

HIGH INTENSITY UV-LED MASK ALIGNER FOR APPLICATIONS IN INDUSTRIAL RESEARCH

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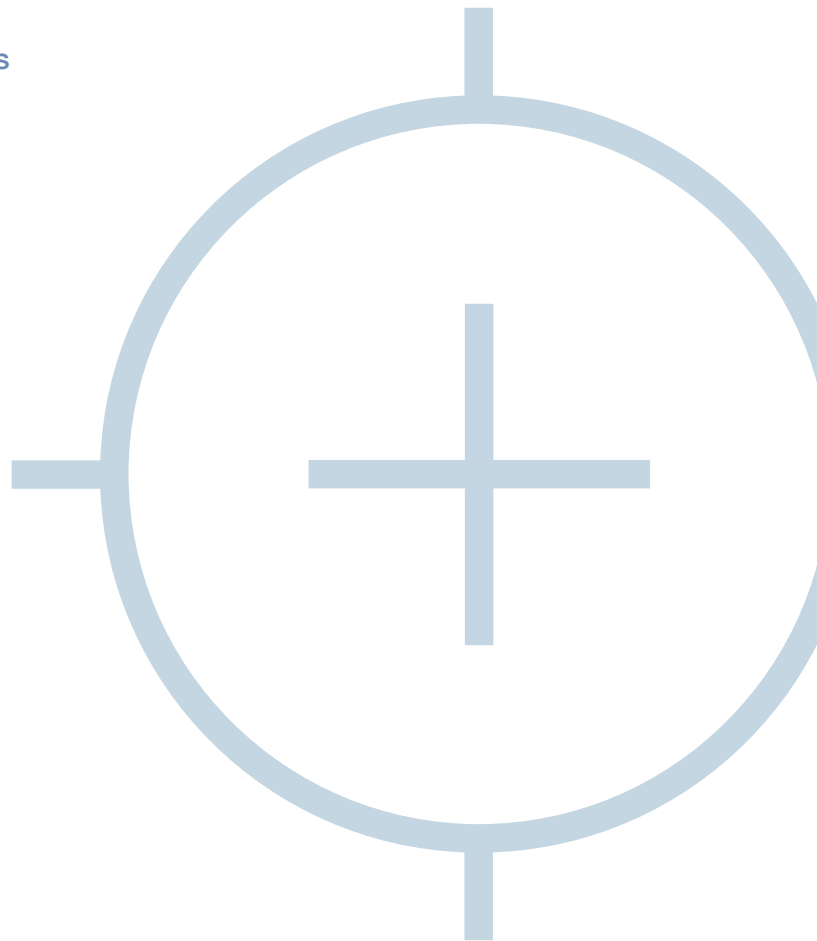
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Recent rapid technological progress in the field of UV-light emitting diodes promises great opportunities. Ecological UV-LED light sources can replace traditional mercury lamps with tremendous less power consumption, no hazardous waste and no need for special safety measures^[1]. Moreover, new processes and applications become possible thanks to the unprecedented flexibility in illumination control.

Already today UV-LEDs offer a cost-effective, green and flexible replacement for Hg-lamps in main-stream water purification, counterfeit detection and curing applications. First benchtop lithography investigations with UV-LEDs date back to 2005^[2]. Since then many research teams working on a multitude of materials have demonstrated good print performance of UV-LEDs in all types of lithographic processes^[3-7]. However, they also showed that the limits of home-made benchtop setups needed to be overcome to qualify UV-LED illumination for commercial lithographic manufacturing.

In this paper we show first results on a semi-automatic mask aligner with UV-LED illumination, SUSS MA/BA8 Gen4 *Pro* equipped with a UV-LED lamp house and MO Exposure Optics^[8]. The tool offers a customer-controllable spectrum with three wavelengths corresponding to the mercury i, g and h-line. The field-proven MO Exposure Optics guarantees a reliable smooth angular spectrum that can be fully customized. Full 8 inch wafers were exposed with the same high intensity and light uniformity as with standard 1 kW mercury lamps. Broadband and single line exposures were performed on several standard processes. The resolution and appearance of the produced features compared well to traditional exposures with a mercury lamp.

In addition we present an analysis of the eco-fingerprint of our UV-LED-lithography system. For a semi-automatic system used under typical research institute conditions the LED light source can survive a machine life-time. LEDs don't require warm up times and thus are switched on during exposure only. Moreover, low power consumption of the LEDs during operation and no need for nitrogen flow cooling also contribute to very low running cost and a green footprint.

In summary, the lithography industry will greatly benefit from UV-LED illumination paving the way for future process innovations in a mercury-free and safe environment.

INTRODUCTION

Ecological and safety concerns call for a reliable and energy effective replacement of mercury lamps in lithographic applications. Many researchers have already shown good print performance of UV-LEDs in laboratory test setups^[2-7, 9-10]. To qualify UV-LED illumination for commercial lithographic manufacturing reliable machine integration, high intensities, good light uniformity^[7,9], reproducible dose and illumination conditions^[10] and control of the angular spectrum^[5] are necessary.

Here, we compare the lithographic performance of a standard 1 kW mercury lamp with a multi-wavelength UV-LED source with essentially identical light intensity. In addition, we discuss the typical wavelength spectrum of the UV-LED source and its user customizable composition and present the results of lithographic exposures and imprints on full 8 inch wafers. We demonstrate that the light source choice has no significant impact on pattern resolution and appearance. Further, an investigation of its eco-finger-

print reveals that the UV-LED source reduces the mask aligner energy consumption.

FLEXIBLE WAVELENGTH SPECTRUM

Multi-wavelength UV-LED light sources imitate the emission line spectrum of mercury vapour lamps. To compare both light sources, intensity spectra of the 1 kW mercury lamp and of the UV-LED source were recorded in a wavelength range between 350 and 470 nm. Figure 3 shows a comparison of the recorded spectra. The spectrum of the MA/BA8 Gen4 *Pro* mask aligner equipped with the LED light source (solid orange line) shows light intensities of about the same magnitude (compare the area under the intensity curve around the peak wavelength) and at essentially the same wavelengths as the spectrum of the 1 kW mercury lamp (dark blue line). The recorded intensity uniformity with MO Exposure Optics^[9] is better than 2.5 % for both the LED source and the mercury lamp. The LED arrays emit light around the characteristic mercury lines 365 nm (i-line), 405 nm (h-line) and 436 nm (g-line). The emission peaks are broader as compared to the mercury lamp. However, these results show that strong intensities at the sensitive regions of typical resist materials can be achieved easily with the LED light source.

In addition, the LED source offers the possibility to separately control the LED arrays. The orange solid line in Figure 3 shows a broadband UV-LED spectrum with full intensity of all three lines. A user can adapt the wavelength spectrum to a specific application (e.g. Figure 1 and 2) and store the light configuration in the machine recipe. For example, i-line exposures can be performed without filter exchange by switching on only the i-line LEDs.

In some cases the user might want to reach the best possible match to a specific best practise process. For this purpose the LED light source allows adapting the composition of the i-, h- and g-line intensities to a known mercury lamp spec-

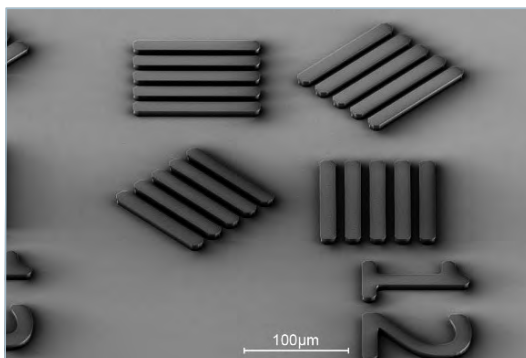


Figure 1 UV-LED broadband exposure in 8 μm thick AZ2070nLof at 20 μm proximity gap. FIB image of 12 μm structures with Pt-coating for resist protection

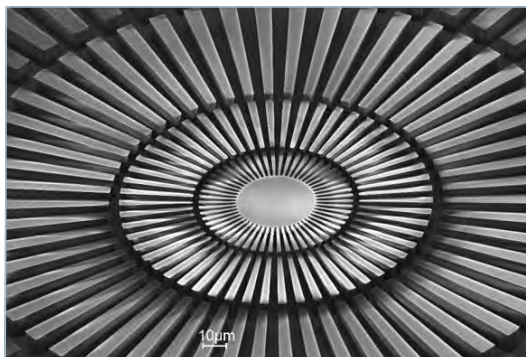


Figure 2 SEM image depicting Siemens star pattern exposed with g-line UV-LEDs in 10 μm thick AZ9260 in hard contact mode

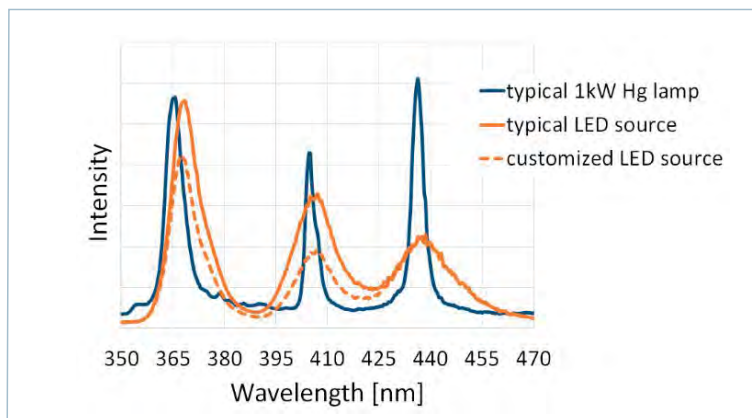


Figure 3 Spectrum of a typical 1 kW mercury lamp (dark blue), a typical LED light source (solid orange) and example of an LED source with customized composition (dashed orange)

trum (e.g. to a 350W lamp or 1 kW lamp spectral composition). Here the area below the intensity-wavelength curve in Figure 3 and the spectral resist absorption characteristics of the resist ^[11] can be taken into account. The dashed line in Figure 3 shows the spectrum of an LED source that was adjusted to closely mimic the 1 kW lamp spectral response for AZ4110.

The flexibility in adjusting or composing the wavelength spectrum offers new opportunities. Even machine-to-machine matching of the illumination becomes possible. The MO Exposure Optics additionally guarantees a reliable smooth angular spectrum where also the exposure angle composition can be fully customized ^[8].

LED AND HG LAMP PRINTS MATCH

Many research groups showed that SU8 ^[5,7,10] and i-line resist ^[6] exposures can successfully be performed with UV-LEDs. Here, a test series of full 8 inch wafers with typical resists and several resist thicknesses was exposed under varying exposure conditions. For direct comparison each test was performed with the LED lamp house and with a traditional 1 kW mercury lamp under comparable conditions.

The LED spectrum was customized to closely match the 1 kW Hg lamp exposure for AZ4110 (dashed line in Figure 3). But, even in tests without customization of the LED source (maximum intensity on all i, h and g-line LEDs) no significant difference was found in feature shape and resolution.

Figure 4 shows secondary electron microscope images of Line/Space patterns produced in 1.2 μm thick AZ4110 resist with the LED source (left) and the traditional 1 kW Hg lamp (right). All three mercury lines (broadband) were used to generate the patterns. These shadow print exposures were performed with a proximity gap between mask and wafer of 20 μm . For each source we used an optimized dose as determined with test exposures. The process parameters were identical for both light sources, however no effort was taken to fully optimize the process for e.g. suppression of standing waves, best possible side wall angles or best possible resolution. Similar tests were performed with AZ4110 at other proximity gaps up to 100 μm . The smallest reproducibly resolved feature size over the whole wafer was 3 μm for exposures with 20 μm proximity gap (Figure 4) and 6 μm for 100 μm proximity gap.

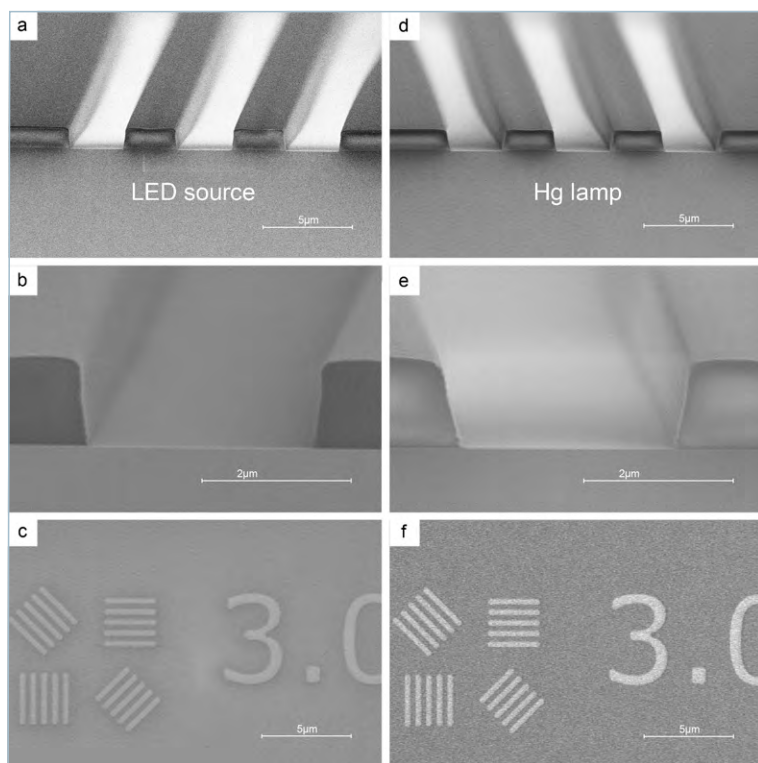


Figure 4 Broadband exposures of 3 μm Line/Space patterns with LED source (a-c) and with mercury lamp (d-f) in 1.2 μm thick AZ4110 resist exposed at 20 μm proximity gap

Figure 5 shows SEM images of Line/Space patterns in thick resist ($10\mu\text{m}$ thick AZ9260) exposed with a large exposure gap of $100\mu\text{m}$, a typical process used for etch mask definition for dry etch processes or redistribution layer formation on wafers with topography. The feature shapes produced by the LED source (left) and the mercury lamp (right) are almost identical.

For additional tests with monochromatic light we used filters with the Hg lamp and selected only a single LED array, e.g. i-line, in the machine recipe of the LED tool. In all cases the feature shapes and side wall angles produced by the LED source are very similar to the mercury lamp prints. No significant impact of the light source is visible in any of the exposures neither in the feature shape nor in the resolution.

UV-LED exposures were successfully utilized in diverse other applications. Figure 6 shows an example of an array of microlenses manufactured using the SMILE (SUSS MicroTec Imprint Lithography Equipment) technology wherein the imprinting material is brought into the required 3D shape via a stamp. In this process, the illumination with UV-light triggers the cross-linking within the imprint polymer and therefore leads to its solidification. The lens array shown in Figure 6 was imprinted on 200 mm wafers using the DELO OM 6610 material. During all imprint tests, the LED source produced equivalent results compared to traditional Hg lamps. Moreover, imprint applications favor particularly high exposure doses to achieve best performances, making high power LED-sources (equivalent to 1 kW lamps) the optimal solution.

ECO-FINGERPRINT

LED technology allows for the fabrication of extremely long-lasting light sources. UV-LEDs have typical life times of 5,000 to 30,000 hours. They are switched on only during the wafer exposure itself, which typically takes one to a few seconds.

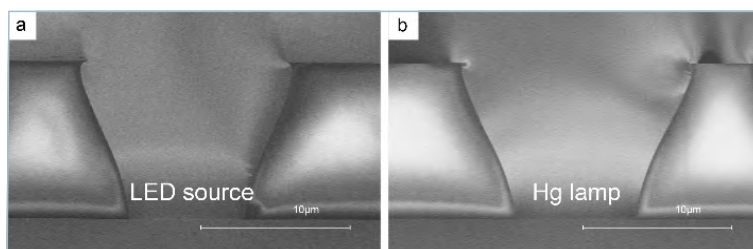


Figure 5 Identical shape of Line/Space features in $10\mu\text{m}$ thick AZ9260 resist exposed in $100\mu\text{m}$ proximity gap with LED source and 1 kW Hg-lamp

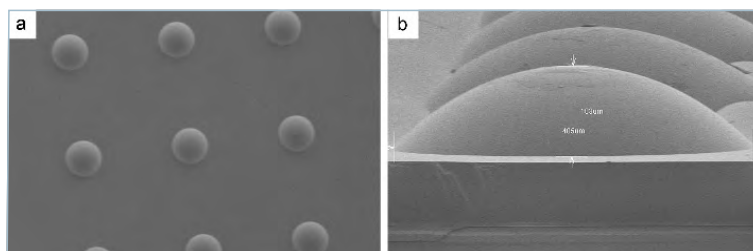


Figure 6 Imprinted arrays of microlenses produced using SMILE technology with LED source

An LED-source module may thus last for a full manual aligner machine life of more than 10 years without the need for replacement^[12].

Today's mercury lamps on the contrary have to be replaced regularly (life time 1,000 to 2,250 hrs). In a typical industrial or laboratory environment they are usually switched on at the beginning of a shift and kept burning until the end of the day. Consequently replacement is needed every 4 to 9 months^[12]. In addition, conventional mercury lamps have further drawbacks: machine use of a lithography system with a mercury lamp can only start after about half an hour warm-up time. The bulbs need to be stored and disposed of properly as they contain hazardous mercury. Their handling poses human safety risks and needs to be done by specially trained personnel. Furthermore the supply, use and disposal of mercury lamps will become more difficult and uncertain in a foreseeable future based on the UN Minamata

Convention, the EU Mercury Strategy, the US Mercury Management and other shortly upcoming national and international regulations.

UV-LEDs are a green and safe alternative to mercury lamps. They produce no hazardous waste and there are no human safety concerns. UV-LEDs do not require warm-up times. In addition, LED lamps need much less energy than their Hg counterparts. Figure 7 shows a direct comparison of the energy consumption of a typical MA/BA Gen4 Pro mask aligner equipped with a 1 kW Hg-lamp (left) and with an LED source (right). Both offer the same light intensity for exposures. The LED machine requires approximately 60 % less energy during normal operation^[12]: the electrical energy consumption is reduced and no exhaust system or special flow cooling is necessary. Some remaining clean dry air and nitrogen volumes are used for wafer processing.

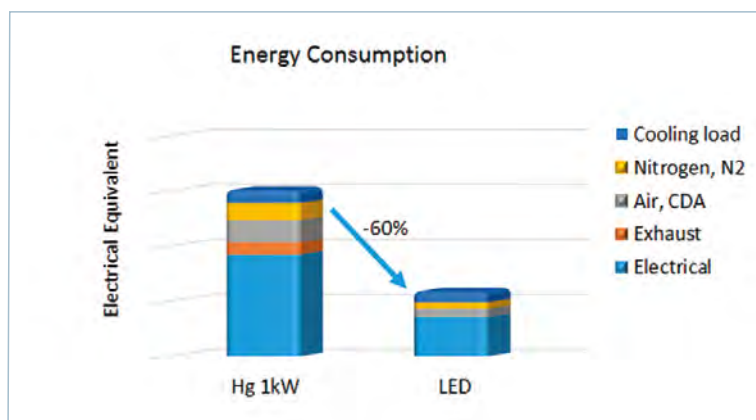


Figure 7 Energy consumption of a MA/BA Gen4 Pro mask aligner with LED source and equivalent 1 kW Hg- lamp.

CONCLUSION

We have shown that LED light sources in mask aligners offer strong illumination flexibility by allowing to customize both the intensity and the spectrum of the illumination light. Thus, LED light sources allow optimizing the illumination characteristics for different illumination scenarios and resist materials. We showed that our LED light source has no negative impact on pattern resolution and appearance when compared to a conventional 1 kW Hg-lamp. It offers superior lifetime, reduced power consumption, needs no exhaust system and does not suffer from the disposal problem of conventional Hg-lamps. In combination with SUSS MO Exposure Optics it is now possible to customize the illumination in all three main parameters: wavelength, intensity and illumination angle while at the same time highly homogenous illumination is guaranteed at every point in the mask plane.

In a nutshell the high intensity multi-wavelength UV-LED source is an adequate, green and highly flexible next generation light source for mask aligner lithography.

Acknowledgements

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- [11] Typical mask aligner resists are strongly sensitive to i-line and less sensitive to h- and g-line light.
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[Aug. 2017]
- [12] Assuming manual aligner operation for small production with about 12 to 24 wafer exposures per hour during one 8 hour shift per day on 7 days per week, with 1 to 2 sec exposure time

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Katrin graduated in technical physics at the Technical University of Ilmenau, Germany and KTH Stockholm, Sweden. She obtained her doctorate degree in physics on magnetic semiconductor nanostructures at Würzburg University. Before joining SUSS MicroTec in 2010 she worked as application development engineer at ASMLs technology center in Linkou, Taiwan.

