PSI Center for Photon Science

Advancements in Fabricating High-Precision VLS Blazed Gratings on Non-Flat Silicon Substrates

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Outline

Goal
Fabricating sawtooth profiles on curved Silicon substrates for x-ray diffraction gratings

Grayscale lithography

- Dose gradient shapes → a new design element for height varying resist exposures
- Through-mask oxidation → transfer technique from resist to Si substrate

Variable line spacing (VLS) gratings

- Curved substrates → important for focusing x-ray optics
- Mainfield scaling → high precision placement changing the grid ever so slightly

Blazed x-ray diffraction gratings

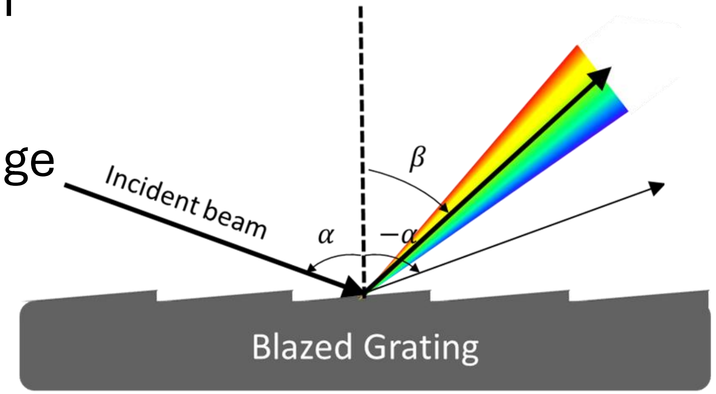
PSI

Blaze angle is optimized for a specific wavelength and diffraction order

- Highly efficient → as much light into the desired order

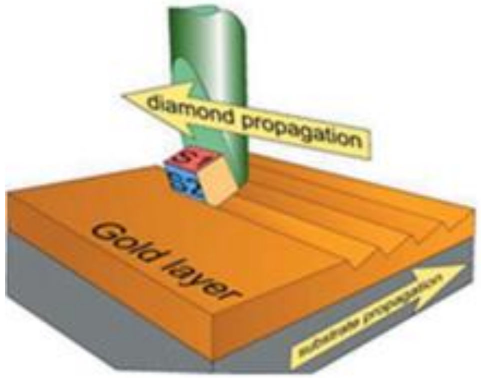
Application at Synchrotrons and XFELs in the soft and tender x-ray range

- Monochromators
- Analyzers for inelastic scattering
- Self-seeding and pulse compression



Issue: Long lead times and shortage of supply

- Commonly used manufacturing method is mechanical ruling
- Higher line densities → longer manufacturing times
- Highly specialized equipment (one in Europe)



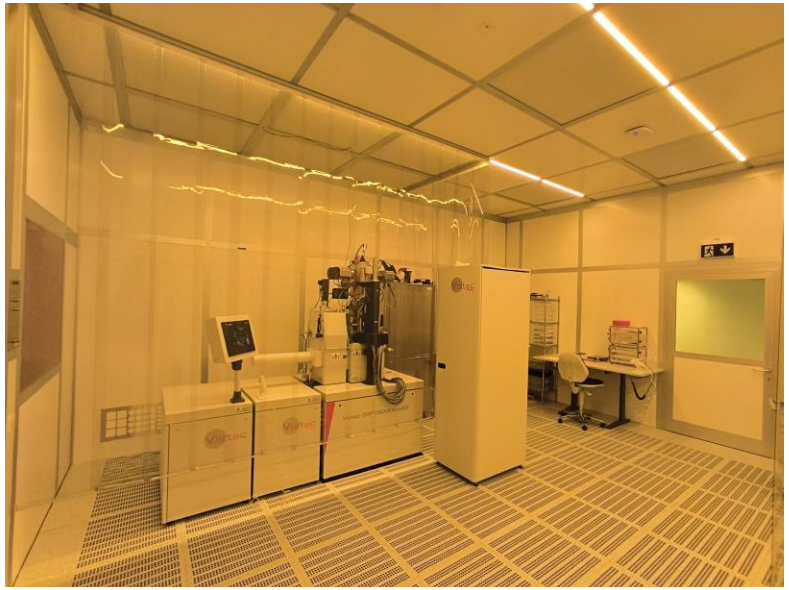
LEAPS Innov proposed solution is electron beam lithography

LEAPS INNOVATION

Our e-beam machine and location

EBPG 5000+ with UPG (Universal Pattern Generator)

- Beyond trapezoid fracturing
- Nanometer placement (< 1 nm)
- Sufficient throughput at exposure rates of 1 cm^2/hr
  - Even for higher line densities
- Substrates up to 140 x 30 x 10 mm^3

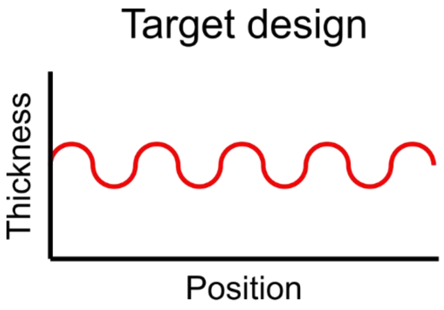


E-beam at PICO
The new cleanroom in PiA

Park InnovAare

Grayscale lithography - concept

Grayscale = thickness/height variations

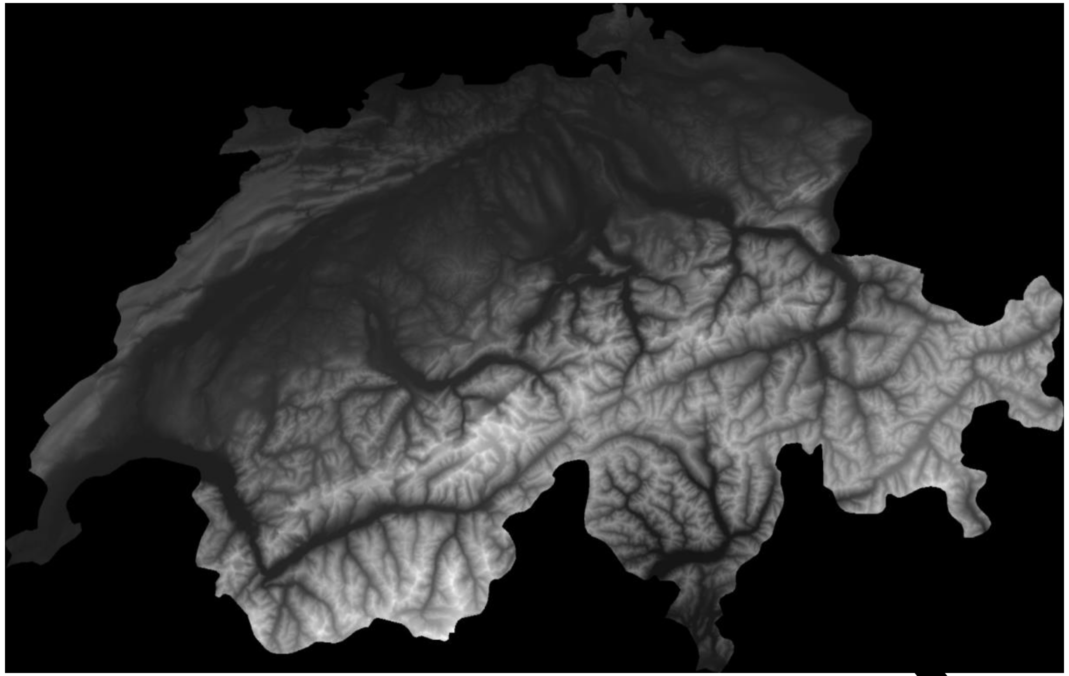


New developments
1. Dose gradient primitive shape
2. Efficient exposure
3. Through-mask oxidation using HSQ resist

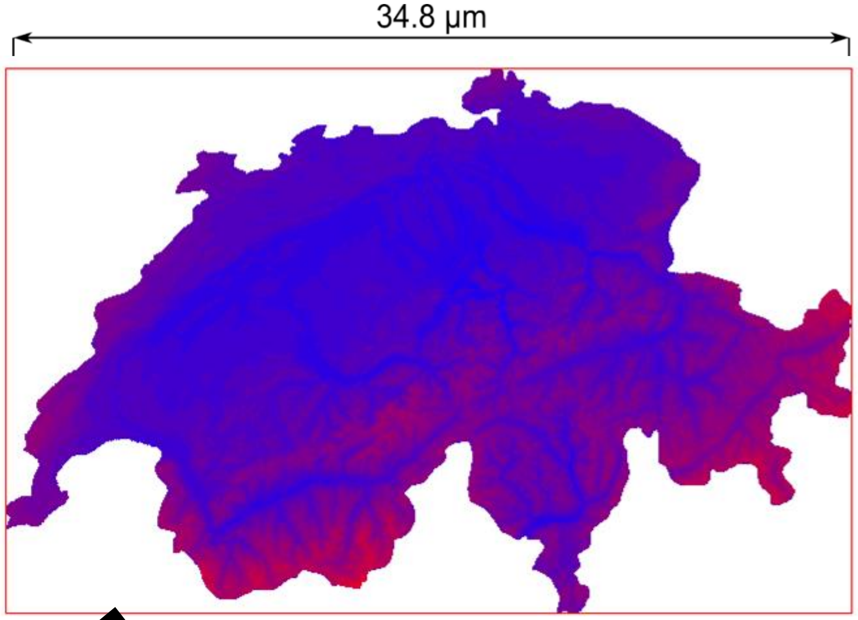
Let's go through an example

Grayscale lithography - example

Target: Grayscale 16bit map

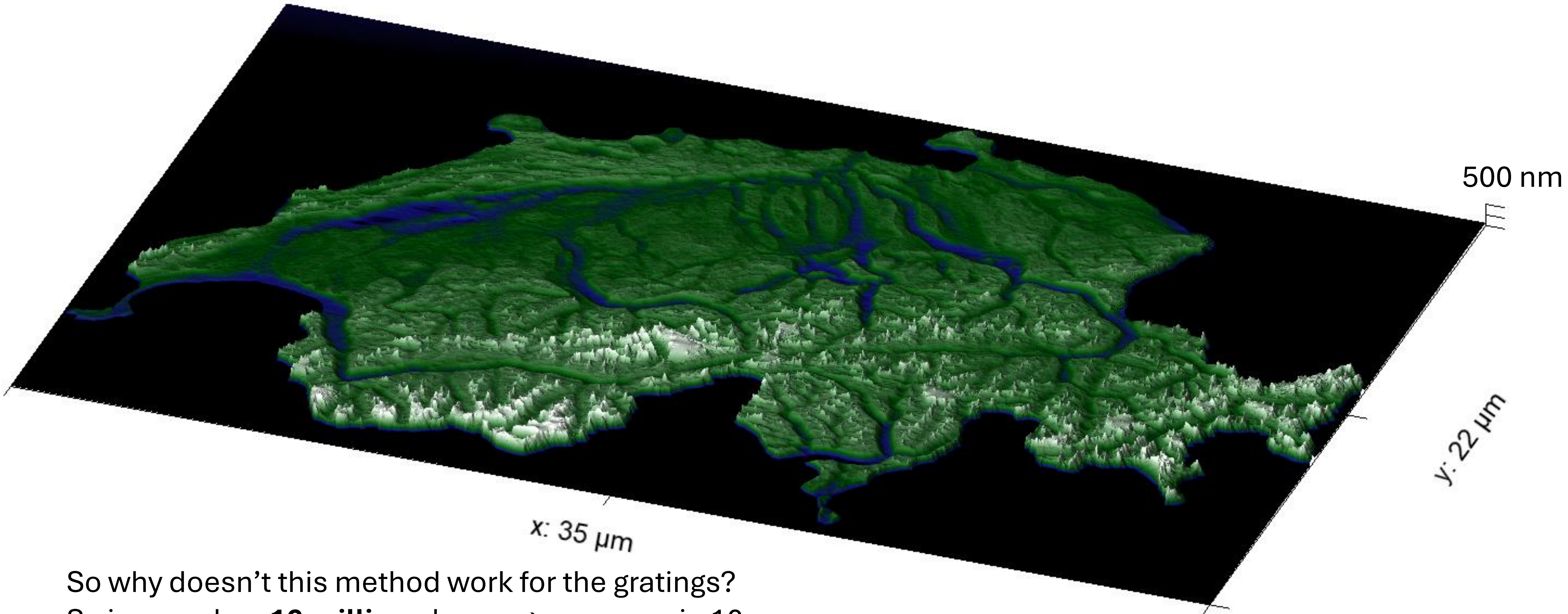


Data prep: 46 MB for 35 doses



BEAMER w/ 3D Surface PEC

Grayscale lithography - results

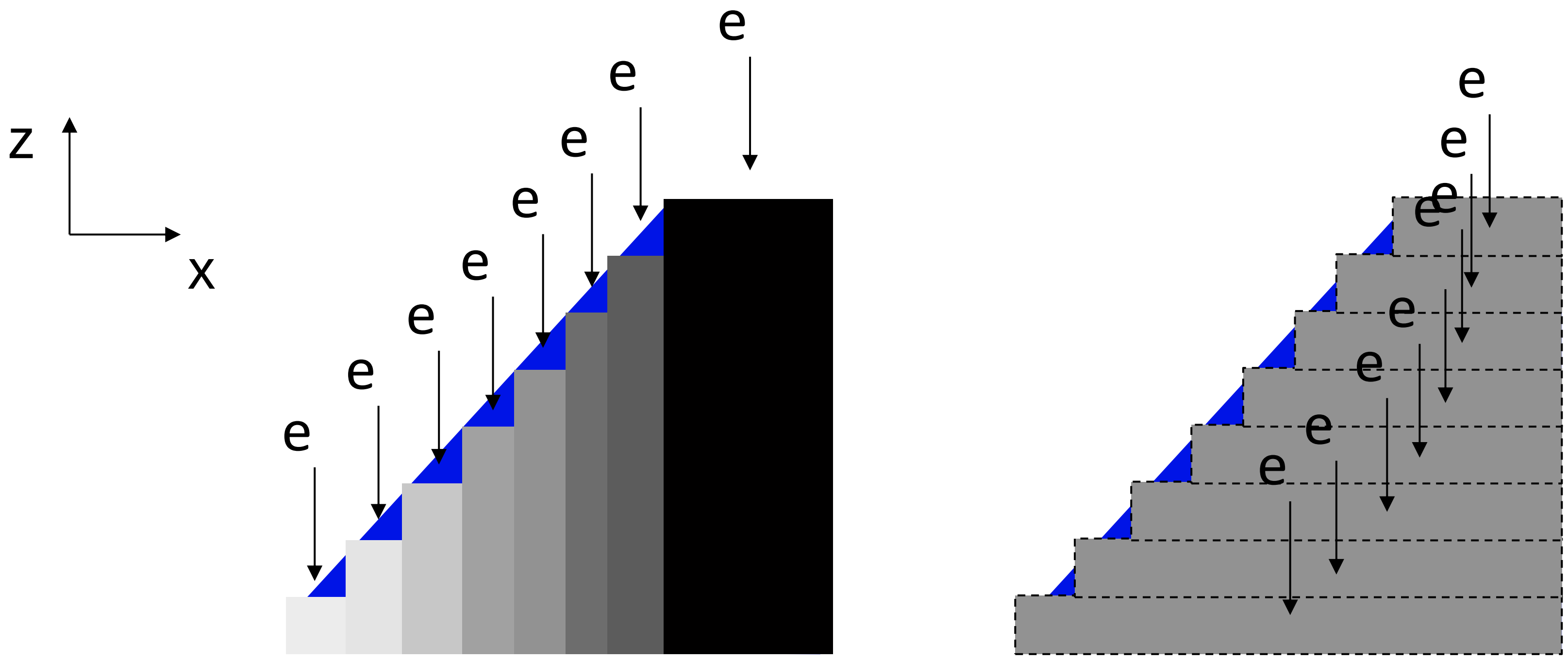


So why doesn’t this method work for the gratings?
Swissmap has **16 million** shapes → exposure in 10 sec
Grating is **12 million** times larger

AFM measurements by B. Frederiksen

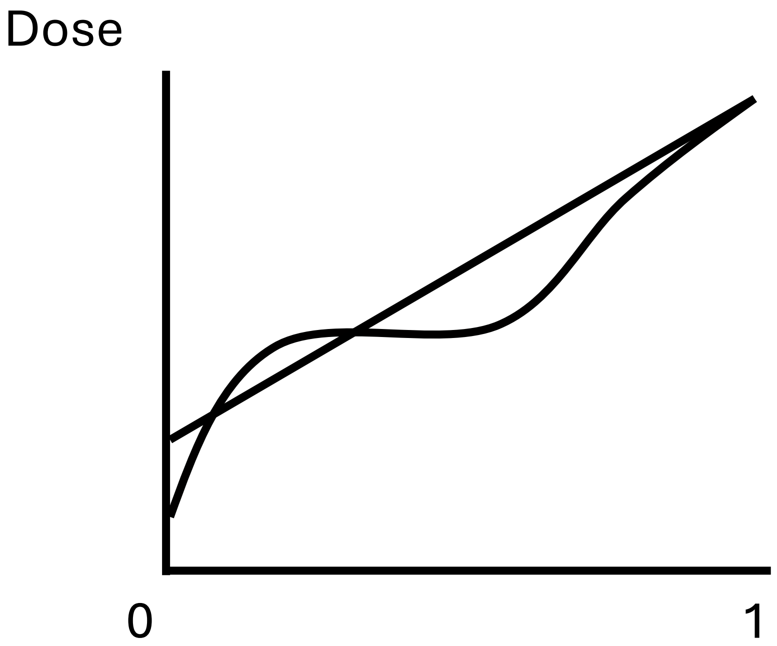
Grayscale data preparation - fracturing

Current methods of fracturing

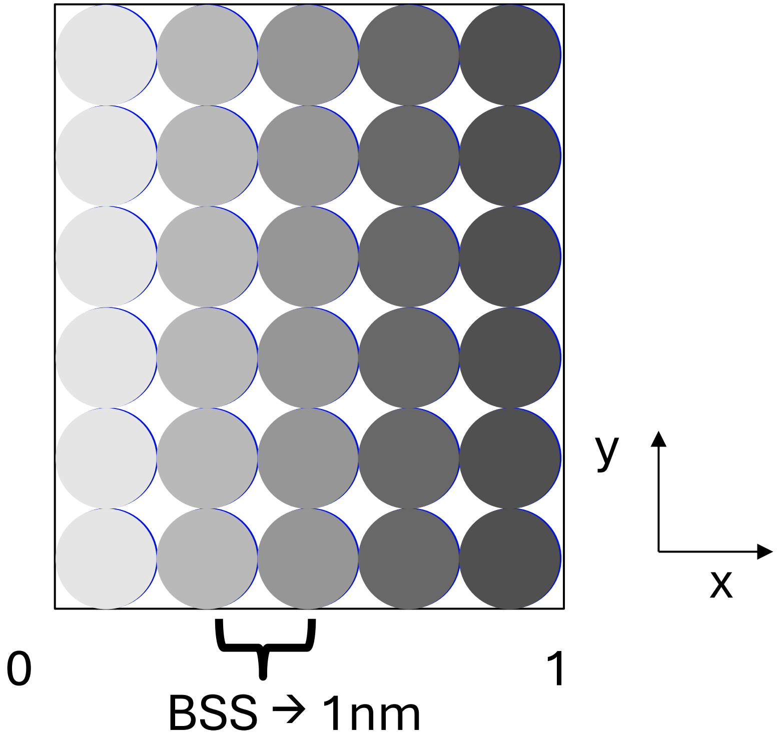


Each change in dose needs another new shape
Amount of shapes explodes!

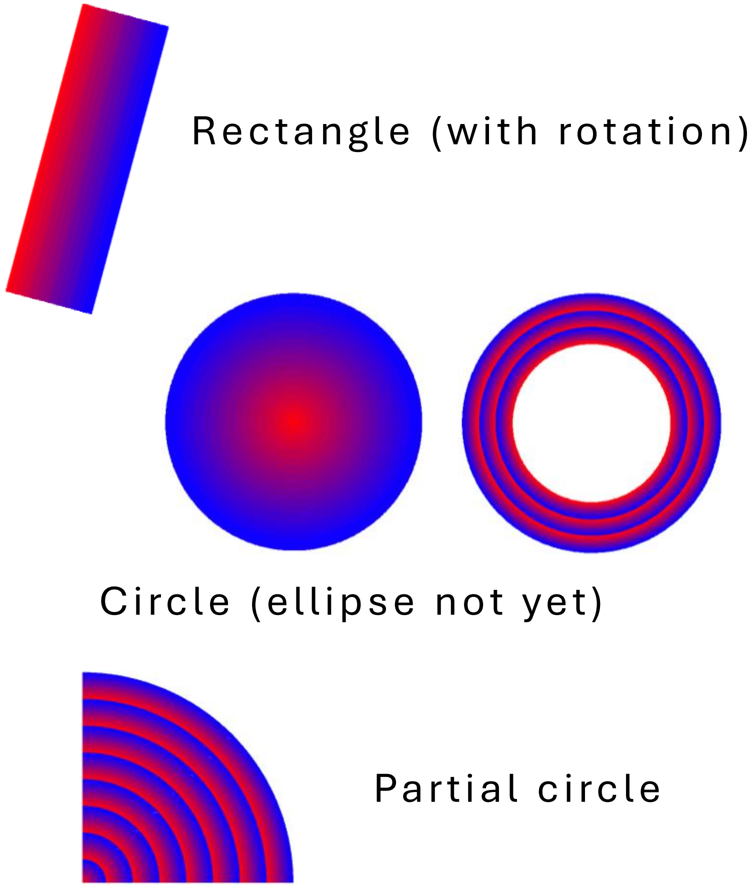
Dose mapping



Dose gradient cube



Basic shapes



Result: Efficient grayscale lithography data preparation

Large area VLS gratings

Comparing old vs new method

Design VLS of 120 x 20 mm^2

Old method

146 GB gtx (ascii)

11 GB gpf (binary)

38 billion shapes

New method

30 MB gtx (ascii)

9 MB gpf (binary)

950 million shapes

Result: Storing the dose information inside the shape reduces the file size drastically, and is easier to program/debug

Grayscale EBL and through-mask oxidation

Spin coating

- HSQ as resist, Thickness ~300 nm

Grayscale exposure

- Exposed area is converted to SiO_x

Development

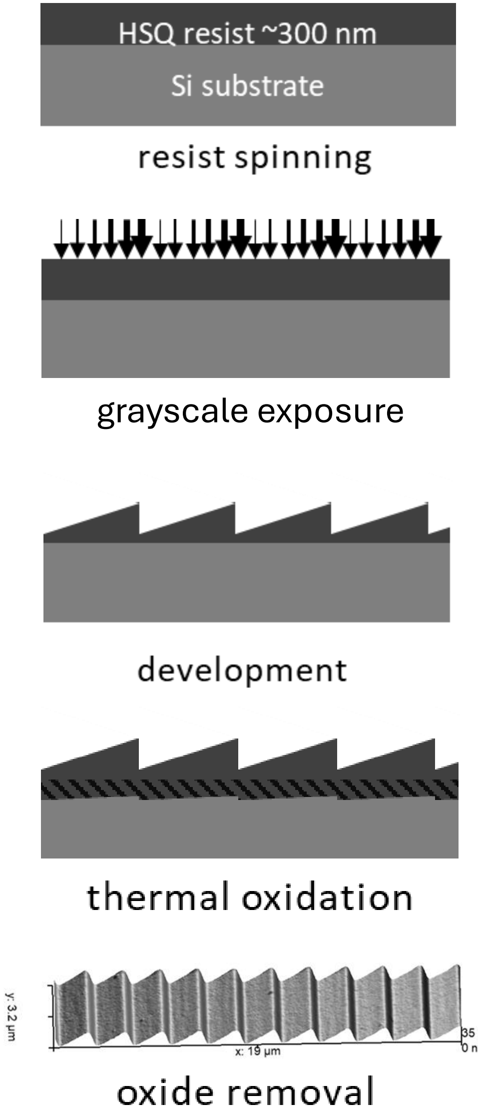
- NaOH based developer

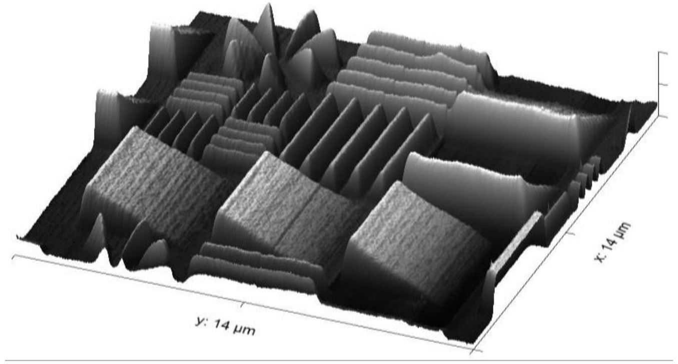
Thermal oxidation

- Dry oxidation, Different SiO_x thickness → different oxidation speed

Oxide removal

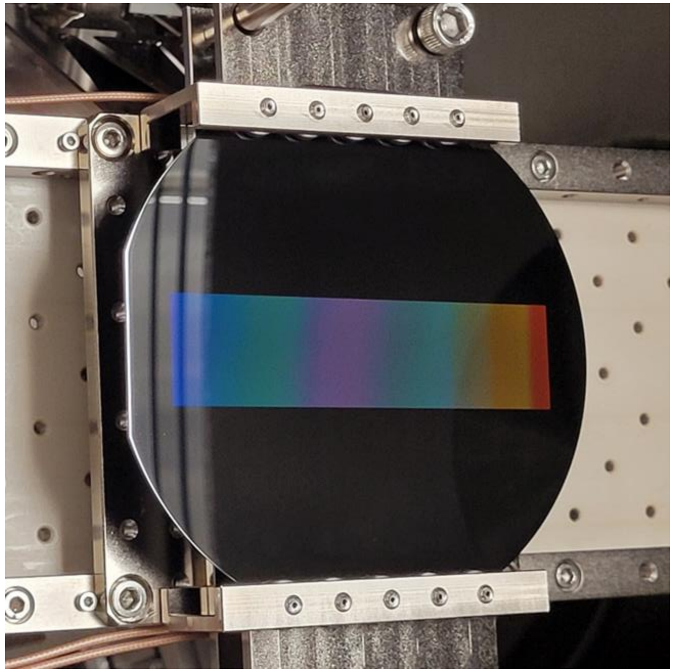
- Wet chemical oxide removal with HF → reduces the roughness

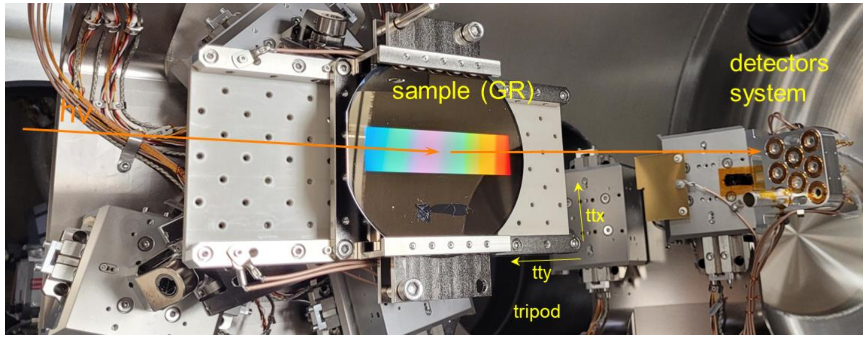




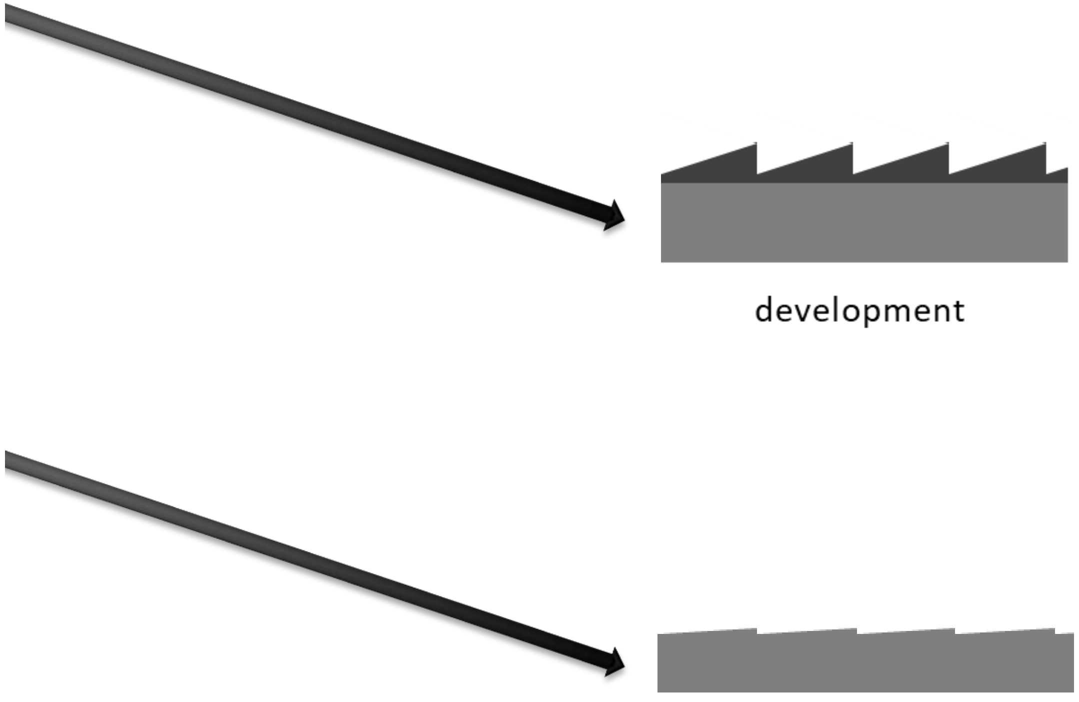
Patent pending: V.A. Guzenko, C. David: *Fabrication of blazed diffractive optics by through-mask oxidation,* 2019P20969WO

Grayscale EBL and through-mask oxidation



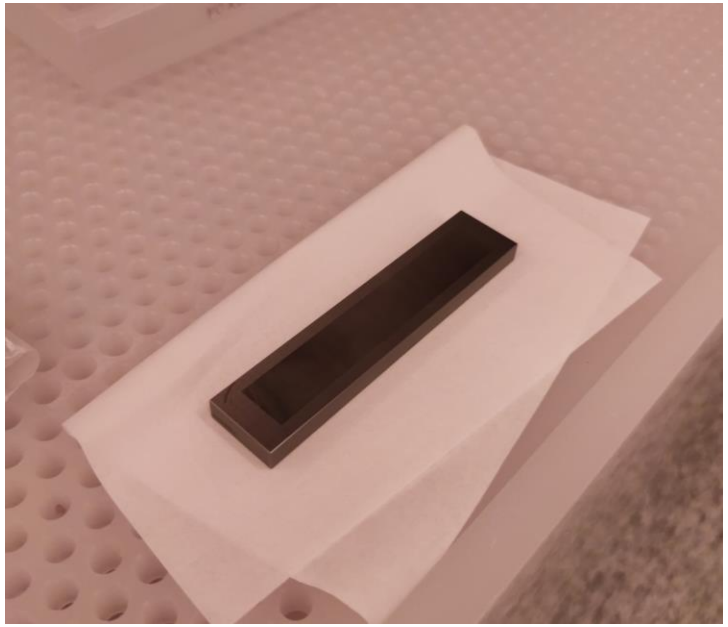


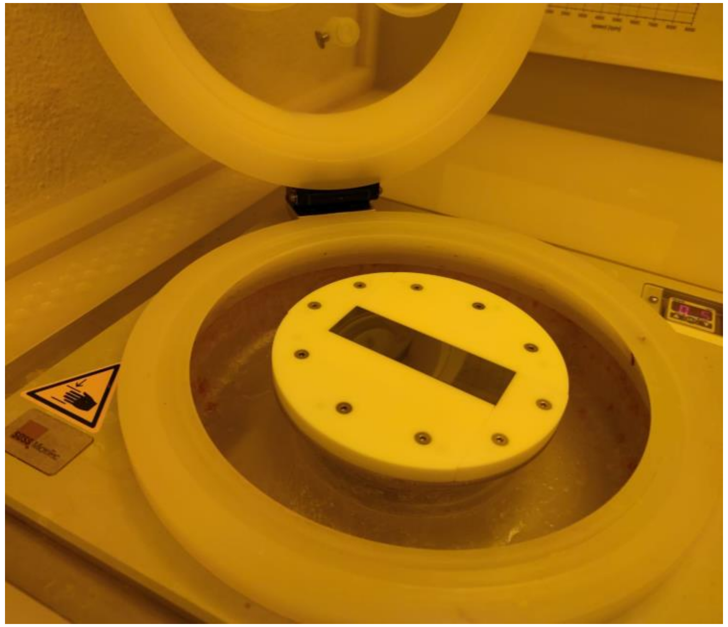
Result: Smooth surface due to height feature reduction (10x)

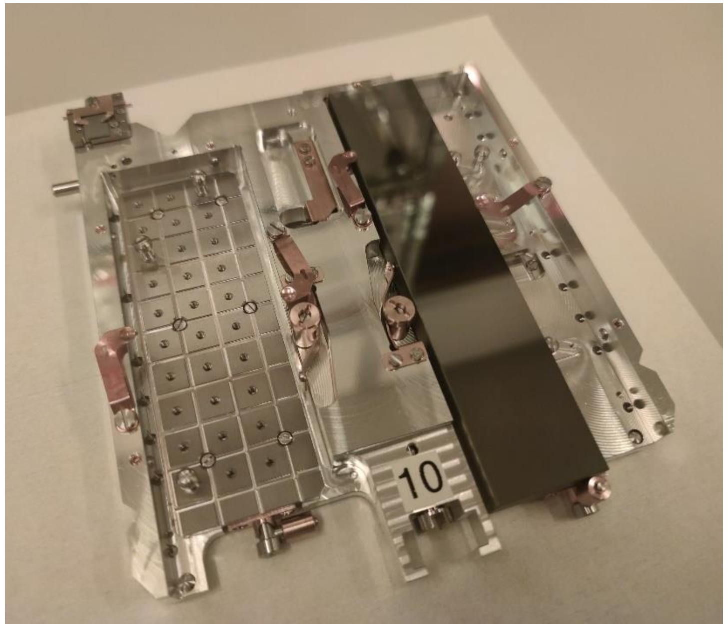


AFM measurements by N. Samadi @ PSI & Patent pending: V. A. Guzenko, C. David 2019P20969WO

Thick curved substrates







Radius of curvature is 28 m or 12 m

- Maximum height difference: 100 µm to 200 µm (tool limit)

In the near future: Z-stage in 2025 with up to 10 mm range

Combined with a new feature for tilt corrections → even curvier substrates

High-precision placement

Example: Write lines with a pitch of 100.4 nm

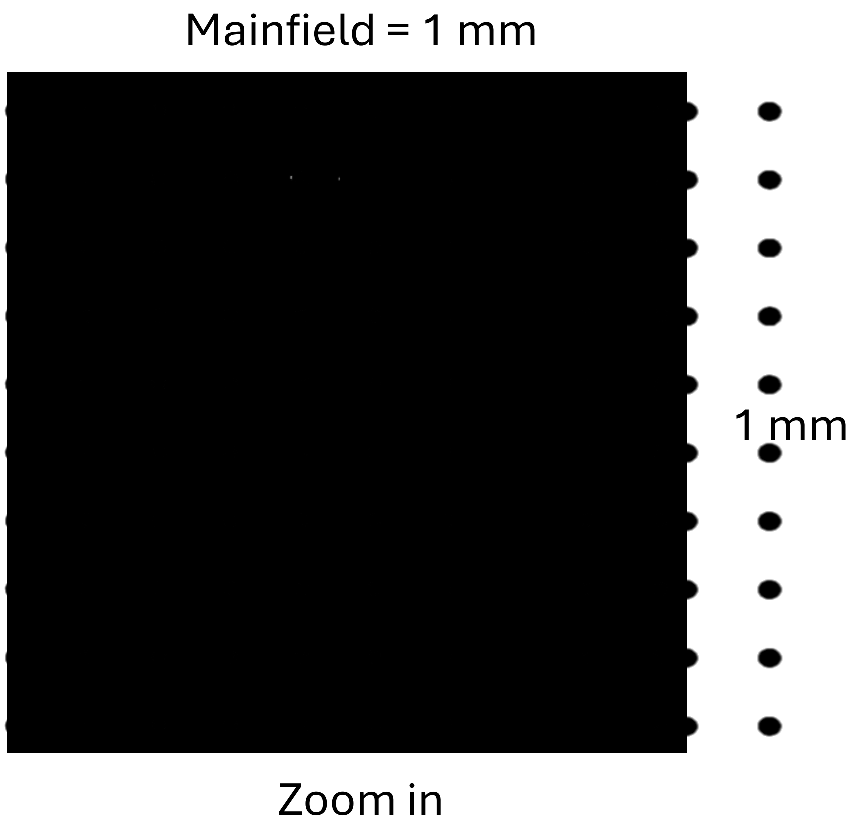
- Grid = 1 nm (20 bits → min 0.07 nm)

Problem: Grid snapping

Solution: Mainfield scaling

- Stretching or compressing the mainfield
- Maximum scaling ±1%

How about VLS gratings where pitch is continuously changing?



Continuous high-precision placement

Density (lines/mm) = $a_0 + a_1x + a_2x^2 + a_3x^3$

Settings

- Mainfield = 80 µm
- Grid = 0.5 nm

Scaling each mainfield goes as follows

Parameter	Specified
Grating Period (a_0)	800
1st Coefficient (a_1)	2.81 mm^{-1}
2nd Coefficient (a_2)	2.2e-3 mm^{-2}
3rd Coefficient (a_3)	6.4e-6 mm^{-3}

	Pitch (nm)	Nom. Pitch (nm)	Scaling factor
Field 1:	1346.804249	1347	-14532
Step 40 µm			
Field 2:	1346.738446	1346.5	17708
Step 40 µm			
Field 3:	1346.672648	1346.5	12821
etc…			
#3202:	1152.851544	1153	-12875

Advantages

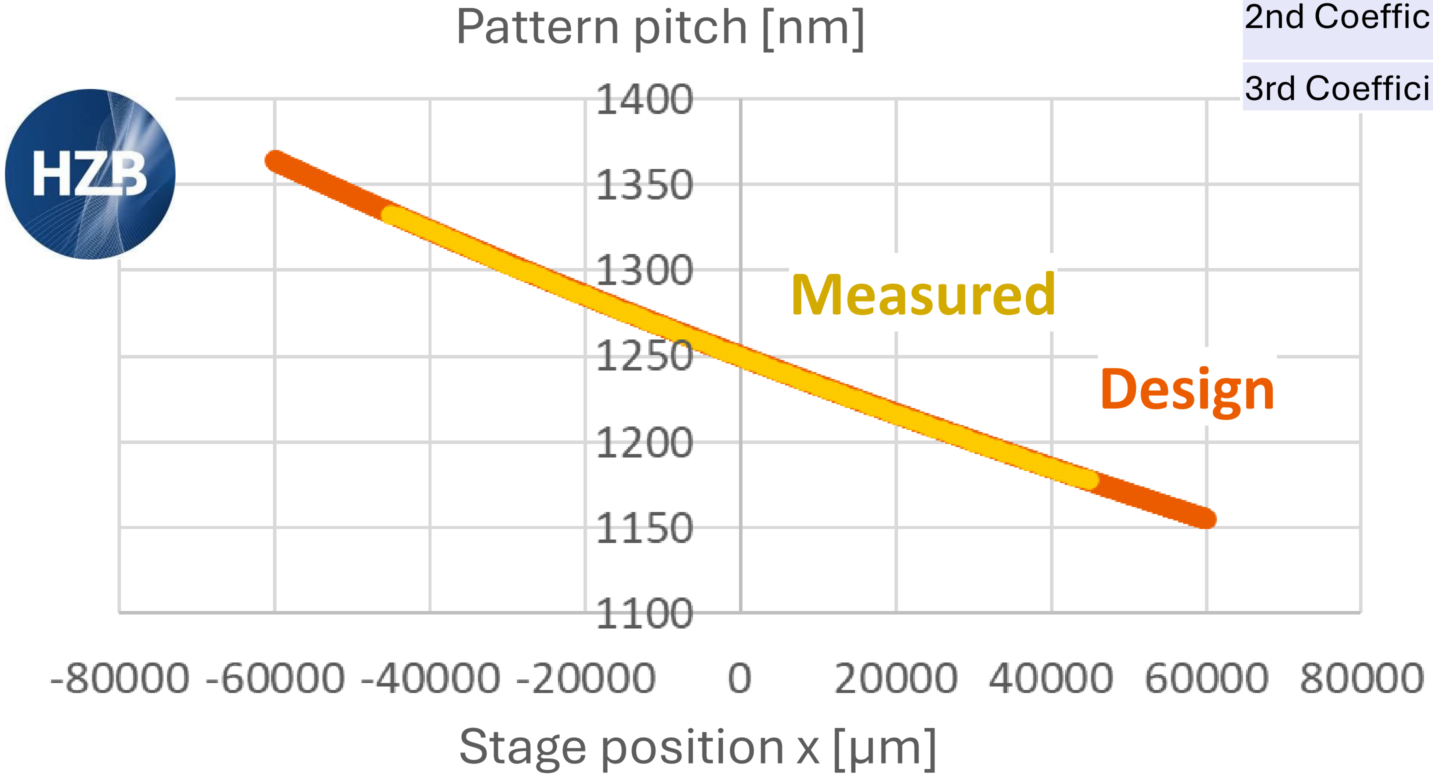
- Multipass averages out the errors at the edges of the mainfields
- Each mainfield writes 60 lines reducing stage movements (time saving)
- Accuracy better than addressing grid

VLS gratings – early results

Variable line spacing using cont. scaling of the grid

Density (lines/mm) = $a_0 + a_1x + a_2x^2 + a_3x^3$

Parameter
Grating Period (a_0)
1st Coefficient (a_1)
2nd Coefficient (a_2)
3rd Coefficient (a_3)



Max. residual in pattern pitch
< 80 picometers

Laser measurements by A.F. Herrero @ HZB

Latest X-ray results - ESRF

Beamline ID 32 XES spectrometer

Mainfield settings show up,

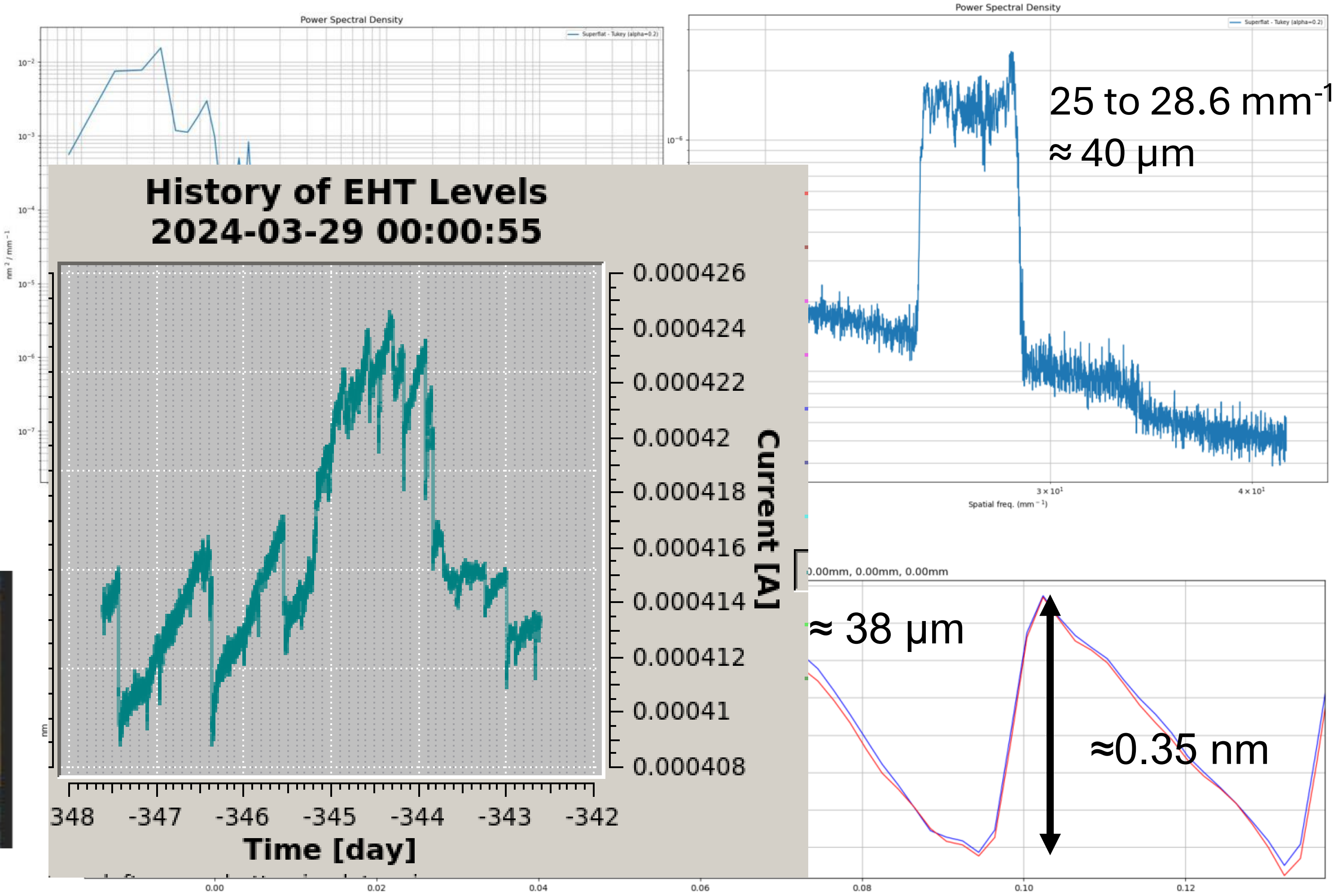
- Mainfield = 80 x 860 µm^2

MP = 2 so ≈ 40 µm

6 Steps visible by naked eye

Period ≈ 18.6 mm

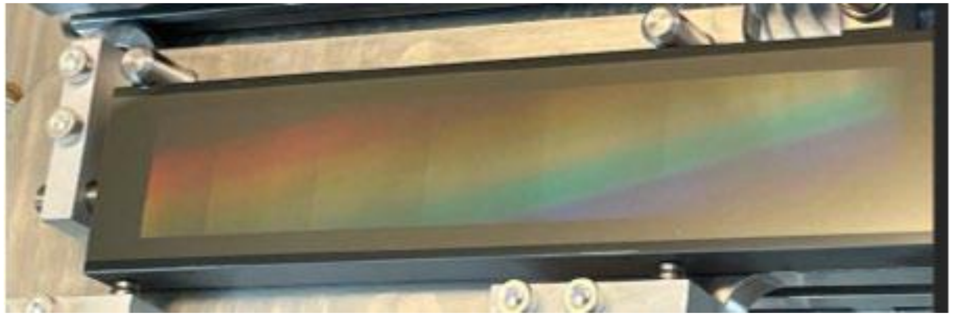
Amplitude ≈ 0.2 / 0.3 nm

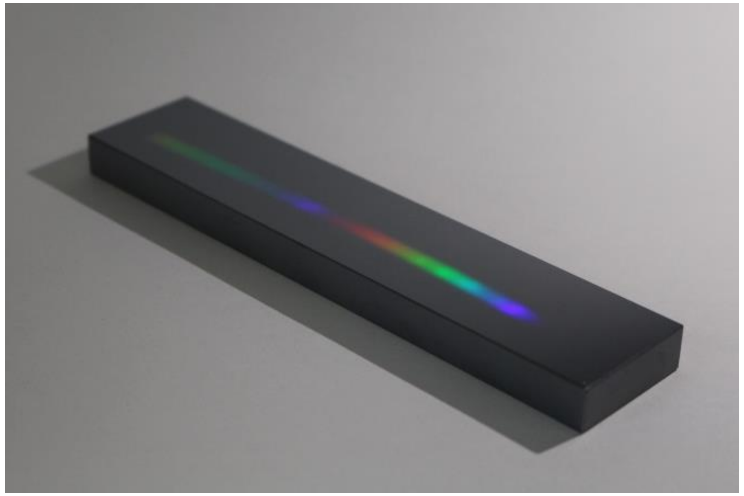


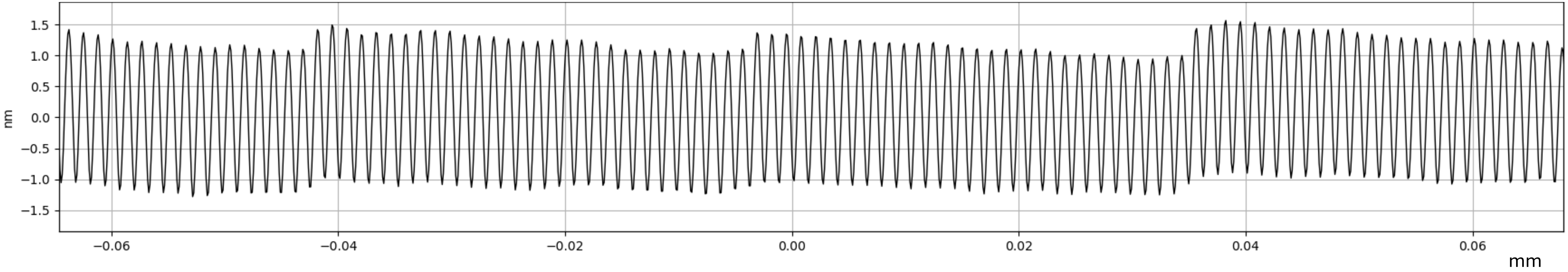
25 to 28.6 mm^{-1}
≈ 40 µm

≈ 38 µm

≈0.35 nm







Effect of curvature?

Conclusion

- VLS gratings in thick curved Silicon
  - Up to 140 x 30 x 10 mm^3
- Picometer precision pitches
- Tests ongoing at the beamline(s)
- Soon commercially available at XRnanotech
- Through-mask oxidation process for smooth structures

Future developments:

- New tool in 2025
- Expanding applications to metalenses and photonic devices

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Andrey Sokolov
Frank Siewert

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Bas Ketelaars
and the entire team

LEAPS INNOVATION

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Thank you for listening!

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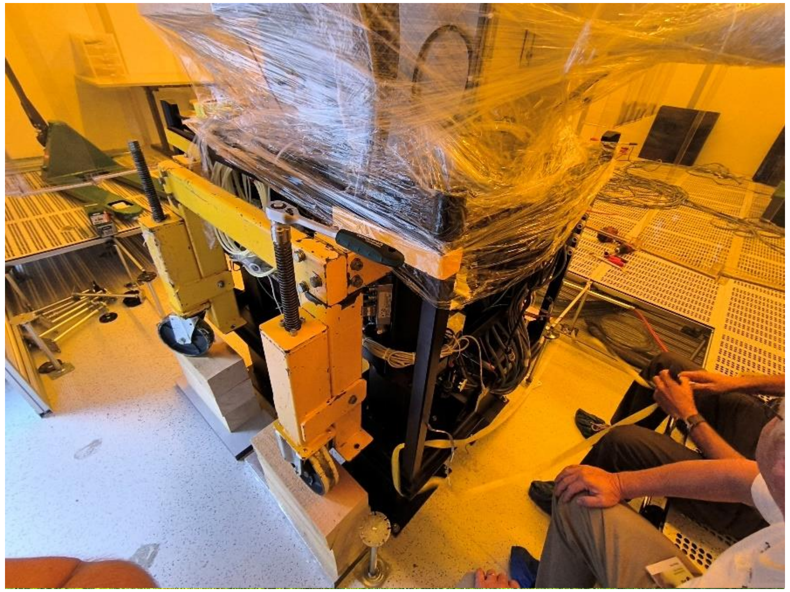
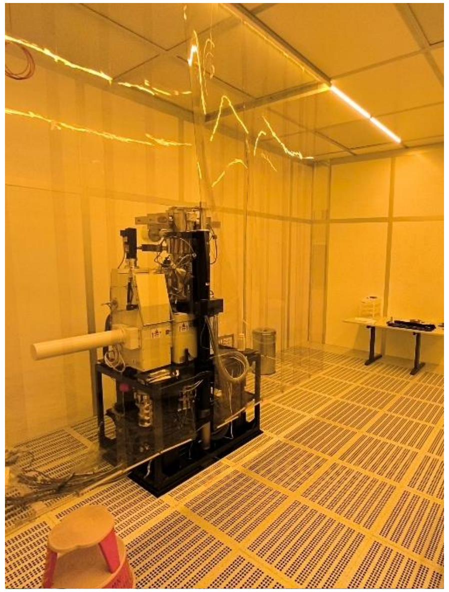
E-beam tools - move and acquisition





PMO cleanroom

LMN cleanroom

Park Innovaare

Through-mask oxidation for metalenses (preliminary results)

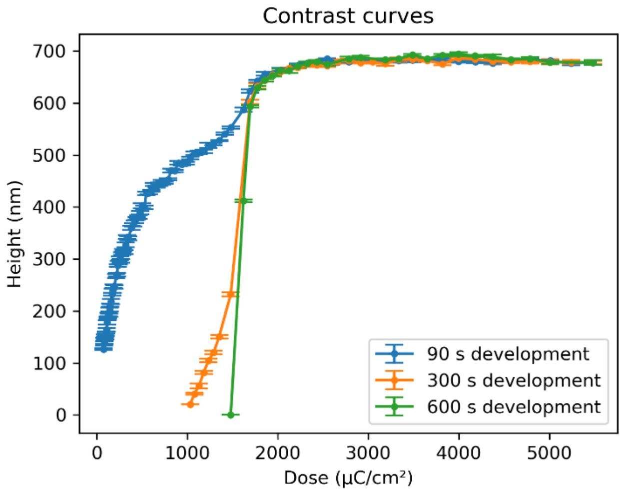
Benchmarking tests (ongoing)

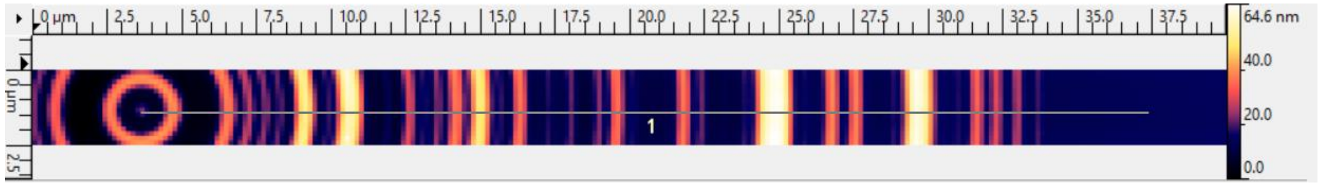
- Smoothly varying structures
- Abrupt changing is possible

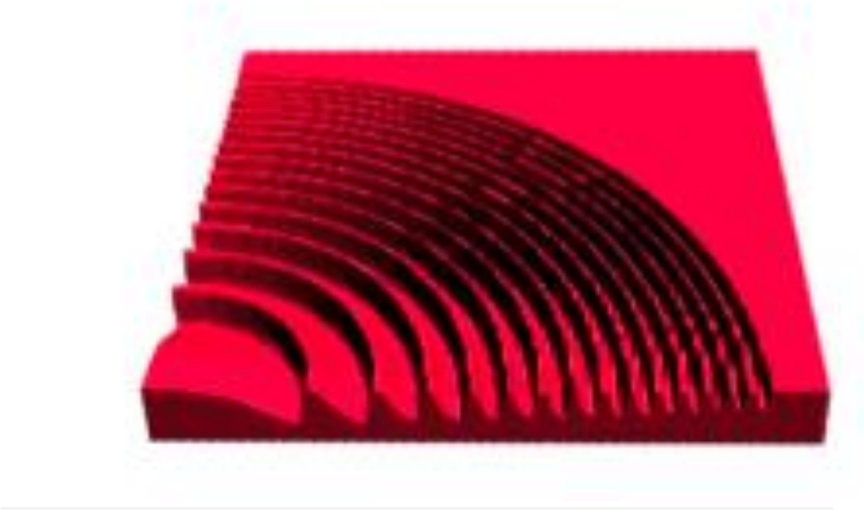
Silicon structuring

- Metalenses
- Photonic devices
- Pushing the limits for gratings
  - High line densities, Kinoform, sharper/larger angles

End goal: Stacking metasurfaces with high precision







Measurements by B. Frederiksen (DTU Summer student)

Going from one MF to the next (MP=2)

x='	'stageposX='	Polynomial line density	polynomial pitch	'scaleforchirp ='	'patternpitch='	'roundedpatternpitch='	'scaleX='	scaled pitch correction	final pitch (nm)	final line density	MF (um)
0	-60000	742.4984	1346.804249	1.077443399	1346.804249	1347	-14532	-0.19574604	1346.804254	742.4983973	40.406
1	-59959.596	742.534679	1346.738446	1.077390757	1346.738446	1346.5	17708	0.23843822	1346.738438	742.5346835	40.404
2	-59919.194	742.570959	1346.672648	1.077338118	1346.672648	1346.5	12821	0.172634765	1346.672635	742.5709665	40.402
3	-59878.794	742.607241	1346.606854	1.077285483	1346.606854	1346.5	7935	0.106844775	1346.606845	742.6072457	40.4
4	-59838.396	742.643522	1346.541065	1.077232852	1346.541065	1346.5	3049	0.041054785	1346.541055	742.6435284	40.398
5	-59798	742.679805	1346.475282	1.077180225	1346.475282	1346.5	-1835	-0.024708275	1346.475292	742.6797997	40.396
6	-59757.606	742.716089	1346.409503	1.077127602	1346.409503	1346.5	-6720	-0.0904848	1346.409515	742.7160821	40.394
7	-59717.214	742.752374	1346.343728	1.077074983	1346.343728	1346.5	-11605	-0.156261325	1346.343739	742.752368	40.392
8	-59676.824	742.788659	1346.277959	1.077022367	1346.277959	1346.5	-16490	-0.22203785	1346.277962	742.7886574	40.39
9	-59636.436	742.824946	1346.212194	1.076969755	1346.212194	1346	15764	0.21218344	1346.212183	742.8249516	40.388
10	-59596.05	742.861233	1346.146434	1.076917148	1346.146434	1346	10879	0.14643134	1346.146431	742.8612346	40.386
11	-59555.666	742.897521	1346.080679	1.076864543	1346.080679	1346	5994	0.08067924	1346.080679	742.8975212	40.384
12	-59515.284	742.93381	1346.014929	1.076811943	1346.014929	1346	1109	0.01492714	1346.014927	742.9338114	40.382
13	-59474.904	742.9701	1345.949184	1.076759347	1345.949184	1346	-3775	-0.0508115	1345.949189	742.9700976	40.38
14	-59434.526	743.006391	1345.883443	1.076706754	1345.883443	1346	-8659	-0.11655014	1345.88345	743.0063874	40.378
15	-59394.149	743.042684	1345.817706	1.076654164	1345.817706	1346	-13543	-0.18228878	1345.817711	743.0426808	40.377
16	-59353.774	743.078978	1345.751973	1.076601578	1345.751973	1346	-18426	-0.24801396	1345.751986	743.0789703	40.375
17	-59313.401	743.115272	1345.686245	1.076548996	1345.686245	1345.5	13842	0.18624411	1345.686244	743.1152725	40.373
18	-59273.03	743.151567	1345.620522	1.076496418	1345.620522	1345.5	8957	0.120516435	1345.620516	743.1515704	40.371
19	-59232.661	743.187864	1345.554804	1.076443843	1345.554804	1345.5	4073	0.054802215	1345.554802	743.1878645	40.369
20	-59192.294	743.224161	1345.48909	1.076391272	1345.48909	1345.5	-810	-0.01089855	1345.489101	743.2241546	40.367