UV LEDs

Fundamentals on the technology and on its use for UV LED applications

Content:

1 Introduction

The use of UV radiation for the curing of inks and lacquers has been established in the market for many years. The radiation sources that are most frequently used for this purpose are UV medium-pressure lamps. Their emitted radiation spectrum can be adapted by doping to the photo initiators of the inks and lacquers used. However, it is the infrared range (IR) that accounts for the largest proportion of the emitted radiation, and therefore, it is not primarily needed for initiating the polymerisation reaction of the UV reactive inks and lacquers. Cold-light mirrors or multilayer-coated glass, so called UV transmitters, can filter out part of the IR radiation.

It is therefore obvious that research regarding alternative radiation sources has been going on for years, aiming, on the one hand, at generating “cold UV light”, and, on the other hand, at providing a radiation source that allows for easy switching on and off without start-up and cooling times that are features of UV medium-pressure lamps. At the same time, this new source must show a good long-term behaviour.
Light-emitting diodes (LEDs) meet these requirements. However, after both the discoveries of the semiconductor effect (pn effect) by Karl Ferdinand Braun in 1876 and the so-called Round effect – the light emission by applying a potential to an inorganic semi-conductive material – by Henry Joseph Round in the year 1907, it took a great deal of research until the first UV LEDs were presented in the 1990s.

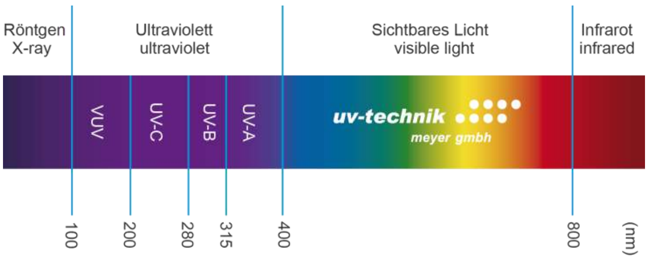


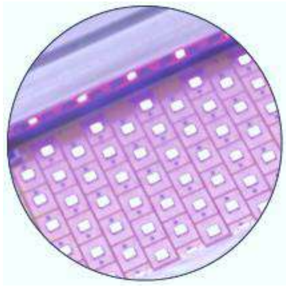
Fig.1:
Part of the electromagnetic spectrum

These explanations are intended to provide the user with the physical background knowledge and to show both the possibilities and limitations of curing using UV LEDs.

2 Typical applications

The limitations due to technical reasons (low total power, no short-wave UV radiation) have resulted in UV LEDs mainly being used in niche applications. These include, for example:

- Ink Jet
- Small-area point-by point curing
- Adhesive cross linking
- Curing of sealing compounds
- Pinning (pre-gelling)
- curing applications (e.g. for personalisation)
- Dental applications
- Fluorescence examinations (e.g. in forensics)
- …



3 Advantages and disadvantages of UV LED systems

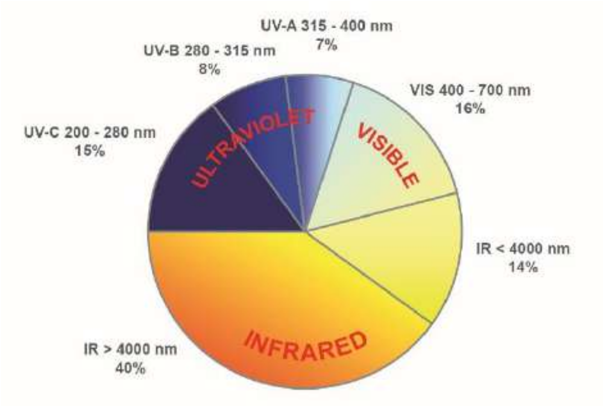


Fig. 2: Power distribution of a standard medium pressure UV lamp (Hg)

It is necessary to weigh the advantages against the disadvantages by comparing a conventional uv curing system which uses an uv medium pressure lamp with an uv LED system. To table mentioned below should give a little help:

Advantages	Disadvantages
Spectrum of the uv radiation	
• Only the specified (usually one) wavelength is emitted towards the substrate. Heat is only a result of the absorption of uv into the substrate or is produced from a chemical reaction because of the curing process.	• A subsequent change of emitted wavelength requirement means in most cases a change of the complete uv LED head. With conventional uv medium pressure systems, only the (relatively low cost) uv lamp has to be changed.
• Some UV LED heads can be equipped with diodes which emit at different “mixed” wavelengths.	• Most of the LED systems have quasi monochromatic radiation. The smaller the wavelength the lower the efficiency is. • Shorter wavelength uv radiation with UV LED is only available with limited power.

Advantages	Disadvantages
Applications and operating	
• No significant start-up time. Compared to conventional medium pressure systems shutters are unnecessary.	• Relatively high initial investment.
• Short switching-on/switching-off times (< 100 ns).	• Limited possible applications.
• Compact UV module designs possible (e.g. for point light sources)	• Specially “tuned” (and therefore sometimes costly) coatings are required
• No IR radiation is the directed at the substrate (positive for heat sensitive products).	• The curing process is initiated only by the quasi-monochromatic LED light. Radiant heat (IR) is not emitted onto the substrate. In some cases some heat is positive for the curing process.
• The irradiation length can be varied (sections can be switched “in” and “out” or “format variable”)	• Relatively low efficiency (up to 35%). Currently lower than medium pressure lamps.
	• Efficiency (especially LEDs with wavelengths < 385 nm).
• No ozone production because only longer wavelengths are produced	• The distance between UV LED and the substrate is more critical than with conventional systems. A UV LED system must be as close as possible to the substrate. This makes larger or 3D applications more complex.
	• UV-LED tuned inks are often reactive to daylight.
• The dimming of UV LEDs is unlimited (UV medium pressure lamps can be dimmed in practice down to around 20%)	• UV LED’s emit divergent UV light. Focusing or “parallel” UV light can only be achieved with systems which have collimator lenses.

Advantages	Disadvantages
Maintenance and cooling	
• Long lifetime (even if it is switched on/off very often or pulsed)	• Easy replacement of single defective chips only possible with few UV LED module designs.
• Cooling is achieved in most cases by an active water cooling system (chiller). No exhaust air pipes etc. are necessary. If cooled water is available at the machine, the conversion to UV LED heads can be possible.	• Active water cooling system (chiller) required when using ultra high power UV LED systems. Conventional medium pressure uv lamp systems usually need low cost air cooling.
• Vibration resistant	• With water cooled UV LED systems, care must be taken to avoid condensation in the head and algae formation in the water system.
• Mercury-free	

4 UV LEDs in practice

4.1 Efficiency of UV LEDs – Generation of radiation

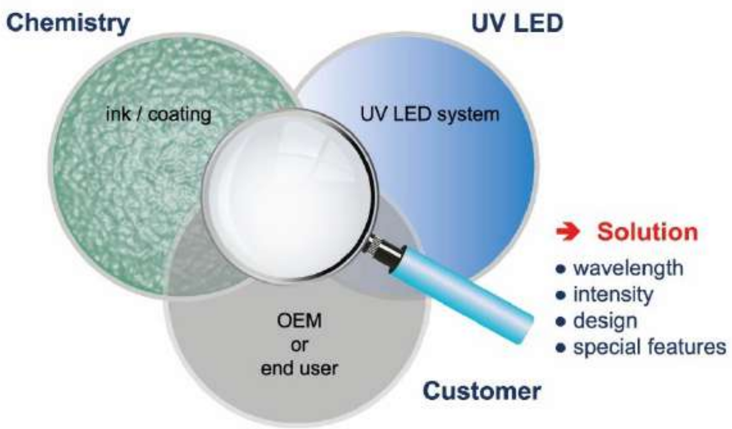


Fig. 3: To find the best solution for the customer the LED supplier, ink supplier and the machine manufacturer must be involved.

Some publications praise the high efficiency of UV LEDs. This may be due to the fact that LEDs are increasingly used for general lighting purposes, and indeed, the efficiency of LEDs in comparison with gas discharge lamps (e.g. high-pressure sodium lamps) has meanwhile become more favourable.

Due to the semiconductor materials used for UV LEDs, such favourable yields can by far not be currently achieved by UV-LEDs. It can be assumed that the efficiency is around 30 to 40% for the common wavelength range between 385 and 395 nm. A value for comparison: a UV medium-pressure lamp emits 15% within the UV-C range and 30% in the full uv range (200…400 nm).

An argument that is often put forward in favour of UV LEDs is cold UV radiation. It is indeed a fact that no IR radiation is emitted in the direction of the substrate to be cured. Nevertheless, the power loss generated in the UV LED (i.e. approx. 30%) must be dissipated, as otherwise it will harm the structure of the semiconductors, thus dramatically decreasing their service life. As high power is generated within a small space (the thickness of the semiconductor layers is in the nanometre range), effective cooling of the chips is necessary. With high-output systems, this is realised by water cooling, which in turn means that a cooling unit must be provided. Some manufacturers' advertising UV LEDs as an environmentally friendly ("green") source of UV radiation can therefore only be interpreted as a marketing campaign.

4.2 Efficiency of UV LEDs - Curing

The efficiency issue can also be looked at from a completely different point of view:
If an UV LED segment is measured using an appropriate spectrometer, it can quickly be established that the irradiance of the wavelength emitted by the UV LED (e.g. 395 nm) for powerful UV LED segments is significantly higher than the irradiance of a UV medium-pressure lamp for the same wavelength. The reason for this is that the UV radiation emitted
by a UV LED is exclusively generated for a single wavelength.

An example of this is shown in Figure 4. The green solid line shows that the 395 nm peak is sligthly higher than the 365 nm peak of a mercury lamp. However LEDs with shorter wavelengths show a lower intensity.
This is the reason why currently, almost exclusively "long-wave" UV LEDs are used in the market. The efficiency of the shorter wavelengths (365 nm or shorter) has not yet reached the level of 395 nm diodes; the irradiance levels that can be achieved are therefore often too low.

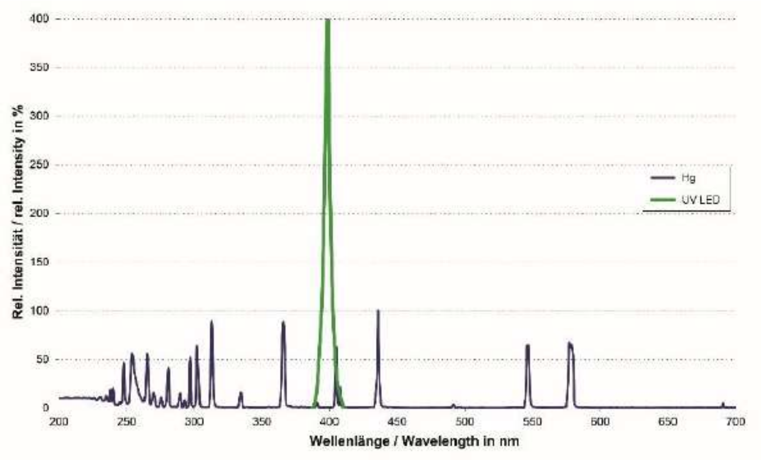


Fig. 4: Comparison of the spectra of a UV medium-pressure lamp and a UV LED.

Although UV LED's have a higher peak at a specific wavelength they have a narrower bandwidth of energy, this is the reason why specially tuned and "sensitised" "long-wave" inks and coatings are commonly used in the market with a higher level of photo initiator ("UV LED inks"). Different photo initiators have a wavelength-specific sensitivity curve. Therefore the photo initiators used must accurately match the radiation source:

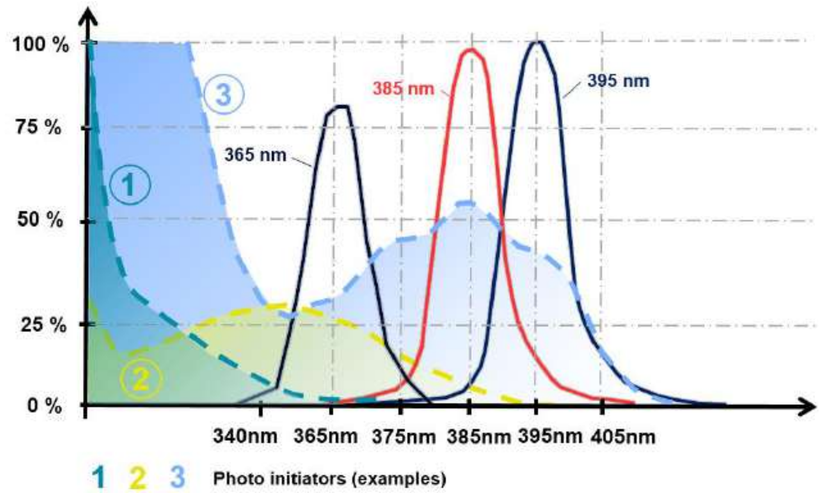


Fig. 5: Three different emitted wavelengths of UV LEDs and their proportional outputs are shown. You can see that sensitivity curves of photo initiator **1** or **2** will not result in a good match. However photo initiator type **3** is compatible with the 385 nm UV LED.

It should be noted here that the photo initiator curves shown above only refer to their own wavelength-dependent sensitivity. In practice, the "reactivity" of an ink with the photo initiators contained therein deviates from this quite often.

4.3 The required irradiance

If UV LEDs are used for curing purposes, ink and UV LED must match each other to achieve a satisfying result. This concerns not only the selection of the virtually monochromatic radiation, i.e. the wavelength of the UV LED, but of course also the irradiance (in W/cm²) and the radiation (dose in J/cm²).

It makes sense that the irradiance value, colloquially often called intensity, refers to the radiation hitting the substrate, i.e. the place where the curing should occur. The irradiance for UV medium-pressure lamp applications is stated in mW/cm².

Due to the high peak for one emitted wavelength, the irradiance of UV LEDs is indicated in W/cm². It is difficult for the user to find out how "powerful" a UV LED module really is, as this basically depends on the distance. Manufacturers' specifications mostly refer to the exit surface or to calculated values with reference to the chip surface. Figure 6 is intended to provide an estimation of the drop in irradiance depending on the distance from the exit surface. In this case, the decrease of irradiance is measured in the middle of the module. If the measurement is not carried out centrally, the values of the drop in irradiance are higher.

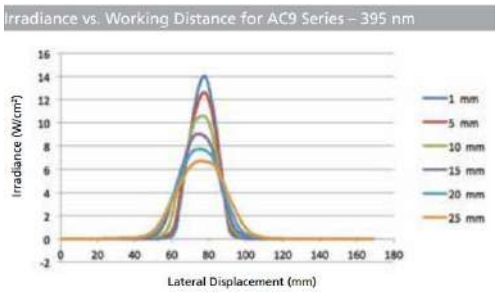


Fig. 6: Irradiance depending on the distance to the substrate, measured in the centre of the module

The required UV radiation dose is normally determined empirically, by experimentation, just as with the UV medium-pressure lamps. The aim however should be to position the UV LED unit as close as possible to the substrate to be cured. However, you can choose among many OmniCure UV LED heads between a version with lens (for longer distances) or plane front-end optic (for very short distances to the substrate; version 'P').

4.4 Cascadability

UV-LED heads are available in a variety of different irradiation lengths. At small distances to the substrate an almost uniform irradiance is achieved in the middle and at the edges. At greater distances to the substrate a more or less sligth irradiance decrease can be observed due to physical reasons:

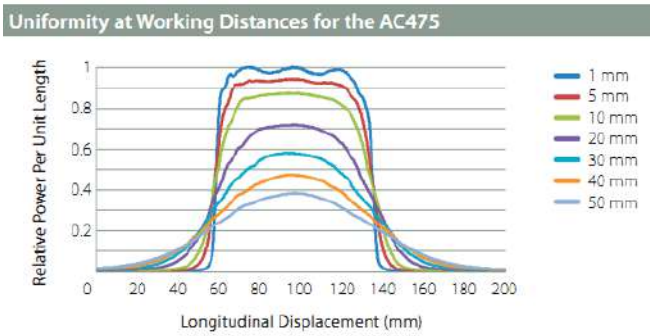


Fig. 7: Irradiance over the length depending on the distance to the substrate

In order to achieve longer irradiation lengths, most OmniCure® UV LED heads are stackable. Also with adjoined LED heads good uniformity is achieved:

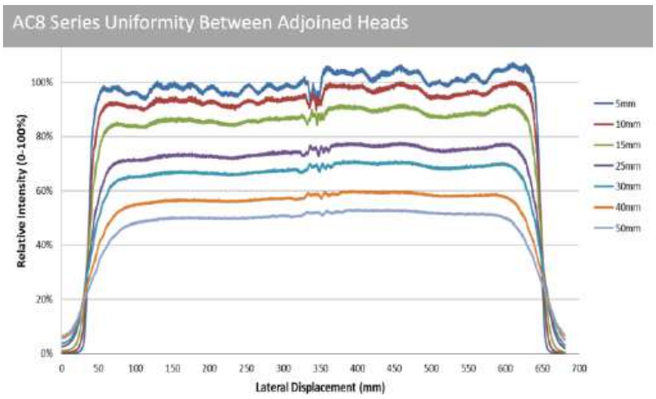


Fig.8: Uniformity between two adjoined AC8 UV LED heads

4.5 Service life and maintenance

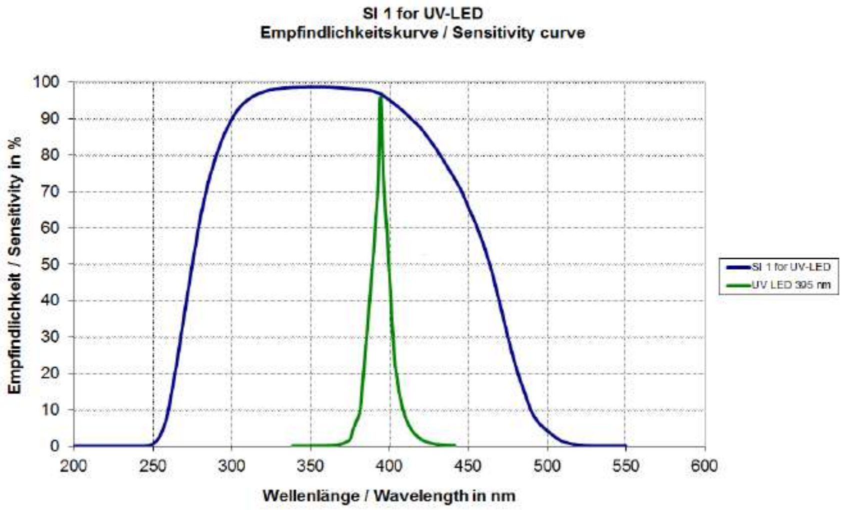
The service life of UV LED modules can only be estimated. Even the chip suppliers do not provide more than estimated data. It can be assumed that the service life amounts to more than 10,000 hours without any significant drop in irradiance, provided that the cooling of the module works perfectly. uv-technik grants a warranty period of one year for these products.

As regards the cooling, it must be ensured that the water meets the requirements regarding temperature, flow rate and, for water-glycol mixtures, the composition specified by the supplier of the heat exchanger. Details can be found in the comprehensive operating manual.

5 Irradiance measurement on UV LED modules

Measuring the irradiance of UV LED modules requires appropriate UV measuring equipment.

A radiometerc measuring system specially adapted to the UV LED radiation is sufficient for most practical applications. It is important that the correct UV sensor with regard to irradiance and wavelength is selected for the narrow-band LED radiation.



Handheld HI 1 with
UV sensor SI 1 for
UV LED measurements

Fig. 9: UV LED 395 nm and sensitivity curve of the UV sensor
SI 1 for UV LED measurements for wavelengths between 320 and 395 nm.

The wavelength tolerance of UV LEDs is usually indicated with λ± 5 nm. Figure 5 shows that the resulting measurement error for wavelengths between 320 and 395 nm is < 10%. This is generally acceptable for most measurements. If the measurements are carried out for the same radiation source, the measurement error is usually smaller, as the wavelength of an LED does not change over time.

For the measurement, we recommend a radiometer for short-term measurement that is designed for high irradiance, as the *UV sensor SI 1* with the *handheld unit HI 1* shown above. If other wavelength ranges, e.g. for medium-pressure lamps, are to be measured, suitable sensors are also available. The handheld unit does not need to be exchanged for this purpose, as the calibration data are stored in the intelligent sensor connector.

If possible, a continuous flow unit such as the UV integrator UV Control (see picture on the right) can also be used The UV LED Control 3C LED (or 3CT LED) is even suitable for measurements of medium-pressure UV lamps or switched to UV LED measurements.

UV integrator
UV Control
UV-3C LED /
UV-3CT LED

6 Safety

LED systems are classed with other incoherent radiation sources, such as, e.g. UV medium-pressure lamps. As far as occupational safety is concerned, the Directive 2006/25/EC of April 5, 2006, which came into force on April 27, 2010, applies within the European Union. This Directive governs the minimum health and safety requirements regarding the exposure of the workers to risks arising from physical agents (artificial optical radiation).

The photobiological safety of lamps and lamp systems has been specified in DIN EN 62471 (VDE 0837-471).

UV LED systems are regarded as “multiple sources of light”. DIN EN 62471 is applicable:

Wavelength range	Limit value acc. to DIN EN 62471, 2006/25/EC	Remark
UV (100 – 400 nm)	< 30 J/m^2 Note $S(\lambda)$.	Skin: sunburn (temporary) Skin cancer (mainly > 300 nm, no distinction in the standards context)
		Eye: Photokeratitis (“sand in the eyes”, flash burns, typical for welding processes) UV cataract, cataractogenesis (290 – 325/400 nm), irreversible lens opacities, sum effect possible.
UV-A (315 – 400 nm)	Unweighted dose < 10,000 J/m^2 Power density < 10 W/m^2, if t > 1000 s	UV cataract, cataractogenesis, irreversible
300 – 700 nm small source	< 100/t W/m^2 Weighting function $B(\lambda)$	Photoretinitis, UV-blue photic retinopathy, damage to the retina particularly due to 400-500 nm radiation. Effects at 310-700 nm, irreversible
300 – 700 nm small source	< 0.01 W/m^2 Weighting function $B(\lambda)$ t > 10,000 s	

7 UV-LEDs – Physical basics, manufacture and features

LEDs, e.g. as red signallers, have been widely used for years. The reason why the development of UV emitting LEDs has taken such a long time is the large band gap required for generating short-wave radiation.

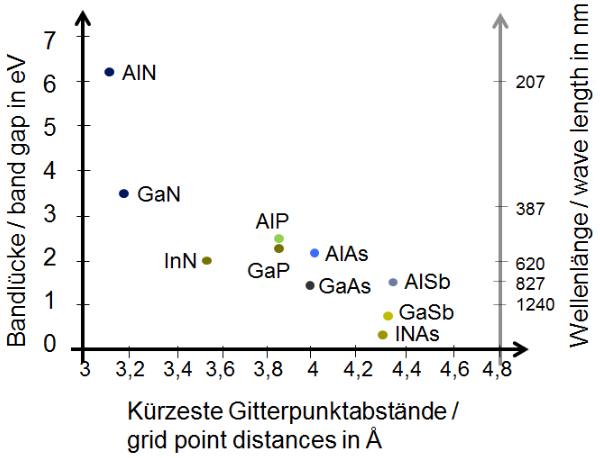


Fig. 10: Band gap and emitted wavelength as a function of the grid point distance. 1Å = 0.1 nm

As Figure 10 illustrates, the band gap must exceed 3.5 eV in order to emit short-wave radiation. This is achieved by creating a semiconductor built up of several p- and n-doped thin layers.

For the manufacture of UV LEDs (λ), chemical elements of the 3rd and 5th main group are used, e.g. aluminium gallium nitride (AlGaN).

III	IV	V	Band gap
^{5}B	^{6}C	^{7}N	↓ Band gap gets larger
^{13}Al	^{14}Si	^{15}P	
^{31}Ga	^{32}Ge	^{33}As	
^{49}IN	^{50}Sn	^{51}Sb	

Fig. 11: Periodic Table of Elements (extract) Semiconductor materials for typical UV LEDs

The wavelength emitted when electric current flows is only determined by the selection of the correct semiconductor materials and their proportion of the pn layer. This means that a UV LED only emits a single wavelength.

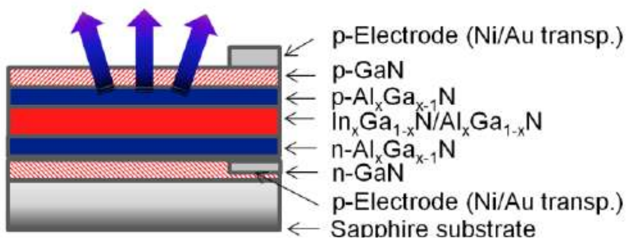


Fig. 12: Basic structure of a pn layer of a UV-LED [1]

A UV LED module contains a large number of so-called chips. A number of individual LEDs are arranged on a *chip* in a compact way in a small area in order to achieve irradiance values as high as possible. Instead of the term "chip", the word "die" is also frequently used; the origin of this expression gives some information about the manufacture of semiconductor chips. So-called "wafers" are cut out of the "carrier material" (usually silicon ingots). Rectangular parts are obtained by sawing or breaking up the finished wafers. These parts are "chopped", thus producing dies. This description sounds quite strange in view of the extremely thin wafers; however, these are the main steps of the process.

The electrical contacting of the chips is made via bond wires. Bond wires for high-power UV LEDs are usually made of gold and have a diameter of approx. 30 µm. Thermal overload of one or several chips can not only result in damage to the chip(s), but also result in the bond connection being destroyed so that the affected chip consequently cannot generate any more radiation.

The metal-organic vapour-phase epitaxy (MOVPE) has developed to become the leading epitaxy process for the industrial manufacture of GaN / AlGaN layers. During the growth processes of the individual layers, temperatures exceeding 900 °C are required.

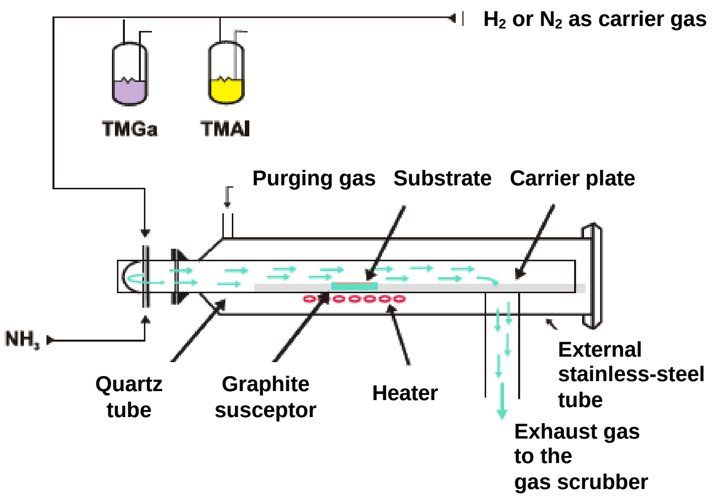


Fig. 13: MOVPE principle:
As metal-organic sources, trimethylgallium (TMGa) and Trimethylaluminium (TMAl) are transported to the heated substrate by means of a carrier gas (H_2 or N_2) [2]

The difficulty to be faced when manufacturing ternary and quaternary group III nitride compound semiconductors is the lack of a specific similar substrate, i.e. the layers must necessarily grow on dissimilar substrate materials. This lattice mismatch between substrate and epitaxial layer results in crystalline defects that restrict the performance.

8 Conclusion

Will UV-LED's replace medium pressure UV curing lamps?

In some industries and applications they offer a significant heat, instant switching and size advantage. However the lack of energy at the shorter wavelengths, efficiency and the required use of specialised and "loaded" coatings, coupled with initial investment costs, will undoubtedly limit their short to medium term potential. It can however be said that in many cases they create new opportunities rather than replace them.

As with all technologies they are constantly evolving and most market leading UV manufacturers are consistently evaluating and developing new applications and power levels to meet the demands of the growing UV market.

For further information and downloads please visit our website uv-technik.co.uk

References

[1] Nitrides company information: www.nitride.co.jp
[2] K. Knese – Magnetotransport an AlGaN /GaN – Heterostrukturen in hohen Magnetfeldern, 2006, 34