Micro Lens Array Milling on Large Wafers

More Design Freedom for Micro Optics – Aspheric Lenslets with Imaging Quality

Micro Lens Arrays (MLA) containing thousands of lenses with an aspheric shape and a precise position on large substrates are used in sensor devices directly or as master moulds for the low-cost replication of micro lenses in an array. They have to fulfill the high requirements in wafer scale manufacturing of small optics. This high volume manufacturing method for low-cost but effective micro optics relies on the sandwich-like assembly of the sensors and optical components like lenses as well as mechanical components like apertures and spacers on wafer level. After joining all components the dicing results in a batch of wafer level cameras for the use in cellular phones or webcams.

Micro Lens Arrays are also a centrepiece of today's sensor products, either to raise the fill factor and collect more light on each pixel or to deflect the incoming beam to measure the aberrations of the wavefront, the working principle of the Hartmann-Shack sensor. Within illumination optics, MLA are commonly used for beam homogenization in projection systems. In all fields of application ranging from automotive, medical, consumer and industrial optics to high-end sensors for space instrumentation, high quality lens arrays for direct use or replication must be provided.

Micro Optics Fabrication

The field of application is closely connected to the requirements on the micro optic and the suitable manufacturing technology. While Micro Lens Arrays for illumination purposes are less demanding regarding the form and surface quality, MLA for imaging optics are challenging to manufacture. Typically the form deviation from the aspheric shape of each lenslet shall not exceed 500 nm (peak to valley – p-v). Also the roughness must be kept as small as possible. Typical values are ranging from 5 nm (root mean square – rms) to 1 nm (rms),

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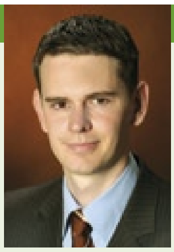

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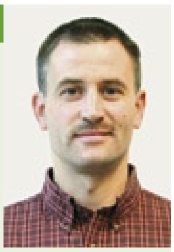

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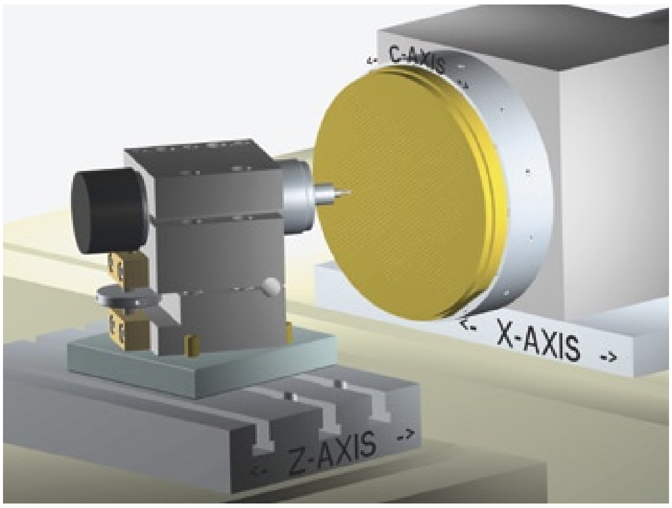

FIGURE 1: **Setup for micro milling on an ultra precison lathe.**

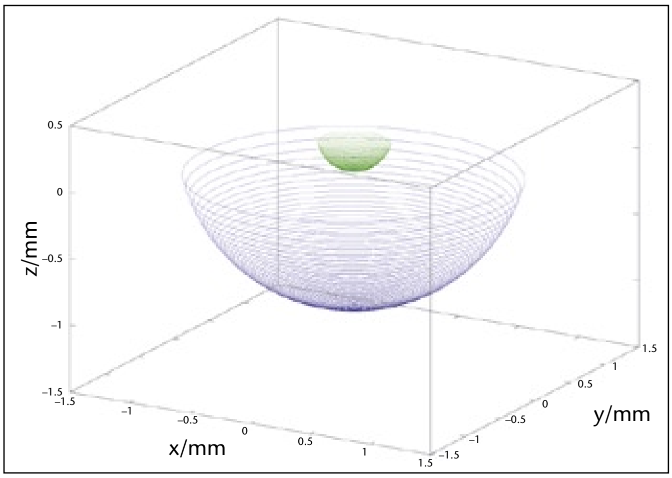

FIGURE 2: **Tool path calculation of an aspheric lenslet: cutting location (blue); calculated tool center trajectory (green).**

depending on the wavelength of the designated application. The position of the lenses on the wafer must be accurate on a micrometer level. Each misalignment would lead to a decentration in the assembly.

A variety of micro technology manufacturing methods can be used for MLA structuring [1]. Lithographic approaches with a subsequent reflow process, laser lithography, UV-curing of resin droplets and step- and repeat moulding of polymers are state of the art processes for the master manufacturing. The lithographic approach is based on exposing and developing resist columns on a substrate. Therefore, the resulting profile is determined by the shape of the lens' footprint and the volume of the resist to be melted. In case of the most relevant rotationally symmetric lenses, the footprint of the lens is a circle and the resulting profile is spherical due to the surface tension of the liquid melt.

Another way to manufacture very similar MLA with spherical or slightly aspherical lenslets is to apply a number of liquid resin droplets on a substrate. The wetting angle, the volume of resin and the gravitation can be used to shape the lenslets. The subsequent UV-exposure cures the resin droplets to their final form under a volume lost due to the shrinkage during the reaction.

More design freedom offers laser lithography, which is a direct writing technique that enables the generation of freeform profiles, not limited to spherical shapes. Here, a laser beam is scanned over a photo resist layer while the intensity of the beam is modulated [1]. The height of the resulting profile at a given position is determined by the local dose of the writing beam. However, the technology is limited to structures of several ten micrometers in height.

All technologies of this kind have in common that a large number of lenslets can be manufactured. Lenses that are shaped in a fluid phase have an excellent surface quality. On the other hand the surface figure and the design freedom regarding true aspheres or freeform surfaces are process limited. Nevertheless, these techniques are proven tools for a widespread field of application and used by Scientists at Fraunhofer IOF for MLA structuring.

Besides the above mentioned technologies, diamond chipping of arrays or master arrays for replication is emerging into the market due to its potential to structure truly aspheric or freeform lenslets.

Micro milling of MLA

The recently developed approach to mill aspheric MLA on an ultra precision lathe is promising for the operators of the more common turning machines. The chipping is based on cutting with a hard and geometrically defined diamond cutting edge, which is fed into the softer material [2]. The diamond ball end mill rotates about its axis with high speed and removes µm-sized chips. Non ferrous metals like aluminium, brass, copper and their alloys are machinable metals, but also plastics and some crystals can be milled with diamond tools.

An additional milling spindle, which holds the diamond tool, is integrated into an ultra precision diamond lathe for structuring the small optics on the wafer. Three machine axes are used to position the tool relative to the substrate and to feed the tool on its spiral tool path. In case of a turning machine these axes are two linear axes (X, Z) and one rotational axis (C) as shown in figure 1. In contrast to conventional diamond turning, the rotational axis is operated discontinuously in C – axis mode. It can be positioned like a rotary table to arbitrary angles.

Although the MLA is machined on an ultra precision turning machine, the structure on the wafer is not rotationally symmetric

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The Fraunhofer IOF was founded in 1992 and has approx. 140 employees. The Fraunhofer IOF is a competent partner to the industry and is also supplier to the public sector. Research and development at Fraunhofer IOF focuses on optical systems technology with a view to continually improving the control of light from generation via guiding and manipulation up to its application.

The core competences include opto-mechanical design and simulation, multifunctional optical coatings, manufacturing and integration techniques of optical components and systems, opto-mechanical precision systems, measurement systems and sensors. The Fraunhofer IOF escorts their clients all the way from the idea to prototype.

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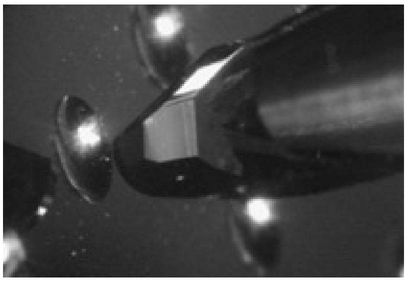
Diamond Machining



The unique properties of mono crystalline diamonds as cutting edge enable the production of high quality micro- and macroscopic optics. The diamond turning shows a constant development from the manufacturing of rotationally symmetric spheres or aspheres to modern freeform optics. The ability to machine an optical shape and a microstructure like gratings on top in a common process opens new perspectives for optic designers.

Besides the well developed ultra precision turning, micro milling with diamond tools emerges more and more into practice. Recently developed processes provide more freedom to optic designers regarding design and quality.

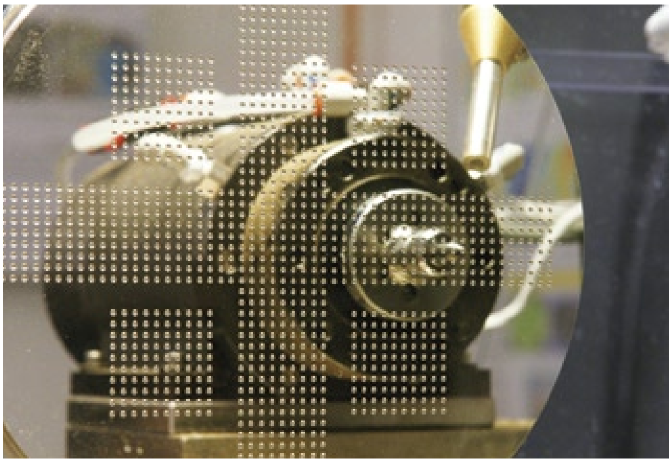


FIGURE 3: **Micro lens array for wafer scale replication during the micro milling with monocrystalline diamond tool.**

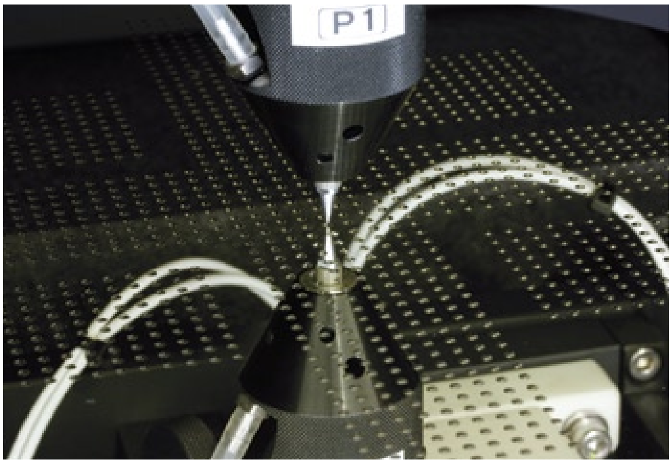


FIGURE 4: **Lens array during tactil measurement for quality ensurance on an Ultra Accuracy 3D Profilometer (UA3P).**

to the C-axis. Hence the MLA has to be handled like a freeform regarding operation mode and commands. The programming of the numeric control is based on the calculation of nodes on a spiral tool trajectory. The tool center points are derived from the 3D surface information of the design asphere and the radius dimension of the diamond tool tip, considering the slope of the lenses. The contact zone of the tool can be described as an Archimedean spiral from the lens rim to its center as shown in figure 2. The command set of each lenslet contains the shifted tool center point of each node. The resulting machine program for the whole array sums up the cutting data of every lens in the array and additional information about speeds and feeds. The motion of the machine during the cutting process is a slow and harmonized oscillation of the linear and the rotary axis, while the linear feed-axis plunges the tool into the material.

Tool setting

The setting of the diamond tool in the machine is important for the high quality of the MLA regarding a minimal form error and high position accuracy. The tool's axis of rotation must be aligned within sub-µm accuracy to the C-axis due to the special setup. This is accomplished using test samples, to set the tool position in the X-Z-plane and normal to this plane independently. The high surface quality and low wear of the diamond tip can be ensured by fine balancing the tool in the high speed spindle.

The form quality can be further improved by milling one of the many lenslets in the array and correcting systematic rotational form errors, which are caused by the waviness of the diamond tool tip and the misalignment of the cutting edge in the high speed spindle. The form error of the measured sample is recalculated on the tool path. Achievable minimal form errors are in the range below 200 nm (p-v).

Figure 3 shows an array containing more than 1300 lenses during ultra precision milling on the machine. The equal lenses have a design radius of 1.286 mm and a sag of 257 µm. The edge slope is 37°, which makes it an unfeasible geometry for servo enhanced diamond turning due to the tool's clearance angle of around 22° since this would cause a collision with the material [3]. The milling of 1310 lenses is accomplished in three milling steps, two for rough cutting and one super finish. To reduce the cusp height and the chip size, the machine's high speed spindle rotates at 40,000 rpm – 60,000 rpm. The cutting parameters are optimized for an adequate kinematic roughness at acceptable cutting times. Each cut takes around 30 h due to the feed rate of around 50 mm/min and the low feed on the spiral trajectory of around 20 µm.

Measuring the quality of MLA

The measurement of one lens with an accuracy of a fraction of a micrometer is challenging. Measuring the form and alignment of a large number of lenses in an array is even more demanding. The form error of spherical concave lenses or ones with a small deviation from a sphere can be measured interferometrically. The metrology with light is an appropriate method for simple geometries and test samples for the setting of the machine.

For the characterization of an array containing a large number of wild aspheres, a different measurement technology has to be applied. Tactile measurement is beneficial regarding the ability to measure the aspheric shape of lenses directly and also monitor their position on the wafer. On the Ultra Accuracy 3D Profilometer (shown in

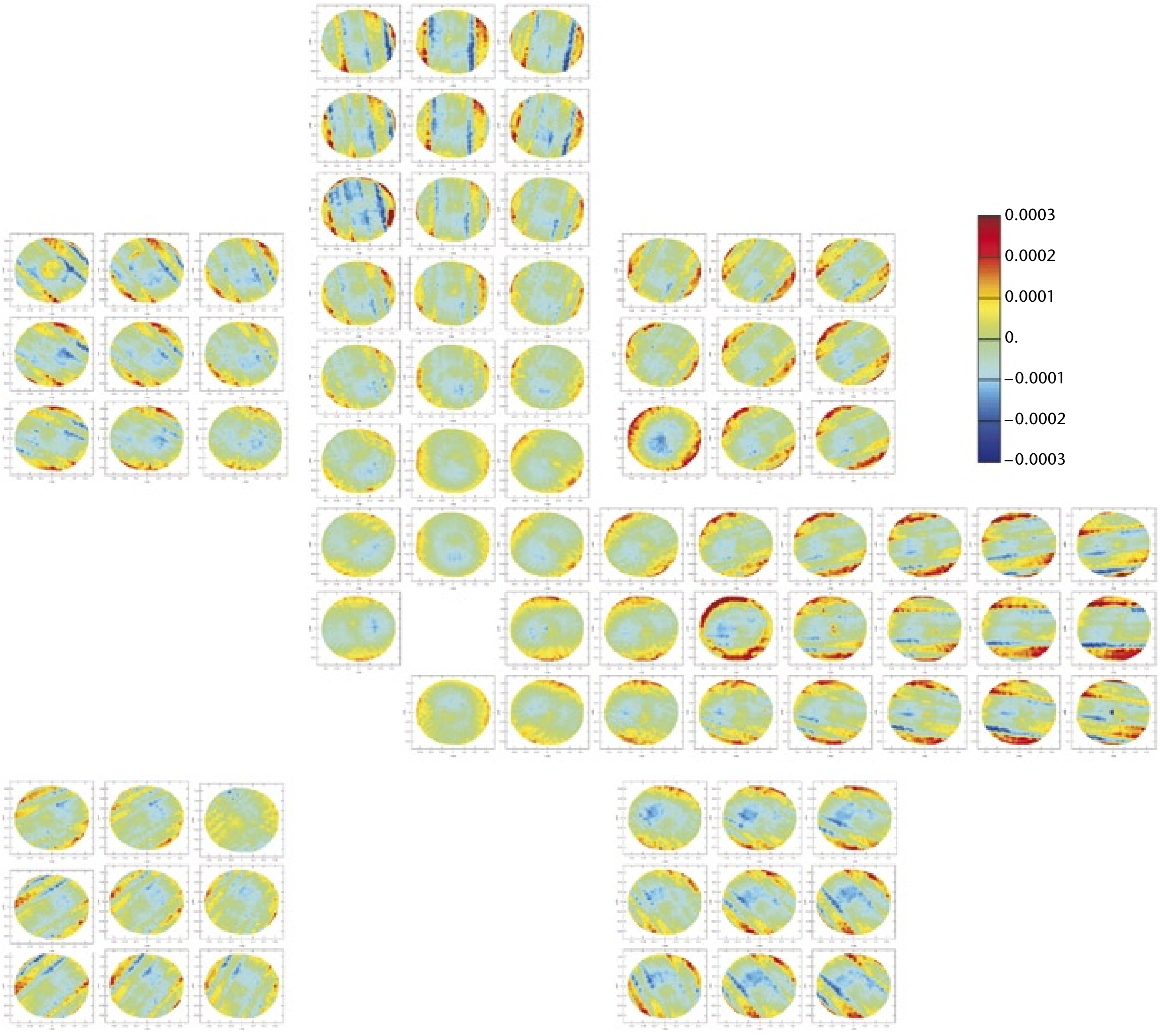


FIGURE 5: **Form deviation of lenslets on their position in the array (scale in mm).**

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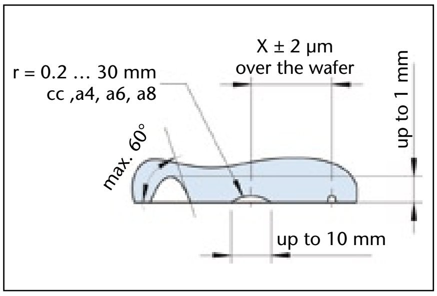
Geometries for Micro Milling

Typical designs are spherical or aspherical MLA with radii ranging from 0.2 mm to several mm. The lenses are a few micrometers to mm in depth. The edge slope should not exceed 60°, in certain cases 90°. Often more than 1000 lenses are demanded on a wafer up to diameter 300 mm. The number of lenses is limited by the growing cutting time, depending on the lens geometry. The distribution of lenses on the substrate is determined by the optics design and can be rectangular or arbitrary, free standing or intersecting. Also different patterns or arbitrary spacings on one substrate are possible. The geometry of the lenses may differ over the diameter or in sections. The achievable quality is promising for a variety of applications including imaging with micro optical lenses. The form deviation depends on the size of the array and ranges around 500 nm (p-v). The micro roughness is comparable to diamond turning with typically 5 nm (rms).



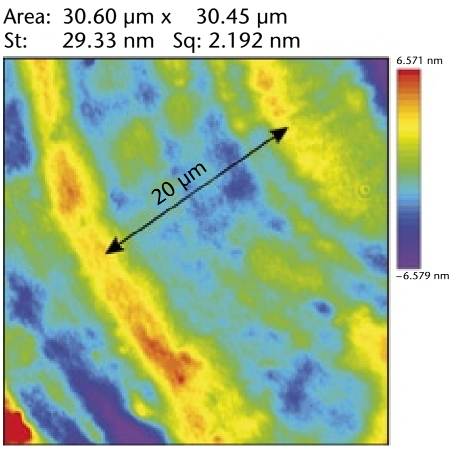


FIGURE 6: **Micro roughness of a sample lens measured with white light interferometry; 2.2 nm (rms), kinematic roughness is visible.**

figure 4), a stylus with a precision diamond probe scans the surface of sample lenses in three dimensions. The form deviation is determined by comparing the measured data with the ideal aspheric surface of sample lenses.

The measurement machine has an effective range of 200 mm x 200 mm, which enables the acquisition of the vertex points in their relative position on the wafer. Of course not each of more than 1000 lenses can be measured using this time consuming, but automated measuring technique, but a well distributed selection over the whole wafer shows the achieved form quality.

Figure 5 images the form deviation of every fourth lens of the described MLA. The form error of the measured lenslets is below 750 nm (p-v) but depends on its position on the wafer. While the error near the axis of rotation is around 250 nm it grows to 750 nm (p-v) on the outer diameter. It is noticeable that the form error is rotationally symmetric to the center of the C – axis and has the shape of a star. This pattern is caused by the limited resolution of the incremental rotary encoder of the C – axis. The digital angular interpolation error causes a form irregularity, which grows with higher axial distance. It can be narrowed using a higher resolution of the incremental encoder with twice the number of radial lines. Nevertheless these results show the potential of this manufacturing method.

The imaging quality of lenses strongly depends on the surface roughness after the finished cut. Measurement methods are either white light interferometry, Atomic Force Microscopy or tactile metrology methods. The micro roughness of this chipping process is determined by cutting parameters like chip thickness and feed as well as the grain structure of the substrate material. Typical values for different materials and an adequate process are below 10 nm (rms). The white light interferogram of one of the lenses of the brass array is shown in figure 6. Its roughness value, measured in a field of 30 µm x 30 µm, is 2.1 nm (rms), which makes this master array suitable for imaging micro optics.

Conclusion

Scaled micro optics and their manufacturing methods are a key issue for mass production of consumer optics and smart sensors. Besides other well understood manufacturing methods, diamond milling emerges into the market of micro optic manufacturing. The ability to manufacture deep lenslets with true aspheric shapes on arbitrary positions on large substrates offers an additional degree of freedom for the design of high quality Micro Lens Arrays, either way directly structured or as master for the replication. These achievements show potential for the development of micro imaging systems on the wafer level for cellular phone or computer cameras. The Micro Lens Array will be presented at the Photonics West 2010 in San Francisco, Both # 4601.

References

[1] Wippermann, F.C. *et al.*: "Fabrication technologies for chirped refractive microlens arrays". Proc. SPIE, Vol. 6288, San Diego, CA, USA, (2006)

[2] Roblee, J.W.: "Recent Advancements in Slow Tool Servo and Fast Tool Servo Machining". Proc. Optonet – Ultra Precision Workshop, Jena, Germany (2008)

[3] Badrawy, S.: "Micro Milling – An Alternative Solution for Diamond Turning of Lens Arrays". Proc. Optonet – Ultra Precision Workshop, Jena, Germany (2008)

[4] Scheiding, S. *et al.*: "Lens array manufacturing using a driven diamond tool on an ultra precision lathe". Proc. 9th int. EUSPEN Conference, San Sebastian, Spain, Vol II, p. 423–426 (2009)