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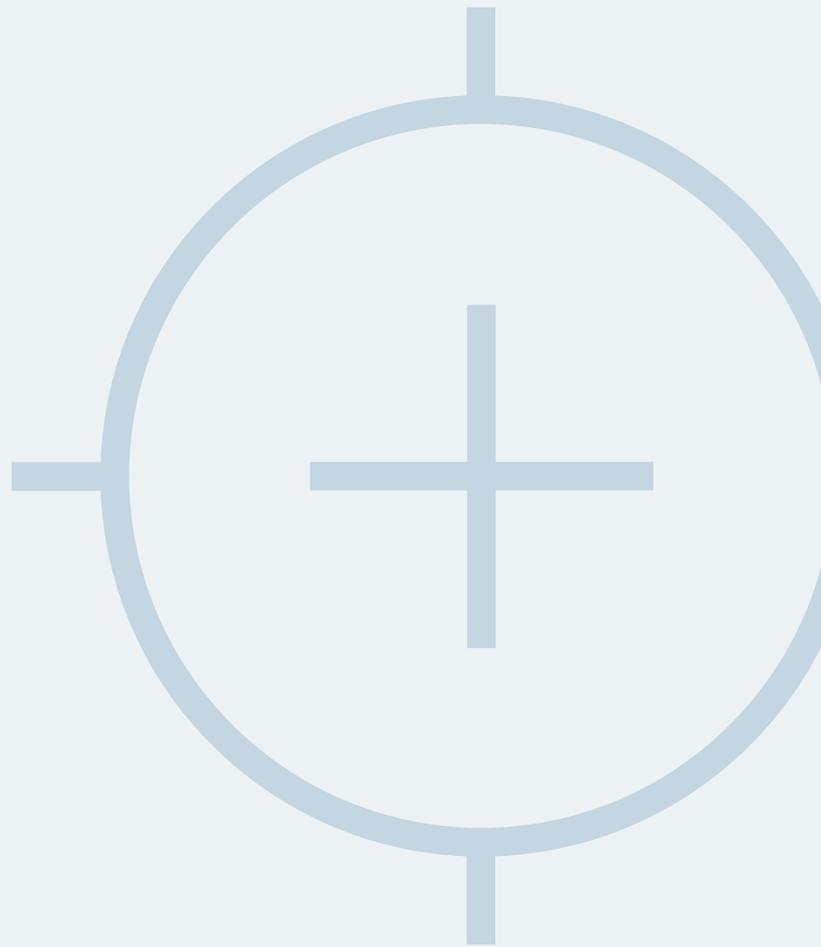
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EVALUATION OF A NOVEL EXPOSURE CONCEPT TO ENHANCE THE CAPABILITIES OF MASK ALIGNER LITHOGRAPHY AT LARGE PROXIMITY GAPS

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In the first instance, mask aligner lithography seems to be quite simple. A geometric pattern on a photomask is transferred into a light-sensitive photoresist by exposing both with ultraviolet light. The mask and the wafer can be in close contact or in a certain proximity gap. Contact prints deliver the best resolution down to the order of the wavelength of the illumination light. The drawback is, that contact between mask and wafer can lead to a contamination or even result in a damage of the mask or the wafer. Contamination deteriorates the best possible contact whereby small features will not be transferred sufficiently into the resist. Therefore in mass production usually a proximity gap is used, which ensures that wafer and mask will not get in contact. Depending on the process and the

substrate, for most applications the gap is between 20 and 200µm. As the resolution decreases with bigger gaps, the smallest mask feature size must be increased. Enhancement of the capabilities of conventional mask aligners allows cost effective lithography and will meet the strong demand to increase on-chip routing density in the field of 2.5/3D integration and advanced packaging. Here, the novel SUSS MO Exposure Optics was used in combination with diffractive mask patterns to improve the lithographic capabilities. Using Fresnel zone plates (FZP) as diffractive elements on the chromium mask in combination with the novel MO Exposure Optics allows minimizing the structure size at large exposure gaps. This enables the usage of conventional mask aligner technology to structure photosensitive materials for a wider application field, e.g.: structuring inside deep features (like fluid channels, backside through silicon vias), on high topographies or inside Taiko wafer cavities and achieve higher resolution at the same time [1, 2].

The MO Exposure Optics stabilizes the illumination and creates a defined angular spectrum at the mask plane. The optics makes it possible to design and shape this angular spectrum. The principle of the illumination optics is shown in Figure 1. It consists of two microlens-based Köhler integrators. The first integrator decouples the light source from the rest of the system. This means that the optical

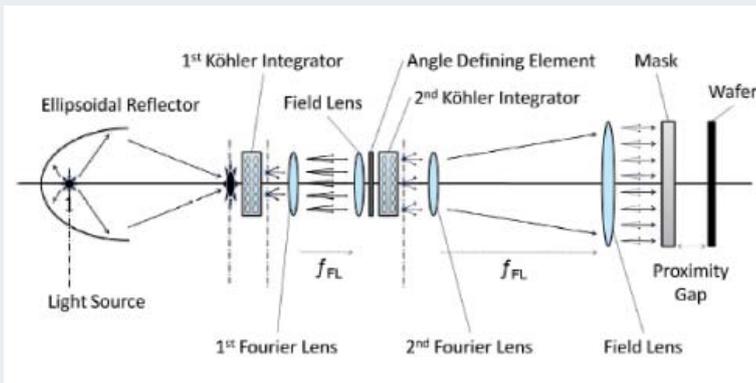


Figure 1 Simplified view of a Mask Aligner illumination system referred to as MO Exposure Optics



performance after this integrator will not be influenced by the small adjustment errors of the light source. In production, this will lead to significantly decreasing adjustment times. The second function of the first integrator is to illuminate the area of the second integrator uniformly. The second microlens integrator illuminates the mask plane. The huge amount of lenses ensures not only a uniform irradiance of radiation but also an absolute stable angular spectrum of the radiation. Because the integrator 2 is illuminated uniform by the first integrator, the radiation is also uniform within the angular spectrum. To define the angular spectrum, apertures can be placed before the integrator 2. They are referred to as Illumination Filter Plates (IFPs)/angle defining element. So it is possible to print with a mask aligner with a never seen stability and a free to design angular spectrum [3].

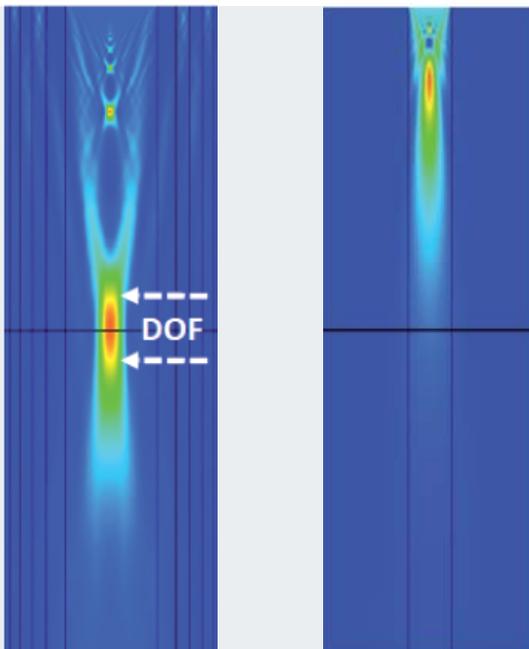


Figure 2 Light distribution behind a mask with a Fresnel zone plate and a single circular element in the range of 0µm till 600µm

DIFFRACTIVE MASK ELEMENTS

The following approach shows the design of diffractive optical elements – so called Fresnel Zone Plates – on the mask. The Fresnel zone plate (FZP) was invented by Augustin-Jean Fresnel. It focuses light at a certain focal length, similar to a refractive lens, but using diffraction. It consists of circular absorbing and transmitting zones. All zones have the same area. The most economical way to realize a FZP for mask aligner lithography is to use transparent glass and opaque chrome zones that alternate. For a certain focal length f the radii of the ring-shaped zones r_n are given by the relation

$$r_n = \sqrt{n\lambda f + \frac{n^2 \lambda^2}{4}}$$

where n is the order of the zone and λ is the wavelength. As can be seen from the above formula, for best results single line exposures have to be performed. Since the mask aligner has its peak intensity at the 365nm-wavelength (i-line) and also many photosensitive materials are i-line sensitive,

the following simulations and experiments were all made at i-line wavelength. In Figure 2 the difference in the mode of function between a FZP and a conventional mask structure is shown. For a conventional structure the pattern shape is casted 1 by 1 on the image plane directly under the mask. The bigger the distance of the image plane from the mask gets the more the shape gets deformed by diffraction and the more light is scattered out of the area under the opening. Caused by this the contrast gets too small to transfer the structure 1 by 1 into the resist at a certain proximity gap.

In contrast, the FZP produces a focal point like a refractive lens at a certain focal distance, whereas smaller gaps lead to images, which will be not usable. The focal distance of the FZP is defined by its geometrical layout. When keeping the number of zones and therefore the numerical aperture of the FZP constant, the focus spot size is proportional to the chosen focal distance. Identical to a refractive lens, the distance range in which the distribution of irradiance is stable, defines the

depth of focus (DOF). By increasing the number of rings, it is possible to achieve smaller resolutions at the same focal distance, but the size of the DOF will decrease. FZP are originally designed for illumination with totally collimated light. By engineering the collimation angle of the incident light it is possible to tune the size of the focus point to the desired spot size. This tuning capability is of course limited by the maximum collimation angles available in the optics.

In Figure 3, you can see the cross section through the focal plane of FZPs for certain proximity gaps. All FZPs consisted of three transparent Fresnel zones.

EXPERIMENTAL

In order to demonstrate the lithographic performance of such FZP structures a 14" sodalime glass mask with 8 different FZP designs was created. Examples of the FZP design are shown in Figure 4.

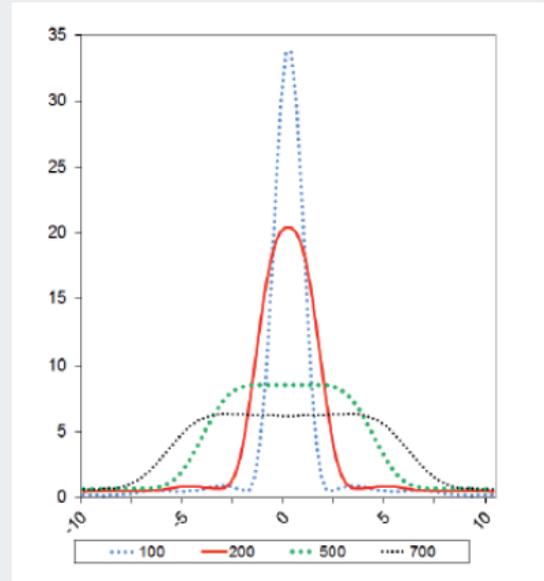


Figure 3 The size of the focal point depends on the design of the FZP, which is defined through gap and number of rings. The graph shows the cross section of the focal point for different gaps and FZPs with 3 rings

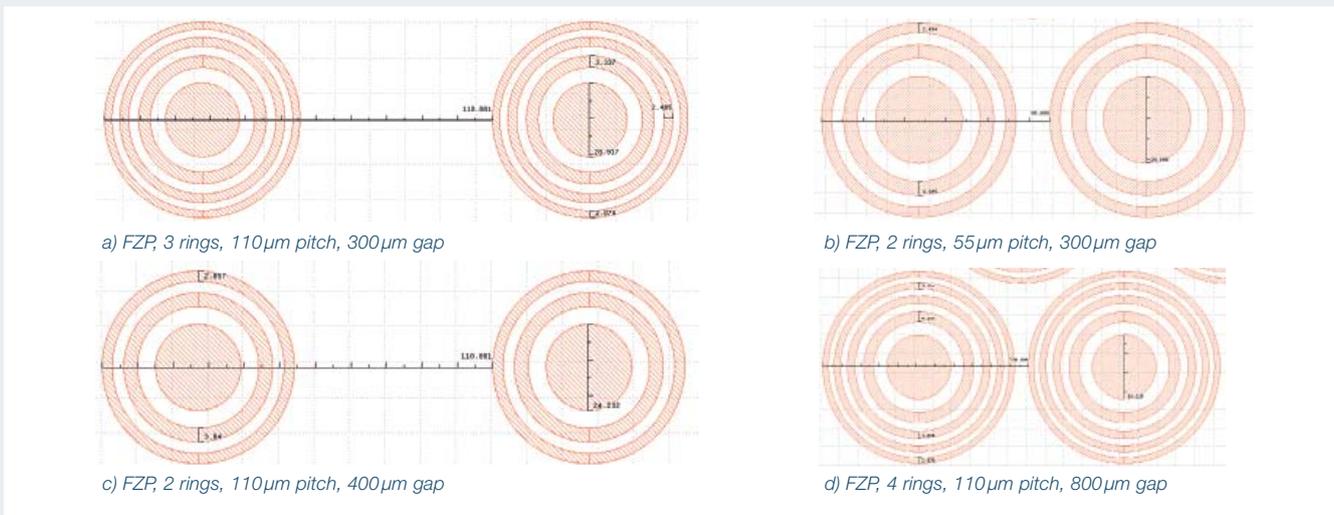


Figure 4 Overview of 4 FZP designs with 55µm and 110µm pitch and variable ring number

Each FZP is designed with a specific number of Fresnel rings and optimized to a theoretical proximity gap, equivalent to the selected focal distance. The pitch was either 55µm or 110µm. The number

of rings is limited by the desired pitch. A higher ring number leads to partial overlapped FZP structures, when the pitch is getting too small. This will affect the focus properties of the FZP.

Table 1 gives a detailed overview of all 8 FZP designs on the test mask. The CD tolerance for generating the chromium mask requires low writing tolerances. The FZP mask was manufactured with a CD tolerance of $\pm 0.25\mu\text{m}$. The minimal feature size for the smallest ring was $1.4\mu\text{m}$. 2 testchips with $20\times 20\text{mm}$ size were created and divided into 4 sub-dies by $10\times 10\text{mm}$ area each. Each sub-die corresponds to one FZP design, respectively. These two testchips were alternatively repeated over the entire 14" glass mask to cover the 300mm substrate.

The testmask was used to investigate the lithographic printing performance using two different photoresist materials. A standard positive tone AZ9260 resist with $10\mu\text{m}$ film thickness was used as one material. The second material was a chemical amplified resist used usually for bumping and μPillar applications. Therefore, the thick film positive tone photoresist AZ IPS528 was coated in a thickness range of $50\mu\text{m}$. The experiments were done at Fraunhofer IZM-ASSID on 300mm silicon substrates primed with HMDS using a SUSS MA300 mask aligner. As Illumination Filter Plate (IFP) an in diameter variable circle aperture – an iris diaphragm – was used in the optics setup to adjust the UV light power and the maximum collimation angle.

Beginning with the FZP designed for $300\mu\text{m}$ proximity gap and the $10\mu\text{m}$ thick AZ9260 photoresist the impact of the IFP diameter was studied at constant exposure times ($t=40\text{s}$). The proximity gap was adjusted to $300\mu\text{m}$ and the IFP diameter was varied to adjust the light power between $0.8\text{mW}/\text{cm}^2$ ($\sim 10\text{mm}$ IFP diameter) to $15.2\text{mW}/\text{cm}^2$ ($\sim 70\text{mm}$ IFP diameter). The SEM X-section results are shown in Figure 5 exemplarily. It is clearly shown that the FZP gives best focus properties, when the iris was adjusted to minimal diameter. A bottom CD in the $5\mu\text{m}$ range is achievable with an impressive steep resist profile at this rather high proximity gap. An increase in the IFP diameter (higher power) leads to bigger CD values due to an

Desired proximity gap [μm]	No. of rings	FZP Diameter [μm]	Inner ring CD [μm]	Smallest ring CD [μm]	Used for test chip No.
Gap 100	2	26,76	12,09	1,42	(1) 55 μm Pitch
Gap 200	2	37,8	17,09	2	(1) 55 μm Pitch
Gap 300	2	46,24	20,94	2,44	(1) 55 μm Pitch
Gap 300	3	54,76	20,94	2,04	(1) 110 μm Pitch
Gap 400	2	53,4	24,17	2,82	(2) 110 μm Pitch
Gap 500	4	80,08	27,02	2,3	(2) 110 μm Pitch
Gap 800	4	101,28	34,18	2,9	(2) 110 μm Pitch
Gap 1000	4	113,24	38,22	3,42	(2) 110 μm Pitch

Table 1 Summary of the Fresnel zone plate design

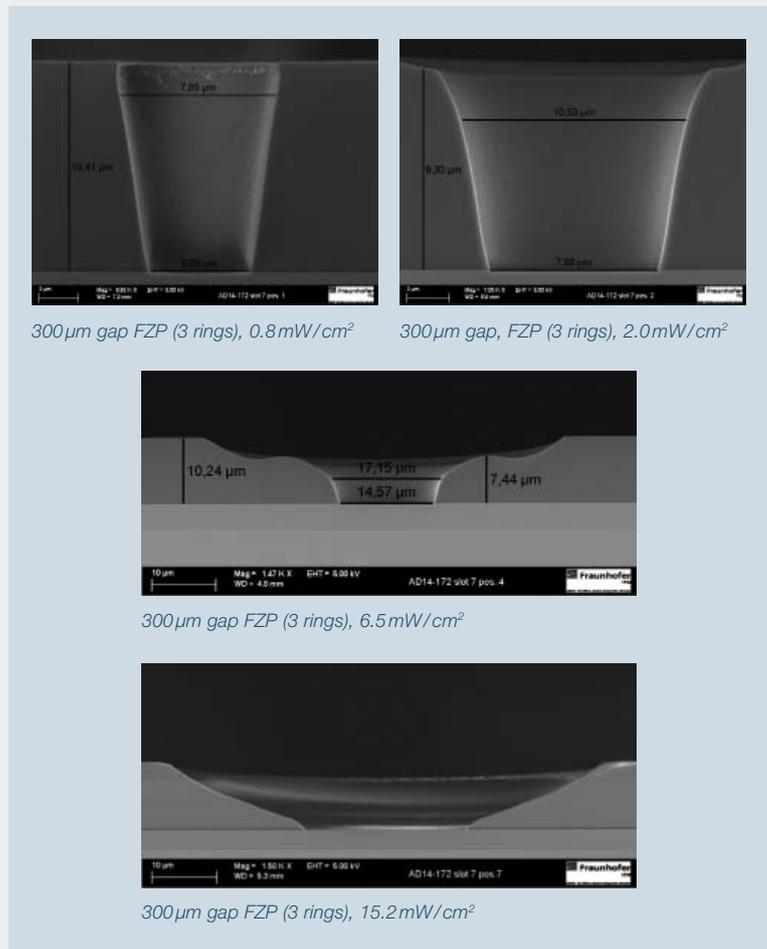


Figure 5 SEM images for $10\mu\text{m}$ thick AZ9260 at $300\mu\text{m}$ proximity gap, 40s exposure time, $300\mu\text{m}$ gap FZP design (3 rings)

increase of the spot diameter and due to higher dose. When the light power is exceeding a certain value, then the focus properties of the FZP will be affected negatively and a stronger degradation in the upper resist area is observed. The higher light power leads to an over-exposed process regime, which can be compensated by a reduction in exposure time. It means conversely, that at a constant low light power the CD parameter can be adjusted by the exposure time quite accurately within sub- μm tolerances.

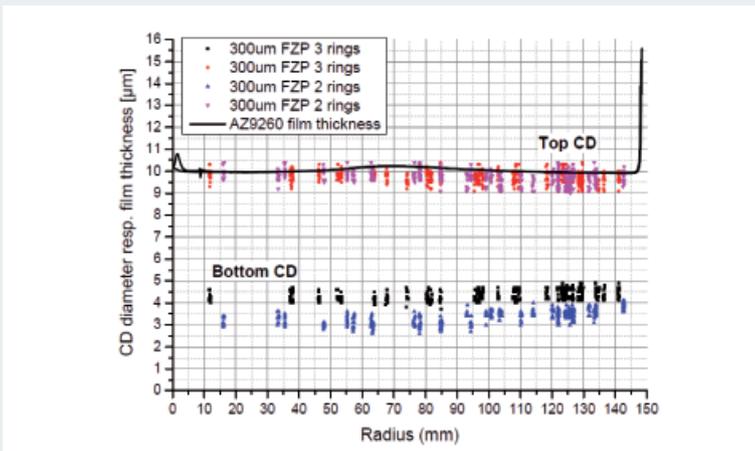


Figure 6 Top/down microscopy CD uniformity measurements on 300mm wafer for 10 μm AZ9260 at 300 μm proximity gap exposed with 2 resp. 3 rings FZP (0.6mW/cm², 40s exposure time)

To investigate the lithographic repeatability over the entire 300mm wafer substrate CD uniformity (CDU) measurements were done by optical top/down microscopy for both 300 μm FZP designs (2 & 3 rings design). In Figure 6 the results of the top and bottom CD measurements in dependence of the wafer radius are shown. Comparing the bottom CD values for the 2 resp. 3 ring FZP design, it can be seen that the 3 rings FZP design leads to a bigger bottom CD value than 2 rings FZP design. The 3 rings FZP focus more UV energy per area and generates therefore a wider CD value. The top CD parameter is more or less independently from the number of Fresnel rings. Comparing the coating uniformity (black line) with the CD values,

it can be seen that the optics is quite insensitive to resist thickness variations. It should be noted that the measured standard deviation is in the range of 0.3 μm , which is within the pixel accuracy of the used optical microscope. The “real” CDU should be therefore more accurate than the measured tolerances, which can be only quantified by CD-SEM metrology measurements. Therefore, it can be concluded, that this exposure concept yields to very accurate CDU tolerances. Changing the proximity gap together with the FZP design transfers the general lithographic concept to other gap ranges and other feature sizes. In Figure 7 two examples at 1000 μm proximity gap are shown. The higher gap and the different FZP design leads to a bigger CD.

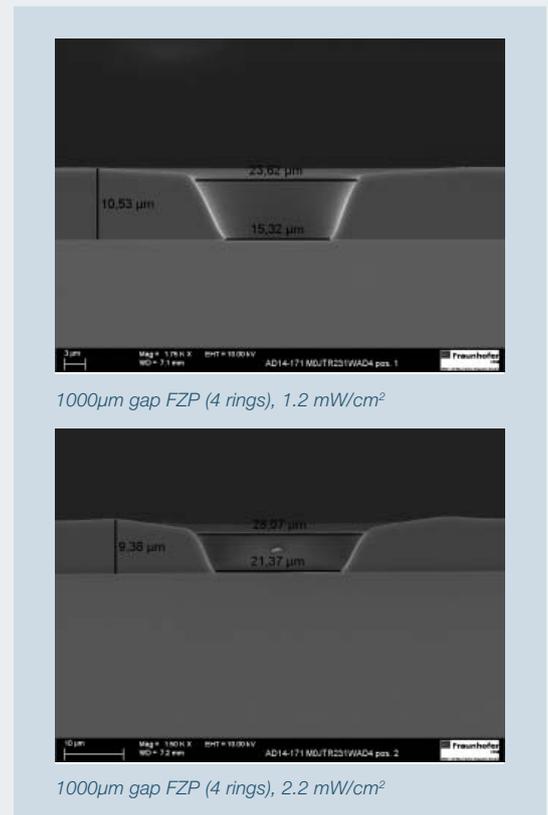


Figure 7 SEM images for 10 μm thick AZ9260 at 1000 μm proximity gap, 60s exposure time, 1000 μm gap FZP design (4 rings)

Evaluation of the exposure concept for the positive tone thick film chemical amplified photoresist AZ IPS528 with 50 μm target thickness is discussed secondly. SEM results with 300 μm proximity gap at a constant exposure time of 190s and variation in the UV light power are shown in Figure 8. Due to the thick resist film of $\sim 50\mu\text{m}$ the FZP designed for 400 μm gap gives good focus properties in this example. The resist profile and CD diameter depends significantly on the used light power and aperture diameter. With increased light power the bottom CD changes between $\sim 14\mu\text{m}$ – 60 μm . When the light power exceeds a certain value, then the resist is heavily degraded. A rather good profile is achieved with 3.9mW/cm². This exposure setting can be applied for instance to a 55 μm Cu-pillar interconnect with aspect ratio 1:1 at 110 μm pitch inside a 300 μm deep cavity.

To get a feeling for the impact of the proximity gap for a certain FZP design (here the 400 μm gap, 2 ring FZP design was used) an evaluation was done with constant exposure settings (90s, 4.1mW/cm²) and varied gap setting. The SEM results are shown in Figure 9. At low gap settings (100–200 μm) the FZP focus point is rather out of the resist plane. This leads to bottom CD values roughly comparable to FZP diameter ($\sim 53\mu\text{m}$). At 100 μm proximity an interesting T-shaped resist profile is generated, which can be used to electroplate T-shaped μPillar interconnect structures with steep profiles. When the proximity gap is increased to 500 μm the FZP focus more light energy to a smaller exposure area, which leads to a reduction in the bottom CD. The trade-off is that the top CD is not reduced in the same way. Therefore the resist profile is less steep. A further increase of the proximity gap to 700 μm increases the CD values with comparable resist profiles.

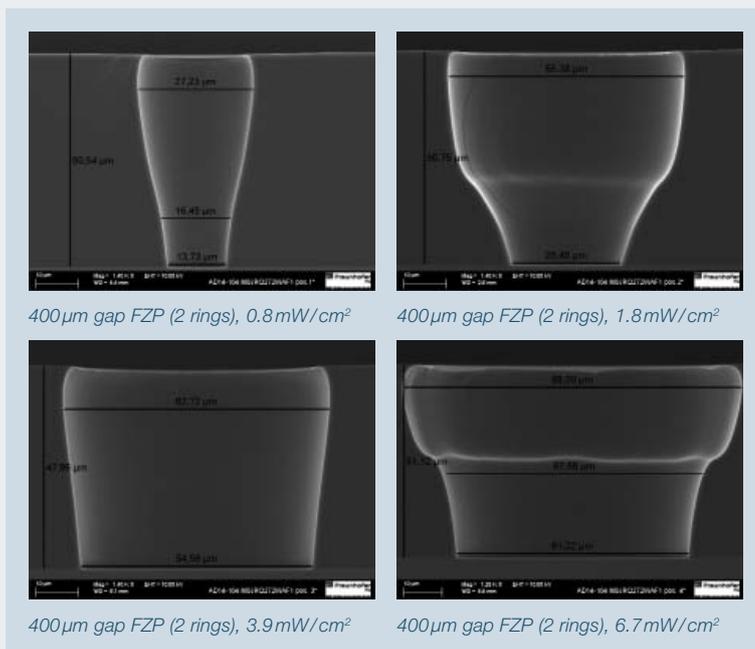


Figure 8 SEM images for 50 μm thick AZ IPS528 at 300 μm proximity gap, 190s exposure time, 400 μm gap FZP design (2 rings)

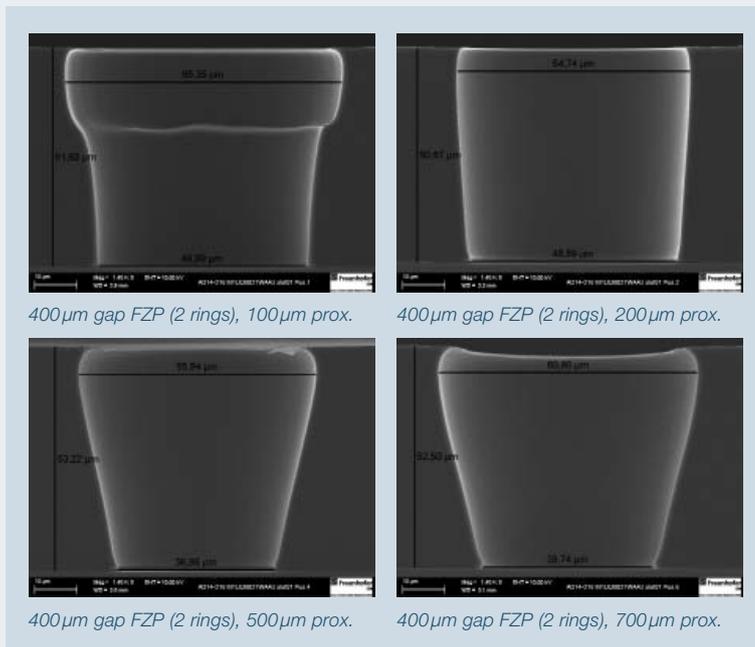


Figure 9 SEM images for 50 μm thick AZ IPS528 at varied proximity gap between 100 to 700 μm , 90s exposure time, power 4.1mW/cm², 400 μm gap FZP design (2 rings)

CONCLUSION

The exemplary discussed FZP concept together with the MO Exposure Optics allows to generate useful resist structures with respect to resolution and resist profile at rather high proximity gaps. This concept allows to transfer well known projection lithography principles to cost-effective mask aligner lithography. This can be applied to structure polymer or oxide openings inside deep cavities, on Taiko wafer or for MEMS applications. Together with unique chemical amplified thick film photoresist chemistry μ Pillar interconnect structures can be formed inside deep cavities or Taiko wafers as well. Also non-conventional μ Pillar shapes (T-shaped) can be generated with this exposure principle. This opens interesting opportunities for 3D integration packaging concepts.

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Frank Windrich graduated in Chemical Engineering from the University of Applied Science Dresden in 2003 and he holds a M. Sc. degree in Chemistry from the Technical University Dresden in 2013. He was with Fuba Printed Circuits from 2003-2009 and worked as process engineer in the PCB industry responsible for all lithography processes (inner layer, outer layer, soldermask). He joined Fraunhofer IZM-ASSID in 2010 and is working as a Scientist responsible for photoresist and polymer dielectric lithography processes in the field of Wafer-Level Packaging and 2.5D/3D Integration. Frank's current research interests are mainly focused on low-temperature cure thin film polymer dielectrics and thick-film photoresist materials for high density interconnects (μ Pillars).

