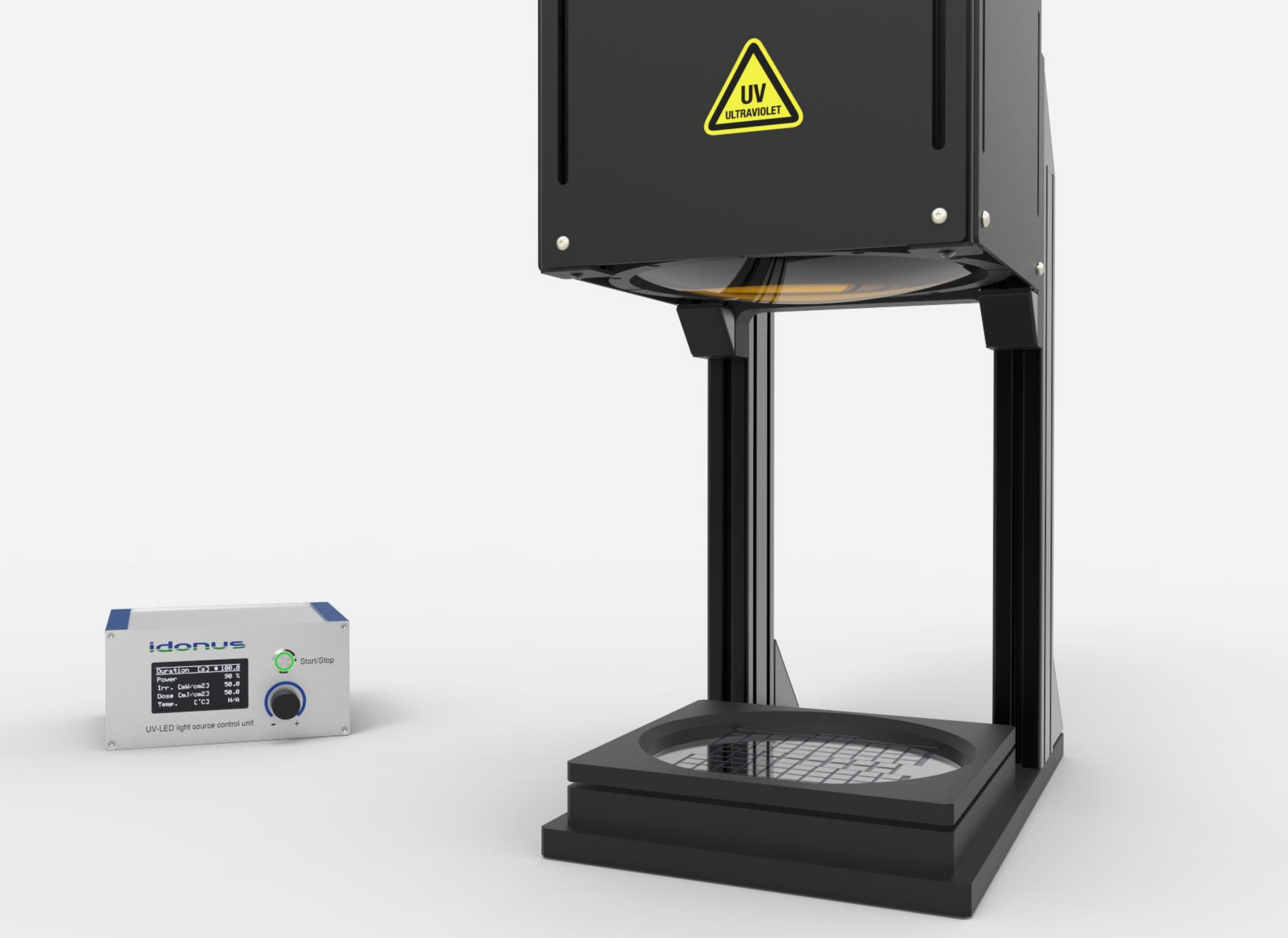


TECHNICAL NOTE

UV-LED light engine for photolithography exposure

Cost of ownership, ease of use and elimination of contaminating substances are important to R&D and manufacturing facilities using UV exposure tools.

The Idonus UV-LED light engine provides solutions using your current UV optics for the retrofit of mercury arc lamp sources or with our optics new sources for mask aligners standalone light sources and other photolithography and UV exposure tools.

www.idonus.com
Document issued in July 2018, updated in December 2020

This brochure has been prepared to assist engineers and technicians in understanding the capabilities offered by the Idonus UV-LED light engine. Performance is illustrated by micrographs taken after exposure of commonly used photolithographic resists. The versatility of the UV-LED light engine is described with the retrofitting of a mask aligner where the mercury arc lamp and housing have been replaced with the compact UV-LED light engine and the configuration of a customized cleanroom photolithography exposure tool combining the UV-LED light engine with standard products from Idonus' catalogue.

Introduction

Breakthroughs in the manufacturing of highly efficient and powerful LEDs (Light Emitting Diodes) has allowed the rapid expansion of this technology in the last decade. This has become obvious in our daily lives: LEDs are now the standard in consumer electronics and in household appliances. Governments worldwide have banned the use of incandescent light bulbs wherever they could be substituted with far more energy efficient solutions, such as LED light bulbs. Regarding industrial equipment, substitution is not straightforward and regulations must be conciliated with economic reality. Thus, although it is expected that mercury arc discharge lamps will be phased out in a near future, their replacement with UV-LED lamps may take as long as the equipment lifetime [1].

Still, every effort must be made by the industry to eliminate the use of mercury. In concrete terms, the UN Minamata Convention on Mercury entered in force in August 2017 and high-pressure mercury vapor (HPMV) lamps for general lighting purposes will be phased-out in 2020.[1] In the medium term, the supply, use and disposal of mercury-based products will become increasingly stringent and economically disadvantageous.

As an innovative company active in the development of special machines for microtechnology, our task is to demonstrate that our high-performance UV-LED exposure systems are **both technically and economically advantageous**. In the following sections, we show that both conditions are fully met with our range of *UV-LED-EXP* products aimed for photolithography. In the last section, we present solutions to easily integrate our products into modern industrial equipment. We also discuss the possibilities offered to retrofit mercury-based systems.

Mercury-vapor versus UV-LED lamp

Mercury arc lamps are high intensity gas discharge lamps. Briefly explained, an electric arc is created that vaporizes mercury (Hg) and produces a very bright light with a well-defined emission spectrum, especially rich in the ultraviolet (UV) wavelength band. A typical spectral distribution of an Hg lamp is shown in Figure 1. This interesting characteristic of the Hg radiation spectrum was first observed by Charles Wheatstone in 1835 [2]. Industrial production of mercury arc lamps started by the end of the 19^{th} century and they have since been a workhorse for many UV applications for more than hundred years. A now obvious issue of these lamps lies in the use of highly hazardous Hg,

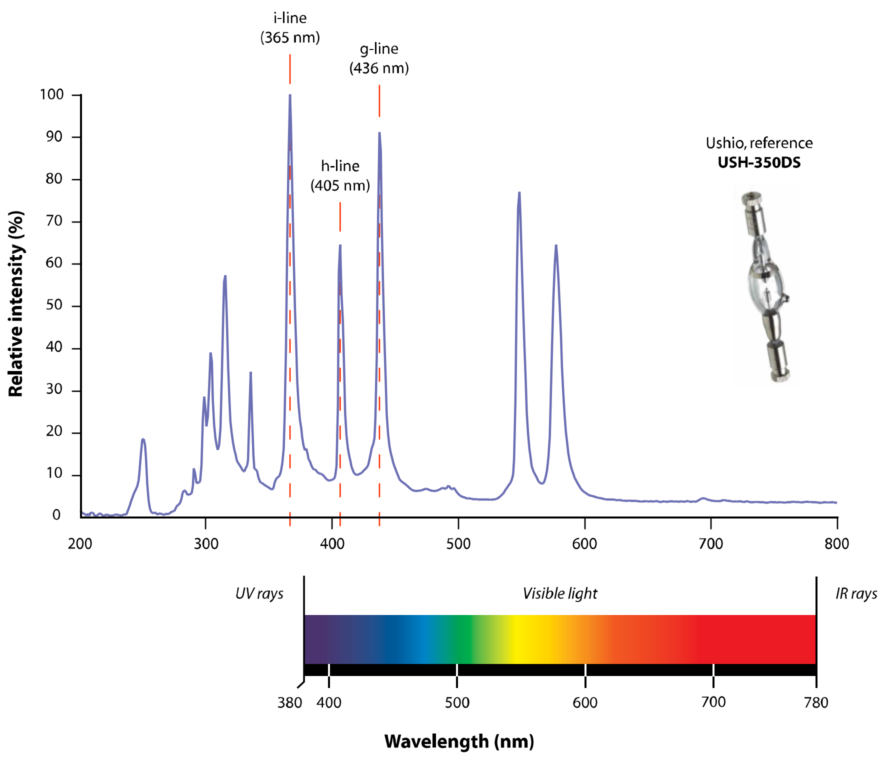


Figure 1: *Typical spectral distribution of a mercury arc lamp. The data shown are those of Ushio's super-high-pressure mercury lamp model USH-350DS (350 W electric power, 1'000 hours rated life, 650~750°C bulb temperature).*

[1] Minamata Convention on Mercury, Article 4.1 and Annex A (see www.mercuryconvention.org). The EU, as a signatory to the treaty, implements this regulation through REACH, namely the registration, evaluation, authorisation and restriction of chemicals.

which implies cautious handling and meticulous recycling. From the production perspective, the main drawbacks of Hg lamps for UV lithography are:

- the **warm-up time** (several minutes) required to vaporize Hg and start the lamp;
- the **limited lifetime** (typically 1'000 hours) of the mercury arc lamps, since they are likely to be operated continuously in cleanroom facilities;
- the **frequent calibration and maintenance**[2] necessary to ensure process repeatability, as one must account for the ageing of the lamp.

As long as there was no alternative to mercury arc lamps, the associated routine tasks were the responsibility of the maintenance staff and rightly so could all these costs be considered as part of the infrastructure and overhead costs. With the emergence of UV-LED lamps, this reasoning must be re-examined.

In high-power UV-LED lamps, all the drawbacks listed above are simply eliminated:

- **switching is instantaneous** and completed electronically, use of a mechanical shutter then becomes superfluous;
- LED dies and their electronic control system have **extended lifetime** (in excess of 10'000 hours), lifetime is therefore virtually unlimited since LEDs are only switched ON during UV lithography;
- LEDs are current-regulated and the irradiance measured during UV exposure is used for closed-loop current control, **auto-calibration** is intrinsic to the UV-LED illumination system.

Not to mention that the irradiance, or optical power density, which is achievable with high-power UV-LEDs has now reached the level of mercury arc lamps used for photolithography. From these reflections, there is no doubt that LED technology is a serious alternative to mercury arc and will become the standard in next generation equipment. To date, UV-LED is the only efficient photolithography lamp without mercury.

"UV-LED is the only efficient photolithography lamp without mercury"

UV-LED exposure system for photolithography

An easy means that comes to mind to perform UV-LED exposure is to use a matrix of LEDs. A pitfall with this approach is that each individual LED die must be controlled individually to guarantee illumination homogeneity. However, this amounts to shifting the complexity to the control electronics. We offer a different approach.

The technical advantage of our UV-LED exposure systems lies in (i) the integration of latest generation high-power UV-LEDs together with (ii) a fully optimized illumination design. Our nonimaging optics is engineered throughout the entire light path, starting from the semiconductor LED dies up to the exposed photolithography plane. As a result, our UV-LED exposure systems show outstanding performance in terms of irradiance, illumination uniformity, and collimation angle.

The high-power UV-LED dies are mounted on a circuit board with high thermal conductivity that allows efficient heat dissipation through an external fan-cooled heat sink. The UV-LED control electronics has a built-in thermistor that monitors the temperature. An external UV sensor is integrated into the exposure system to measure the irradiance (in mW/cm^2) and the exposure fluence (in mJ/cm^2) at the output (*e.g.*, substrate plane). It is thus possible to use our *UV-LED-EXP* system as an OEM equipment that can be easily integrated into customer's product (*e.g.*, controlled through a programmable logic controller, PLC). Optionally, our "UV-LED light source control unit" (see Figure 2) can be conveniently connected to the *UV-LED-EXP* inputs for a standalone control of the system.

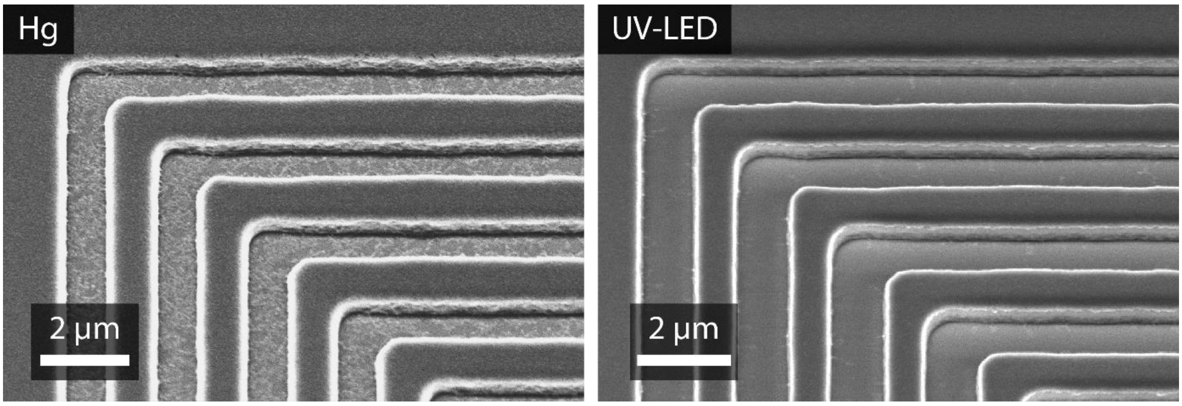
Figure 2: *Idonus' UV-LED light engine. The system consists of a controller box and a high-power UV-LED module. The optical power is optimized thanks to a specially designed nonimaging optics. The dedicated power supply is not shown in the photograph.*

[2] Safety hazards with high-pressure Hg lamps – A risk of explosion can't be excluded. When handling the lamps, protective face shield and gloves are required. If a lamp should break, breathing the vapor must be avoided. Ozone is also produced due to the interaction of the radiation emitted below a wavelength of 250 nm with oxygen.

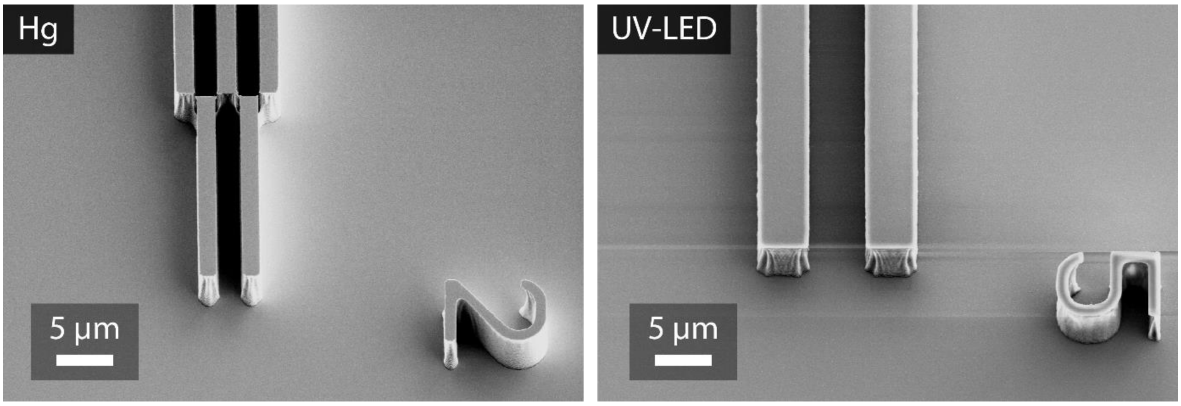
Photoresists exposure results

The most immediate way to evaluate our system is to compare exposure results with those obtained with conventional mercury-based photolithography equipment. Hereafter, we discuss the results of evaluation tests performed with various AZ resists[3] used for microlithography. For confidentiality reasons and to keep this document short, only a selection of results provided by academic partners are disclosed.[4] The results shown below were obtained using three types of positive photoresists (see note "♦" at the end of this section). It goes without saying that they can be generalized to all kinds of resists and even to shadow mask (stencil) lithography.

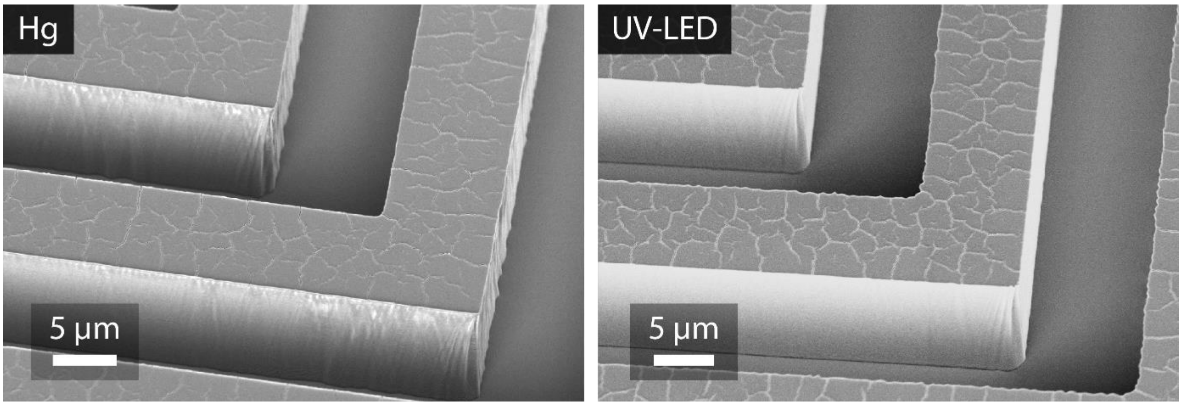
The Scanning Electron Micrographs (SEM) pictures shown in Figure 3 were taken after the development of photoresists AZ ECI 3007, AZ 4533 and AZ 9260. All the results discussed in this document were obtained using



AZ ECI 3007 photoresist, Hg vs UV-LED lamp. SEM images reproduced courtesy of EPFL/CMi, Switzerland.



AZ 4533 photoresist, Hg vs UV-LED lamp. SEM images reproduced courtesy of KIT/IMT, Germany.



AZ 9260 photoresist, Hg vs UV-LED lamp. SEM images reproduced courtesy of EPFL/CMi, Switzerland.

Figure 3: *Scanning Electron Microscope (SEM) micrographs comparing photolithography exposure of different resists exposed to (left) conventional Hg-vapor lamp vs. (right) our UV-LED-EXP equipment.*

[3] AZ® products are specialty chemicals commercialized by the Merck Group.

[4] A *UV-LED-EXP* system can be made available to customers who wish to carry out their own evaluation tests.

365 nm wavelength UV-LEDs whose spectral distribution is shown in Figure 4. Exposures were completed using our *UV-EXP150S* model.[5] Facing each other, it can be clearly seen that the results obtained with the high-power *UV-LED-EXP* system are substantially identical to those obtained with conventional Hg lamp systems. To complete these exposure tests, a few exposure parameters were tested by our academic partners. These exposure tests were performed in the same manner as when replacing a mercury arc lamp. The ease of use and highly comparable results with respect to Hg illumination systems are the foremost feedback received from the users of our *UV-LED-EXP* systems.

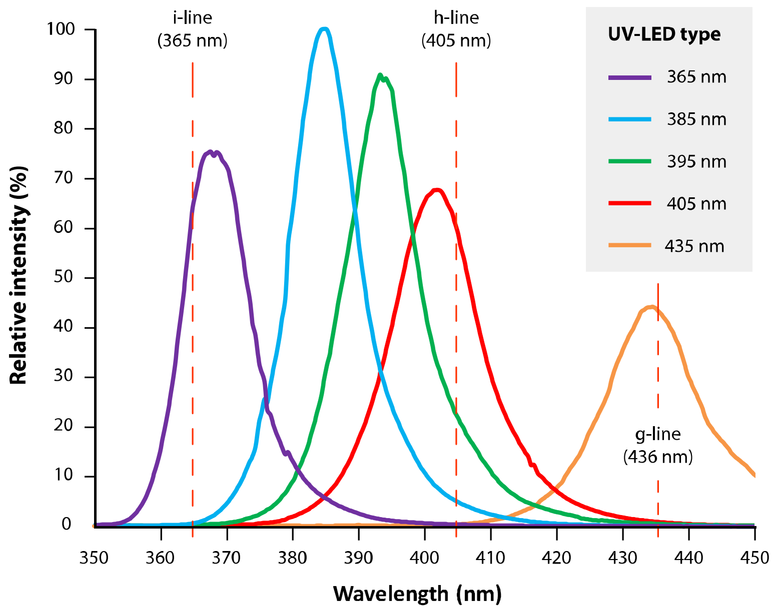


Figure 4: *Spectral distributions of the UV-LEDs integrated into our UV-LED-EXP products. The i-, h- and g-lines typical of Hg light are included for comparison purpose.*

♦ *Note about photoresists* – The AZ ECI 3000 photoresist series is a family of fast positive photoresists suited for i-line (365 nm) as well as broadband exposure covering g- (436 nm), h- (405 nm) and i-line illumination wavelengths. AZ 4500 series of positive photoresists is intended for applications where coating thicknesses above 3 µm are required. AZ 9200 series of thick film photoresists is designed for the more demanding higher-resolution thick resist requirements. It should be noted that photoresist suppliers often refer to the peak spectral g-, h- and i-lines that are characteristic of Hg lamps (see Figure 1). We draw the reader's attention to the fact that photoresists are likely to be well suited for these characteristic wavelengths – more particularly the i-line – but this doesn't mean that they have been specifically optimized for these peaks.

Customized UV-LED photolithography equipment

The customization of Idonus' *UV-LED-EXP* system can take many forms depending on client's needs. There are mainly three possible scenarios that can be considered:

- Idonus can simply act as an **OEM supplier** – clients integrate our *UV-LED-EXP* standard products into their own equipment and benefit from the technical support of our engineering team;
- Idonus can perform the **retrofitting** of old mercury-based equipment;
- Idonus can be fully involved as a manufacturer of **special machines** – custom-made exposure equipment can be entirely developed by Idonus from client's specifications.

The main difference lies in the apportionment of engineering work between Idonus and its clients. By taking standard products from our catalogue, customers can rely on our technical documentation and engineering support to integrate the *UV-LED-EXP* systems and control them directly through their own PLC. In this case, our engineering work may be limited to a small design customization. On the other hand, our expertise in the construction of special machines enables us to offer tailor-made equipment, whether manual or semi-automated.

Let's illustrate these different cases taking a photolithographic mask aligner as an example. We consider an old but functional Karl Suss MA 56 mask alignment and exposure system (see Figure 5, left). This robust equipment is aimed for wafers up to 125 mm in diameter (4.9''). Due to its modular construction, the subassemblies are easily accessible and replaceable. What is of interest here is the lamphouse whose constituting elements are shown in Figure 5 (right). The USH-350DS lamp (see Figure 1) is one of the high-pressure mercury arc lamp models compatible with the MA 56. Light is conducted from the Hg lamp via an ellipsoidal mirror and a 45° cold light mirror (dichroic mirror / beam splitter). The latter filters out the undesired long wave radiations produced by the bulb and deflects only the "cold" UV light required for exposure though the wafer exposure system. The lamphouse also contains two pneumatically actuated shutters. One

[5] For the latest technical specifications of our products, please refer to the dedicated documentation available on our website or contact us directly (info@idonus.com).

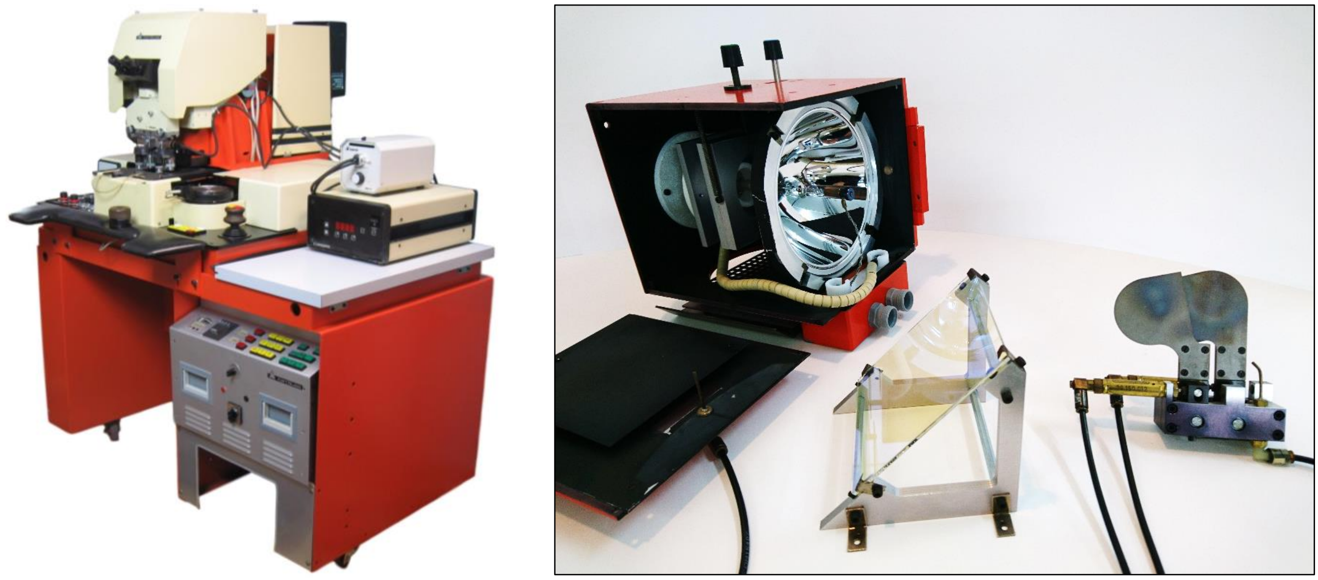


Figure 5: (left) Photograph of a mask aligner Karl Suss MA 56. (right) Hg-vapor lamp of the MA 56. From left to right on this photograph, we show: the mercury lamp with its ellipsoidal mirror; a 45° dichroic mirror; a pneumatically actuated shutter with air jet cooling. During retrofitting, this mercury lamphouse is removed and replaced with our UV-LED light engine shown in Figure 2.

shutter opens to initiate the wafer exposure, while the other shutter closes to complete the exposure. Both shutters then return to their starting positions. This mechanism ensures that the entire wafer receives the same amount of exposure energy. Because the arc lamp must stay continuously ON during operation of the mask aligner, air jet cooling must also be provided to the shutters to evacuate heat.

In Figure 7 (top), we show the working principle of the traditional UV photolithography exposure system described above. As illustrated in this schematic, the bulb is not an ideal point source. To achieve high illumination homogeneity, a beam homogenizer (also known as Köhler integrator) is thus added in the optical path, at the output of the lamphouse. We show in Figure 7 (center) how retrofitting can be completed using our compact UV-LED lighting module shown in Figure 2. To do so, we take advantage of the existing optics and only replace the mercury lamphouse. Tests completed on an MA 56M with our UV-LED lighting module showed that it produces a highly homogeneous illumination and can thus straightforwardly replace the original Hg lamp. It is noteworthy that alignment and exposure systems are decoupled: alignment is performed using the existing mechanics, while exposure is simply completed using our user-friendly control unit. Finally, if we exclude the 45° mirror located between the front lens and the condenser lens, we can clearly see that the upgraded illumination system is comparable to the one found in our standard *UV-LED-EXP* systems, as shown in Figure 7 (bottom).

To illustrate how our *UV-LED-EXP* product can be integrated into a customized equipment, we take the example of a photolithographic exposure bench for R&D. Typical client's specifications can be formulated as follows:

- UV lithography using photoresists optimized for i-line (365 nm) exposure;
- Single-side exposure for 4'' wafers (Ø 102 mm) and 5'' masks (127 mm × 127 mm);
- Equipment to be used by an R&D team in a cleanroom environment (laboratory or industrial use);
- Exposures performed on a daily basis but only intermittently.

A more detailed requirement specification is of course necessary to establish the complete equipment specifications, but the proposed technical solution shown in Figure 6 is applicable independently of these figures. Here, a wafer chuck system with a high-power UV-LED light source is the combination best suited to

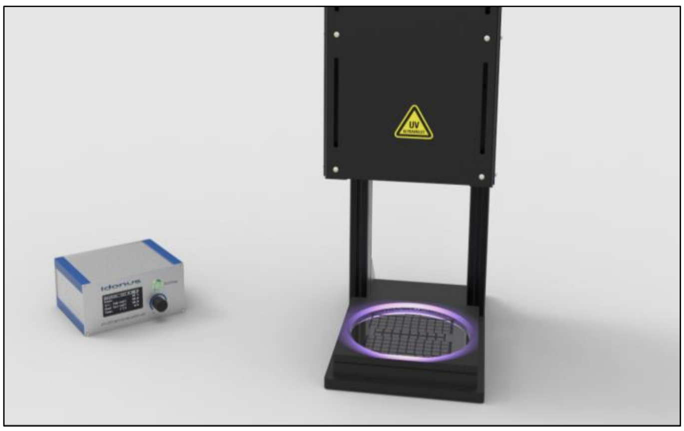


Figure 6: Example of a customized system where the UV-LED-EXP100 system is combined with a wafer and mask system. This 3D rendering was made from CAD models of our products.

meet the customer's needs. The suggested design consists of the following constitutive elements:

- UV illumination using our standard model *UV-LED-EXP100* with its controller box and irradiance meter
  - 100 mm × 100 mm useable exposure area;
  - 365 nm UV-LED type;
  - Adjustable optical power, max. 50 mW/cm^2 (flux density at wafer surface);
  - Collimation angle <2°;
  - Non-uniformity[6] below ±3%.
- Wafer chuck with vacuum clamping (vacuum pump included).

With this example, emphasis was made on the exposure system itself. More sophisticated solutions can of course be imagined. Larger exposure areas are also possible: in standard, we propose *UV-LED-EXP* for up to 300 × 300 mm^2 exposure area. Finally, other wavelengths (including VIS and IR) are also possible.

Conclusion

High-power UV-LED is the new generation exposure source for photolithography. Idonus provides a range of solutions to integrate its *UV-LED-EXP* systems into future equipment or for the retrofitting of mercury-based equipment. Our systems are already installed worldwide in industrial equipment. The roll-to-roll machine shown on the back cover of this document is one such example.

Acknowledgment

The SEM micrographs presented in this document were reproduced with the kind authorizations of their authors. We are thankful to the KIT/IMT (Institut für Mikrostrukturtechnik, Karlsruher Institut für Technologie) and to the EPFL/CMi (Center of Micronanotechnology, Ecole Polytechnique Fédérale de Lausanne).

References

[1] C.-O. Gensch *et al.*, "Assistance to the Commission on Technological Socio-Economic and Cost-Benefit Assessment Related to Exemptions from the Substance Restrictions in Electrical and Electronic Equipment," 7 June 2016.

[2] P. Mathur, K. Mathur et S. Mathur, "Incandescent light bulb, compact fluorescent lamp, and sodium and mercury vapor lamps," *Developments and Changes in Science Based Technologies*, Partridge India, 2014, pp. 24-25.

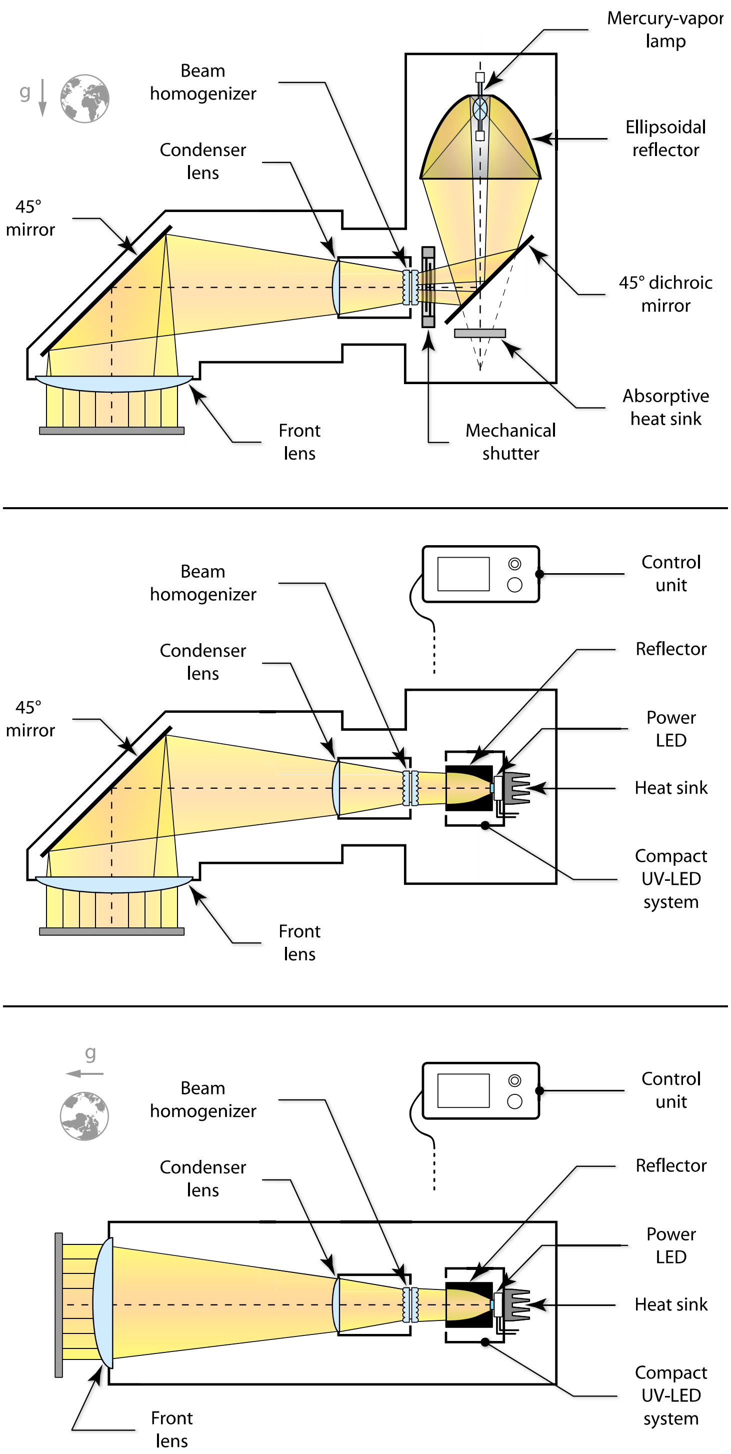
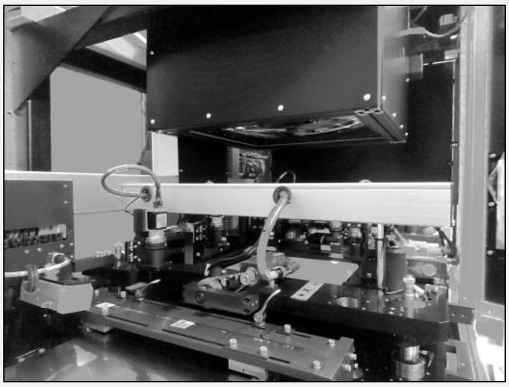


Figure 7: *UV photolithography systems.*

(top) Conventional mask exposure with mercury arc lamp illumination; (center) Revamped mask aligner with a compact UV-LED illumination system and its control unit; (bottom) Main building blocks of Idonus' standard UV-LED-EXP equipment.

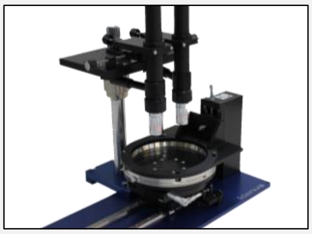
[6] In photolithography, for practical reasons, illumination uniformity is typically measured by local sampling (*e.g.*, with 3×3 = 9 samples). A contrast (or Michelson contrast), *C*, is calculated from the Min. and Max. irradiance measurements: $C = (\text{Max} - \text{Min}) / (\text{Max} + \text{Min})$. Here, we define the non-uniformity as $\pm C$.

Creative engineering and manufacturing • Our engineering team is accustomed to developing products according to client's needs. In-house machining and assembling facilities shorten the time from concept to finished products.

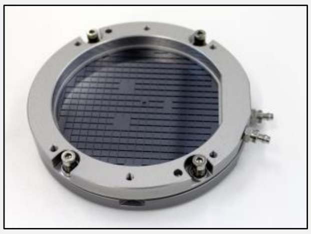


Customized UV-LED exposure system installed on a roll-to-roll machine

Visit our website to have an insight into our other products and activities. Contact us for further technical information and to obtain a quotation.



Double image microscope



A model of wafer chuck

About Idonus

Founded in 2004, Idonus is a Swiss company that develops and manufactures special equipment for the MEMS and watchmaking industries. Our product portfolio includes UV-LED exposure systems for photolithography, IR microscope for wafer inspection, vapor phase chemical etcher for silicon-based devices. Since 2016, we also provide ion implantation services and machines for the surface treatment of materials.

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