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Use of Wavelength- and Angle-Resolved Cathodoluminescence for Spectroscopic Analysis of the Emission Pattern of a Nitride Semiconductor Micro Pillar Array

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Spectroscopic cathodoluminescence (CL) — the analysis of the wavelengths of light emitted from a sample stimulated by (typically) the electron beam of a scanning electron microscope (SEM) — has been used widely to study material quality and compositional variations in compound semiconductors and to study light-matter interactions in nanophotonic applications. Traditionally, CL detectors analyzed only the wavelength distribution of the emitted light however, recent advancements in detector technology also now enable the direction (angle) and polarization distributions to be determined [e.g. 1]. Recently we reported an optimized method to capture the wavelength and angular distributions simultaneously over a large numerical aperture, with virtually no loss in resolutions using a technique termed wavelength- and angle-resolved cathodoluminescence (WARCL) [2]. Here, we extend the WARCL technique to study the emission pattern as a function of wavelength of a nitride semiconductor micro-pillar array.

Despite light emitting diodes (LEDs) displacing incandescent and fluorescent bulbs in many lighting applications, devices based on micro-pillar arrays offer potential improvements in brightness and energy efficiency compared to thin-film technologies. Furthermore, directly addressable micro-pillars (micro-LED) arrays are highly promising candidates as displays where the enhanced light extraction and controllable emission patterns make them an attractive technology [3]. However, to understand and optimize light extraction and uniform color rendering with the desired emission angles it is necessary to correlate and control the structural properties of micro-pillars with spectroscopic analysis of the emission patterns.

We analyzed a 10 x 10 array of core-shell GaN-InGaN micro-pillars using a Monarc cathodoluminescence system (Gatan Inc) attached to an FE-SEM. Intense light emission was observed across the visible spectrum (400 – 720 nm) and angle-resolved (AR) CL revealed significant anisotropy in emission, as shown in the integrated intensity emission pattern (Figure 2). Six emission maxima were observed normal to the six {10-11} facets whereas emission in the direction close to the substrate surface normal was ~5x weaker. The lack of spectral sensitivity in the ARCL technique is a major drawback due to the inability to determine the uniformity in emission color. We used the WARCL technique to overcome this, reconstructing emission patterns at 670 wavelengths across the visible spectrum (spectral resolution ~1.5 nm). Strong variation in the emission pattern as a function of wavelength was observed, Figure 3. Variation in emission patterns was also observed between micro-pillars, believed to be a result of the micro-pillar shape directly influencing light extraction and the effect of optical interference.

Nitride semiconductor micro-pillars offer great promise as display technologies however, the results presented here demonstrate the importance of determining device structure precisely and directly correlating the wavelength and angular distributions of the light emission in developing displays with uniform color rendering.

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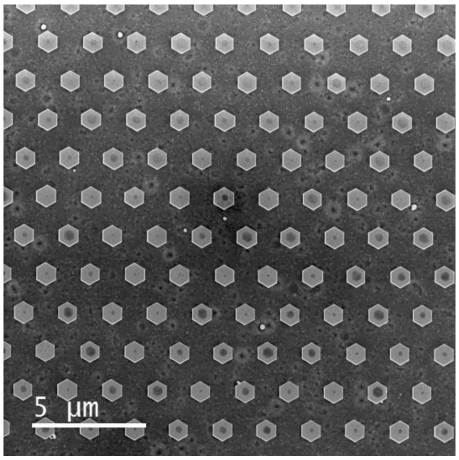

Figure 1. Secondary electron image of the hexagonal micro-pillar array. Individual micro-pillars are nominally 1.4 µm tall, 800 nm wide and separated by 1 µm.

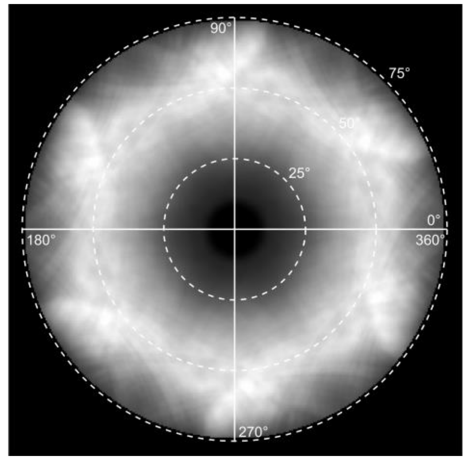

Figure 2. Integrated intensity emission pattern determined by angle-resolved cathodoluminescence.

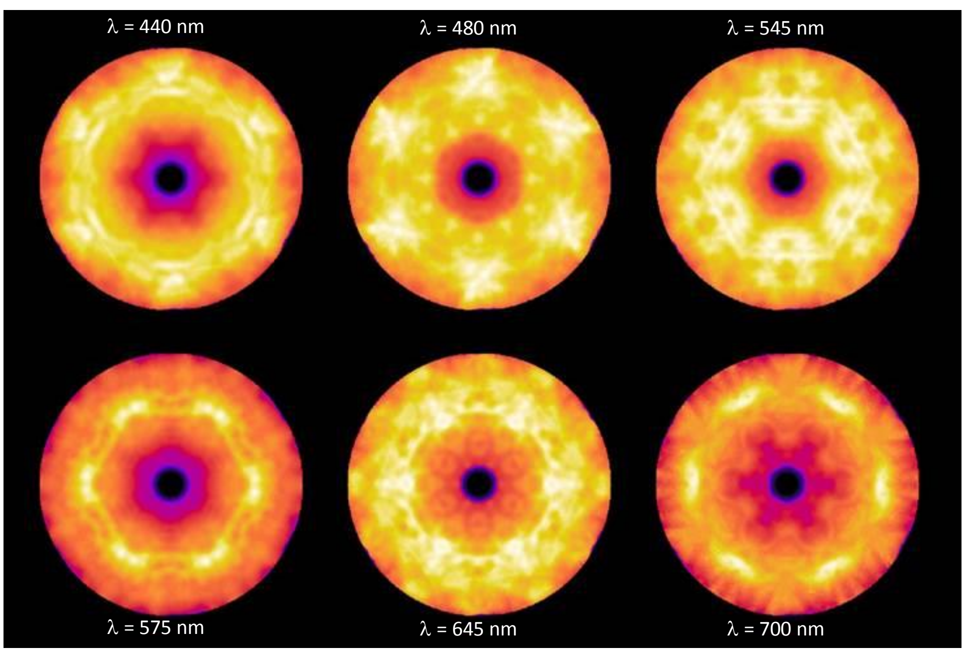

Figure 3. Wavelength-filtered emission patterns (normalized by intensity) extracted from the wavelength- and angle-resolved cathodoluminescence data cube (670 emission patterns in total), central wavelength as indicated, bandpass ± 1.5 nm. Angular scale annotations removed for clarity but are identical to that displayed in Figure 2.

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