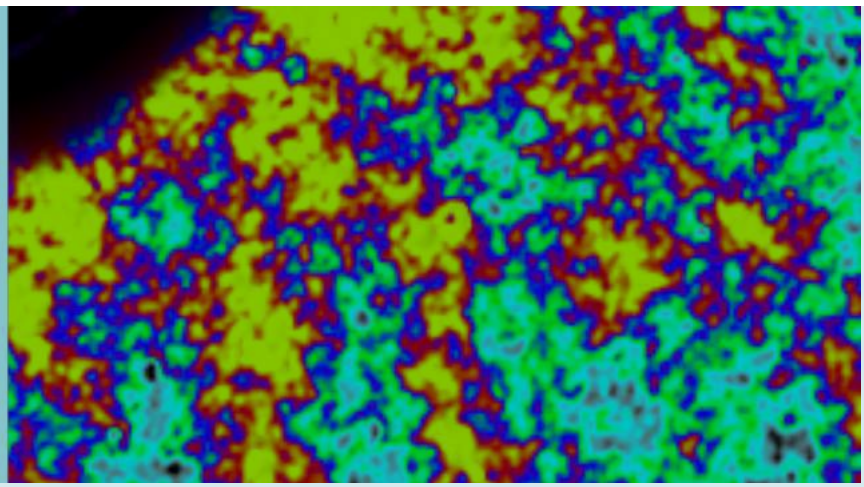
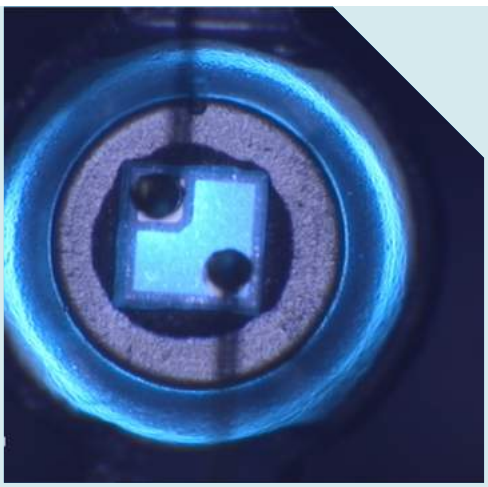
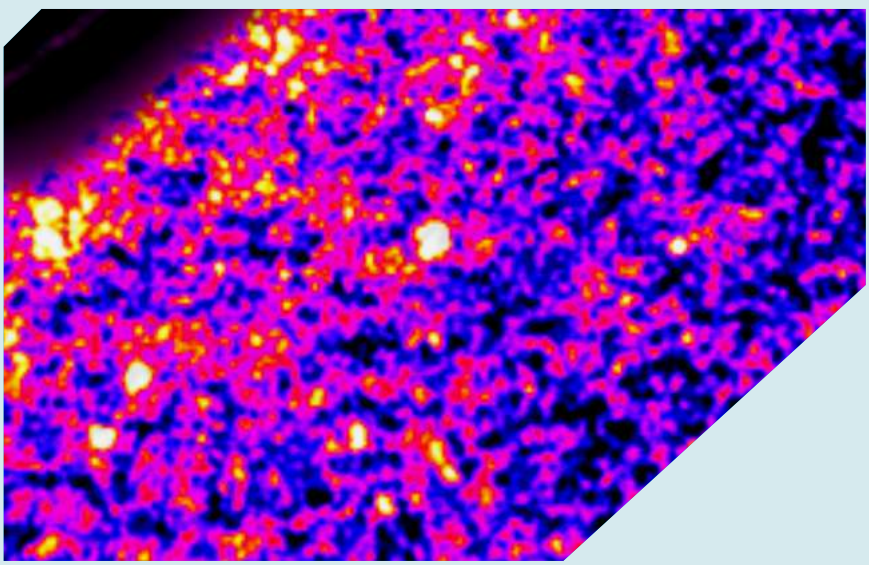
APPLICATION NOTE

Time resolved photoluminescence studies of blue light-emitting diodes (LED)







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Time Correlated Photon Counting Module

The modular design of the WITec microscope series allows the attachment of a time correlated single photon counting module to the alpha300 confocal microscope series. This makes possible several types of spatial and time-resolved measurements such as fluorescence lifetime imaging or electro- and photoluminescence decay imaging. This application note covers spatially resolved electroluminescence studies of a blue, light-emitting diode (LED).

Spatially and Time-Resolved Electro- & Photoluminescence

Spatially resolved electro- and photoluminescence measurements (µEL and µPL) are standard characterization techniques in the manufacturing process of optoelectronic devices. They are used during development to optimize the performance and during process control to ensure the consistent quality of the devices. Additionally they are important tools during lifetime and failure studies. Both methods, µEL and µPL, measure the luminescence decay spectrally and spatially 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. Also external parameters influence the information contained in the 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 an important parameter that can influence the informative content of the data set. In order to investigate the dynamic properties of an optoelectronic device, it is useful to measure the luminescence decay after a short electrical or optical excitation.

Setup

Figure 1 shows the µEL measurement setup based on an alpha300 microscope equipped with a time-correlated single photon counting (TCSPC) module for time-resolved measurements. A pulse generator 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 (60x, NA= 0.7). The image formed by the objective was projected onto a multimode optical fiber (25µm diameter, NA=0.12).

The fiber picks up the light from a single point (0.42 µm diameter, nearly diffraction limited) of the LED and guides it to a spectrometer equipped with a back-illuminated 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 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.

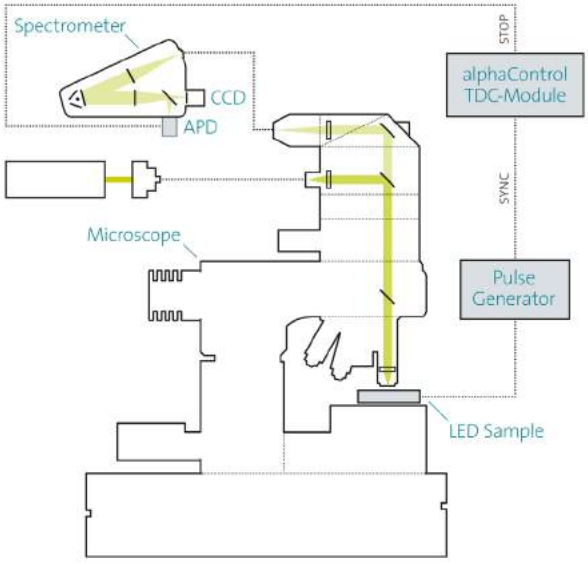

Fig. 1: Micro electroluminescence setup based on an alpha300 for time resolved luminescence measurements

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Sample

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 (1900nm) to UV (355nm). 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 spatially 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.

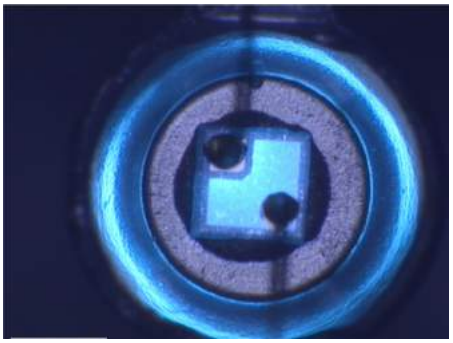

Fig. 2: Video image of blue InGaN LED

Micro-electroluminescence 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 inhomogeneous 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 x 270 = 72900 spectra with a 12ms 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. These spectral differences indicate inhomogeneities in the InGaN matrix.

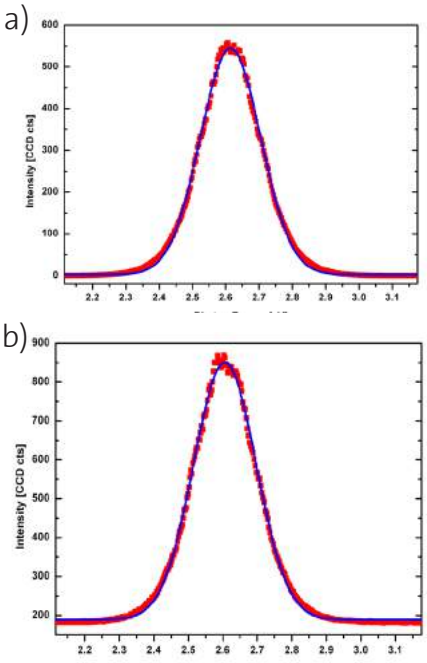

Fig. 3: Gaussian curve fit of the emission spectra. a): Average spectrum of image scan (Fig. 4) together with Gaussian fit curve; b): Single spectrum of image scan (Fig. 4) together with Gaussian fit curve.

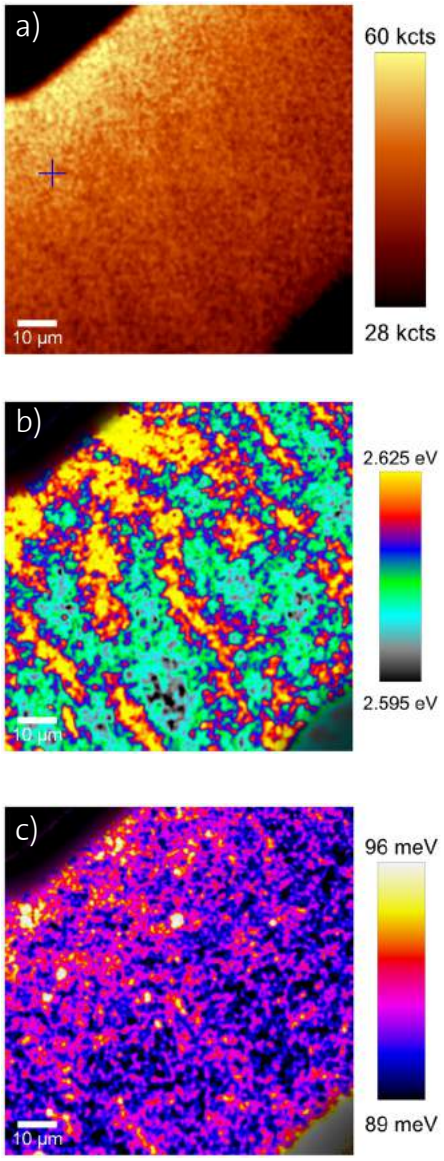

Fig. 4: µEL measurement at the region between the two bond pads on the LED. 4a: Total Intensity 270x270 pixels; 90x90µm; b): Peak Shift; c): Peak Width

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Time-Resolved Emission Spectroscopy (total area)

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 2ns duration at a repetition rate of 2MHz. Figure 5 shows three different time spectra at photon emission energies of 2.756 eV, 2.611 eV and 2.480 eV respectively. 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 15ns to 2ns. The strongest decrease of the relaxation time is observed at the maximum of the emission spectrum.

Time-Resolved Emission Spectroscopy (local)

The relaxation time is not only a function of photon energy, but varies also locally. Using the same setup it is possible to acquire spatially-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 spatially varying relaxation times at photon emission energies of 2.756 eV, 2.611 eV and 2.480 eV respectively. 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 10-50nm, a lateral quantum confinement is formed in 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.

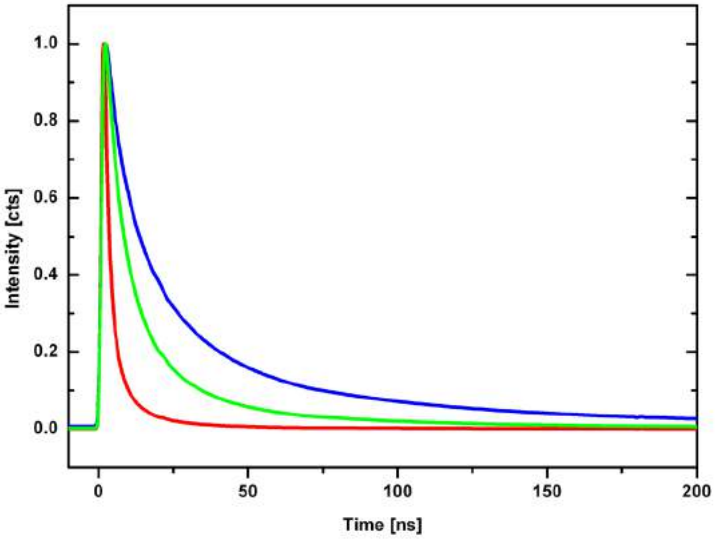

Fig. 5: Time spectra @ 450nm ↔ 2.756 eV (red), 475nm ↔ 2.611 eV (green) and 500nm ↔ 2.480 eV (blue)

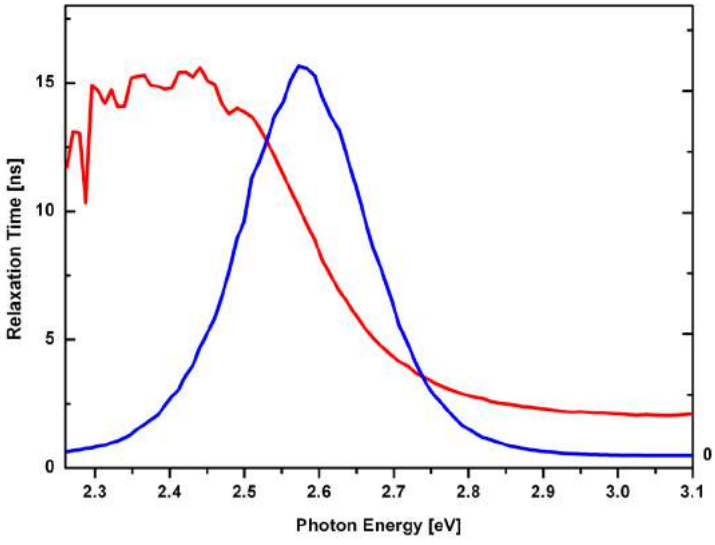

Fig. 6: Relaxation time (red) and intensity (blue) vs. photon energy

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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 8 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 Fig. 9. From the temporal and spatial distances of the red and yellow areas, a propagation speed of about 150km/s can be calculated for the electrical pulse.

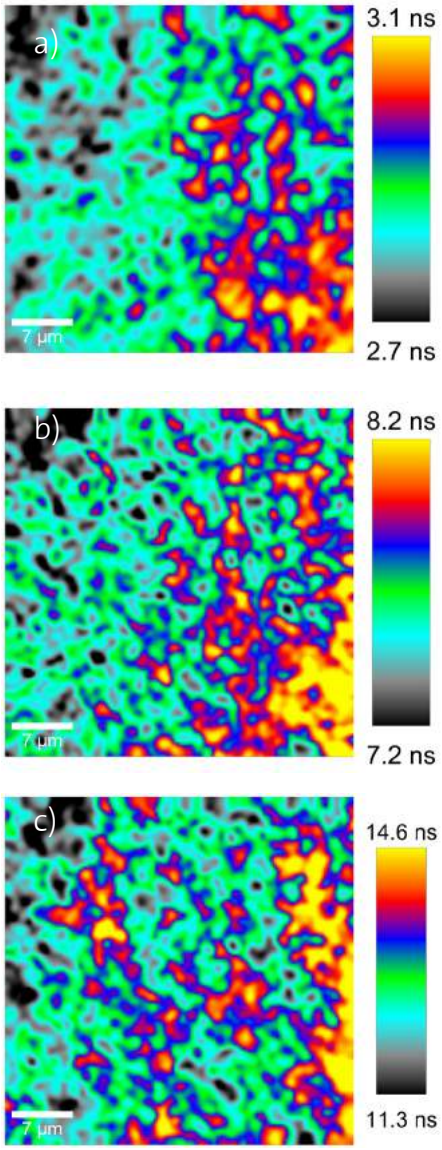

Fig. 7: Spatially varying relaxation times at photon emission energies of 2.756 eV (450 nm), 2.611 eV (475 nm) and 2.480 eV (500 nm) respectively. a): Relaxation time @ 450nm; b): Relaxation time @ 475nm; c): Relaxation time @ 500nm

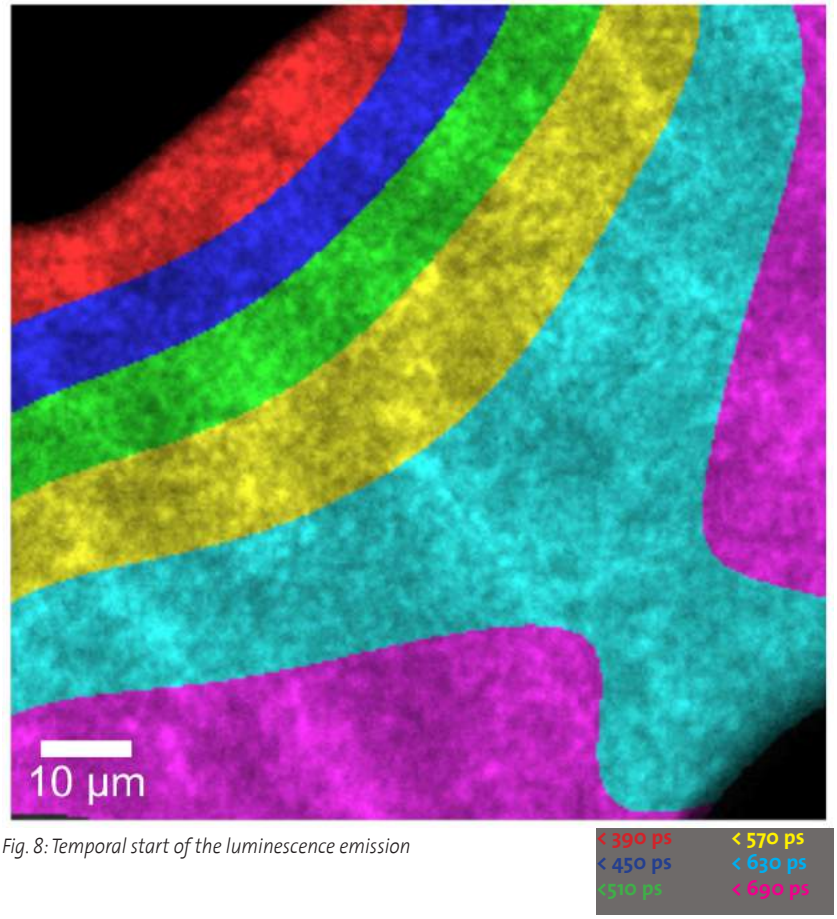

Fig. 8: Temporal start of the luminescence emission

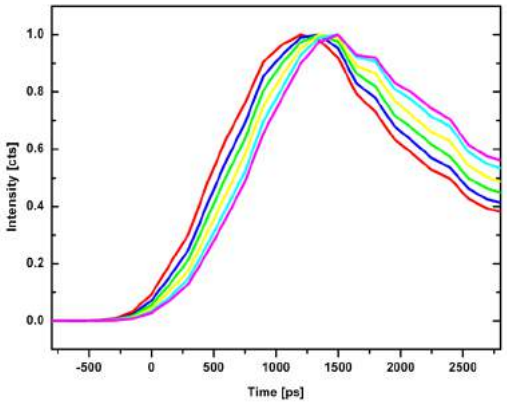

Fig. 9: Average time spectra of the colored areas in Fig. 8