Electro-Optical Characterization of 3D-LEDs

Nondestructive Inspection of 4'' Wafers in Bird’s Eye View by an FE-SEM

The optimization of three dimensional LEDs with core-shell geometry requires adapted characterization methods with high spatial resolution. Integrating manipulators with small probe tips inside a cathodoluminescence scanning electron microscope (CL-SEM) enables the investigation of local electro-optical properties without the need for elaborate contact preparation. Moreover this allows for precise monitoring of the contact position by SEM imaging and to correlate electroluminescence and CL measurements.

Introduction

Three dimensional light emitting diodes (3D-LEDs) with a core-shell geometry are supposed to have substantial advantages over conventional planar LEDs [1–3]. The active area along the sidewalls of the structures can considerably be increased by high aspect ratios - leading to a lower current density inside the InGaN multi quantum well (MQW) at the same operation current per substrate area. Such LEDs were recently developed within the frame of the EU-FP7 funded project GECCO and the DFG research group FOR1616. The production of devices out of arrays of these 3D-LEDs grown by metalorganic vapor phase epitaxy (MOVPE) is already scaling up to substrates with larger areas [4], generating a request for reliable characterization techniques of local electro-optical properties with high spatial resolution on different positions along the substrate. As also subsequent device processing should be performed on a wafer scale the applied techniques need to be non-destructive.

For this purpose, an electron microscope equipped with a field emission gun (FEG) and a large specimen chamber capable for full stage scanning of 4-inch wafers also in bird’s-eye view has been installed in 2015 at the epitaxy competence center (ec²) of Braunschweig University of Technology. Optical characterization inside the view field of the SEM is possible by a CL setup, which consists of a parabolic mirror inserted below the pole piece and a spectrograph attached to the system. The chamber is actively isolated from vibrations and piezo controlled manipulators are
mounted on the sample stage. This combination enables precise mechanical manipulation monitored by SEM imaging as well as electrical and electro-optical characterization of nanostructures.

Using a triax cabling for the electrical probes, also high impedances (e.g. single nanostructures) can be analyzed in a two- or three-point configuration.

**Configuration Details**

The system is based on a Tescan Mira3 GMH FE-SEM including scintillator based detectors for secondary electrons (ET-type SE and In-Beam SE) and backscattered electrons (motorized low-kV BSE) (fig. 1). The electron beam absorbed current (EBAC) as well as the electron beam induced current (EBIC) between two contacts can be measured and imaged by an integrated detector. Precise electrical contacting is performed using Kleindiek MM3A-EM manipulators equipped with low current measurement kits (LCMK). Beside these detectors for electron related signals a Gatan MonoCL4 CL-setup is attached to the microscope chamber to monitor photon-related response from the sample. Its parabolic collection mirror was designed on request for investigation of planar samples at tilt angles up to 30 °.

Due to the FEG a small electron probe spot can be achieved in the optical focus point at a working distance of 10 mm, even with beam energies of only a few keV. This enables a high spatial resolution also in BSE, CL and EBIC imaging, although probing of 3D-structures is influenced by scattering and shadowing of signals in the ensemble. At such conditions, electrical and optical properties of the sample, e.g. the gradient (fig. 2) or fluctuations in the pn-junction and InGaN QW along the sidewall [2,5], can be probed with a high spatial resolution.

The opening figure presents a color overlay of the SE (red) and EBIC (cyan) image of an ensemble of InGaN/GaN core-shell LEDs visualizing the light emitting region of the center structure contacted by a tungsten probe tip.
**Optical Detection**

The optical spectrometer setup is equipped with different diffraction gratings and a CCD camera for parallel detection of a whole spectrum in a single shot as well as a photomultiplier (PMT) for fast band pass detection of luminescence, both covering a broad spectral range from the UV to the NIR. The PMT is used for fast mapping of CL excitation images, in particular for subsequent capturing stacks of monochromatic images taken at different wavelength. Such stacks are used for evaluation of optical properties with a high spatial resolution; arbitrary band pass images can be generated also by post processing or by optical filters (fig. 2). The SEM is able to grab up to four signals simultaneously during the full pixel dwell time (starting at 20 ns). A drift correction of slices in the stack can also be applied afterwards by correlating corresponding SE images. However, with respect to the small drift of samples fixed by clamping this is usually not necessary. CL spectra probed by exciting a small region of the sidewall reveal a gradient of the InGaN/GaN MQW emission along the height (fig. 2). This CL also includes defect related yellow luminescence (YL) and near band edge emission (NBE) from the GaN outside the active region.

**Tilting the Electron Beam**

The electron optics (EO) of this FE-SEM is also capable of rocking the electron beam in a cone of up to ±12° for mapping of electron channeling patterns (ECP) on a small area of about 15 µm in diameter. Such ECP are also used to align the sample (via stage tilt and rotation) in specific diffraction conditions of the crystal structure to evaluate the density of threading dislocations and its type by electron channeling contrast imaging (ECCI) [6]. By switching from the BSE detector to the mirror for light collection also a correlative analysis of ECCI with EBIC and CL can be performed at the same diffraction condition.

This EO tilt can also be used to image the sample by the SEM from a certain direction without affecting the tip contact by stage movement. A subsequent scanning of the sample from different incident directions enables topography reconstruction and generates a three dimensional impression, e.g. by a stereographic image as given in figure 3.

**Beam Blanking for Electrical Measurements**

Beside in situ measurements the point contacts are used to obtain the IV-characteristics and also electroluminescence (EL) utilizing the CL-setup while blanking the electron beam (fig. 2). Care is given to arrange the probe tip for contacting in the position of the optical focus, neither touching nor significantly shadowing the mirror and sample. Due to lack of a contact layer the current is
crowding locally at the contact [5].

EL spectra evolve already at currents of a few nA locally driven through the point contacts on small InGaN/GaN LED structures. The MQW emission of EL is shifted compared to CL which is assigned to the different types of excitation and might also be related to an inhomogeneous MQW stack. No significant current spreading occurs along the p-type GaN shell as it has a lower conductivity than the n-type region; hence the EL is mainly originating from a small volume close to the contact. Subsequent contacting at different positions therefore gives a sub-µm spatial resolution of local electro-optical properties and the gradient of the InGaN composition along the sidewall facet can also be revealed by EL spectra [1,7,8].

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**References**

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