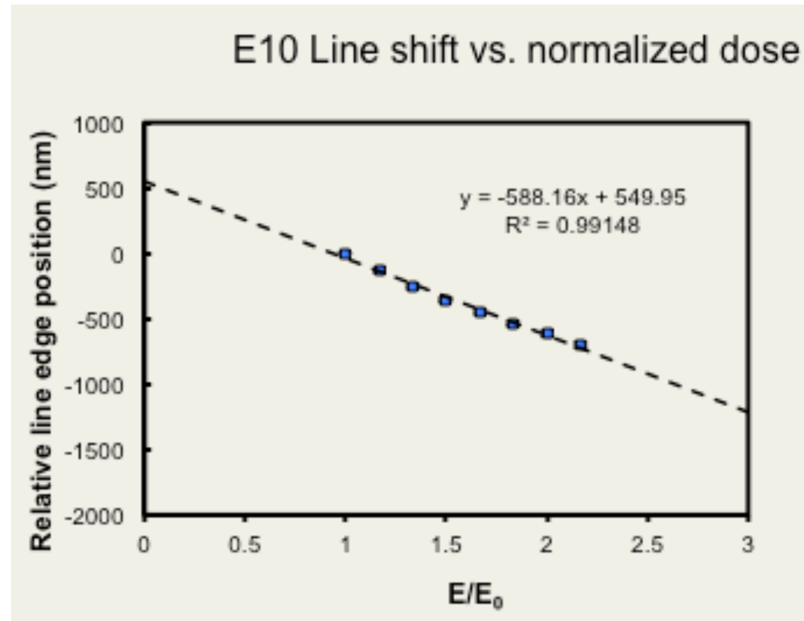




1.1 Process improvements in contact print lithography

Method to understand what UV exposure uniformity is required to achieve grating quality necessary to meet instrument spec.



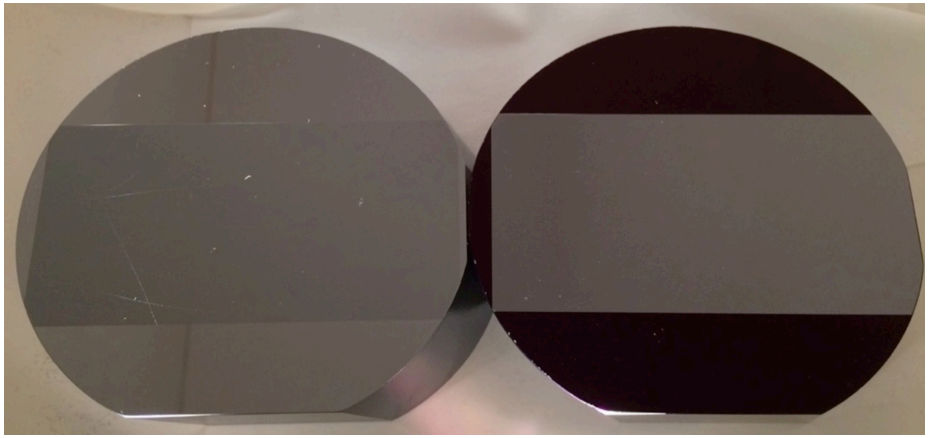


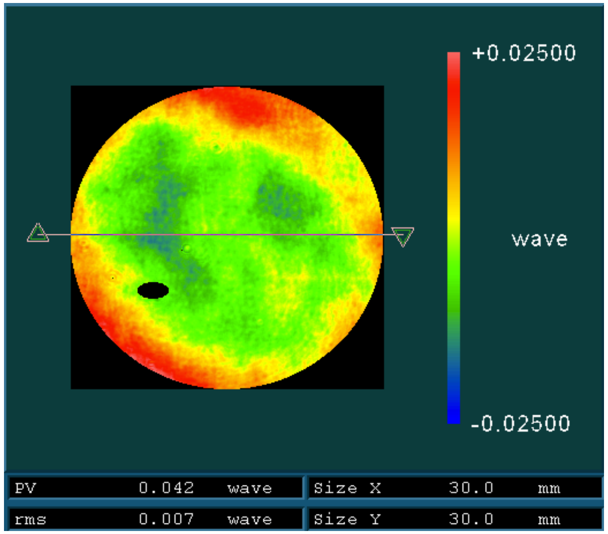
Substrate patterned with varying exposure dose. Phase front with laser interferometry

Line edge has shift with respect to changes in exposure → phase shift vs. dose variation

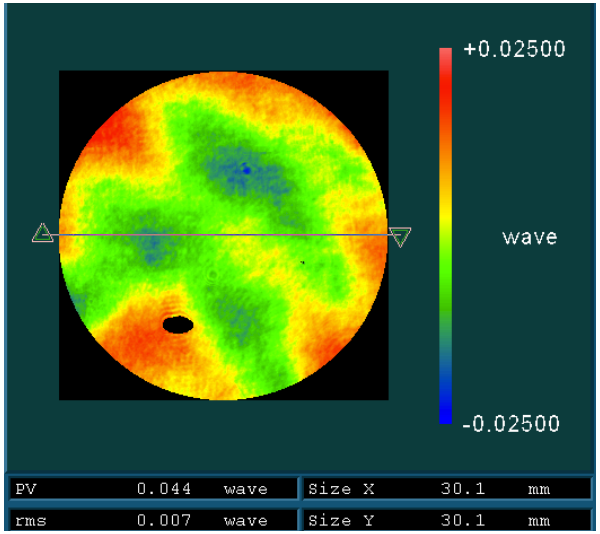
1.2 Manufacture of contact printed grating

Results of gratings manufactured on 18° blazed silicon substrates.



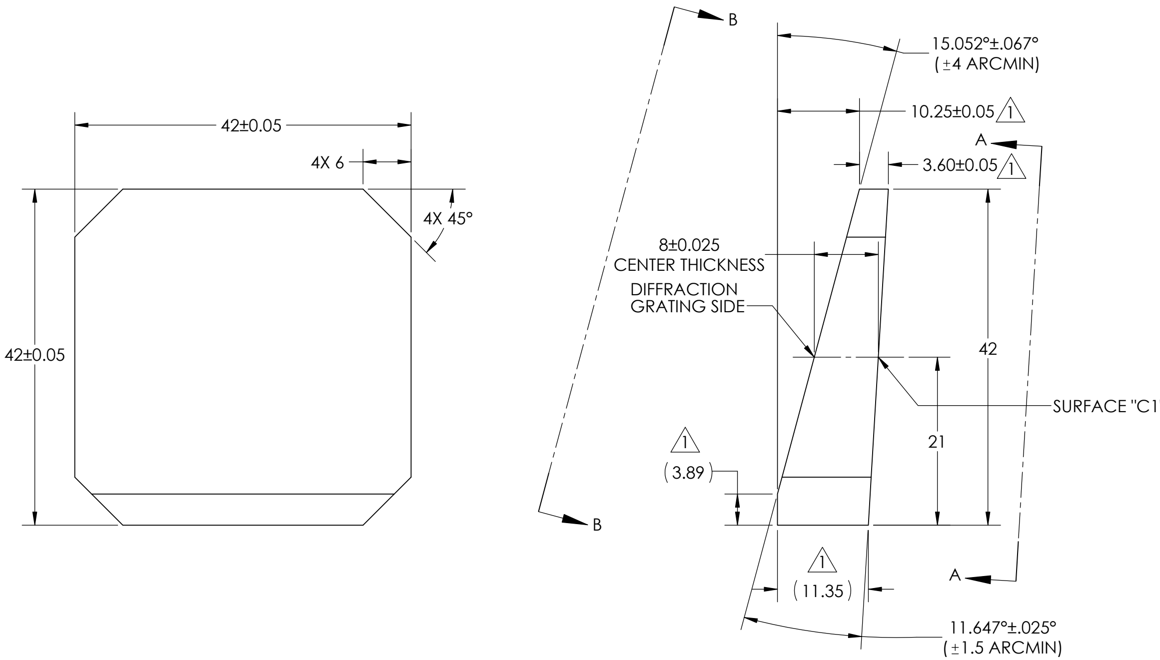


K01 PV phase = 0.042 waves

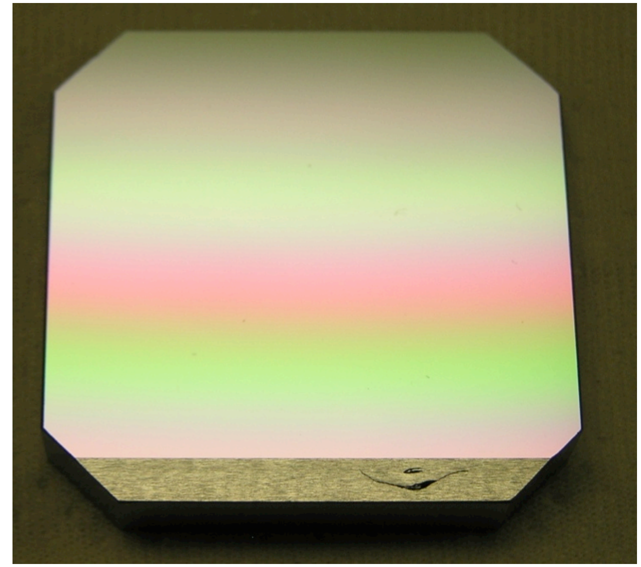


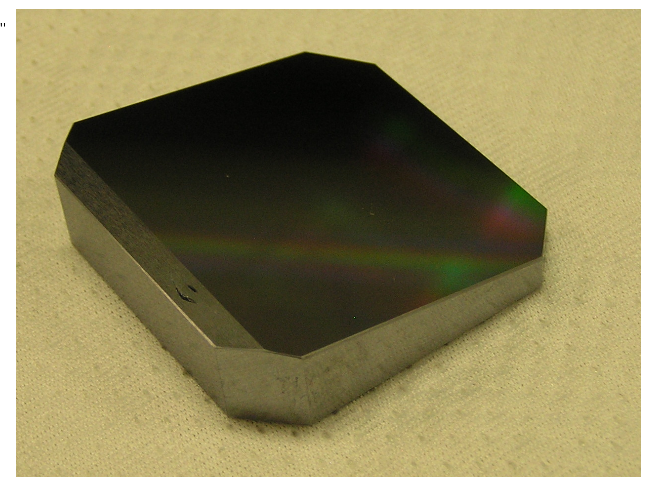
K03 PV phase = 0.044 waves

1.3 Shaping of grating into prism and testing



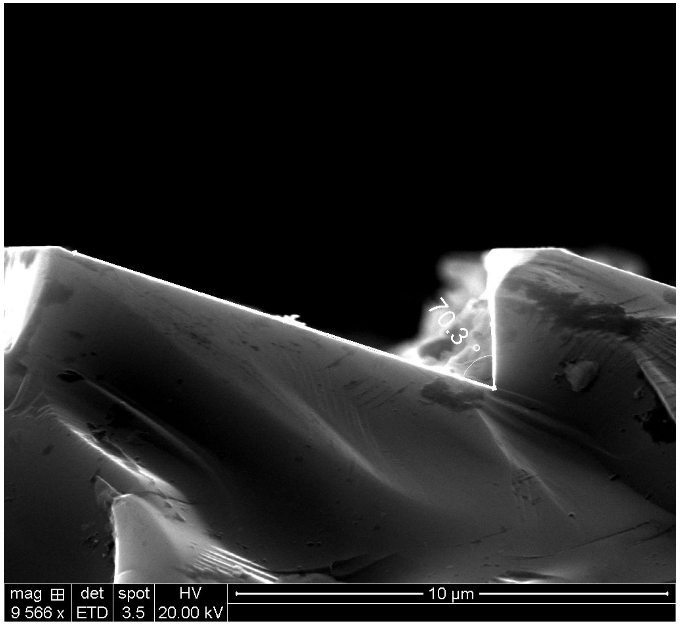
Mechanical drawings of immersion grating prism

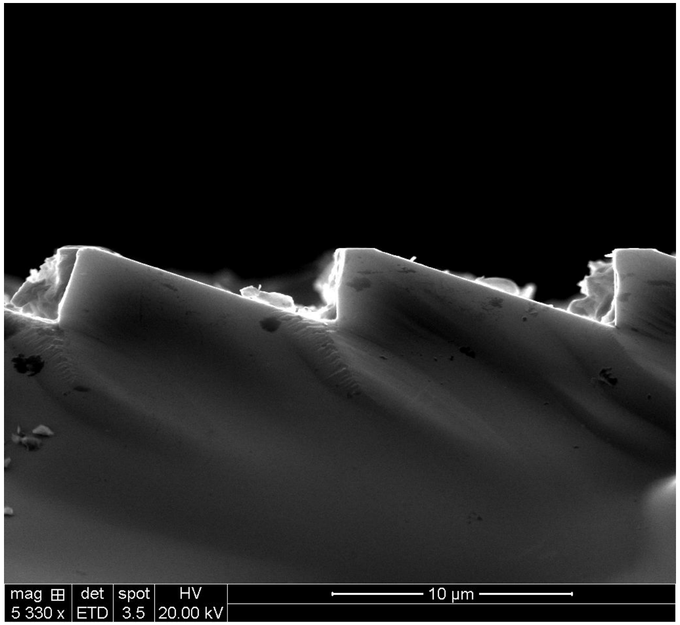




Photos of cut prism

1.3 Shaping of grating into prism and testing

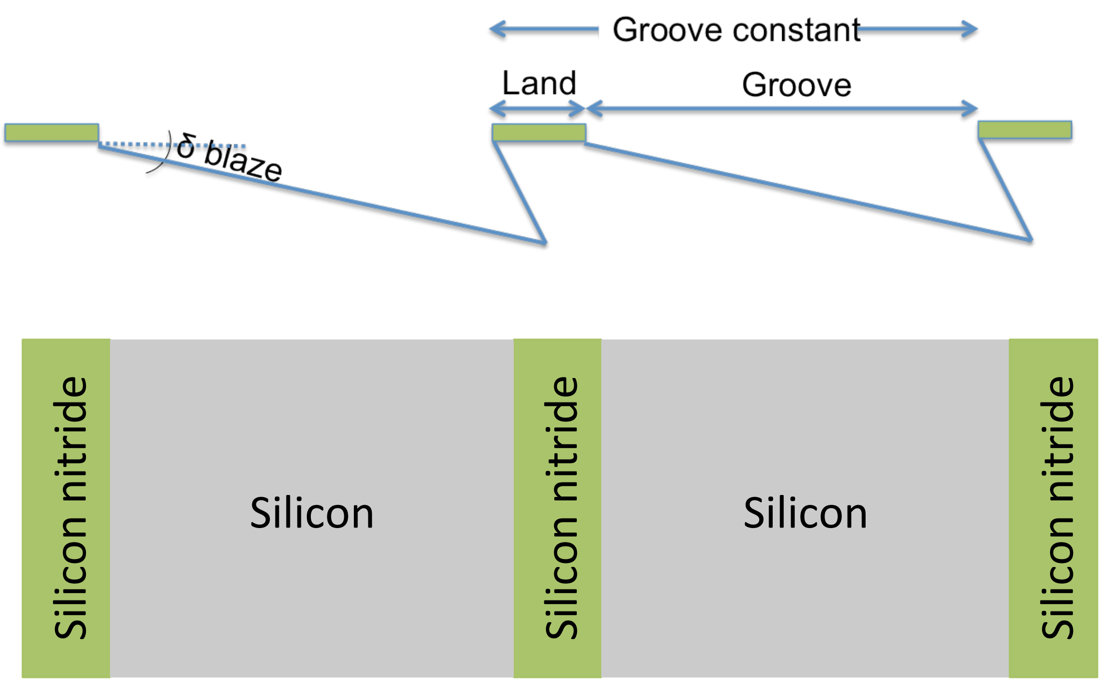




SEM of scrap pieces after cutting showing the v-grooves.

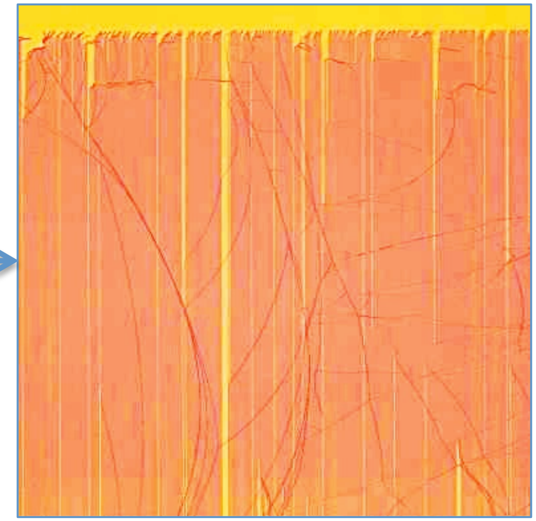
Method 2: Binary e-beam lithography with wet etching of grooves

1. Process development for binary e-beam lithography
2. Manufacture and testing of e-beam grating

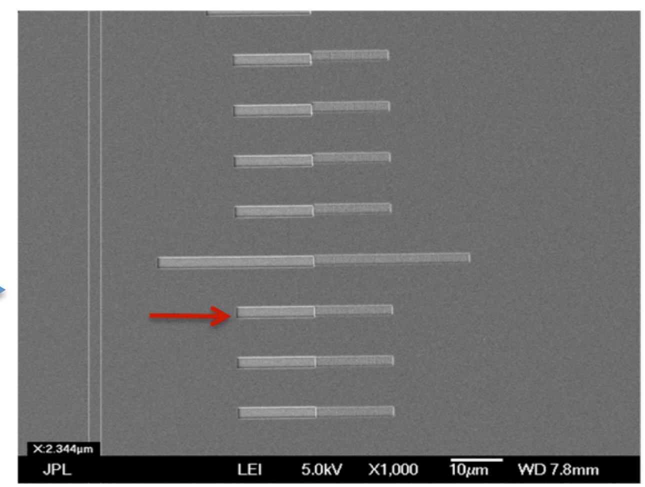


Method 2: Binary e-beam lithography with wet etching of grooves

1. Negative photoresists
   – Limited success



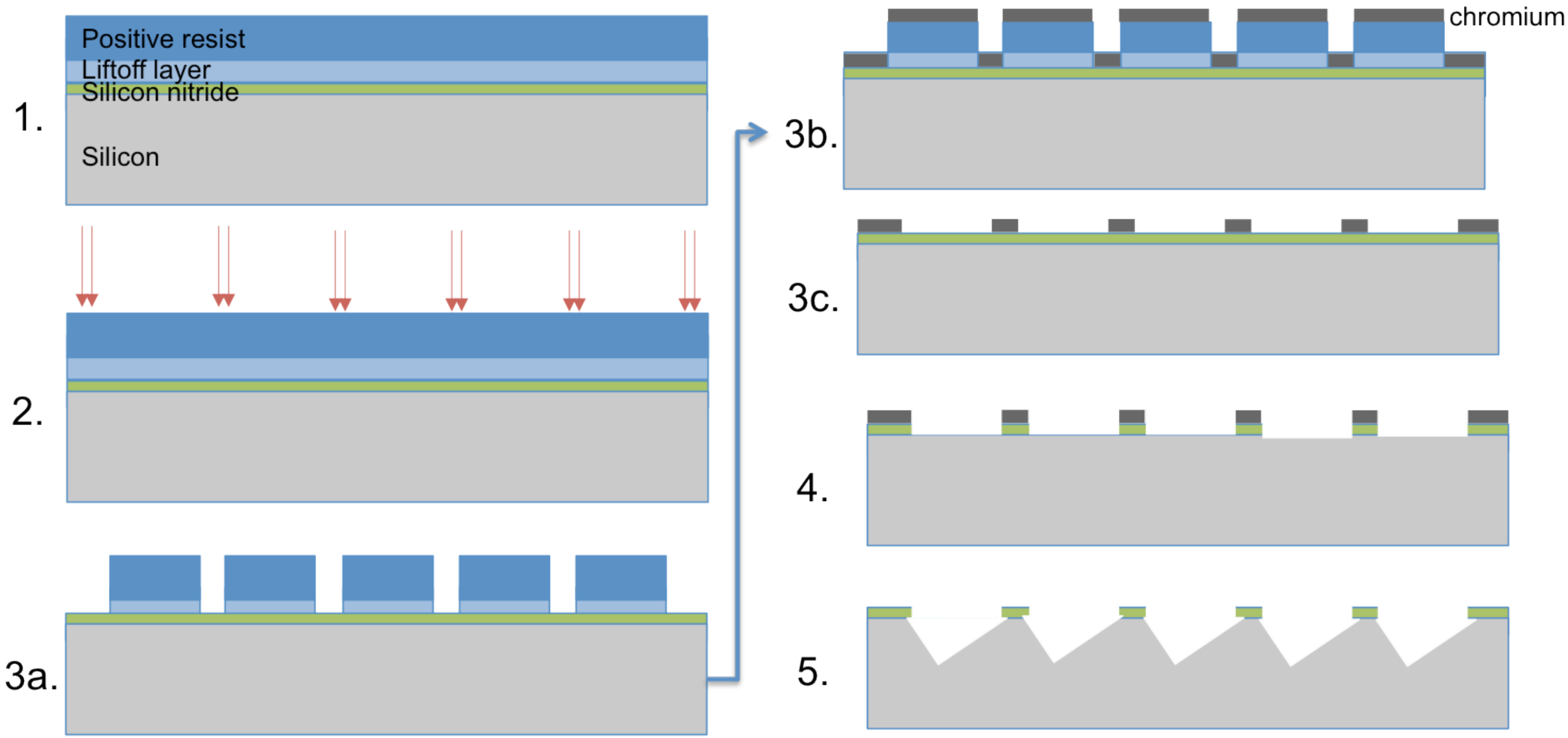
2. Positive resists using two-stage writing
   – Limited success



high current   low current

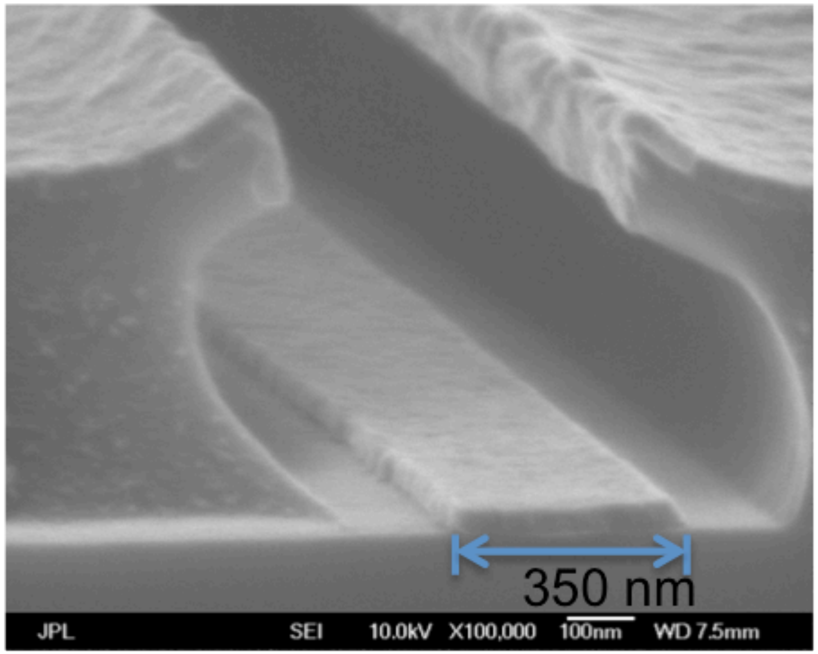
3. Chromium liftoff
   – Successful!

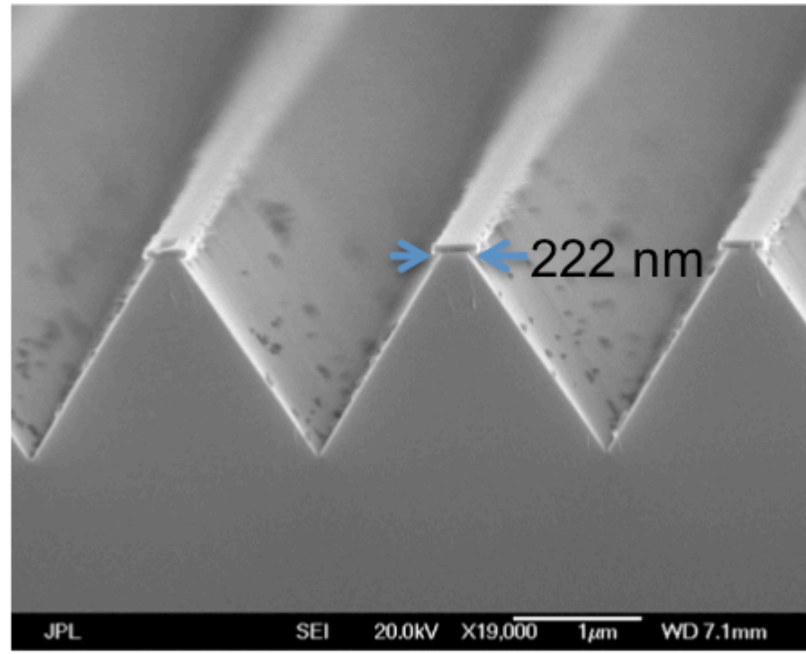
2.3 E-beam with using chromium liftoff



2.3 E-beam lithography with positive resists using chromium liftoff technique

Chromium liftoff results on test wafers



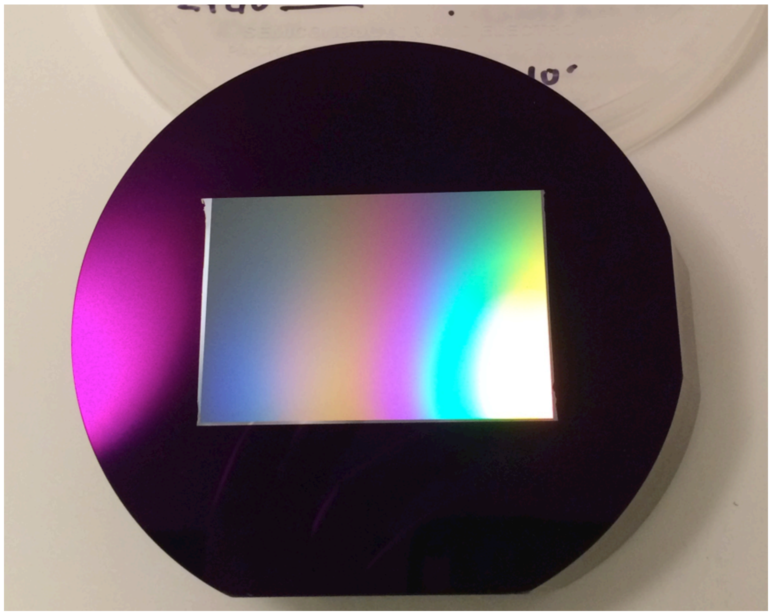


Steps 1-3b have been completed. The chromium line remaining is 350 nm wide.

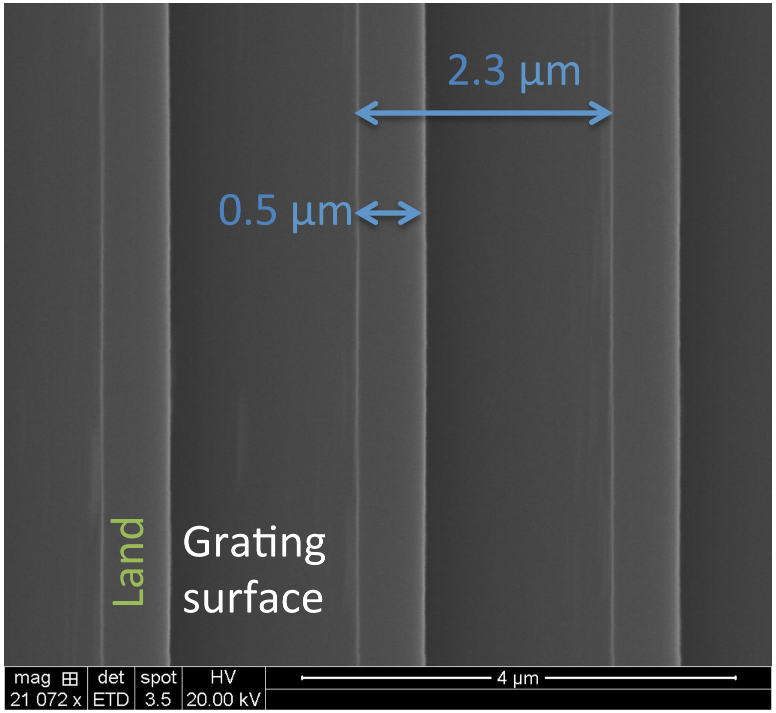
Steps 1-5 have all been completed. Groove top is now 222 nm because of undercutting in step 5, the KOH groove etch.

2.4 Manufacture and testing of e-beam grating

Chromium liftoff results on blazed substrate

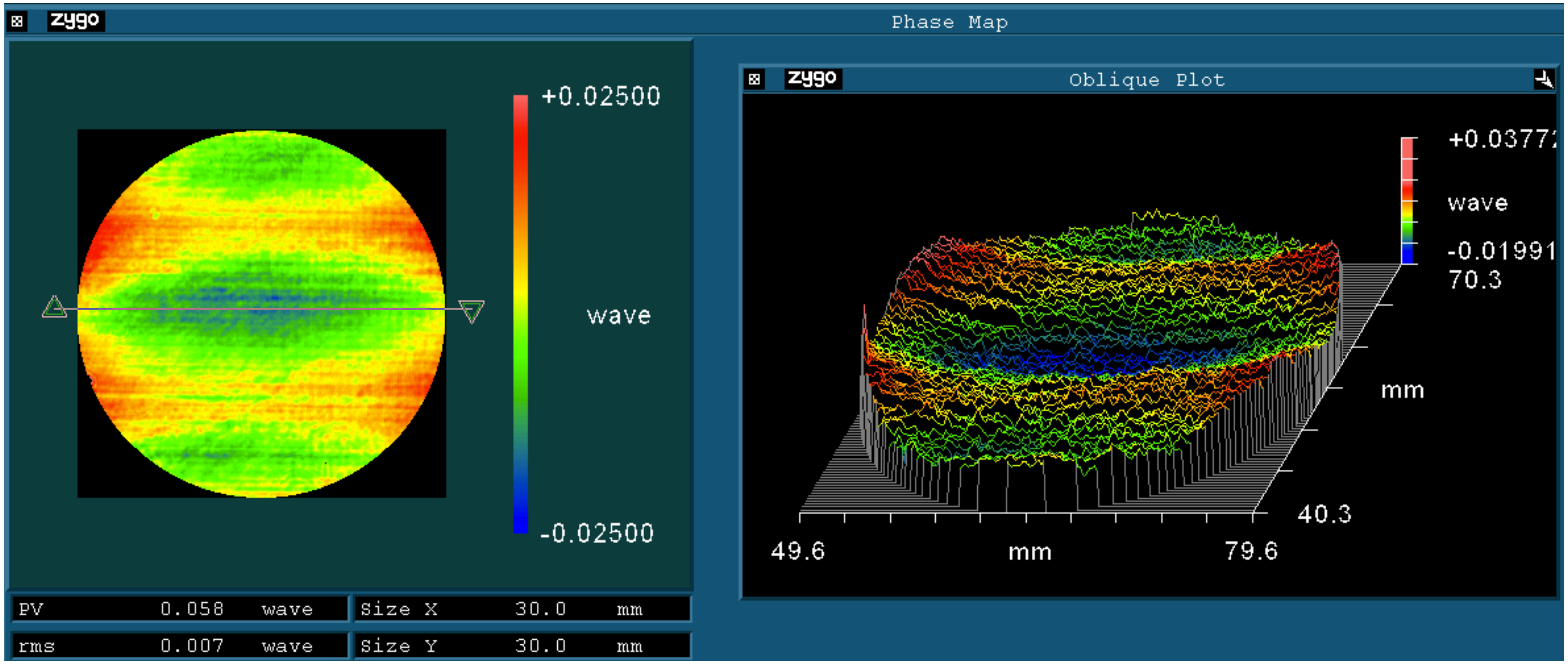


Photograph of part K04 patterned by e-beam and chromium liftoff.



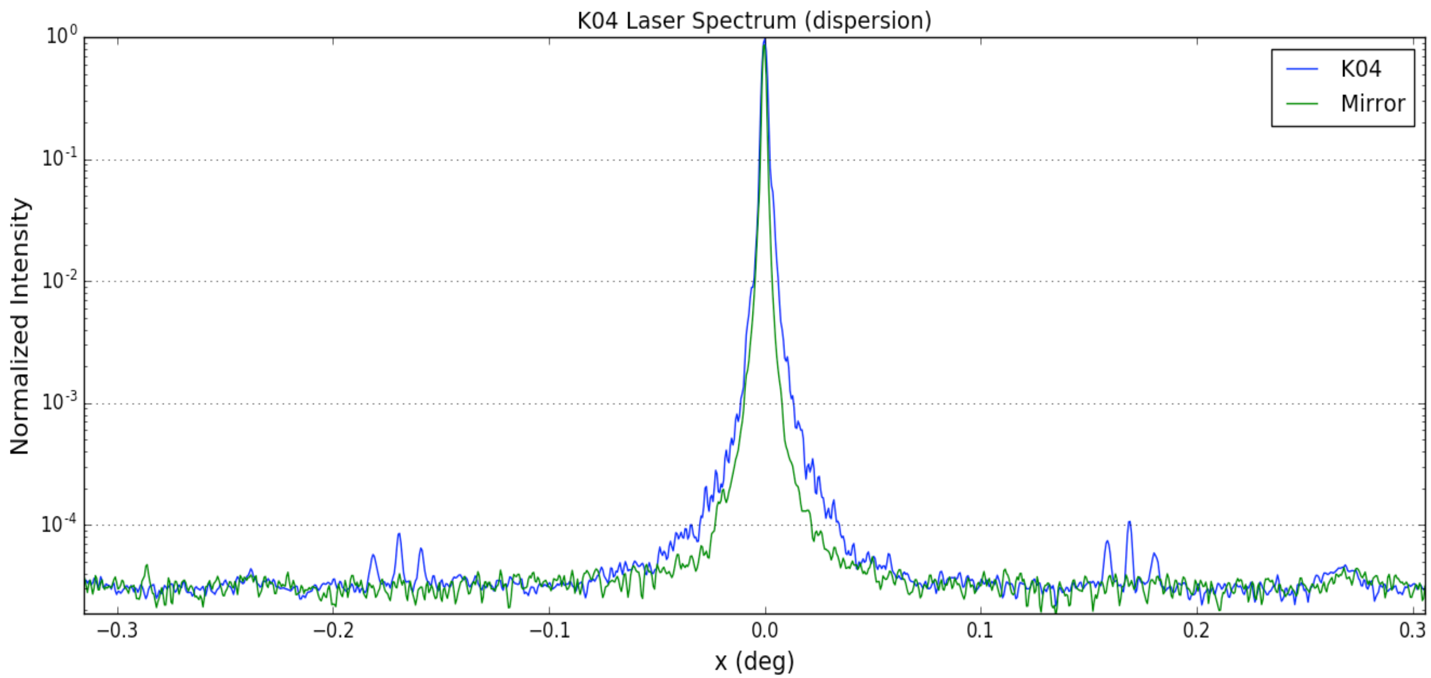
SEM of finished grating K04

2.4 Manufacture and testing of e-beam grating



- Front surface interferogram in Littrow at 18° for a 30 mm beam.
- Phase PV is 0.06 waves at 633 nm, corresponding to ~2.0 µm in immersion.
- Easily meets our specification of < 0.25 waves.

2.4 Manufacture and testing of e-beam grating



High dynamic range, front surface monochromatic spectrum of same grating. Specification for ghosts is that they are < 2×10^{-3} of the central peak; these are $<10^{-4}$.

Method 3: Grayscale e-beam lithography and transfer etching

Dan Wilson and Rich Muller

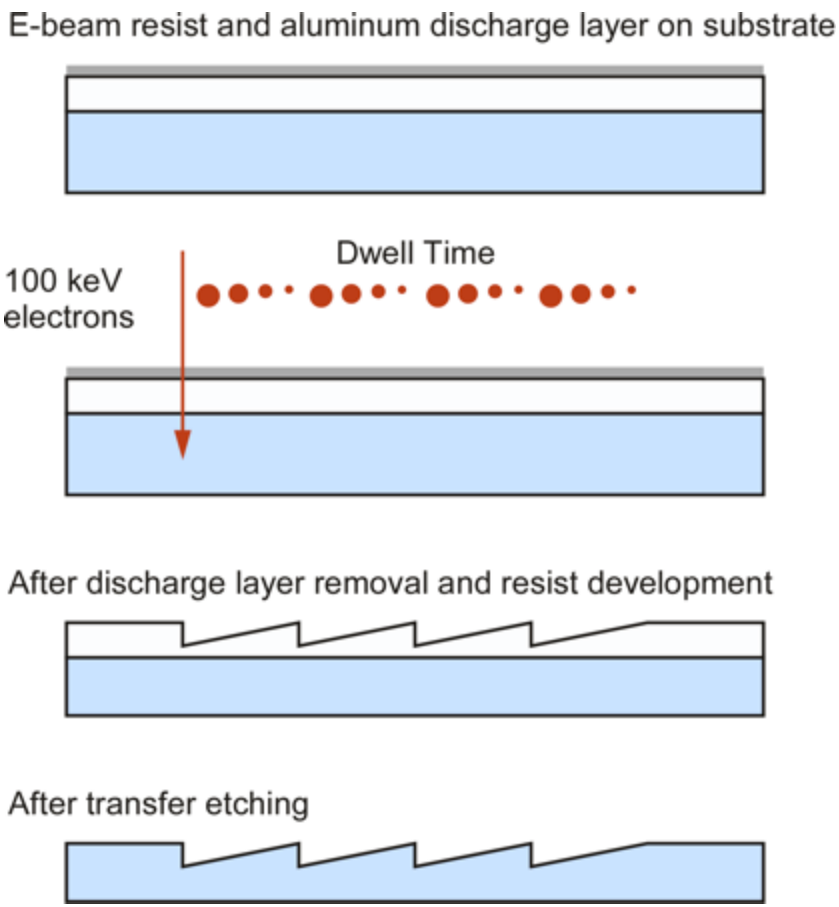
Jet Propulsion Laboratory

Grayscale E-beam Lithography Fabrication of Silicon Immersion Gratings

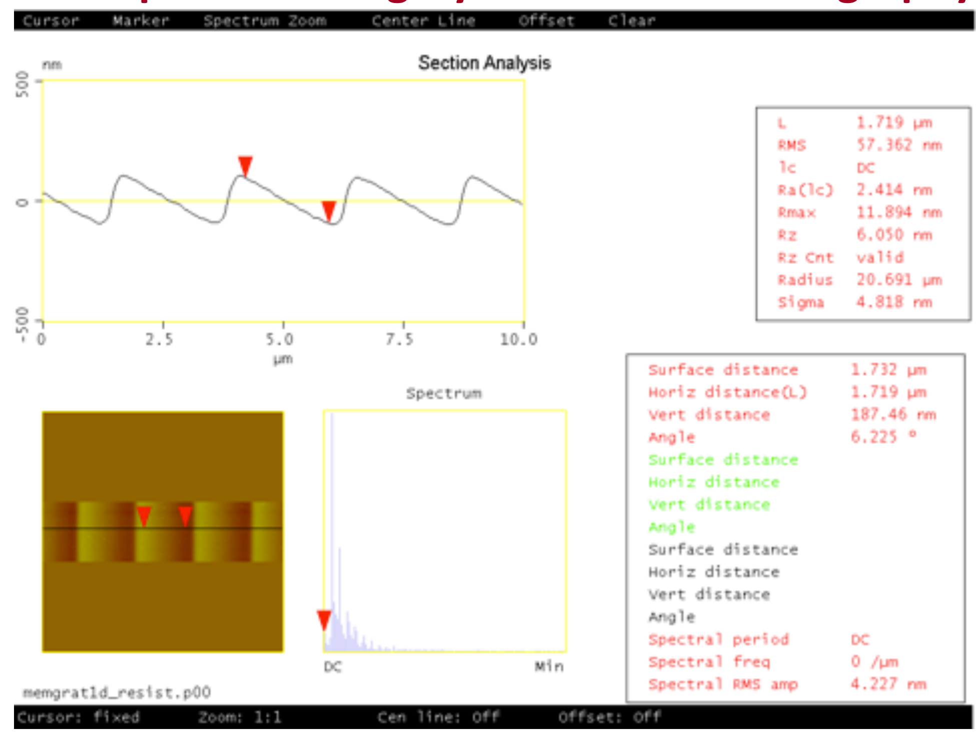
Fabrication of 2.47 µm period grating for the 2.045-2.080 µm spectrometer design

- Chose to demonstrate smallest period required → most challenging, others easier
- Designed e-beam patterns, exposed, and developed resist profile

Process



Resist profile after grayscale e-beam lithography



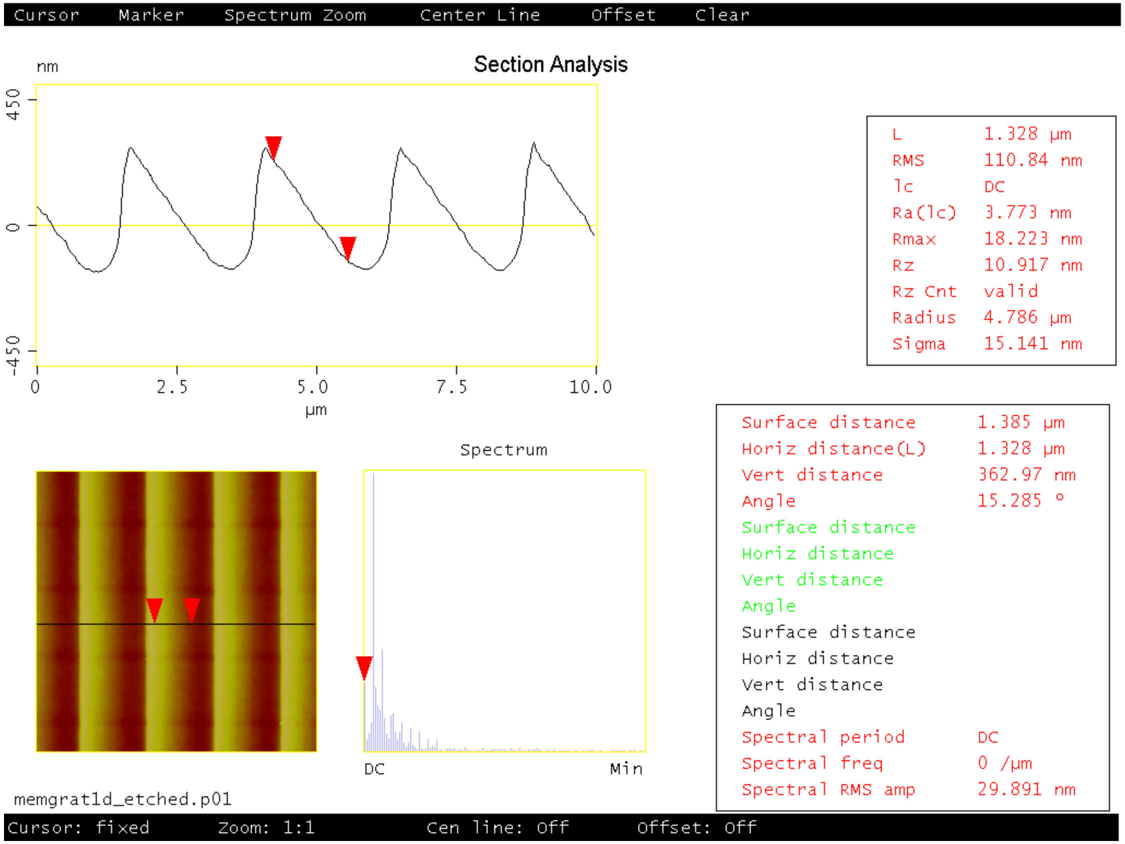
- Blaze angle in resist ≈ 6.2°
- Desired blaze angle in silicon ≈ 21°
- Etch is used to amplify depth

Grayscale E-beam Lithography Fabrication of Silicon Immersion Gratings

Transfer Etch of Resist Profile

- Inductively coupled plasma (ICP) reactive ion etching (RIE) in JPL MDL
- Adjust gas mixture and RF powers to achieve grayscale transfer of resist profile into Si

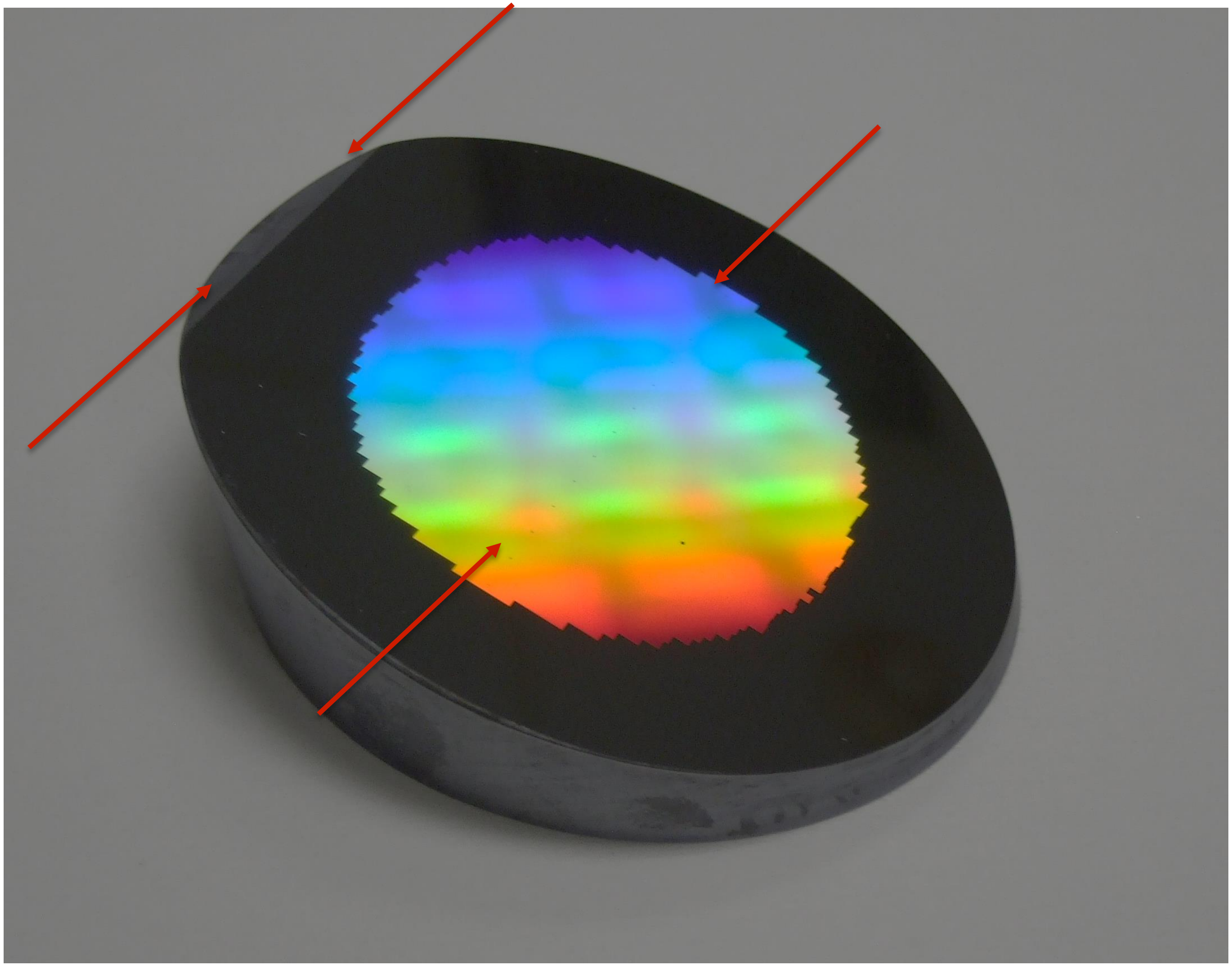
Silicon profile after transfer etching – Atomic Force Microscope (AFM) profile



- Blaze angle in silicon ≈ 15° (goal 21°) with some rounding at bottom
- Simulated diffraction efficiency from AFM profile had peak of ~48%

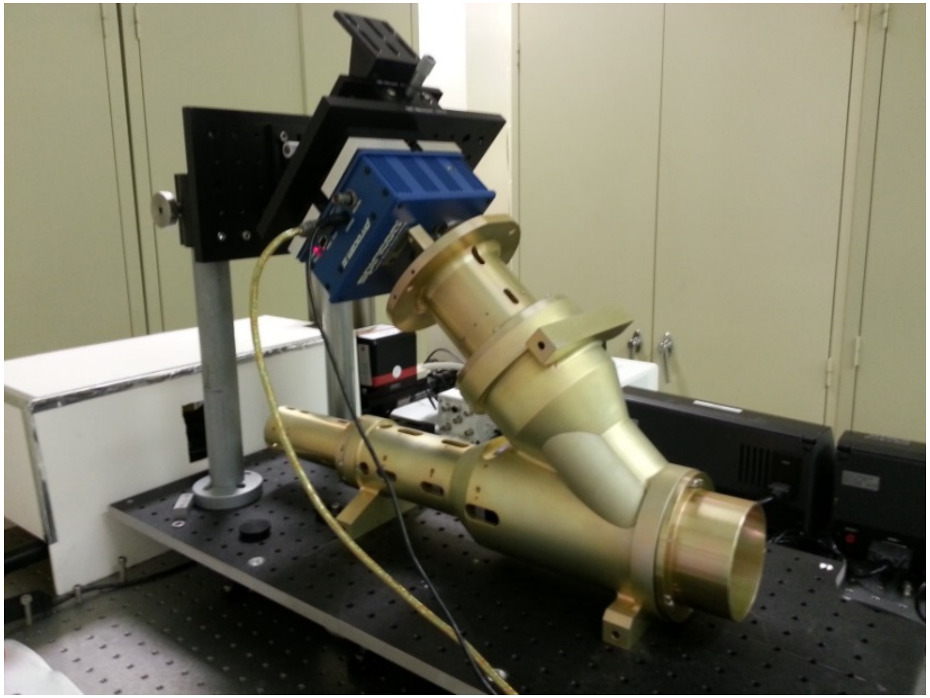
Grayscale E-beam Grating Etched into Silicon Prism

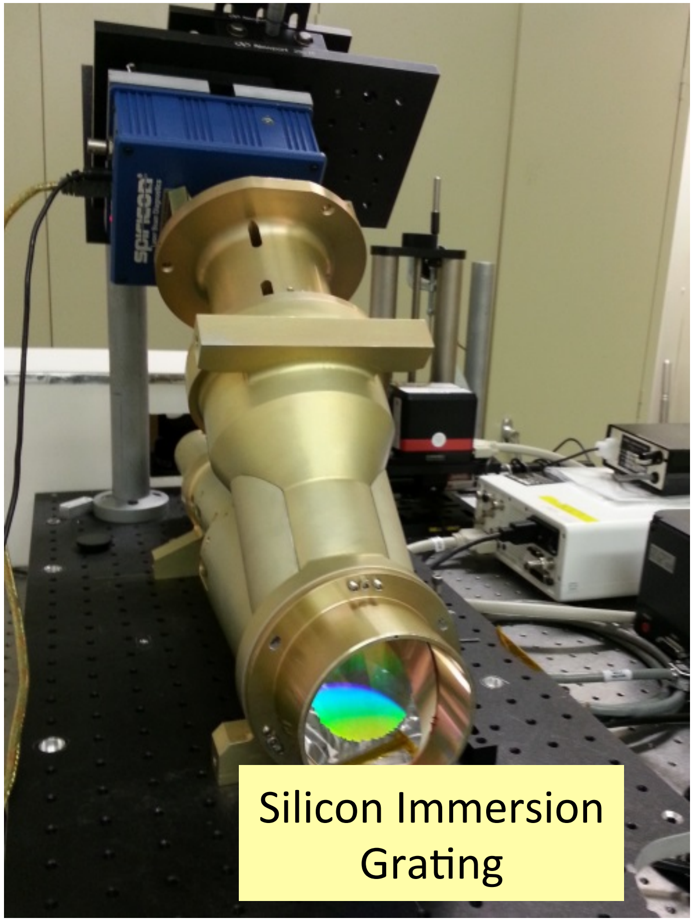
(Grating 55 mm diameter, Prism antireflection-coated on non-grating side)



- Etched grating was measured to be uniform across the full aperture
- Blaze angle ~18 deg, simulated efficiency 53% peak, 43% in band

Silicon Immersion Grating Used in Spectrometer Testbed





- JPL Spectrometer Testbed used to demonstrate modular immersion grating spectrometer design and components
- System was aligned and well-focused images of the slit were observed to move across the detector as the illuminating monochromator wavelength was scanned

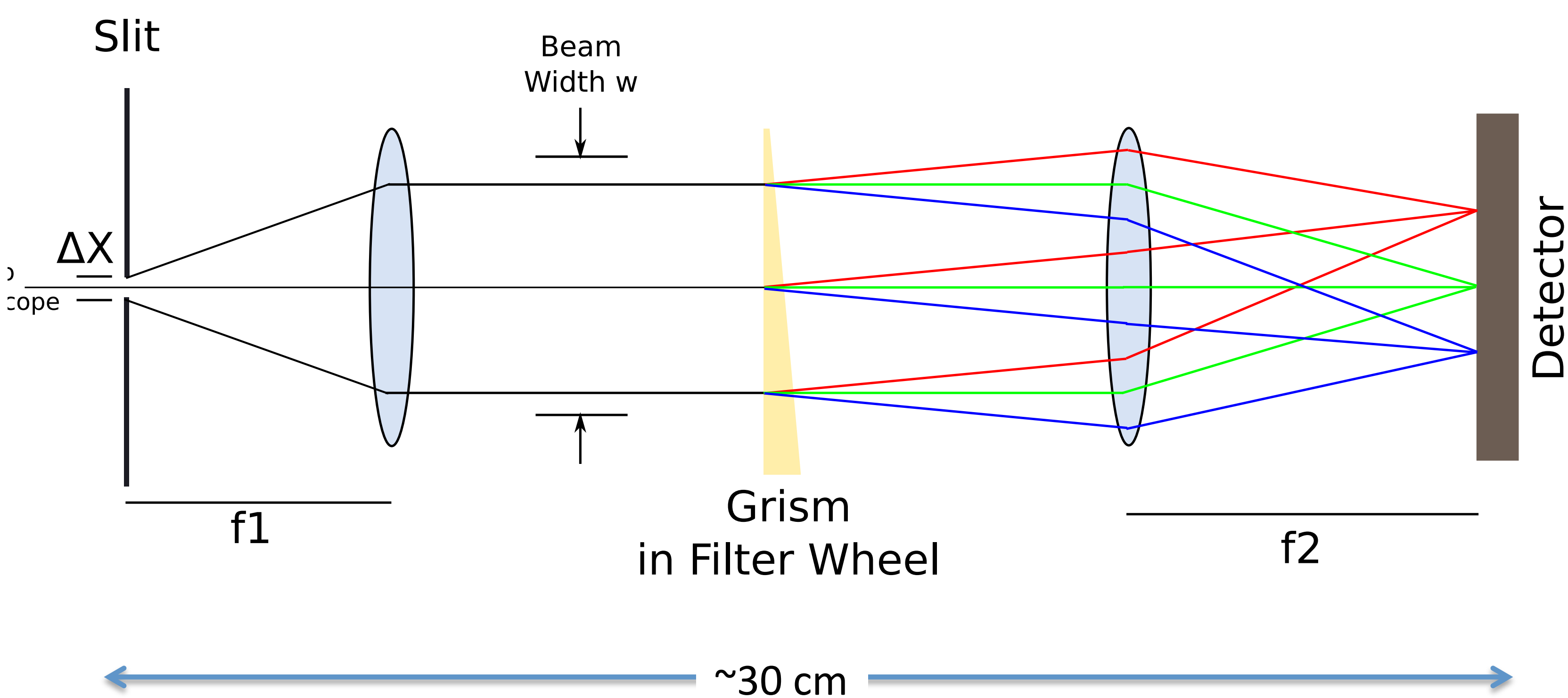
Summary

- Three infrared channel spectrometers designed for Earth science applications
  - 1.6 µm, 2 µm, 2.3 µm
- Manufactured three immersion gratings
  - Contact printing process
  - E-beam patterning with chromium liftoff
  - Grayscale e-beam patterning with plasma transfer
- Placed immersion grating in the JPL Spectrometer Testbed

Instrument designs for Earth science applications

- Take advantage of increased dispersion in silicon (n = 3.4) in the infrared
- Two options to consider:
  - Immersion gratings
    - Complete spectral coverage with cross-disperser configuration
    - Long-slit spectra in side-by side units to increase the field of view
  - Transmission gratings
    - Can be laid out linearly in compact instrument
    - Multiple spectrometers could be stacked in an array

Transmission grating spectrometer



A Grism Design Review and the As-Built Performance of the Silicon Grisms for JWST-NIRCam

Casey P. Deen, Michael Gully-Santiago, Weisong Wang, Jasmina Pozderac, Douglas J. Mar, and Daniel T. Jaffe

Cross-dispersed spectrometer