Miniaturization of Imaging Systems

R. Völkel, M. Eisner and K.J. Weible

Micro-cameras integrated into mobile phones or computers are very popular these days. Such micro-cameras operate with low-priced lenses made of plastics and provide a decent image quality. Having a closer look at the camera, we discover that the optical part is usually a bulky block of some 5x5x5 mm³ on top of a very thin electronic image sensor. Why does optics remain so huge compared with highly miniaturized electronics? Is there a fundamental problem with the miniaturization of a lens system? Yes, there is. The number of image pixels a lens can transmit scales with the square of the lens diameter. If the lens diameter is getting smaller, the image quality will be reduced drastically. This is a fundamental limitation to the further miniaturization of imaging systems. Is there any chance to overcome this problem? A fascinating approach is to look how Mother Nature has found solutions for very small creatures. Nature has distributed the imaging task to an array of lens systems. Microfabrication capabilities now allow implementation of similar design approaches to imaging systems used e.g. for micro-cameras and photolithography machines.

Miniaturization of Lens Systems

Both, the stop number F and the diffraction-limited spot size of a lens are independent of lens scale. A downscaling of a lens does not influence the size of the image pixel; however, downscaling drastically reduces the number of transported pixels. For a diffraction-limited lens system, the number of transported image pixels scales with the square of the lens diameter. Table 1 gives the number of image pixels M for an F/2.4 diffraction-limited system of different lens diameters. A miniaturized imaging system is able to image fine details of a scene, but not many.

Lens diameter	5 mm	2 mm	1 mm	0.5 mm	0.2 mm	0.1 mm
Number of image pixels M	8'680'556	1'388'889	347'222	86'806	13'889	3'472
Pixel in image field	2946 x 2946	1178 x 1178	589 x 589	294 x 294	117 x 117	58 x 58
Lens-to-image distance d_z	17 mm	6.8 mm	3.4 mm	1.7 mm	0.68 mm	0.34 mm

Table 1: Number of image pixels for an F/2.4 diffraction-limited single-aperture system of different lens diameters.

How did Mother Nature solve miniaturization problems in optics? For large vertebrates, Nature implemented single-aperture eyes. Here the volume of the eye is a free design parameter - the optical performance is the key issue. For small invertebrates, evolution preferred to distribute image capturing to a matrix of small eye sensors [1]. Usually the resolution of such so-called compound or fly's eyes is pretty poor. For small animals, this is the only way to avoid a flooding of the animal's neural system. However, the poor image quality makes the fly's eyes concept useless for technical applications.

The most promising natural approach for miniaturization is the eye system of jumping spiders. Jumping spiders have opted for single-lens eyes, but eight of them. Jumping spiders have two high-resolution eyes, two wide-angle eyes and four additional side eyes. The two high-resolution eyes provide a magnified image at a high resolution for a rather small visual field. Jumping spiders use these eyes for detailed inspection of objects of interest. The two wide-angle eyes provide a large visual field at a reduced resolution. The four small side eyes cover the large field left and right of the spider. Jumping spiders do not have compound eyes. Their resolution would be too poor to identify a target worth to jump on. To have single-lens eyes common to vertebrates, spiders are too small. The spider uses a cluster of single-lens eyes, each pair tailored for a different task. Spiders see almost as sharp as we do and likewise have a good idea of what is going on in their surroundings.

Learning from the jumping spider we can derive the following design strategy for miniaturized imaging systems:

1) The first step is to choose the F-number on the basis of the detector resolution, the desired light gathering ability and the numerical aperture of the available optical sub-components.

2) The next step is to derive the maximum lens diameter of the system from the desired overall thickness of the camera system. For an F/2.4 system, the image distance is 2.4 times the aperture diameter. The overall thickness is the image distance plus lens and detector thickness.

3) Knowing lens diameter and stop number F, the maximum number of transferred pixel M is derived. If the number of image pixels of one single imaging channel is not sufficient, multiple channels have to be used. Each imaging channel should only image a limited angular section. A superposition of the partial images is performed either within the signal-processing unit or by spatial superposition in the image plane (see Fig. 1). For spatial superposition, erect imaging is required. Only next neighbor images should superimpose to limit off-axis aberrations.

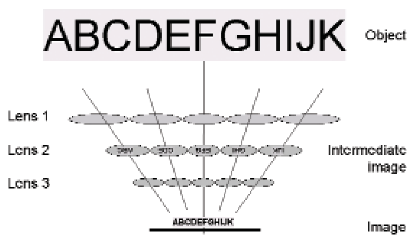

Figure 1: Miniaturized imaging systems based on spatial superposition of the partial erect images created by adjacent imaging channels. Each lens channel images only a limited angular section.

Micro-Optics

Today's micro-optical design and manufacturing is closely tied to ideas, concepts and technologies developed for the semiconductor industry [2]. Three main categories of miniaturized lenses are available: diffractive, refractive and graded index microlenses.

Although animal eyes are based on graded index lenses, the difficult manufacturing process severely limits their availability for technical imaging. For diffractive microlenses, focal length and efficiency depend strongly on the wavelength. The use of diffractive lenses is restricted to monochromatic imaging applications. Refractive microlenses seem to be the best solution. A standard manufacturing technique for refractive microlens arrays is the reflow technique. Photoresist is micro-structured by photolithography and melted. The lens profile is formed by surface tension during melting. The melted resist lens serves as a master for subsequent transfer processes like reactive ion etching or replication. Aspheric lens profiles are obtained by varying the etch parameters.

Apertures, stops, baffles and filters are other essential parts of every optical system. They are necessary to improve the image contrast by blocking aberrant rays, adapting the wavelength spectra and reducing straylight. For miniaturized imaging systems, structured wavelength filters (IR- or color filters) and aperture arrays are realized by thin film deposition, photolithography and consequent etch or lift-off steps.
Packaging and alignment of miniaturized lens systems is a rather difficult task. For micro-optics, standard "classical" mounting is not practical and is too expensive. The preferred solution is manufacturing on the basis of a wafer-scale and a wafer-level packaging approach for mounting. A Mask Aligner is used to align a stack of planar wafers containing both image sensors and optics. The different layers are bonded together by using epoxy, thermal or fusion bonding, or thick-film solder glass bonding. A subsequent dicing step is used to separate the wafer stack into the individual systems or modules. This method allows a cost-efficient mounting of some hundreds of micro-cameras in one step.

In the following we will give two examples of miniaturized imaging systems based on the array concept.

Miniaturized Imaging System

Wafer Level Optics for CMOS Imagers

Miniaturized imaging systems based on the above design rules and multiple imaging channels are currently being investigated within the EU-IST Project WALORI [3]. Spatial superposition of the partial images created by adjacent imaging channels seems to be a promising approach. Each imaging channel images only a very limited angular section. Elliptical lens bases are used to correct astigmatism for oblique incidence. Wafer-scale lens manufacturing and wafer-level packaging are the key objectives of this project (see Figure 2).

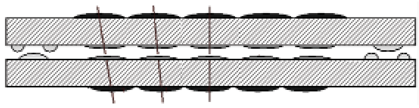

Figure 2: Wafer-scale lens manufacturing and wafer-level packaging for imaging system.

Microlens Projection Lithography

Microlens Projection Lithography (MPL) is a contact-less photolithographic technique that has been developed for SUSS MicroTec Mask Aligners [4]. MPL uses an ultra-flat microlens-based projection system consisting of some 100,000 side-by-side identical lens channels. Each lens channel consists of 4 microlens layers (see Figure 3). Wafer-level packaging of the different optical layers ensures

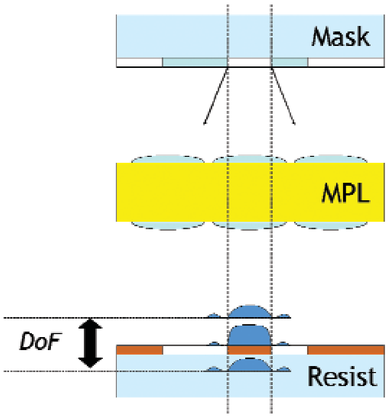

Figure 3: A microlens based projection system projects a photomask onto a resist layer. Each lens channel images a small part of the photomask pattern onto the wafer. The partial images overlap consistently and form a complete aerial image of the photomask. Front- and backside telecentricity provides equal line width over the whole depth of focus DOF.

a precise alignment of the projection system. Figure 4 shows the ultra-flat projection system within a SUSS MA150-MPL Mask Aligner. A fully symmetrical optical design eliminates coma, distortion and lateral color. The lens system is frontal- and backside telecentric to provide a unit magnification over the whole depth of focus DoF. Each lens channel images a small part of the photomask pattern onto the wafer. The partial

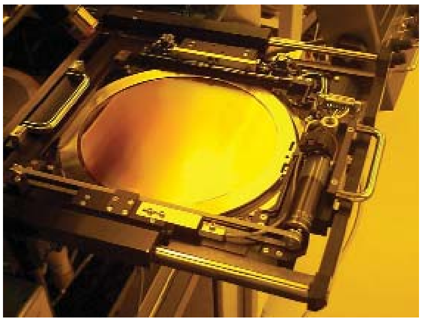

Figure 4: Ultra-flat microlens projection system integrated into the SUSS MicroTec MA150-MPL Mask Aligner. Microlens Projection Lithography allows photolithography on curved or non-planar substrates, in V-grooves, and holes.

images from different channels overlap consistently and form a complete aerial image of the photomask.

Microlens Projection Lithography provides a free working distance of WD = 0.8 mm and a depth of focus DoF > 50 µm for a resolution of 5 µm. The extended DoF allows photolithography on curved or non-planar substrates, in V-grooves, and holes.

Conclusion

A miniaturization of imaging systems cannot be done by simply downscaling the lens. The number of image pixels a lens transmits scales with the square of the lens diameter. If the lens diameter is getting too small, the image quality will be reduced drastically. A possible way out of this dilemma is to use bio-inspired array imaging systems. Highly miniaturized imaging systems based on this concept offer an enormous potential for applications from electronic imaging to high-resolution photolithography.

References

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The Yin and Yang Strategy for a more Economic Hybrid Microsystem Assembly

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A substantial number of microsystems is manufactured in small and medium series where manual assembly still dominates. The main reasons for the reluctant introduction of automatic assembly systems are design unsuitable for automated assembly as well as high investment and still low flexibility of assembly equipment. Design for assembly is still a methodology that is rarely used. Recent years have seen increasing efforts to modularise equipment. Adopting only one of these approaches will fall short. Hence a holistic strategy is proposed that combines measures on the product design side with measures on the equipment side, the Yin and Yang strategy for micro-assembly.

Unlike microelectronics, microsystems technology is not very much in the public eye. Since there are no real, flashy "microsystem inside" products, but microcomponents are rather hidden in cars, printers etc., this technology does not receive much attention. Apart from a few high volume components mostly based on silicon microtechnology (e.g. sensors for automotive industry and components for IT industry), production volumes are comparatively small. Several promising microsystems, such as micro-optical sensors, micro-fluidic devices, are only produced in small and medium batches up to a few 10,000 per year. Quite a number of these products are based on materials other than silicon such as glass, metals, polymers. While the manufacturing of the microcomponents is eventually based on highly automated processes (e.g. CNC micro milling, microinjection moulding or hot embossing), assembly is often based on manual labour. There are two main causes for this situation, which are to some extent interrelated:

1. Technical reasons: While the assembly of silicon microcomponents boils down to the placement and bonding of planar, chip-shaped parts with well-established processes, assembly of hybrid microsystems frequently requires handling of complex shapes and application of novel, non-standard bonding processes.
2. Economic reasons: The small batch sizes of hybrid microsystems scarcely ever justify investment in automatic assembly equipment