Technological Status of LED Techniques - Application in Non Destructive Testing with Special Emphasis on Magnetic Particle, Penetrant, Visual and Thermographic Inspection

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Abstract. After the first introduction of UV-A LED lamps in fluorescent magnetic particle and penetrant inspection further progress could be performed in technology and applicability of the LED technique in many fields of nondestructive testing. The most important development was the ability to produce different compositions of AlGaInN semiconductor layers (Nobel Prize in Physics 2014 by three Japanese Physicists). This led to the rapid introduction of high power LEDs in the whole range of the UV- up to the IR-electromagnetic spectrum. Latest physical and technical developments in LED techniques are described, including Double Heterostructures and Quantum Well structures. Today LEDs are completely replacing common Mercury Vapor Lamps. Practical considerations are explained together with specific applications including all aspects of high quality design. The requirements and comparison on specifications and quality according to the standards in non-destructive testing are presented.

Introduction and History

Light Emitting Diodes (LED) are a physical phenomenon which is also called electroluminescence, a characteristic of some semiconductor materials.

It was discovered by H. J. Round in 1907 in a SiC (“carborundum”).Round contacted SiC with a metal. The light emission arose from the contact area when applying a voltage of about 10 V.

Today SiC semiconductor LEDs are no longer in production commercially, because they have an indirect band gap transition with low luminous efficiency.
It was only in the sixties that one really understood the physical mechanism of semiconductor LEDs, which was the start of rapid development.

Efficient blue LEDs have been developed and introduced by NICHIA Corporation in 1994 (Figure 1), very soon followed by a LED emitting in the UV electromagnetic spectrum.

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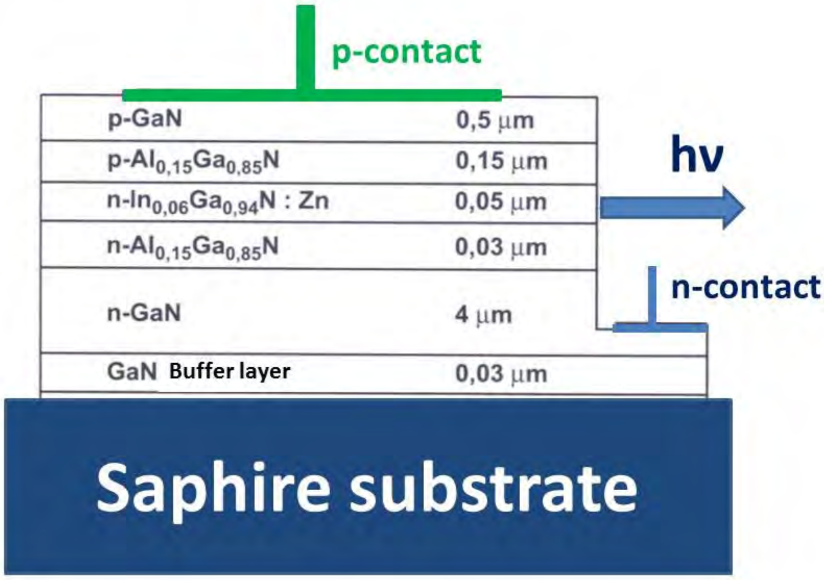

Figure 1: Schematic drawing of the first blue LED by NICHIA corp

It consisted of n-type InGaN doped with Zn.
LEDs are composed of so called III-V semiconductors of the periodic system (Figure 2).

IIIa	IVa	Va
B	C	N
Al	Si	P
Ga	Ge	AS
In	Sn	Sb
Tl	Pb	Bi

Figure 2: Periodic System Elements III-V

With progress in preparing semiconductor compositions with AlGaN and AlInN nearly each wavelength from 200 to 1800 nm can be achieved today (Figure 3).

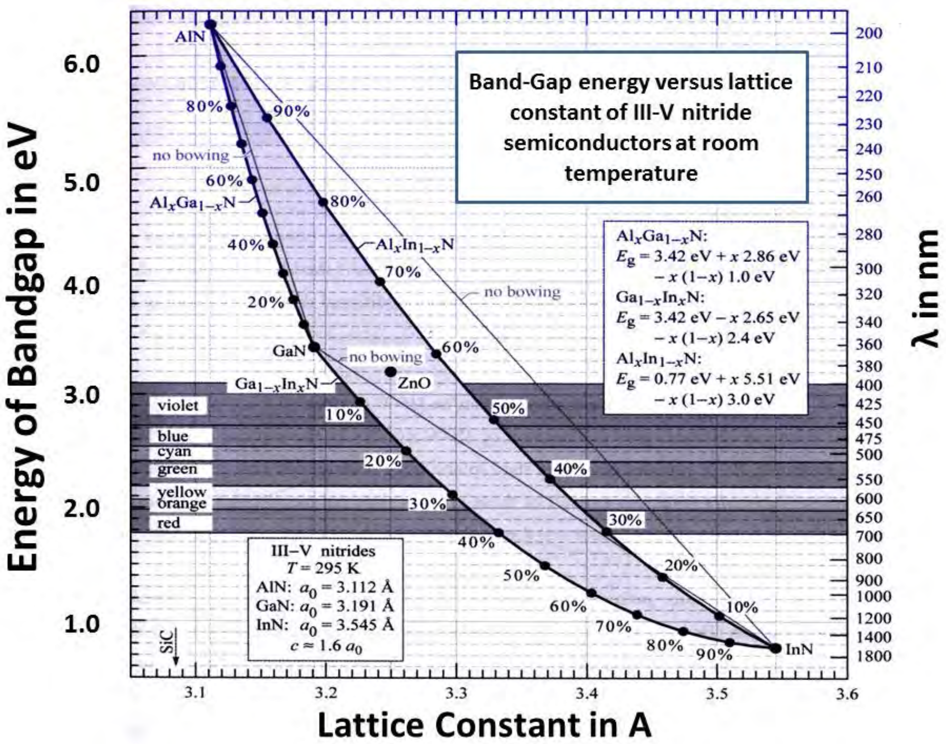

Figure 3: Bandgap energy and wavelength of emitted photons versus lattice constant in Angstrom (A) of III-V nitride semiconductors at room temperature [4,5].

For this development I. Akasaki, H. Amano, S. Makamura received the Nobel Prize in Physics in 2014.

Light Emitting Diodes LED

LEDs are the most simple semiconductor compounds. At a p-n-junction an electron may recombine with a positive hole via a direct transition from the conduction to the valence band. It is emitting the recombination energy to a photon with the band gap energy. Varying the composition of the semiconductor compound the band gap and therefore the wavelength of the photon can be selected according to Figure 3 from infrared to the UV electromagnetic spectrum.

An example for application of infrared LEDs in thermographic inspection is the system OctoLED by the Federal Institute of Materials Testing and Research (BAM) in Berlin. The thermal source for the excitation of the test specimen consists of 8 LED arrays each consisting of 20-25 LEDs (Fig. 4).

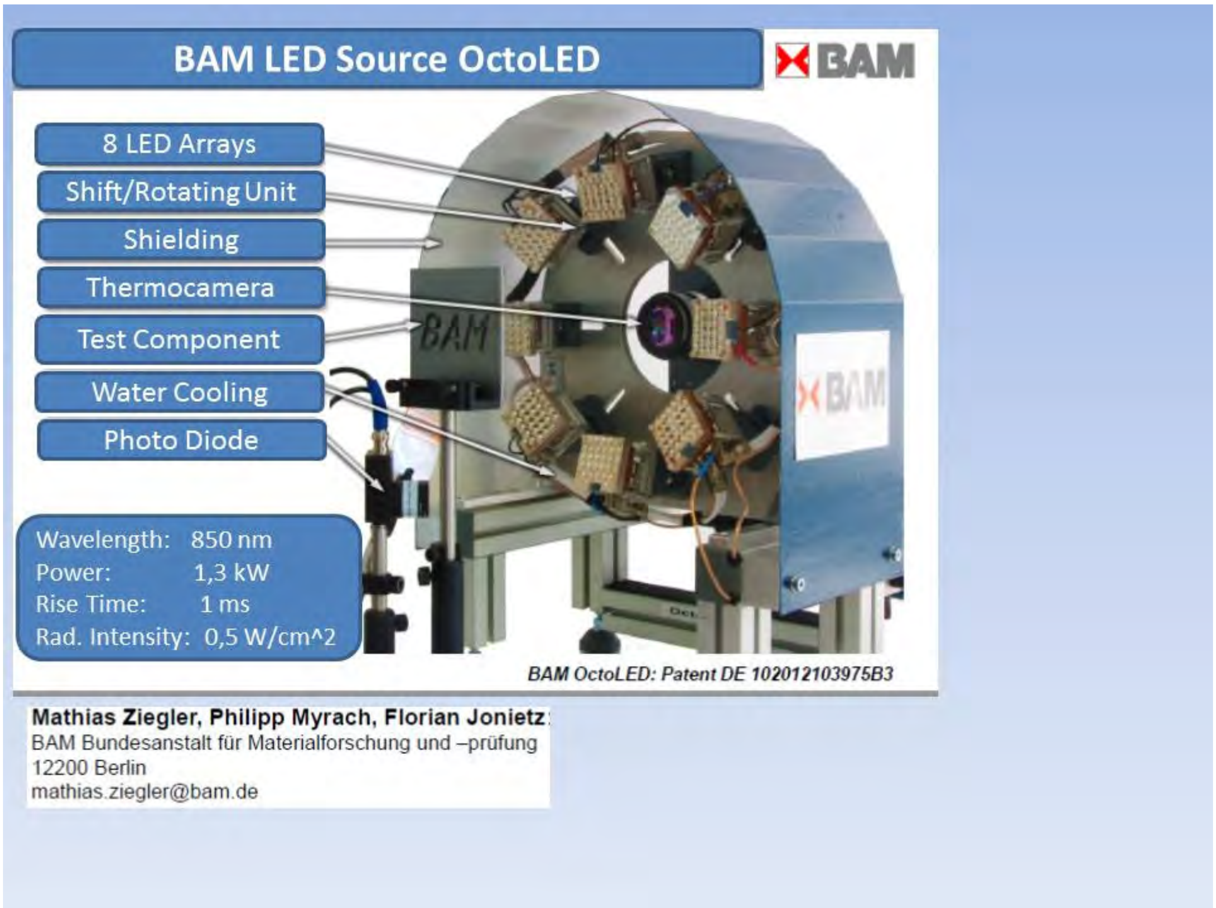

Fig. 4: Thermographic Testing by LED thermal excitation of the Test Specimen (BAM)

In the case of Magnetic Particle and Liquid Penetrant Testing using UV fluorescent magnetic particles or liquid penetrant UV-LEDs with ALGaInN semiconductors are appropriate materials. The intensity I_{em} of the emitted energy spectrum of direct emission semiconductors can be calculated according to the following relation:

$$I_{em} = const. \cdot \sqrt{h\nu - E_g} \cdot \exp(-(h\nu - E_g)/k_B T) \qquad (1)$$

Fig. 5 is displaying this relation.
The temperature dependence of the band gap E_g can be described by the experimentally derived Varshni equation

$$E_g = E_g(T=0K) - \alpha \cdot T^2/(T+\beta)$$
$$GaN:$$
$$E_g(T=0K) = 3.47eV \qquad (2)$$
$$a = 10^{-4} eV/K$$
$$\beta = 600K$$

Example: For AlGaInN the band gap wavelength increases by 4.8 nm for a temperature change from 300 K to 400 K.

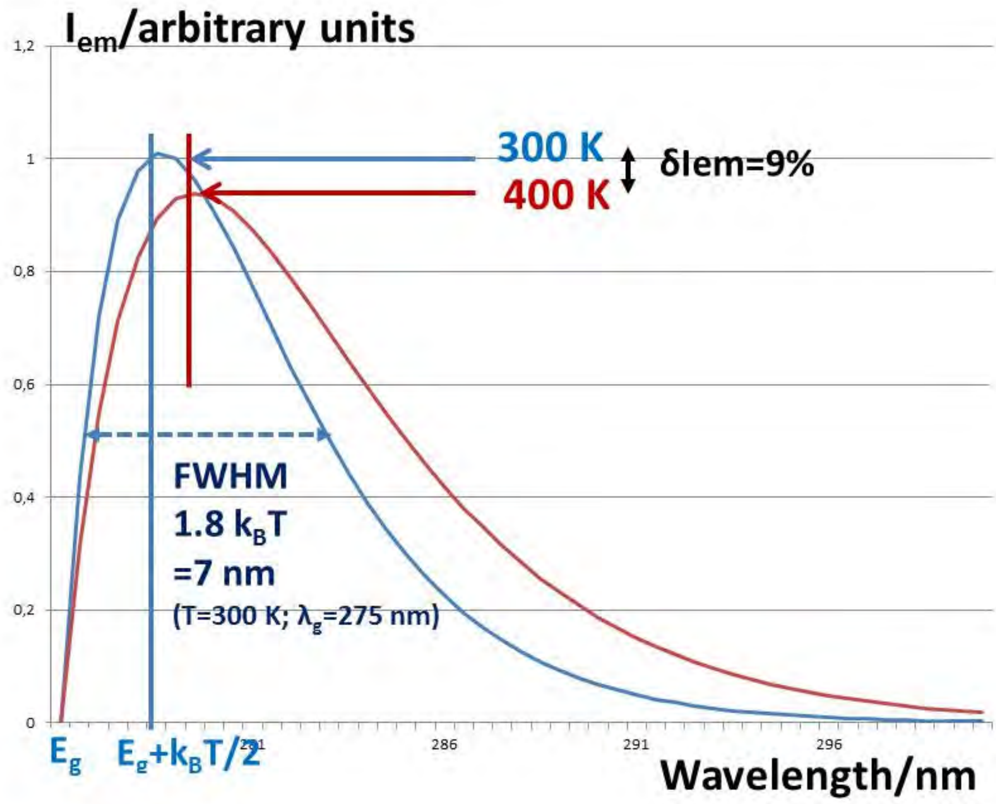

Figure 5: Emission spectra of direct emissions in LED, λ=275 nm

As can be seen, the peak wavelength is slightly shifted with increasing junction temperature, which in practice will not be of great importance for applications using UV-A LED.

However, the intensity in the theoretical emission spectrum is decreasing by nearly 10% in going from 300 K to 400 K. This decrease has to be taken into account especially in applications using UV-A LEDs for nondestructive magnetic particle or penetrant inspection.

Apart from this temperature dependence of the radiative recombination, there are other effects, which influence the emission of photons e. g. the luminescence or efficiency of a LED.

These are a) non-radiative recombination within the semiconductor and b) optical effects of the light output from the semiconductor to ambient air.

The temperature dependence of the non-radiative recombination effects can be described phenomenological by the following relation.

$$I = I_{300K} \cdot \exp(-(T - 300/T_1)) \qquad (3)$$

Here T is the ambient temperature and T_1 is the characteristic temperature of the semiconductor compound.

In Fig. 6 some examples are shown. One can see that the luminous intensity of blue GaInN/GaN LED compounds is rather insensitive against temperature changes.

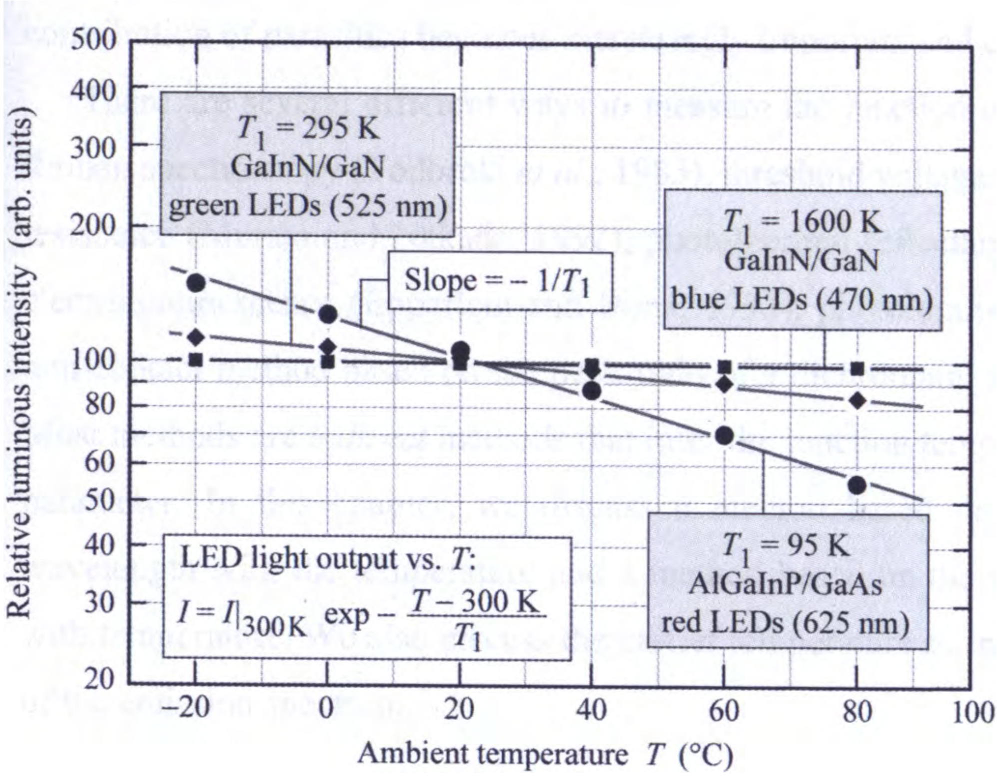

Figure 6: Temperature dependence of the luminous intensity of some LED semiconductor compounds [1,6]

Practical Aspects and Considerations

A typical high power LED for the UV-A wavelength range is schematically shown in Figure 22.

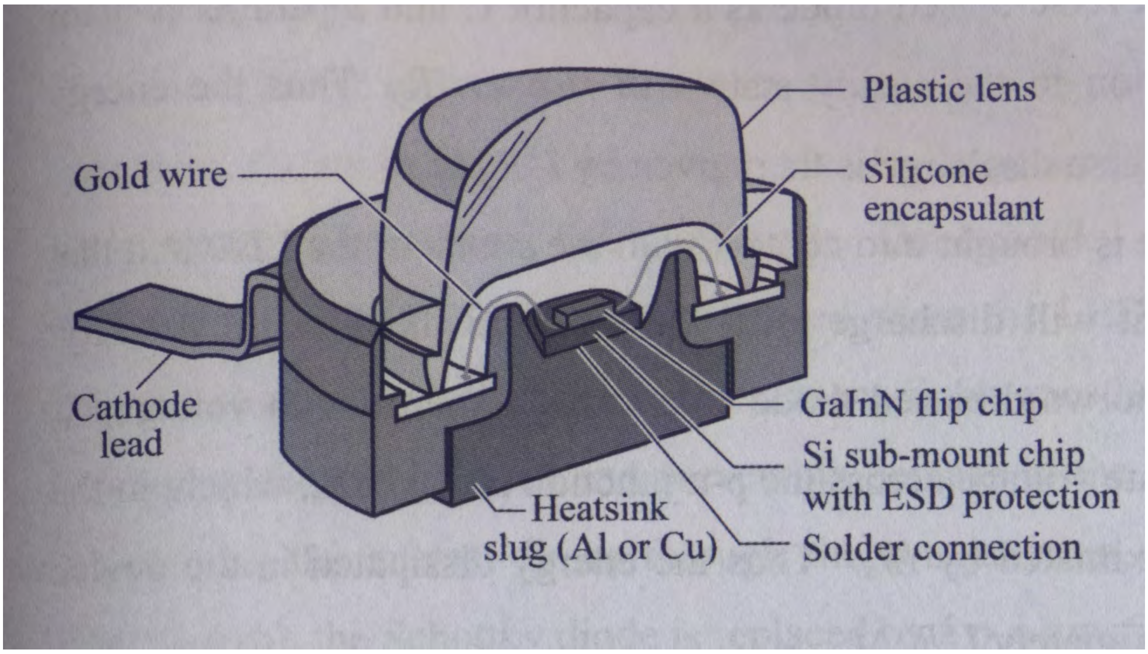

Fig. 7: Schematic drawing of the design of a high power LED [1]

For reasons discussed above the most essential parts are beside the semiconductor, the Silicone encapsulate and the plastic lens for optimal optical efficiency. The Si

semiconductor circuit integrates an ESD device (Electrostatic Discharge Protection Diodes) which is essential to limit the LED reverse current before breakdown.
The cathode lead and gold wire supply the forward voltage to the p-n-junction.
Soldering of the LED requires special care. The maximum temperature and time is specified by the manufacturer of the LED. Typical maximal values are 180-200°C for 120 s and 260°C for 10 s.

As has been shown there are many temperature dependent properties of the LED determining its performance.

It is obvious that the temperature management is very important for reliable operation of the LED for the intended lifetime in the order of 10.000-20.000 hours. Therefor the heat sink of the LED and its connection to the bearing construction are very important. Heat transfer to the ambient environment has to be very effective to prohibit overheating. This is valid for open housings or and even more so for closed LED lamps. With appropriate design even closed housing of the lamps with high power LED can be reliably operated.

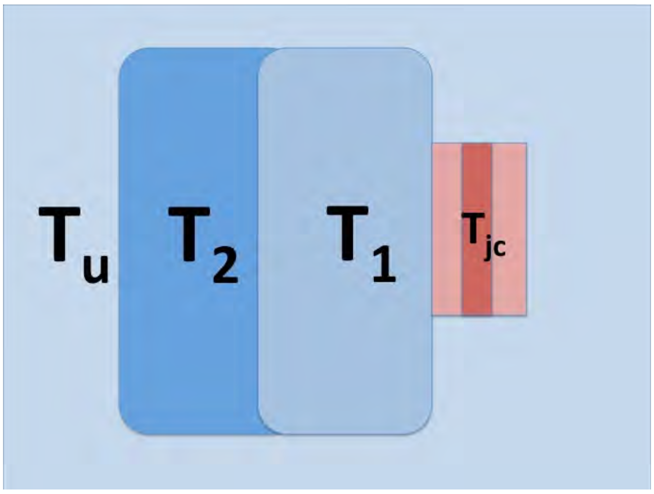

Fig. 8: Temperature management of LED; temperatures measured are: ambient T_u=28°C, housing T_2=39.6°C, LED heat sink $T_{1=}$42.7°C and junction T_{jc}.

For the LED data as given in Fig. 8 in Figure 8 the manufacturer has given a thermal resistance R_J of 11 °C/W with a dissipating energy of 3W. With the measured temperatures (Figure 23) it follows (Equ. 4) that the junction temperature T_{jc} will be 76°C. The manufacturer is accepting up to 85°C.

$$R_{total} = \sum_i R_i \quad i=R_{housing}, R_{heat\ sink}, R_{jc} \qquad (4)$$

In general of course, the specifications of the manufacturer have to be followed very rigorously to guarantee reliable operation and the long potential lifetime of LED.

Requirements of Standards in NDT

The requirements for operation of UV-A lamps in non-destructive testing with penetrants or magnetic particles under UV light are defined in the standards EN ISO 3059: 2012, RRES 90061: 2014, ASTM E3022: 2015.

According to EN ISO 3059:

a) For the removal of excess penetrant the UV-A intensity must be higher than 100 $\mu W/cm^2$. The illuminance has to be smaller than 100 lux.
b) During inspection the UV-A intensity has to be

- greater than 1.000 $\mu W/cm^2$ at a distance from the illuminated surface of 40 cm
- with a wavelength λ=365 nm +- 5 nm
- the FWHM must be smaller than 30 nm
- the ambient illuminance has to be smaller than 20 lux. If the ambient illuminance is higher, the contrast has to be enhanced correspondingly (EN ISO 9934).

The main requirement for all of the above given standards are summarized in Table 1.

These requirements are easily fulfilled if proper quality management of the manufacturers of the LED and of the LED lamp is followed up. It is necessary that the manufacturer of the lamp employs an intensive quality control and measurement of the LEDs eventually of each LED has to be carried out (binning).
Further advantages of LED sources are:

- Insensibility to electromagnetic fields
- Vibration resistance
- Precise UV-A wavelength at 365 nm
- Protection class IP 65 (completely dense for dust and water jets)
- Manifold design options
- No active cooling necessary
- Long Lifetimes

Table 1: The requirements for operation of UV-A lamps in non-destructive testing with penetrants or magnetic particles under UV light as defined in the standards EN ISO 3059: 2012, RRES 90061: 2014, ASTM E3022: 2015.

Parameter	ISO 3059 (2012)	RRES 90061 (2014)	ASTM E3022 (2015)
Type of UV LED Lamp	NA	A (Powered by mains) B (Rechargeable battery; Hand Lamps) C) (Rechargeable battery; Pocket Lamps) D) (Special Applications)	A (Powered by mains) B (Rechargeable battery; Hand Lamps) C) (Rechargeable battery; Pocket Lamps)
Spectral Distribution	λ>330nm	λ>315nm	λ=300-400nm for Lamp 300-800nm Transmission Resolution 0,5 nm; S/N 50:1

Maximum Wavelength	λ=360-370nm	360-370nm	360-370nm
Wave Length Drift		λ between 360-370nm at 10-50℃	+-1nm
Illuminance	<20lx	<5lx for max. Working Distance <20lx for Minimum Working Distance	NA
UV Stability	NA	<20% until UV Stabilization at T_S <3% within 30min Intervals	<+-5%
Irradiation E in $\mu W/cm^2$	1000<E<5000	1500<E(at 380mm)<5000 for $T<T_S$; A)&B) 1200<E(at 380mm)<5000 for $T<T_S$; A)&B)&C)	E(at 381+-6mm)>1000 $\int_{347}^{382} E(\lambda)d\lambda = 2000$ (Distance 381+-6 mm)
$\Delta_{1/2}$ in nm	<30	<20	<15; Largest Wavelength 377nm
$\Delta_{1/10}$ in nm	NA	+<10 -<15	NA
Temperature of Housing during Measurement			43,3℃
White Paper Test for Homogeneity of Irradiation	NA	Required for max und min Working Distance	Required

In the next figures examples (Helling Company) are collected to demonstrate that the LED lamps are complying with the requests of the standards.

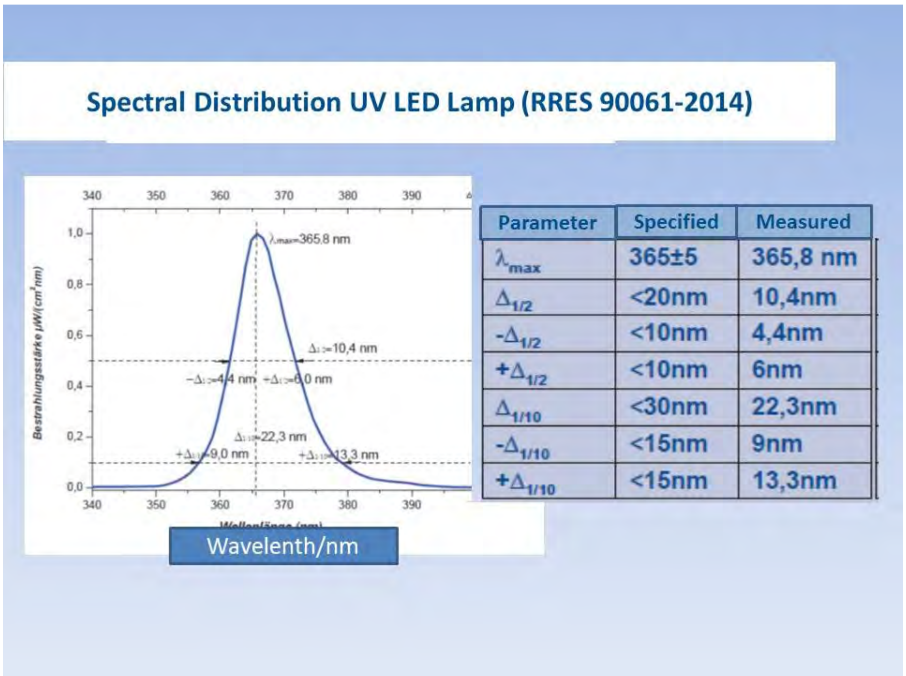

Fig. 9: Spectral Distribution UV LED Lamp, specification according to RRES 90061-2014, measurements at Helling Company

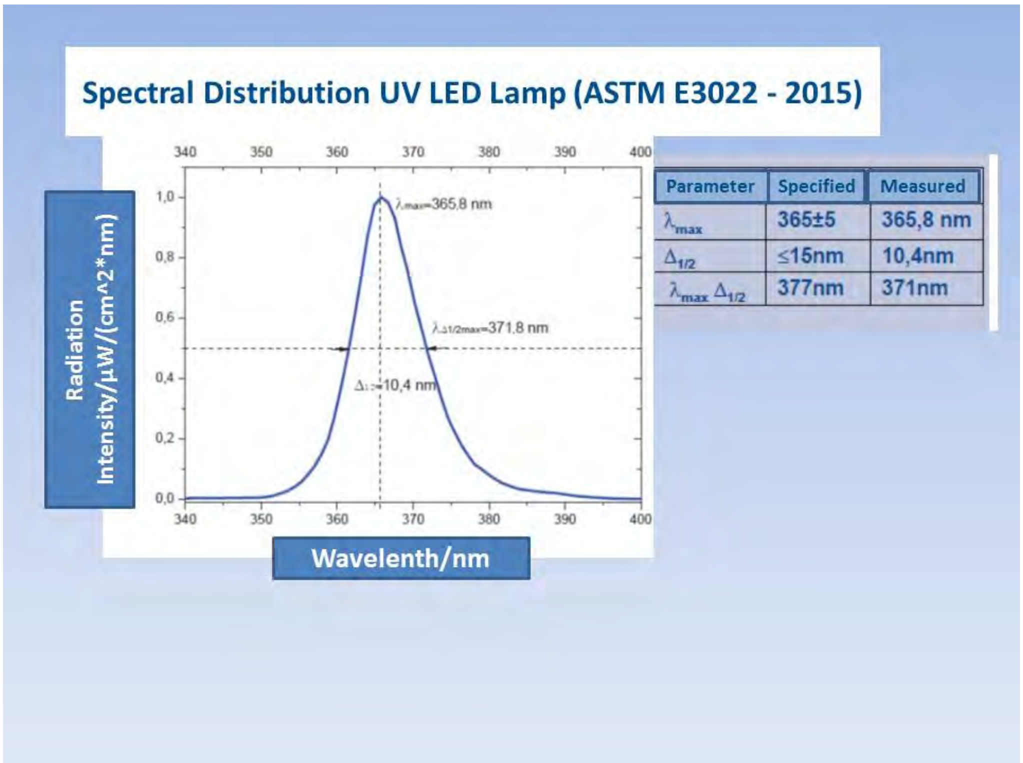

Fig. 10: Spectral Distribution UV LED Lamp, specification according to ASTM E3022: 2015, measurements at Helling Company

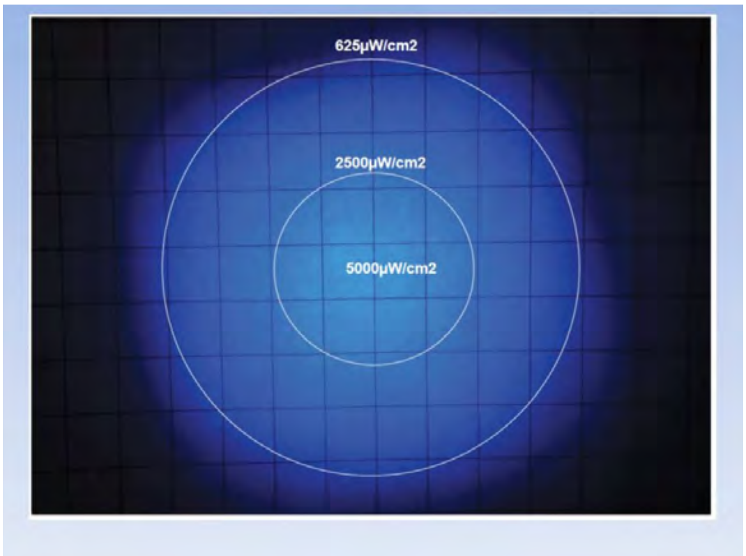

Fig. 11: Test with white paper (ASTM E3022 – 2015, RRES 90061-2014

A further advantage of LEDs over the previously used mercury vapor lamps is the short warm up time to achieve the equilibrium state as shown in Fig. 12.

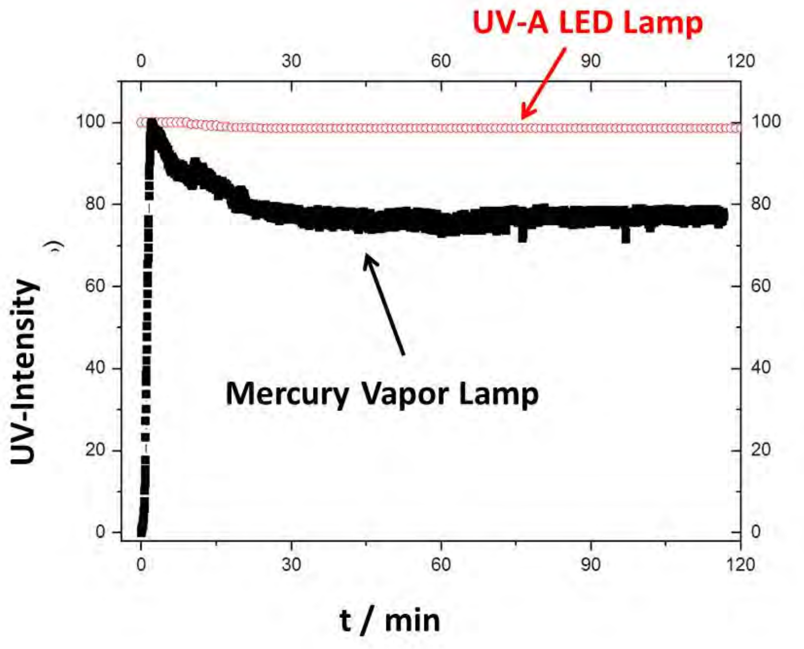

Figure 12: Warm up time for Mercury Vapor and LED UV-A lamps

The future of UV-A light sources in application of non-destructive testing in fluorescent penetrant or magnetic powder testing belongs to the Light Emitting Diodes.

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