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High power modular LED-based illumination system for lithography applications

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ABSTRACT

Mask-aligner lithography is a technology used to transfer patterns with critical dimensions in the micrometer range from below 1 micron for contact printing to a dozen of microns in proximity printing. This technology is widely used in the fabrication of MEMS, micro-optical components, and similar fields. Traditionally, the light sources used for mask-aligners are high-pressure mercury arc lamps, which emit in the UV rang of the spectrum with peaks at 365 nm, 405 nm and 435 nm, respectively the g-, h- and i- lines. These lamps suffer from several disadvantages (inefficient, bulky, dangerous), which makes alternatives interesting. In recent years, high power UV LEDs at the same wavelengths appeared on the market, opening the door to new illumination systems for mask-aligners. We have developed a modular 250 W LED-based illumination system, which can advantageously replace a 1 kW mercury arc lamp illumination. LEDs, arranged in a 7x7 grid array, are placed in the entrance apertures of individual reflectors, which collimate the individual irradiation to an output angle of 10°. A subsequent fly's eye integrator homogenizes the illumination in the mask plane. It is followed by a Fourier lens, superimposing the individual channels in the mask plane, and a field lens to ensure telecentric illumination. This multisource approach allows the shaping of the source by switching individual illumination channels, determining the illumination angles and the spatial coherence in the mask plane. This concept can be used, for example, to do source-mask optimization. Compared to mercury arc lamp illumination, our system is simultaneously more efficient, compact, versatile, economic and sustainable. In our contribution, we present the design of the system as well as lithographic test prints done with different illumination patterns.

Keywords: Illumination design, lithography, concentrator, nonimaging optics.

1. INTRODUCTION

Mask-aligner lithography is a widely used technique in the fabrication of micrometer range structures, which is useful for the fabrication of micro-optical components, the packaging of LEDs, and similar applications. In mask-aligner lithography, the pattern from a planar mask is replicated onto a photo-sensitive substrate by shining light through a mask.[1] Mask-aligner lithography can be done with photomask and substrate in contact, or with a uniform and precisely set gap in between both, hence named contact and proximity printing. The illumination on the mask is crucial and requires a good control over the irradiance uniformity in the mask plane, with fluctuations below ±2.5%. For proximity printing, the preferred mode in production environments, the angular distribution of the illumination in the mask plane is also very critical. The light going through small apertures in the mask is subject to diffraction and interference effects. The angular distribution directly influences the spatial coherence of the light and therefore determines the resulting interference patterns.

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Traditionally, the light sources used are high pressure mercury arc lamps. They have emission lines in near UV range, with peaks at 365 nm, 405 nm and 435 nm. Such lamps present several disadvantages: they need a warm-up time, have a comparatively short lifetime and a low efficiency, are bulky and potentially dangerous, as they contain mercury. Alternative sources to such lamps have appeared on the market, which make it possible to develop new illumination systems for mask-aligners. High power LED sources at the required wavelength range are good candidates to replace the mercury arc lamp in the mask-aligners. LEDs are cheap, safe, have a long lifetime and are electronically switchable. The mercury arc lamps typically have lifetime of 1000 to 2500 hours, where as LEDs have lifetimes of 10000 to 30000 hours.

A number of examples of illumination systems based on LEDs can be found in the literature. These works either relate to a simulation of possible systems or complete realization of a system. Some of them are designed for lighting applications,[2] projectors[3] or lithographic applications.[4,5] In this contribution, the focus is set on the application for mask-aligners, but other lighting application could be found. A complete prototype of LEDs-based illumination is built. It consists of an assembly of high power UV LEDs mounted on individual reflectors. The source formed is a a high power and modular system, which can be mounted in existing mask-aligners. The work presents a description of the system as well as a characterization of the built source. The LED-based system is mounted in a SUSS MicroTec MA/BA8 Gen3 mask-aligner in order to validate the prototype with print tests.

2. DESIGN

An illumination scheme for mask-aligners is shown in Fig. 1. This kind of system represents the current state-of-the-art mask-aligner illumination and is described in detail in the work from Voelkel and al.[6] A mercury arc lamp is placed in one of the focal positions of an ellipsoidal reflector. The light is then directed onto a first fly's eye integrator, also called a Koehler integrator. This device is made of microlens arrays and homogenizes the light field. The subsequent field lenses are used to collimate the light beam. The first lens directly after the fly's eye integrator serves to transform the uniform intensity at the output of the fly's eye integrator into an uniform irradiance pattern. It to superimposes the single channels of the fly's eye integrator, and is therefore called "Fourier lens". The light then passes a second integrator. The irradiance distribution arriving on the second integrator defines the angular distribution in the mask plane. The "IFP", which stands for "illumination filter plate", is an amplitude mask that is used to shape the irradiance in the plane before the fly's eye integrator, and thus the intensity in the mask plane. This allows to shape the angular spectrum according to the type of feature to be printed. Controlling the angular distribution is that off-axis illumination is a widely used technique for resolution enhancement[7]

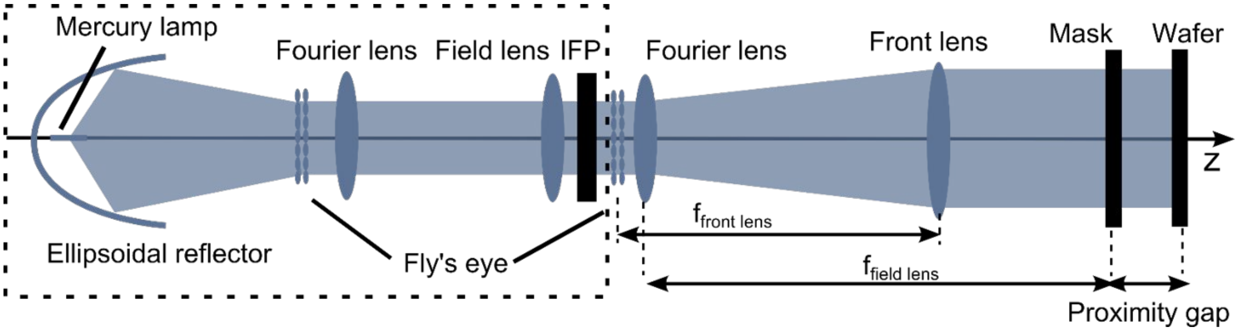


Figure 1. A schematic of the illumination scheme with a mercury arc lamp and the MO Exposure optics. The part in the dashed line box can be replaced by the LEDs-based illumination.

The novel system consists of an array of LEDs. Indeed, single LEDs in the UV range do not have enough power on their own. An array of LEDs is therefore needed. The light is collected from the LEDs by individual parabolic compound concentrators. Such concentrators are very well known for light collection for solar applications.[8] By placing the source at the smaller end, they work as collectors. The combination LEDs with the individual reflectors forms a high power modular source. This source is also very versatile, due to its multiple channels architecture. It can easily be adapted in order to meet wide range of specifications such as power, bulkiness, and collimation.

The reflectors collimate the light such that it lies within the acceptance angle of the following beam shaping elements. The light after the reflectors can hence directly be directed onto the second fly's eye integrator. The first homogenization step is performed by the reflectors themselves. The IFP becomes superfluous as its functionality can be replaced by switching individual channels in the matrix of LEDs and reflectors. The part of the exposure optics that can be replaced by the LED-based system is delimited by the dashed line in Fig. 1. The scheme with the LED-based system is shown in Fig. 2. The entrance apertures of the reflectors fit the emitting areas of the LEDs, which are 1.5 x1.5 mm^2. The light at the output of each reflector has an angular distribution within ±10°. The length of one reflectors is thus 29 mm and it is 9 mm wide.

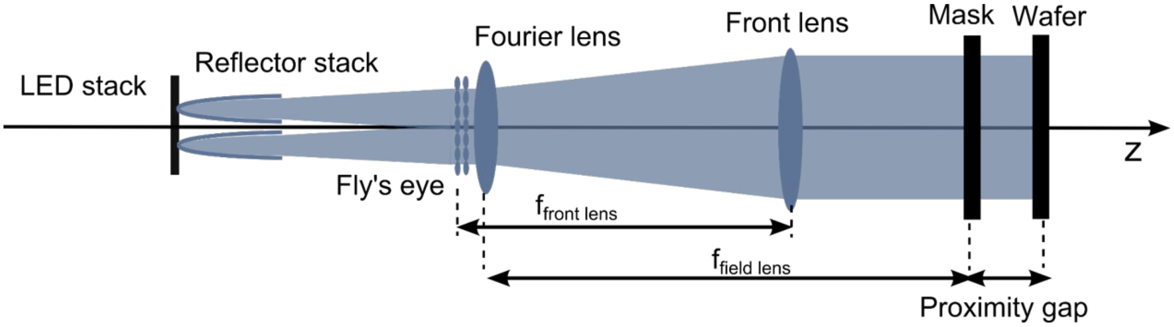


Figure 2. A schematic of the illumination scheme with a stack of LEDs and their reflectors; two reflectors shown. The system is much more compact compared to the canonical system shown in Fig. 1.

3. PROTOTYPE

The reflectors are made of machined and polished aluminum. The LEDs at a wavelength of 365 nm and of 1 W optical power are mounted on an aluminum PCB. In order to realize a source which has a power comparable to a 1 kW mercury arc lamp, the array is made of 7x7 LEDs of 1 W of optical power each. Because of their high power, and with a 25% electro-optical conversion efficiency, a considerable amount of energy is transformed into heat. A water cooling system is thus mounted onto the back of the PCB. This forms a source of 70 x 70 mm^2 of surface, with a depth of about 100 mm. The prototype can be seen in Fig. 3. The electrical and water connexions allow the driver of the LED to be placed away from the optics.

Different illumination patterns can be created to replace the IFP. For this prototype, the LEDs are divided into 4 groups, which can be driven individually. This means that, by combining them, 15 different patterns can be created. Two possible patterns are shown in Fig. 4. The groups are called "the corners", "the large ring", "the small ring" and "the central LED".

The efficiency of the specular reflection of polished aluminum at 365 nm is about 75-80 %. According to the maximum number of reflections that rays passing through encounter and the respective losses, the overall efficiency of the reflectors is approximately 36 %. The rest of the optics has an efficiency of approximately 90%. The overall maximum efficiency of the system is therefore 32 %. With the initial efficiency of the LEDs of 25 % this gives an overall electrical to optical power efficiency of 8 %. In comparison, the mercury arc lamps system has an efficiency of 1.5 % at 365 nm. Additionally, the duty cycle of the processes has to be taken into account. The mercury arc lamps remain continuously on where as the LED can be switched on only for the duration of the exposure time. This means that for example, if the exposure time per substrate represents about 20 % of usage time, the efficiency of a LED-based illumination system increases by a factor 5 compared to a classical mercury arc lamp system.

The maximum obtainable irradiance in the mask plane was found to be of 31 mW/cm^2 with all of the LEDs switched on. This level of irradiance corresponds to the specifications of irradiance in the mask plane of a mask-aligner equipped with a 1 kW mercury arc lamp. This means that this module could replace a 1 kW lamp in a mask-aligner at 365 nm and still produce the same level of irradiance in the mask plane.

Once the LED-based source is mounted in a mask-aligner, the first test to make is to check the irradiance uniformity. To do so, the irradiance level is measured at 13 different points in the mask plane of the mask-aligner. The uniformity is determined by computing the contrast between the point with the highest level of irradiance and the point with the lowest level of irradiance, according to the equation:

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

The LED-based system has a uniformity within ±1.2 % to ±2 %, depending on the pattern used. For comparison, the homogeneity obtained with the mercury arc lamp is ±2.4 %. The LED-based illumination system therefore can achieve a better uniformity than the system with the mercury arc lamp.

4. PRINT TESTS

To evaluate the real performance of the LED illumination system, test prints were performed in the mask-aligner. The LEDs and reflectors system were mounted just before the fly's eye integrator of a SUSS MicroTec MA/BA8 Gen3 mask-aligner. A test mask with lines and spaces test patterns was used to quantify the achieved resolution.

The prints are done with a proximity gap set to 30 μm. The structures are replicated in a layer of 1 μm of thickness of AZ1518 resist. The resist is deposited on 4 inch silicon wafers. The exposure dose used was set to 63 mJ/cm^2, which has been determined experimentally with a dose test. The development was done for 45 seconds in AZ351B 4/1 from AZ Electronic Materials.

In Fig. 4, the results of the test prints are shown for each separated group of LEDs and for the complete array of 7x7 LEDs switched on. The illumination pattern as it arrives on the mask plane is shown by the small inset picture. For the patterns in Fig. 4 (a) and (b), one can see that the corners of the illumination pattern

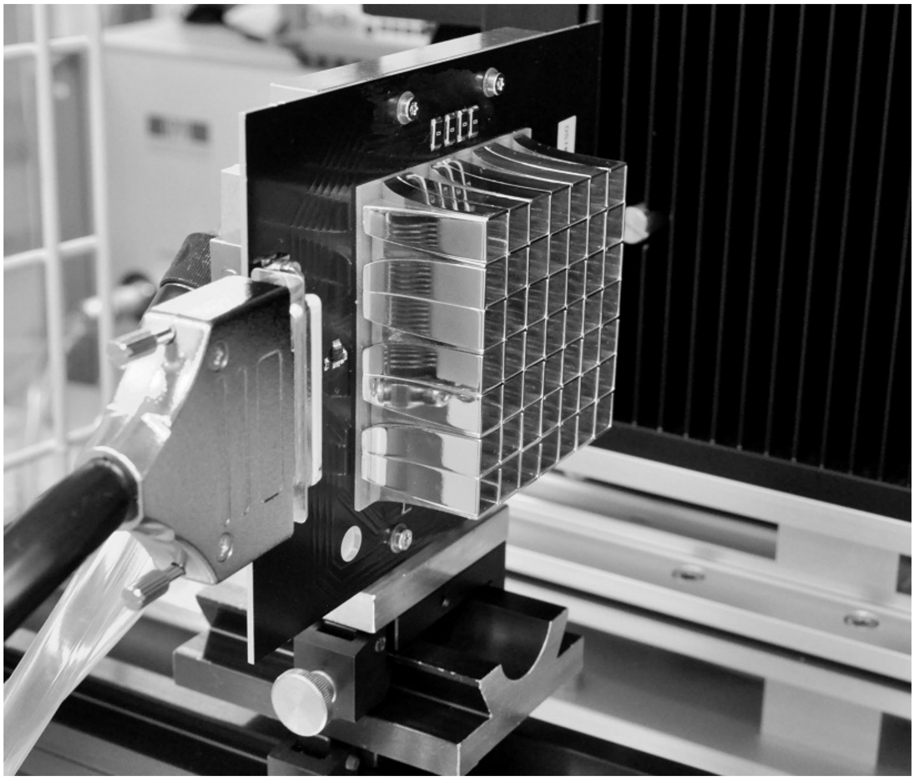


Figure 3. A picture of the 7x7 LEDs and reflectors system. The water pipe, which ensures a proper cooling, can be seen on the left, along the electrical connections.

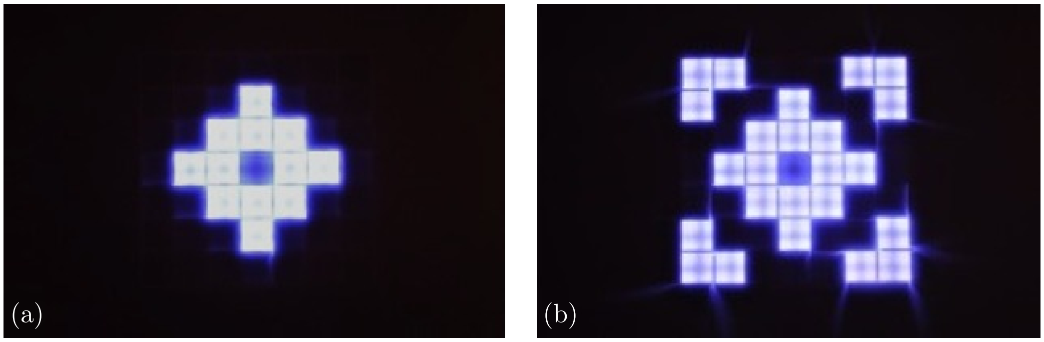


Figure 4. Pictures of two of the possible patterns at the output of the the 7x7 array of reflectors. There are 4 distinct groups of LEDs, which can be switched on individually: the four corners, the large ring, the small ring and the central LED. (a) shows the small ring pattern and (b) the combination of the small ring and the corners.

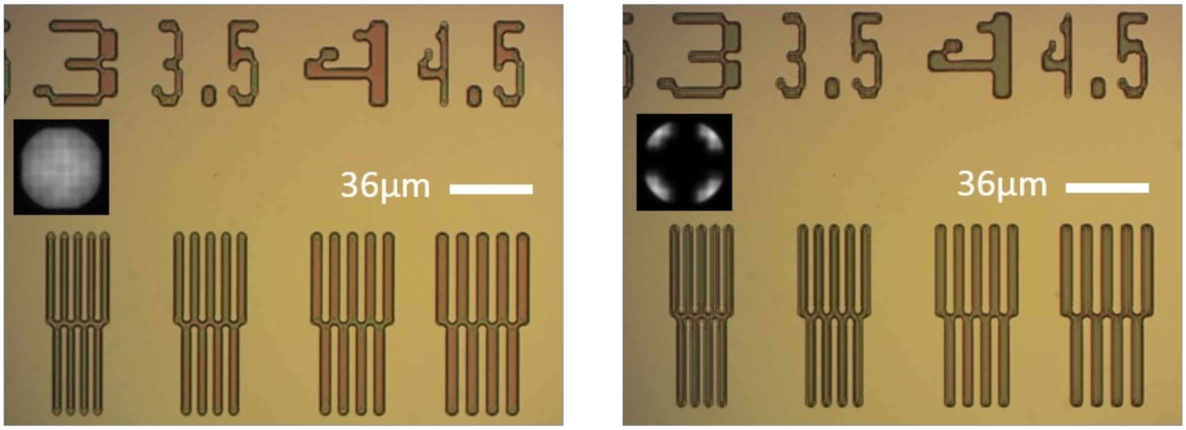
is rounded. This is due to the lens following the fly's eye integrator. The numbers printed indicate the critical dimension of the lines and spaces, the period being twice these numbers. The resolution achieved with a 30 μm proximity gap, is 3.5 μm, but with strong diffraction effects. The diffraction effects are expected because of the small angles of incidence in the mask plane, which are between 1° to 3.5°, depending on the illumination pattern used. The 4.5 μm structures are well printed. Those results correspond to the expected printing resolutions.

The influence of the illumination pattern, hence the angular spectrum, can be seen in the different representation of the lines. The central LED in Fig. 4 (e), for example, results in an angular distribution within $\pm 1°$. This implies that the light in the mask plane has a high degree of spatial coherence. It leads to interference patterns with a higher contrast in the substrate than for other, less coherent patterns. This is important as diffraction effects appearing in proximity printing are very dependent on the coherence properties of the light. Something else to notice is, when looking at the 4.5μm lines, for example, it can be seen that there is more corner rounding of the upper part of the lines for the 7x7 LEDs pattern in Fig. 4 (a) than for the corners pattern in Fig. 4 (b). These different examples illustrate the importance of having a good control over the angular distribution.

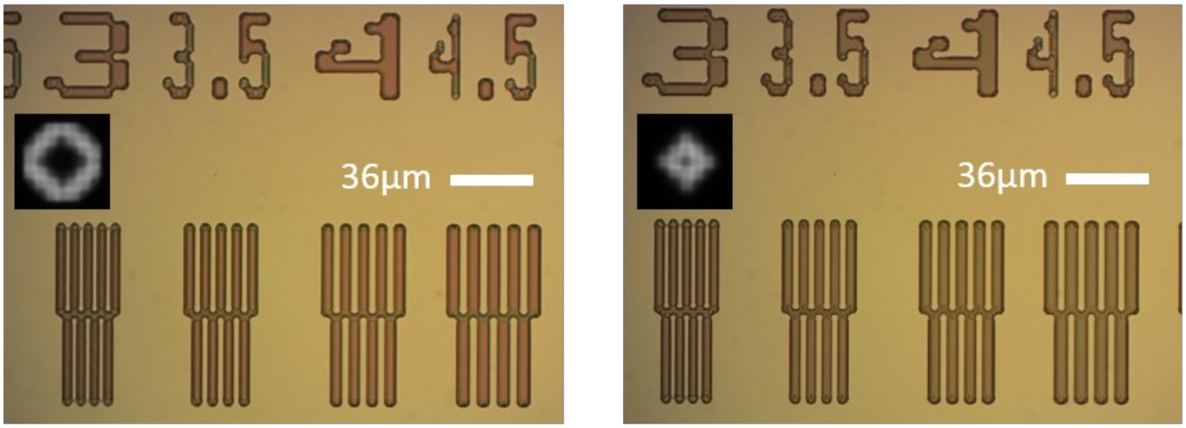
5. CONCLUSION

The prototype of an LED-based system at 365 nm was built with 7x7 LEDs and reflectors. This forms a source of 17 W of optical power, which can replace a 1 kW mercury arc lamp. Different illumination patterns can be created, determining the angular distribution in the mask plane, without the use of physical apertures. The system was mounted in a SUSS MicroTec MA/BA8 Gen3 mask-aligner. The maximum irradiance measured in the mask plane is 31 mW/cm^2. The measured uniformity in the mask plane was found to be between $\pm$1.2%-$\pm$2% depending on the illumination pattern chosen. Prints tests were carried out and a resolution of 3.5 μm was found when printing with a proximity gap of 30 μm. Those measurements are similar to or better than the specifications of a high-pressure mercury arc lamp operated at 365 nm. These results prove that it is possible to replace mercury arc lamps with an LED-based system in mask-aligner illumination systems, which is more versatile, efficient and sustainable.

(a) 7x7 LEDs (b) corners



(c) large ring (d) small ring



(e) center LED

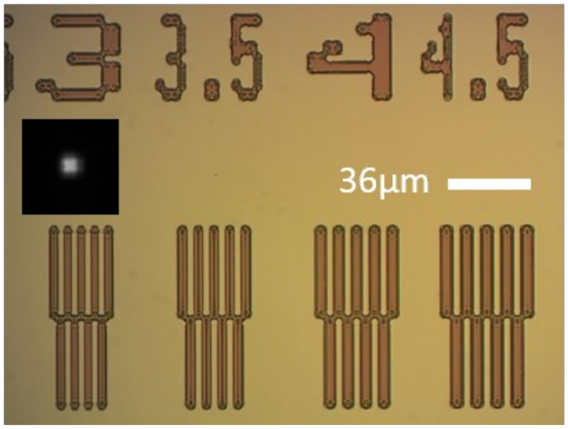


Figure 5. Bright-field micrographs of printed lines and spaces (50% duty cycle). The numbers indicate the linewidth in micron. The angular spectrum given by the pattern of contributing LED channels used for each print is shown in the inset image. The rounding of the corners of the angular spectrum in (a) and (b) is caused by the lens following the fly's eye integrator.

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