High-Power 365 nm UV LED Mercury Arc Lamp Replacement for Photochemistry and Chemical Photolithography

K. Hölz, † J. Lietard, † and M. M. Somoza*

Institute of Inorganic Chemistry, Faculty of Chemistry, University of Vienna, Althanstraße 14 (UZA II), A-1090 Vienna, Austria

ABSTRACT: Ultraviolet light emitting diodes (UV LEDs) have become widespread in chemical research as highly efficient light sources for photochemistry and photopolymerization. However, in more complex experimental setups requiring highly concentrated light and highly spatially resolved patterning of the light, high-pressure mercury arc lamps are still widely used because they emit intense UV light from a compact arc volume that can be efficiently coupled into optical systems. Advances in the deposition and p-type doping of gallium nitride have recently permitted the manufacture of UV LEDs capable of replacing mercury arc lamps in these applications. These UV LEDs exceed the spectral radiance of mercury lamps even at the intense I-line at 365 nm. Here we present the successful exchange of a high-pressure mercury arc lamp for a new generation UV LED as a light source in photolithographic chemistry and its use in the fabrication of high-density DNA microarrays. We show that the improved light radiance and efficiency of these LEDs offer substantial practical, economic and ecological advantages, including faster synthesis, lower hardware costs, very long lifetime, an >85-fold reduction in electricity consumption and the elimination of mercury waste and contamination.

KEYWORDS: Green photochemistry, Ultraviolet light emitting diode, Energy efficiency, Biopolymer microarray synthesis, Spatial patterning

INTRODUCTION

Light is a highly versatile energy source for triggering and controlling chemical reactions.¹ Unlike conventional reagents, light can be conveniently generated during use and leaves behind only the completed photochemical reaction.² An important additional benefit is the possibility to use light to direct reactions with both high temporal and spatial accuracy. Spatial patterning of light can be obtained using an optical imaging system and is the basis for photolithography. Photolithography, usually by means of light-directed polymer chemistry, includes not only the synthesis of integrated electronic circuits and most printed materials but also many more specialized chemical applications, such as three-dimensional fabrication and printing,³,⁴ surface functionalization,⁵ and the synthesis of biopolymer microarrays.⁶⁻¹² The primary drawback to photochemistry has been the inability of most molecules to absorb visible light efficiently, requiring specialized sources to generate the necessary ultraviolet radiation. This concern has driven significant interest in solar and visible light photochemistry, as a more continent and sustainable source of light for organic transformations.¹³⁻¹⁶ Daylight itself, however, is complex to control accurately and reliably in most industrial or research settings. Artificial sources of white light are very inefficient, particularly because, in almost all cases, only certain wavelength ranges are relevant. Furthermore, because most sources, such as low pressure mercury, incandescent, and excimer lamps, emit from extended surfaces or volumes, the light cannot be efficiently collected and directed to a reaction site. Recent advances in the manufacture of ultraviolet light emitting diodes (UV LEDs) allow very energy efficient, reliable, and simple generation of the near UV light, which is most suitable for photochemistry and chemical photolithography. These LEDs are simple to assemble into useful light sources capable of outperforming traditional sources of high intensity UV light, particularly mercury arc lamps, which are widely used in photochemistry applications. Mercury vapor lamps are quite efficient in converting electricity to light and have found widespread use. For many scientific and technical applications, the ultraviolet component of high-pressure mercury lamps makes them particularly useful because few other light sources efficiently generate such large amounts of UV light. Another major advantage of high pressure mercury arc lamps is that the light is generated in the small arc volume between anode and cathode. The small source size is important in any application where an optical system is used to transfer the light to a target. The optical principle of geometrical extent, or étendue, dictates that efficient light power transmission requires a small source.¹⁷ Because of these two key advantages, efficient UV generation and small source size, high pressure mercury arc lamps have been essential tools in all areas of photochemistry and chemical photolithography for many decades. Nevertheless, these light sources have a significant drawback. Mercury is acutely toxic and is a major persistent environmental pollutant.¹⁸,¹⁹ The high pressure arc lamps of the sizes typically used in laboratories...
contain hundreds of milligrams of mercury, necessitating careful storage, handling and disposal.\textsuperscript{20} The lamps also have short lifetimes, usually in the range of 500 to 1000 h, requiring frequent and costly replacement. The short lifetime is exacerbated by their inability to withstand multiple on–off cycles, so that in many applications they must be operated continuously throughout their lifetimes.\textsuperscript{20} Also, because many applications make use of a single spectral line, often the very intense I-line at 365 nm, the majority of the light output must be filtered out, resulting in very poor overall energy efficiency.

Recent advances in the manufacture of gallium nitride-based LEDs with indium gallium nitride (In\textsubscript{GaN}) quantum wells have provided very efficient solid-state sources of blue light.\textsuperscript{21} These sources, in conjunction with phosphors to generate additional colors, are rapidly replacing incandescent and low pressure fluorescent mercury lamps in general ambient lighting.\textsuperscript{22,23} The same technology can be used to generate near UV light very efficiently (external quantum efficiency: \textsim\textasciitilde 50\%) at the same wavelength as the very strong mercury I-line at 365 nm.\textsuperscript{24,25} In addition to high quantum efficiency, these LEDs have very long lifetimes and can be switched on and off as needed, which further enhances their overall energy efficiency and practical lifetime.

Only in the past year have surface-mount UV LEDs that can compete very favorably with mercury arc sources become available. Here we describe a simple high power 365 nm UV LED source that significantly outperforms mercury arc sources in applications in photochemistry and chemical photolithography. Specifically, we have constructed and evaluated such an LED source for maskless array synthesis (MAS), a chemical photolithographic application that uses an optical imaging system centered around a digital micromirror device (DMD) to direct the chemical synthesis of complex microarrays of photolabile protecting groups.\textsuperscript{8} These LEDs have very long lifetimes and can be switched on and off as needed, which further enhances their overall energy efficiency and practical lifetime.

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\section*{Experimental Section}

\textbf{UV LED Source Construction.} The source consists primarily of a single Nichia NVSU333A U365 surface-mount LED,\textsuperscript{31} a heat-spreading copper block with embedded anode and cathode terminals, a CPU heat sink and fan, and an aspheric condenser lens (Figure 1). Only LEDs from the P15d21 radiant flux ranks (3760 to 4100 mW) were available; the Nichia manufacturing process also yields 365 nm LEDs in radiant flux ranks up to P16d22 (4870 to 5310 mW), but the higher power rank LEDs could not be obtained. The LEDs have a rank-dependent, typical conversion efficiency of \textsim\textasciitilde 27\% when operated with a forward current of 3.5 A and well cooled. At a forward voltage of 3.85 V, this corresponds to a thermal dissipation of 11 W. Because the mass of the LED is only \textsim\textasciitilde 0.25 g, a very efficient thermal dissipative path is required, particularly because both the radiant flux and lifespan of LEDs are inversely related to the temperature of the emitting semiconductor die. A 40 \texttimes\texttimes\texttimes 6 mm copper block was used to transfer heat away from the LED. The copper block includes two slots fitted with copper anode and cathode terminals. Each terminal was electrically isolated from the block with high-temperature epoxy (Aremco-Bond 526-N). After epoxy curing, the front face of the copper block was sanded to a smooth and flat finish in preparation for soldering.

The back sides of the LEDs have a large central die heat-sink pad flanked by the anode and cathode pads. Each of these was soldered to the copper block and terminals, respectively, using the recommended soldering pad pattern. The soldering pad pattern was cut into \textsim\textasciitilde 50 \mu m thick packing tape, which was then adhered to the copper block and terminals. The solder paste (EDSYN SR11 Sn42-Bi58 low-temperature solder alloy) was spread over the tape solder stencil using a razor blade. After the stencil was peeled off, the three LED pads were carefully aligned with the appropriate solder pads. The copper block was then placed on a laboratory heat plate, set to \textasciitilde 180 \degree C, until the solder melted (138 \degree C). After it was checked that the heat sink and terminals remained electrically isolated from each other, the copper block was removed from the heat plate to cool slowly to room temperature. The copper block was then thermally coupled to a CPU heat sink (Arctic Copper Silent 3 AMD CPU cooler) using a thin layer of thermal grease (Shin-Etsu X-23-7921-5), and then fastened with four screws. Light from the emitting surface was focused using a 10 mm diameter 6.6 mm FL aspheric condenser lens (Edmund Optics 888-283). Four screws on the lens holder allow accurate positioning of the lens relative to the LED.

\textbf{LED Power Supply and Control.} Because current flow through LEDs increases exponentially with voltage, constant-current supplies are used to accurately control light output. In addition to a power supply, a trigger circuit is necessary to turn the current on or off under computer control. Figure 2A shows a schematic for the LED control electronics. An adjustable power supply in constant current mode (B&K Precision 1687B) provides an adjustable regulated current for the LED. Computer switching control is enabled by a low on-resistance \textit{n}-type power MOSFET (IR AUIRF88409) in parallel with the UV LED. A 5 V trigger signal, electrically isolated from the power circuit via an optocoupler, disables current flow through the MOSFET, turning on the LED. In the absence of the trigger signal, resistance between the MOSFET drain and source terminals is close to zero, forcing the constant-current source to reduce its output voltage to close to zero and hence eliminating any current flow through the LED, which has a conduction threshold of \textsim\textasciitilde 3 V. Interrupting the current through the LED with a shunt circuit is advantageous because it forces the constant-current supply to reduce its output voltage, which in turn...
Figure 2. (A) Power and control circuit for the Nichia NVSU333A U365 LED. An adjustable current source powers the LED. The LED is turned on or off via an n-type MOSFET shunt triggered by a 5 V logic signal. Oscilloscope traces for trigger on (B) and trigger off (C) (blue) show that the circuit behavior is optimal, with a 30 ms soft-start output voltage to the LED (red) and an instant turn off (10 ms per div. horizontal and 50 and 800 mV per div. vertical for blue and red channels, respectively).

prevents damage to the LED from a current spike each time the LED is turned back on. The electrical characteristics of the circuits were measured using a Rigol DS1054 oscilloscope. The power supply output response is shown in Figure 2B,C. With this circuit, the time to reach full power depends on the response time of the current source; in this case about 30 ms, whereas the turn-off time is close to instantaneous due to the fast (~30 ns) response time of the MOSFET.

Intensity and Stability Measurements. LED intensity stability was measured using (1) passive cooling (heat sink fan off), (2) fan cooling (heat sink fan on), and (3) regulated active cooling using a Peltier thermoelectric device between the copper heat sink and the CPU cooler. For the thermoelectric cooling, the hot and cold sides of a Peltier device (European Thermodynamics APH-161-12-14-E) were connected to the CPU cooler. For the thermoelectric cooling, the hot and cold sides of a Peltier device (European Thermodynamics APH-161-12-14-E) were connected to the CPU cooler.

Microarray Synthesis and Hybridization. Microarrays were synthesized using a chemical photolithographic method termed Maskless Array Synthesis (MAS).15,26 MAS uses a computer controlled optical imaging system, synchronized with a chemical delivery system, to direct the stepwise synthesis of complex, high-density microarrays of nucleic acid oligomers on glass substrates. A UV light source and associated condenser lens(es) fill the entrance to a light pipe, which spatially shapes and homogenizes the intensity of the light beam via multiple reflections on the first surface aluminum mirrors that constitute the inner surface of the light pipe.22 The output of the light homogenizer functions as a rectangular, highly spatially homogeneous source for illuminating, via a 2X magnification telescope, a 0.7” (diagonal) digital micromirror device (DMD). The DMD is imaged, via 1:1 Offner relay optics, to the surface of the substrate in the reaction chamber22 where the microarray synthesis is taking place. One of two tilt positions of each of the mirrors of the DMD, either ON or OFF, determines whether photodeprotection will take place at each microarray position. The low numerical aperture of the system, combined with the large number of reflections needed to form a highly homogeneous beam of light, as well as to modulate it spatially and direct it to the target, results in very low system light throughput. The optimum source has previously been a 350 W Hg arc lamp, which has an effective plasma size (0.8 × 2.7 mm) that is a reasonably good match to the entrance optics. Higher power lamps have larger plasma dimensions which would overfill the entrance pupil and not result in the collection of significantly more light. The mercury lamp source is a 350 W high pressure short arc mercury lamp (Newport 6286) in an F/0.7 500 W housing (Newport 66905). The light from the lamp was filtered using two 350–450 nm primary-range dichroic mirrors (Newport). Ozone generated in the lamp housing was catalytically converted to O2 using an Ozone Eater (Newport 66087). For both the mercury lamp and the UV LED, the radiant intensity of light reaching the reaction cell was measured using a calibrated SÜSS MicroTec Model 1001 UV intensity meter with a 365 nm probe.

Microarray synthesis chemistry is quite similar to the standard phosphoramidite chemistry used in solid phase synthesis.34 The primary modification is the use of a (2-(2-nitrophenyl)propoxy)carboxyl (NPPOC) photolabile protecting group in the place of the acid labile dimethoxytrityl (DMT) group. During photodeprotection, the reaction chamber is filled with a solution of 1% imidazole in DMSO, as the photoinduced β-elimination pathway of the NPPOC group is favored by the presence of a small amount of an amine base.35 The substitution of light for the acid deblocking step greatly reduces the requirement for oxidizing the phosphite triester resulting from the coupling reaction, which is unstable under acidic conditions, to the fully stable phosphophotriester.34 Thus, photolithographic microarray synthesis, in comparison with normal solid-phase synthesis, eliminates the health and environmental toxicity associated with the use of the deblock solution (di- or trichloroacetic acid in dichloromethane), and greatly reduces the use of tetrahydrofuran, as well as pyridine, a “red category” solvent that is an essential component of the oxidizer solution.

To test the light exposure needed to remove the NPPOC or SPB-NPPOC 5′-hydroxyl protecting groups on the growing oligonucleotide, and to verify that the exposure and synthesis outcome using the UV LED source are the same as with a Hg source, microarrays bearing a single oligonucleotide sequence (5′-GTC ATC ATG AAC CAC CCT GGT C) were synthesized, but photodeprotection was carried out using a spatial gradient of light exposures.29,36 After synthesis, the protecting groups on the DNA oligonucleotides were removed using a solution of 1:1 (v/v) ethylenediamine/ethanol for 2 h at room temperature. After the deprotection solution was washed off with deionized water, the exposure gradient microarrays were hybridized for 2 h at 42 °C with the Cy3-labeled complementary sequence and then washed. The hybridization buffer consisted of 150 μL of 2X 2-(N-morpholino)ethanesulfonic acid (MES), 110 μL of nuclease free water, 13.3 μL of acetylated bovine serum albumin (BSA), and 26.7 μL of 100 nM 5′-Cy3-labeled complementary oligonucleotide. The washing steps start with vigorous shaking in a 50 mL centrifuge tube filled with 30 mL nonstringent wash buffer (SSPE; 0.9 M NaCl, 0.06 M phosphate, 6 mM EDTA, 0.01% Tween 20) for 2 min, followed by a stringent wash (100 mM MES, 0.1 M NaCl, 0.01% Tween 20) for 1 min, and a quick dip in final wash buffer (0.1X saline–sodium citrate buffer) to remove excess salt. The arrays were imaged in a microarray scanner at a resolution of 5 μm using the 532 nm laser and the 550–600 nm bandpass filter. Data was extracted from the scan image using NimbleScan v2.1. Data was normalized and fit with the four parameter sigmoidal function in SigmaPlot.

RESULTS AND DISCUSSION

UV LEDs with useful outputs have been available for several years and have been used in photolithography37,38 and photochemistry, primarily as arrays of LEDs to expose and cure inks, adhesives, and coatings. In chemistry research, they have been used in recent years primarily for photopolymerization and photocatalysis.39–43 However, in all of these applications the UV-LED output was directed onto the reaction site without the use of an optical system. For chemical
photolithography, such as surface functionalization patterning and microarrays synthesis, the optical requirements are often very strict in order to achieve spatial control with lateral resolution of a few micrometers over surface areas of a few square centimeters. For these applications, a very large percentage of the emitted light cannot be coupled into the optical system and/or is lost in the optical system. We have found that with the current generation of 365 nm UV-LEDs, these losses are significantly lower than with mercury arc sources, which, combined with the very high radiance from the LED, results in improved light throughput, far lower electricity and resource consumption.

**UV LED Output, Stability, and Lifetime.** The 365 nm output of the Nichia NVSU333A U365 surface mount LED is significantly lower than that of a high-pressure Hg lamp, ~4 vs ~20 W. Nevertheless, in most applications in photochemistry and chemical photolithography, the relevant metric is the amount of light that can be collected and directed to the reaction chamber where the chemistry is being performed. This metric greatly favors the LED because the light emission from the LED surface follows a Lambertian pattern, \(I(\theta) = I_0 \cos(\theta)\), where \(I_0\) is the intensity normal to the surface, and because the emitting surface is small and geometrically simple. This is a distinct advantage over arc sources, which emit almost isotropically and from an irregularly shaped plasma, and therefore make light collection complex and inefficient. In addition, the size of the quartz envelope and the high heat output of the plasma require much larger lenses placed more distally in the case of arc sources. Efficient LED light collection can make use of either reflective or refractive optics or a combination of both, and may be nonimaging.44,45 In the case of the Nichia NVSU333A LEDs and our application in chemical photolithography, a single 10 mm diameter, 6.6 mm FL aspheric condenser lens appears to be an inexpensive, near optimal solution. The small focal length and high NA of aspheric condenser lenses allows them to be placed a few millimeters from the emitting surface in order to collect and collimate more light. With a back focal length of 3.3 mm, approximately 75% of the light emitted by the LED is collected by the lens. Because the LED is not a point source, but has an emitting surface with dimensions of 2 × 2 mm, the light is not fully collimated by the lens; instead, the light exiting the lens has an angular divergence of about 5°, similar to the light acceptance angle determined by the 0.08 NA of the imaging optics of our photolithographic system. Such a low NA is necessary to reach a sufficient depth-of-focus (DOF ∝ λ/NA²; ~60 μm), to achieve a sufficient lateral resolution (\(r ∝ λ/2NA; ~2.7 \mu m\)) and to reduce synthesis errors due to scattered light, which scales ∝ NA⁴.46 In this context, more than 140 mW of 365 nm light (100 mW/cm² over an area of 1.4 cm²), about 3% of the output of UV LED source, could be transmitted to the target at a forward current of 3.9 A. This amount is greater than the typical amount of 365 nm light available from the arc lamp in the same imaging system. The LEDs are rated for forward currents up to 4.5 A, so a small amount of additional output is available, which may eventually be used to compensate for LED aging.

Sensitive photochemistry experiments, as well as chemical photolithography synthesis, require light sources with stable outputs over many hours. Mercury arc sources are fairly satisfactory in this regard, although the light output decreases steadily as the plasma erodes the anode and cathode. The erosion degrades the efficiency and stability of the plasma and deposits tungsten on the quartz envelope. In our experience and usage pattern with short arc Hg lamps, the light output drops by ~1% per day. LEDs have far greater expected lifetimes, particularly because the LEDs can be turned on and off as needed. However, because their output is temperature sensitive and they have very low thermal mass, their output can fall quickly if they are inadequately cooled. To test the effectiveness of our cooling system (Figure 1), we measured the output intensity for three different cooling methods: (1) passive cooling (fan off), (2) fan on, and (3) regulated active cooling using a Peltier thermoelectric device between the copper heat sink and the CPU cooler.

To simulate our normal use, the LED was run with a current of 3.9 A and was switched on and off at 1 min intervals. The results are shown in Figure 3. With passive cooling, there is a ~2% drop in output during each on cycle as well as a steady downward drift in the output due to a gradual warming of the heat sink. With active fan cooling, the output drops by about 1% during each on cycle and the longer-term drift disappears. With Peltier cooling, a somewhat higher light output can be achieved without output drop. Oscillations in the output during the Peltier experiments are due to unstable temperature control and could be minimized with a more complex control feedback loop, such as proportional-integral-derivative (PID) controller. Because our application is not sensitive to the 1% drop in intensity during on cycles, we considered the fan cooling an optimum compromise between stability and the additional complexity inherent in the thermoelectric cooling.

**Photolithographic Microarray Synthesis.** To verify that the chemical photodeprotection afforded by the UV LED is equivalent to that provided by the mercury arc source, we synthesized microarrays using a spatial light exposure gradient on the synthesis surface. With this microarray design, which we use to calibrate optimum light exposure, e.g., when testing new photolabile group chemistry, only a single DNA sequence (GTC ATC ATC ATG AAC CAC CCT GGT C) is synthesized everywhere on the surface, but using a range of exposures from 0 to 10 J/cm². At low light exposure, microarray oligonucleotides have a large number of deletion errors and hybridize poorly with fluorescently labeled complementary oligonucleotides. As the exposure increases, the number of deletion errors drops until an optimum radiant exposure is
reached. Beyond this optimum, the synthesis time increases due to the longer exposures but the hybridization signal intensity does not increase significantly, and in the case of highly complex microarrays (e.g., gene expression microarrays), synthesis errors increase due to the increase in scattered light. For microarray synthesis with phosphoramidites bearing the 2-(2-nitrophenyl)propanoylcarbonyl (NPPOC) photobleachable group, we consider 6 J/cm² as the optimum for typical hybridization-based DNA microarray applications. For synthesis with thiophenyl-2-(2-nitrophenyl)propoxycarbonyl (SPh-NPPOC), the optimum is 12 times less, 0.5 J/cm². The results for the comparison between the two light sources are shown in Figure 4 and demonstrate that there are no synthesis differences between the sources.

Figure 4. Hybridization intensities for microarrays of a DNA 25-mer synthesized with a 356 nm UV-LED exposure gradient using NPPOC (black circle) or SPh-NPPOC (red triangles) DNA phosphoramidites. Radiant exposure values for SPh-NPPOC are multiplied by 12.0, respectively, with original data position indicated by the red dashed line. The solid blue line is a fit for the equivalent data obtained using the 350 to 450 nm output of an Hg arc lamp.

**Lifetime and Electricity Consumption.** LED lifetime was estimated based on 7 months of daily use in the photolithographic synthesis of microarrays. During this time, 140 microarray syntheses were performed, with typical cumulative UV exposures of ~100 min per microarray using an LED current of 3.8 to 3.9 A. Syntheses with NPPOC phosphoramidites require a photodeprotection radiant exposure of ~6 J/cm², which is achieved in 1 min with a radiant power of 100 mW/cm². This power could be achieved using the LED source, even after 7 months of use, with an LED current of 3.8 to 3.9 A. Photodeprotection in microarray synthesis was performed by switching on the LED only during the 1 min exposure. The remaining chemical steps in each synthesis cycle require approximately one additional minute, during which the LED and heat sink can cool down. This on-off cycle length was used to estimate the electricity consumption of the LED system. For this purpose, the electrical power consumption of the system (LED, power supply and cooling fan) was measured, using an Arendel power meter, in both the LED on (40 W) and LED off (20 W) states and consumption was calculated based on typical use patterns, including turning the system fully off between synthesis. Similar measurements were used to calculate the equivalent consumption using a 350 W Hg arc lamp. In this case, the calculations were based on running the lamp at 380 W during the entire synthesis time (system power consumption = 480 W) and at an “idle” lamp power of 200 W between syntheses (system power consumption = 270 W). The electrical consumption included the arc lamp power supply, lamp cooling fan, and the fan of the ozone eater. Room cooling was not included in the calculations but could be expected to add ~20% to electricity use.

The nominal lifetime of the Newport Hg lamp is 1000 h. In our usage pattern, in which the lamp is run at an average power of 380 W during synthesis and 200 W at all other times, we have achieved an average life of ~1400 h. Our end-of-life criterion was that the lamp was unable to supply more than 60 mW/cm² (0.084 W total power) of 365 nm light to the synthesis plane at an operating power of 399 W. An attempt to extend effective Hg lamp life by turning it off between syntheses resulted in a high probability of lamp explosion, which resulted in significant damage to the optics in the lamp housing in addition to mercury contamination. The lifetime of the LED source is too long to be accurately measurable at this point. Nichia estimates a 10% output drop after 2000 h, even when the LEDs are operated with a current of 4.5 A, and a lifetime (30% output drop) of 15 000 h when operated at a junction temperature of 70 °C. With our fan-cooled heat sink, the estimated junction temperature is under 70 °C at an operating current of 4 A; with the Peltier cooling, the junction temperature could be lowered to under 40 °C at 4 A, corresponding to a theoretical lifetime of >20 000 h.

**Consumption and Cost.** Both the initial investment and the running costs are important considerations in equipment choice. Consumable costs are based on the running schedule above and include only the Hg arc lamp itself or the UV LED. The initial costs to purchase the light sources and necessary associated power supplies and components are based on the 2016 prices of the equipment described herein (sources, housing, power supplies, optics) and are summarized in Table 1. In the case of the UV LED, a two year lifetime is assumed primarily because improvements in the manufacturing process may favor replacing the current UV LED with a more efficient version. Nevertheless, if the lifetime estimates by Nichia are correct, our usage pattern would result in a lifetime approaching 40 years or 10 000 microarrays.

| Table 1. Electricity Consumption, Initial Cost and Consumables Cost Comparison between Mercury Arc and LED Sources |
|-----------------|-----------------|-----------------|
| source          | electricity<sup>a</sup> (kW/h/year) | initial cost<sup>b</sup> (€) | consumables<sup>c</sup> (€/year) |
| Hg arc          | 2600            | 12000           | 2400            |
| UV LED          | 30              | 1500            | 50              |
|<sup>a</sup> Assumptions: arc lamp at full power (380 W) for 20 h/week and at idle power (200 W) 148 h/week; LED at 3.8 A (50% duty cycle for 20 h/week) and fully off 148 h/week. |
|<sup>b</sup> Estimated 2016 hardware costs. |
|<sup>c</sup> Six replacement arc lamps/year or one LED every second year. |

**CONCLUSIONS**

Ultraviolet LED sources, not only in the near UV region at 365 nm but also up to 400 nm and in the blue and violet regions of the visible spectrum, are now superior to high pressure mercury arc lamps in terms of their ability to deliver highly concentrated light via optical imaging systems. For photochemical applications, UV LEDs now offer higher near-UV intensities at the reaction site as well as far lower setup and operating costs while avoiding the use of mercury and greatly reducing electricity consumption.
Research Article

ACCOUNTING

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