The attachment of a time correlated single photon counting module to a confocal microscope enables several types of spatial and time resolved measurements such as fluorescence lifetime imaging or electro- and photoluminescence decay imaging. In this article spatial and time resolved μElectroluminescence (μEL) studies of a blue, light-emitting diode (LED) are described.

Spatial resolved electro- and photoluminescence measurements (μEL and μPL) are standard characterization techniques for optoelectronic devices. They are used during the development of an optoelectronic device to optimize their performance and during process control to ensure that the quality of the devices remains constant. Additionally they are important tools during lifetime and failure studies. Both methods, μEL and μPL, measure the luminescence decay spectrally and spatial resolved through a microscope objective, while in μEL a bias voltage and in μPL a laser is used to excite the luminescence. The final (hyperspectral) dataset contains spectral and spatial information which can be analyzed in many different ways. In addition, the variation of external parameters will further expand the hyperspectral data set. In case of the μEL, the device can be driven under different electrical conditions, while in μPL the power and excitation wavelength of the exciting laser can be changed. In both cases the device temperature is also an important parameter. In order to investigate the dynamic properties of an optoelectronic device, it is very useful to measure the luminescence decay after a short electrical or optical excitation.

**Setup Assembly**

Figure 1 shows the μEL measurement setup based on a WITec alpha300 microscope equipped with a time correlated single photon counting (TCSPC) module for time resolved measurements. A pulse generator (HP 81082A) was used to generate a short electrical pulse to excite the LED emission. The light emitted from the LED was collected with a high numerical aperture (NA) objective (60×, NA=0.7). The image formed by the objective was projected onto a multimode optical fiber (25 μm diameter, NA=0.12). The fiber picks up the light from a single
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point (0.42 μm diameter, nearly diffraction limited) of the LED and guides it to a spectrometer equipped with a BI-CCD camera and single photon counting detector. A piezo-electric scan stage was used to scan the sample with respect to the detection fiber. By using the CCD detector it was possible to acquire full luminescence spectra at every sample position, while the single photon counting APD was used to measure the time resolved luminescence decay at selected spectral positions. For this purpose, the NIM output of the APD (MPD PDMICTC) was connected to a time-to-digital converter (TDC) extension board in the alphaControl microscope controller. This extension board measures the time between the excitation pulse and the arrival of a luminescence photon at the APD. A histogram of these arrival times is the luminescence decay curve.

With this setup, a commercial blue/green LED was examined. These LEDs are typically based on InGaN III-V-compound semiconductors. By varying the ratio between Indium (In) and Gallium (Ga) the band gap of the semiconductor can be changed from 3.49 eV (GaN) to 0.65 eV (InN). This covers the complete visible spectrum from near infrared (1900 nm) to UV (355 nm). Usually LEDs and semiconductor lasers consist of multi quantum well structures (MQWs). These are alternating ultra-thin layers with high and low indium concentration which confine electrons and holes in a two dimensional electron gas in order to enhance the optical properties of the diode. The production of homogeneous InGaN layers is a big challenge in thin-film epitaxy. Due to phase separation, Indium tends to form small clusters inside the InGaN matrix. The varying Indium concentration results in a spatial varying band gap, which changes the local emission spectrum of the diode. Figure 2 shows a microscope image of a blue LED at low magnification. The inhomogeneous distribution of the emission spectrum can already be seen.

Experiments and Results

μElectroluminescence Measurement

With a μEL measurement at higher resolution, it is possible to quantify the variation of the emission spectra. Although each spectrum is a local spectrum from a small region of the sample, it already shows in-

![Figure 3](image1.png)

**Fig. 3** Shown are an average spectrum (a) and a single spectrum (b) of the image scan (Fig. 4) with the Gaussian fit curves (blue lines) which are a good approximation for the emission spectra.

![Figure 4](image2.png)

**Fig. 4** μElectroluminescence measurement at the region between the two bond pads on the LED: shown are the intensity (a), the spectral center (b) and the spectral width (c). The μEL image contains $270 \times 270 = 72,900$ spectra.
homogeneous broadening. Therefore a Gaussian curve fit is a good approximation for the emission spectra (Fig. 3a-b). Figure 4a-c show the region between the two bond pads. The μEL image contains $270 \times 270 = 72900$ spectra with a 12 ms integration time per spectrum. A Gaussian curve is fitted to the spectra delivering the intensity, the spectral position and the spectral width of each spectrum. The intensity is shown in Fig. 4a, the spectral center in Fig. 4b and the spectral width in Fig. 4c.

**Total Time Resolved Emission Spectroscopy**

With a TDC extension board it is possible to measure the temporal decay of the emission at different wavelengths. For this experiment, the diode was excited with a short electrical pulse of 2 ns duration at a repetition rate of 2 MHz. Figure 5 shows three different time spectra at different photon emission energies. Due to the inhomogeneous Gallium and Indium distribution, these time spectra are far from single exponential. Electrons and holes with higher energies can perform a direct recombination associated with light emission or they can relax into lower energy states caused by Indium rich clusters.

All of these relaxation channels have different decay times and populations, so that the temporal decay looks like a stretched exponential function. In order to obtain an average relaxation time, the full width at half maximum (FWHM) of the emission time spectra have been evaluated. Figure 6 shows the relaxation time vs. photon emission energy. With increasing energy, the relaxation time falls from 14.6 ns to 2.7 ns. The strongest decrease of the relaxation time is observed at the maximum of the emission spectrum.

**Local Time Resolved Emission Spectroscopy**

The relaxation time is not only a function of photon energy, but varies also locally. Using the same setup it is possible to acquire spatial-resolved time spectra at fixed wavelengths instead of emission spectra. From these time spectra, a map of local relaxation times can be calculated. Figure 7 shows the spatial varying relaxation times at different photon emission energies.

The reason for this variation is multi-layered. The variation of the Indium concentration creates a potential landscape for electrons and holes. At large and flat potential valleys, the diffusion of the carriers is limited. This affects also the local relaxation time, because surrounding carriers will flow into this valley. On the other hand, if the potential valleys are deep and smaller than about 10 to 50 nm, a lateral quantum confinement is formed in

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**Fig. 5** Time spectra for different photon emission energies  
**Fig. 6** Relaxation time and intensity vs. photon energy

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**Fig. 7** Spatial varying relaxation times at different photon emission energies (see text).
addition to the MQW. In these so-called quantum dots, electrons and holes are trapped. This localization process increases the lifetime of the direct electron-hole recombination dramatically.

**Signal Propagation through the Device**

Not only does the temporal decay of the emission vary in space, but also its starting point. The luminescence emission is delayed for areas that have a larger distance to the bond pad of the back-side contact. Figure 8a shows this effect as a contour plot. The black area in the upper left is the bond pad of the back-side contact, while the lower black area is the bond pad for the front-side contact of the diode. The corresponding time spectra are shown in Figure 8b. From the temporal and spatial distances of the red and yellow areas, a propagation speed of about 150 km/s can be calculated for the electrical pulse.

**Summary**

Combination of a confocal microscope with a time correlated single photon counting module facilitates spatial and time resolved optoelectronic analyses. This setup enables spectrally and spatial resolved analyses e.g. for µElectroluminescence measurements to detect luminescence decay of a blue, light-emitting diode. An additional time-to-digital converter (TDC) extension board is suitable for time resolved spectral analyses either of the complete sample area or of local measurement points. Thus this combined microscopic setup has the potential for broad sample characterization.