APPLICATION NOTE

Design Rules for Wafer Level Optics (WLO)

Nanoimprint, Optical Replication & Wafer-Level Assembly

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Abstract

This application note summarizes the key design rules and process guidelines for Wafer Level Optics (WLO) based on optical replication and nanoimprint technologies. It covers the complete WLO workflow, from mastering and stamp fabrication through wafer imprinting, stacking, singulation, and reliability qualification. This document will provide engineers with actionable tolerances, material specifications, and quality benchmarks required to design-for-manufacturability (DFM) compliant optical components.

WLO enables high-volume, cost-effective manufacturing of micro- and nano-optical structures including Micro Lens Arrays (MLAs), Diffractive Optical Elements (DOEs), Fresnel lenses, and Polymer-on-Glass (POG) elements with demonstrated monthly capacities exceeding 5 million units.

1. Introduction to Wafer Level Optics

Wafer Level Optics (WLO) is a scalable manufacturing paradigm in which optical structures are fabricated across an entire semiconductor-style wafer substrate, enabling batch production of hundreds to thousands of optical elements per process cycle. By leveraging precision nanoimprint lithography and optical replication, WLO achieves nano-to-meso scale feature sizes with tight dimensional control.

1.1 Production Techniques Overview

WLO fabrication encompasses several complementary techniques, each suited to specific feature size ranges and volume requirements:

- Micro Injection Molding — for larger features (≥ 0.85 mm), using thermoplastic materials
- Optical Replication (Monolithic & Hybrid) — UV or heat-curable resins replicated onto film or glass substrates

- Wafer Level Optics (Nanoimprint) — high-density patterning for features from 1 µm to several hundred microns
- Hot Embossing Lithography — for flat optic structures in the sub-millimeter range

Typical volume products include:

- Polymer-on-Glass (POG): 5 million units/month
- Diffractive Optical Elements (DOE): 3.5 million units/month
- Micro Lens Arrays (MLA): 200,000 units/month
- Fresnel Lenses: 30,000–55,000 units/month

1.2 General Process Flow

The WLO replication process follows two primary routes depending on whether the product is monolithic (single-layer polymer) or hybrid (polymer on glass/silicon substrate):

- Route 1 — Monolithic Replication: Design Finalization → Master Stamp Creation → Working Stamps → Replication (film/Si substrate) → Curing → Demolding → Singulation → Inspection
- Route 2 — Hybrid Replication: Design Finalization → Master Stamp Creation → Working Stamps → Replication on substrate → Curing → Demolding → Singulation → Inspection

2. Core Design Rules

2.1 Nanoimprint Process Design Rules

The following table defines the primary design rules for the nanoimprint replication process. These constraints arise from the physics of polymer flow, UV curing kinetics, demolding forces, and metrology limits.

Parameter	Design Rule / Value	Notes
Structure Width	Min. 2 µm	Minimum feature size achievable by nanoimprint process
Residual Layer Thickness	~2 – 20 µm	Dependent on structure height
Aspect Ratio	> 2:1 (Width:Height)	Critical for demolding and structural integrity
Substrate Thickness	0.08 mm – 3.00 mm	Glass or silicon wafer substrate
Substrate Size	50 mm to 200 mm (wafer diameter)	Ø6" common; Ø8" in development
Profile Tolerances	±3%	Surface profile accuracy after replication

Key Design Guidance for Nanoimprinting

- Residual layer thickness scales with structure height — deeper features require thicker residual layers to ensure uniform fill
- Aspect ratio > 2:1 is critical for reliable demolding without structure deformation
- Substrate stiffness must be sufficient to prevent warping — especially for thin polymer-only substrates (monolithic replication)
- For Ø6" wafers, a 1.5×1.5 mm MLA can accommodate approximately 6,000 lens elements per wafer

2.2 Wafer Level Stacking Design Rules

When assembling multiple optical wafers into a stack (e.g., illumination + imaging MLA pairs, or lenses separated by glass spacers), the following dimensional constraints must be respected to ensure optical alignment and structural reliability:

Parameter	Value	Remarks
Lens Decentering Tolerance	+/- 10 µm	Alignment accuracy between stacked wafers
Glass Spacer Min. Wafer Thickness	0.18 mm	For structural integrity
Min. Through-Hole Width	0.10 mm	Minimum opening for adhesive flow or optical path
Min. Distance Between Through-Holes	0.30 mm	Prevents structural weakness between apertures
Wafer Alignment Accuracy	+/- 5 µm	Equipment (WLO4/5/6) imprinting accuracy
Measurement Equipment Accuracy	+/- 1 µm	OGP SmartScope measurement system

The wafer-to-wafer repeatability has been characterized across multiple production lots. Measured across four reference points (A, B, C, D) on Ø6" wafers, the wafer-to-wafer range was confirmed to be within 2–7 µm, well within the ±10 µm lens decentering budget.

3. Mastering Process Design Rules

3.1 Mastering Technique Comparison

Three complementary mastering techniques are available, each with distinct capabilities and trade-offs. Selection depends on feature size, throughput requirements, and surface form complexity:

Attribute	2PP (Nanoscribe)	DLW (Heidelberg)	Diamond Turning
Master Size	50 × 50 mm	Ø200 mm	100 × 100 mm
Resolution (Ra)	143 nm (Ra < 15 nm)	160 nm (Ra < 15 nm)	Ra < 8 nm
Aspect Ratio	1:20 or more	1:3 or less	1:2 max (geometry dependent)
Write Time (2×2 mm MLA)	45–60 hours	25–30 minutes	5–8 hours
Form Capability	No limitations	Spheric, Aspheres (freeform challenging)	Spheric, Aspheres, Fresnel, Prismatic
Materials	Photoresist	Photoresist	Polymer, Al, Ni, Cu, Zn, etc.

3.2 Feature Size Decision Flow

The choice of mastering technology follows a structured decision process based on minimum feature size:

- Feature ≥ 30 µm: Diamond Turning (DT) — follow conventional DT insert fabrication flow. Spherical and aspherical profiles possible; elliptical features are not achievable due to cutter constraints; density > 900 lenslets per 1×1 mm footprint is achievable.
- Feature < 30 µm (lithography range): Direct Laser Writing (DLW) or 2-Photon Polymerization (2PP). Millions of features on small footprint; aspect ratios up to 1:10 possible; aspheric profiles not achievable via lithography; sharp peaks/valleys achievable (R1 µm).
- Feature < 300 nm (DOE, multi-level): E-Beam lithography or maskless lithography. 4–16 level DOE structures; feature sizes < 300 nm; requires Ni-shim for working stamp or mold insert fabrication.

3.3 Translation Loss Through Stamp Hierarchy

Each generation of stamp replication introduces cumulative positional error. The following table captures the translation and rotation losses at each stage of the stamp hierarchy from silicon master to Gen3 working stamp and final wafer imprint:

Stage	Type	Magnitude	Remarks
Master → Gen3 Stamp (Translation)	Translation (X,Y)	< 15 µm	Stamp shrinkage/swelling + machine accuracy
Master → Gen3 Stamp (Rotation)	Rotation (α)	< 0.5°	Machine rotational accuracy
Stamp → Wafer Alignment	X, Y Translation	< 3 µm	Per imprint process on Ø6" wafer
Stamp → Wafer (Rotation, no flat)	Rotation	< 0.3°	Without wafer flat reference

Stamp → Wafer (Rotation, with flat)	Rotation	< 0.2°	With wafer flat reference for alignment
Top to Bottom (Double-sided)	Decentering	< 10 µm	Double-sided imprint alignment

These tolerances represent the combined effect of stamp material shrinkage/swelling and equipment positioning accuracy. The total positional budget from master to final wafer must be tracked during product tolerance stack-up analysis.

4. Production Process Comparison

4.1 Injection Molding vs. Optical Replication

The following table compares the key attributes of injection molding and optical replication/WLO to guide technology selection during product development:

Property	Injection Molding	Replication / WLO	Remarks
Materials	PC, PMMA, PS, PI, PCO, COP	Epoxy, PU, Silicones, Acrylic	UV/heat curable in replication
Cycle Time	15–60 s/cycle	UV: 10–120 s; Heat: 1–2 hrs	Depends on cavities and design
Typical Cavities	Multiple (cold or hot runner)	100–500 typical	Higher cavitation with replication
NRE Cost	Mid–High	Mid–High (lithography adds cost)	Master stamp adds NRE
HVM Tooling Leadtime	6–8 weeks	8–12 weeks typical	Lithography process needed for nano masters
Solder Stability	Not stable (exc. PEI, PI – not clear)	Solder-reflowable materials available	Critical for SMT assembly

4.2 MLA Form Factor Design Rules by Process

For Micro Lens Array (MLA) products, the achievable form factor varies significantly by manufacturing approach. The following table provides the dimensional design space for each process:

Attribute	Injection Molding	Replication (Monolithic)	Replication (Hybrid WLO)
Materials	PC, Acrylic, COC, COP, PEI, LSR	Epoxy, Acrylates	Epoxy, Acrylates on Glass/Silicon
Lens Size L (µm)	500 µm – 5 cm	500 µm – 3 mm (typical)	500 µm – 3 mm (typical)

Thickness T (µm)	300 – 5000 µm	500 – 2000 µm	20 – 50 µm
Pitch / Diameter P (µm)	200 – 5000 µm (flexible)	20 – 1000 µm	20 – 40 µm
Sag S (µm)	200 – 5000 µm (flexible)	10 – 500 µm	10 – 30 µm
Residual Layer RL (µm)	N/A	~50 µm	5 – 10 µm

Material Selection Notes

- Thermoplastic materials (PC, PMMA, COP) are NOT solder-stable — not suitable for SMT reflow assembly
- UV/heat-curable thermosets (epoxy, acrylates) are widely available in solder-reflowable grades for hybrid WLO
- Refractive index range: 1.48 (low-n acrylates) to 1.71 (high-n epoxies) — select based on optical power requirement
- Abbe number range: 27–55 — critical for achromatic and polychromatic designs
- Penchem UV-782 and Micro resist OrmoStamp are commonly used stamp materials for WLO production

5. Lens Design Limitations

5.1 Feature Geometry Constraints

Certain optical geometries impose fundamental constraints depending on the production method chosen:

- Diamond Turning: Elliptical features are not achievable due to cutter geometry constraints. Deep recesses may require electro-formed inserts. Sharp peaks or valleys may not be achievable depending on polarity. Customized cutters (< R5 µm radius) may be required for fine features.
- Nanoimprinting / Lithography: Aspherical profiles are generally not achievable via lithography. Maximum aspect ratio ~1:10 (width:height). 2PP (2-Photon Polymerization) supports freeform shapes without limitation.
- Prismatic and angular profiles: Require feasibility study for all processes — contact engineering for evaluation.

5.2 Tolerance Analysis Guidelines

Tolerance analysis is performed using Zemax OpticStudio (refractive optics) and LightTrans VirtualLab (diffractive optics). Key parameters to include in the tolerance budget include:

- Lens rotation (tilt of MLA layers relative to each other)
- Z-axis tilt (out-of-plane tilt of MLA surfaces)

- Refractive index variation (material batch-to-batch)
- Radius of curvature of lenslets (ROC tolerance ±2%)
- Lens pitch and X/Y dimensions (size tolerance ±20 µm for 1.5 mm pitch)
- Lens axial thickness (least critical parameter — no pattern shift observed at ±30 µm)

A representative tolerance study on a double-sided MLA (3.209 mm thick, 1.5×1.5 mm lenslets, R1 = -2.067 mm, R2 = -92.07 mm) found:

- Lenslet ROC is the most critical parameter — ±2% shift causes visible blurriness in the projection pattern
- Lens thickness variation (±30 µm) produces no observable pattern shift
- All tolerances within machining capability produce acceptable image quality

6. In-Process Quality & Test Capabilities

6.1 Metrology Capabilities

The following metrology and test capabilities are available for in-process quality control and final acceptance testing:

Test Type	Equipment / Method	Specification / Notes
Lens Profile Measurement	Zygo interferometer / Keyence profilometer	Surface form accuracy verification
Decentering / Wafer Alignment	OGP SmartScope	Accuracy: +/- 1 µm; Wafer alignment: +/- 5 µm
MTF Testing	Customized tester (Trioptics / Optikos)	Tailored to product spec
Dimensional GR&R	Metrology equipment	< 10% GR&R
Spectrometer (R%, T%)	Spectrophotometer	< 20% GR&R
White Light Interferometry	In-house WLI system	Sub-nm surface roughness measurement
SEM / Confocal Microscopy	SEM, Confocal Microscope	Nanostructure characterization

6.2 Stray Light Analysis

Stray light simulation is performed using TracePro and FRED Optimum ray-tracing software. Analysis follows a ray-path sorting methodology to identify dominant and secondary light paths. Key design guidance from stray light analysis:

- Surfaces of lenses outside the clear aperture must be made opaque to suppress secondary reflected paths

- Internal reflections from the second surface of lens elements can redirect stray rays to the detector if the surrounding region is transparent
- Stray light simulations are run at field angles of 0°, 20°, 40°, 60°, 80°, 90°, and 95° FOV for complete characterization

7. Reliability & Environmental Testing

All WLO products are qualified through a comprehensive environmental reliability test suite. The following tests are performed using in-house equipment:

Test	Equipment	Conditions / Specification
High Temperature Storage	Memmert UF110+ Universal Oven	+30°C to +300°C; 560×480×400 mm chamber
Heat Soak (85/85)	Memmert HCP105 Humidity Chamber	85°C / 85% RH; active humidity control 20–95% rh
Temperature Cycling	Combined temp/humidity chamber	-42°C to +190°C (dry); +10°C to +95°C (wet, 10–98% rh)
Cold Storage	Liebherr refrigerator	-10°C to -45°C
UV Weathering	Biuged BGD860 (Q-Lab xenon lamp)	1.8 kW xenon; 0.3–0.75 W/m² @ 340 nm; exposure area 2200 cm²
Reflow Solder Profiling	Autotronik BT301 Bench-Top Oven	Standard reflow profile; working area 250×200 mm

Reliability Design Notes

- Heat soak at 85°C/85% RH (JEDEC standard condition) is the primary moisture sensitivity qualification test
- Temperature cycling range (-42°C to +190°C) covers automotive and industrial application environments
- UV weathering exposure area of 2,200 cm² allows batch testing of ~22 samples (70×70 mm each) simultaneously
- Reflow solder qualification is essential for WLO components integrated via SMT — verify material grade before committing to solder-attach design

8. Production Capacity Considerations

WLO production throughput is governed by the throughput of individual process stations, station yield, and rolled yield through the full production flow. For a representative two-wafer stack assembly:

Process Station	Cycle Time (s)	UPH (wafers)	Yield Assumption
Adhesive Dispensing (1st)	300	264	95%
Wafer Alignment (1st)	300	264	95%
Wafer Stacking (1st)	600	132	92%
Adhesive Dispensing (2nd)	300	264	95%
Wafer Alignment (2nd)	300	264	95%
Wafer Stacking (2nd)	600	132	90%
Singulation (Disco DFD641)	3600	22	90%

The bottleneck station (singulation at 3,600 s cycle time) constrains total output to approximately 10 wafers/day after rolled yield. Total rolled yield through the full 7-station flow is approximately 61%, yielding ~10 singulated wafer stacks per 22-hour production day.

9. Design-for-Manufacturability (DFM) Checklist

Before submitting a WLO design for prototype or HVM, verify the following:

Optical Structure Design

- Minimum feature width ≥ 2 µm (nanoimprint) or ≥ 30 µm (diamond turning)
- Aspect ratio confirmed < 2:1 (nanoimprint) or < 1:2 (DT)
- No elliptical features if diamond turning is planned
- Prismatic/angular profiles have been reviewed by mastering engineering
- Lens density and footprint reviewed against substrate size (Ø6" or Ø8")

Tolerancing & Alignment

- Tolerance stack-up analysis completed (Zemax or VirtualLab)
- Lens decentering budget: ≤ ±10 µm (wafer stacking)
- Translation loss from master → Gen3 stamp included in stack-up (< 15 µm XY, < 0.5°)
- Stamp-to-wafer imprint alignment included (< 3 µm XY, < 0.3°)
- Double-sided alignment budget: ≤ 10 µm top-to-bottom

Material & Process Compatibility

- Material refractive index and Abbe number confirmed for optical performance
- Solder-stability requirement clarified — UV-cure thermoset grades selected if SMT assembly required

- Substrate thickness within range (0.08–3.00 mm for nanoimprint)
- Glass spacer through-hole dimensions: width ≥ 0.10 mm, pitch ≥ 0.30 mm, substrate ≥ 0.18 mm
- Reliability qualification plan aligned with product application environment

10. Conclusion

Wafer Level Optics manufacturing offers a highly capable and scalable platform for producing micro- and nano-optical components in high volume. By adhering to the design rules documented in this application note — spanning nanoimprint lithography constraints, mastering technique selection, wafer stacking alignment budgets, material properties, and reliability qualification — designers can efficiently develop DFM-compliant optical products with predictable yield and performance.

Key takeaways for designers:

- Minimum feature width of 2 µm is achievable via nanoimprint; sub-300 nm structures require lithographic mastering
- Lens decentering must be budgeted within ±10 µm across all wafer stacking operations
- Material selection must account for solder stability, refractive index, Abbe number, and reliability requirements
- Tolerance analysis (Zemax/VirtualLab) is mandatory — ROC of lenslets is the most critical parameter
- Plan for 61% rolled yield on two-wafer stack assemblies in capacity planning

Document Revision History

Rev	Date	Author	Changes
1.0	2024	Engineering	Initial release — based on WLO process capability presentation