Characterization of InGaAs/GaAs quantum dots optimized for room temperature emission in the 935 - 955 nm range for application in water vapor detection with broadly tunable VCSELs

P. Szott[1], **S. Tripathi**[2], **S. Gorantla**[3], **B. Kamiński**[1,4], **D. Pucicki**[3,5], **S. Rodt**[2], **A. Musiał**[1],**W. Rudno-Rudziński**[1], **S. Reitzenstein**[2] **and G. Sęk**[1]

[1] *Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland*
[2] *Institute of Solid State Physics, Technical University of Berlin, Berlin, Germany*
[3] *Łukasiewicz Research Network – Polish Center for Technology Development, Wrocław, Poland*
[4] *Airoptic Sp. z o.o, Poznań, Poland*
[5] *Department of Nanometrology, Faculty of Electronics, Photonics and Microsystems, Wrocław University of Science and Technology, Wrocław, Poland*

Vertical-cavity surface-emitting lasers (VCSELs) offer several advantages over typical edge-emitting devices, for instance excellent beam properties or direct coupling to optical fibers. Their production yield is high, and they can be easily processed into monolithic 2D arrays due to a small footprint. In addition, low power consumption makes them suitable for integration into portable devices. All these features are demanded for application in the laser-based gas analyzers, which would benefit from reduction in production costs, whereas wide spectral tunability would make such VCSELs ideally suited for multi-line gas detection. However, it requires a wideband gain medium which is offered by an ensemble of epitaxial quantum dots (QDs), with their intrinsic nonuniformities causing large inhomogeneous broadening of any spectral response. In that context, we have performed optimization of MOCVD-grown InGaAs QDs on GaAs substrates to make them suitable for active region of a VCSEL operating in the range of 935 – 955 nm at room temperature, to match the characteristic absorption lines of water vapor. It is the most commonly measured component in many industrial process control and emission monitoring systems today, including especially the production and transfer of natural gas, liquefied natural gas or hydrogen, which all require efficient and reliable moisture control. However, the spectral range of interest is hardly reachable by InGaAs/GaAs QDs. Therefore, our work focused on a multistep optimization of such QD structures in a form of low-strain (low In content) InGaAs QDs embedded in GaAs or AlGaAs barriers, and stacked into multilayers necessary to maximize the gain of an operational device. Modifications in the composition of QDs and barriers were used to tailor both, the spectral range of emission and radiative efficiency. In addition, rapid thermal annealing was employed for the post-growth tuning to further blue shift the emission and enhance its intensity via defect curing. The optimization feedback loop involved also cross-sectional transmission electron microscopy, combined with energy-dispersive X-ray spectroscopy, to probe both, the dots morphology and the composition profiles. Those constituted the input parameters for electronic structure modeling performed with the commercial nextnano software. Eventually, we also investigated temperature dependence of PL to characterize the main intensity decay mechanisms and to probe changes in the strength of carrier confinement. Bright and spectrally broad emission (above 50 nm) has been obtained in the targeted range at room temperature, which is a milestone requirement on the way to develop a low-cost VCSEL-based spectroscopic system capable of sensing low concentrations of water vapor for industrial applications.

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