Fabrication of ISHELL Immersion Gratings

UT Si Diffraction Grating Group

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Principle of an immersion grating: (Fraunhofer 1823)

Infrared immersion gratings are an enabling technology because they can shrink instrument volumes by about an order of magnitude.

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

\[ R_{\text{max}} = \frac{2n_G L \sin \delta}{\lambda} \]

\[ \frac{d\beta}{d\lambda} = \frac{2n_G \tan \beta}{\lambda} \]
By cutting the crystalline silicon at the right angle, we determine the blaze.

*Cutting angle depends on desired blaze angle $\delta$
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.
iShell grating G1 for NASA Infrared Telescope Facility

FORCAST grating G3 (mid/near IR camera for NASA’s SOFIA airborne observatory)

63.4°, 80µm

6.16°, 15.36µm

32.6°, 87µm

JWST NIRCam grism A6-F
Views of the CA1 (IGRINS Grating Completed Surface)

Images of CA1 post KOH etching, but before nitride stripping
Immersion Grating CA1, After Coating, August 2011

Grating along side a solid model mockup

View of the AR coated entrance face
Front-Surface Interferogram of CA1

Interferogram with a 25 mm beam, front surface at 632 nm Peak to Valley deviation is 0.16 waves 5nm repetitive error leads to 0.2% ghosts
Measured efficiency in immersion:

Measured efficiency at 1.523 (close to the blaze but not on it) is 79 +/-6%
IGRINS Concept of the Instrument

IGRINS is a high resolution near-IR spectrograph:
R= 40,000
Slit 1”x 15” on the McDonald 2.7m, proportionally smaller on larger telescopes.
Stable and simple to use:
no moving parts

Very large spectral grasp
(all of H and K at once)
Good efficiency/sensitivity
Slit viewing camera for efficient observations
Pipeline reduction software for normal use.
University of Texas immersion grating process and development

UT

JPL

Reactive ion etching

KOH etching

Shaping, polishing, metallization and AR coating

Entrance face

Bottom

Aluminum
Slit
FZ Silicon
Silicon nitride
Photoresist
Mask
UV patterning of photoresist

- The UV exposure system operates by moving the mask-substrate unit beneath a stationary UV light source.
- The exposed photoresist is then developed out in the wet processing bench in our main lab.
Plasma etching of silicon nitride mask

• After patterning the photoresist, a silicon nitride layer is etched using a Trion Oracle inductively-coupled plasma (ICP) etch system.

• The interior of the etch chamber has a custom cathode cover manufactured to hold our thick silicon disks.
Etching grating into silicon

- The grating surfaces are etched into silicon using a solution containing potassium hydroxide (KOH). The silicon nitride film previously etched acts as a hard mask during the silicon etching.
- The KOH setup includes a circulating chiller for temperature control of the ultrasonic batch in which the KOH etching solution is immersed.
Metrology during processing

- A number of instruments are used for *in situ* process monitoring
- Non-destructive film thickness is measured using a Woollam ellipsometer and feature profile is measured using a Dektak profiler
Electron microscopy

- The TMI houses a Quanta environmental scanning electron microscope
- This SEM has a large sample chamber so that we can place the entire thick silicon substrates in the chamber allowing us to non-destructively image the gratings.
Optical interferometry

- We have recently purchased a Fizeau-type laser interferometer manufactured by Zygo corporation that is housed in the CNM.
- This tool creates an optical interferogram that we use to characterize the quality of the grating after patterning is completed.
Efficiency characterization

- The efficiency measurement setup is located in our main lab.
- This measurement compares the signal from the immersion grating to that of an aluminum mirror.

![Efficiency graph](image)

The measurements for $\lambda > 600$ nm cover orders to $\lambda = 2000$ nm. The peak efficiency is typically about 95% of an aluminum reference mirror, as shown by the horizontal dotted line at $\lambda = 1500$ nm. The vertical dashed lines at $\lambda = 600$ and $\lambda = 800$ nm demarcate the designed wavelength range of IGRINS $H$ band channel. Similarly, the vertical dashed dotted lines demarcate the $K$ band channel. The faint gray line in the background is the atmospheric transmission over Kitt Peak.

Measurements at $\lambda > 600$ nm were not performed at the time of writing. The slightly suppressed efficiency at $\lambda = 600$ nm may result from visible light leakage in the reference mirror measurement from our $\lambda = 600$ nm low pass filter operated in uncollimated light, or perhaps from real polarization sensitive effects. See the notes on the next figure’s caption regarding the difference in measurements shortward and longward of $\lambda = 800$ nm except for order $p$ which has a peak efficiency of merely 90%. CApa was measured with an out of plane angle $\gamma \sim 45^\circ$. This angle is comparable to the out of plane angle in the IGRINS design, $\gamma = 30^\circ$. We only coarsely controlled the incidence angle $\alpha$ in our efficiency measurement, with $\alpha \sim 5^\circ$ to within about $1^\circ$. Accordingly, we measured some angularly dependent discrimination loss that one would expect if orders diffracted into the grating sidewalls. It is best to have $\alpha > 5^\circ$ so that the blaze envelope is centered at $\beta < 5^\circ$.

There are a few potential loss mechanisms which lead to the observed efficiency:

- Fresnel loss from entrance through the front vacuum/Si interface
- Loss from microscopic groove and entrance face surface roughness that goes into scattered light
- Loss at the Si/Al interface due to dielectric effects
ISHELL Requires two immersion gratings:

Long wave: (2.7-5.4 microns): 80 micron period
Short wave: (1.15-2.5 microns) 48.5 micron period

Both are R3 with a 30.5x35 mm entrance face.

The plan is to fabricate the long wavelength grating using contact lithography (a la CA1) but to fabricate the short wavelength grating using e-beam lithography with the JEOL writer at JPL.
Residue is from undercut of nitride mask; part has not been cleaned yet.

Left-right asymmetry due to slight tilt on SEM.
Interferogram of E03 30mm thick piece for ISHELL L&M grating. This is a 30mm diameter aperture at 633 nm. This is about \( \lambda/3 \) p to v in immersion at 4 microns on a 25mm aperture.
ISHELL possible grating
Same piece (G03) at a slightly different position. This realization would be lambda/4 over a 30mm aperture but note that the entrance face cannot be that perfect all the way to the edge.
Status and plans:

L&M: We have a marginally acceptable surface now. We are making tests now to our setup to understand the origin of the large-scale errors. This will involve sacrificing a 30mm thick part. After that, we should be able to re-make the part.

JHK: Has been in recovery from the destruction of a 100 hour write ISHELL part last year. We now understand the process issues that caused this and the groove samples you see demonstrate that we can safely write a thick part. The one issue remaining is to test this sample for ghosts.

Expect to write both types of parts in the next 2-3 months.