Abstract:

This dissertation presents the results of spectroscopic studies that enabled the experimental verification of the optical properties of novel solutions supporting the development of VCSEL (Vertical Cavity Surface Emitting Lasers) emitting in the mid- and long-wavelength infrared range. The development of light sources in this spectral range is crucial for applications such as optical gas detection. In this context, VCSELs offer a promising alternative to traditional edge-emitting lasers, providing high beam quality, single-mode operation, and wavelength tunability. The presented research focuses on the key components of these lasers that form the resonant cavity, such as Distributed Bragg Reflectors (DBRs) and High Contrast Gratings (HCGs). Extensive spectroscopic investigations supported by numerical simulations were conducted, allowing for the selection and optimization of the geometric parameters of these semiconductor structures.

The first part of the dissertation provides a theoretical introduction to the research topic, explaining the motivation behind the study and discussing the most important optical gas detection techniques. It then describes semiconductor light sources operating in the mid- and long-wavelength infrared range and their key components, with particular emphasis on quantum wells and reflective elements (mirrors) forming the resonant cavities. The following section of the dissertation discusses in detail the epitaxial growth techniques, modifications of semiconductor structures, and spectroscopic techniques used for optical characterization. The final part presents the experimental results.

One of the key achievements of this work is demonstrating the feasibility of fabricating HCGs with a high reflectivity and tunability achieved solely through etching depth variation, operating in the mid-infrared range. In the case of HCGs etched into the core of a quantum cascade laser, a 1500% increase in photoluminescence intensity was observed when an appropriately etched grating was applied. The studies confirmed that properly designed gratings can control the polarization of transmitted or reflected light, making them potential components for VCSELs based on quantum cascade laser active regions.

Further research focused on developing novel Bragg reflectors, including hybrid DBRs with metallic layers and so-called plasmonic mirrors, where the refractive index contrast was achieved by using layers with significantly different doping levels. These mirrors achieved reflectivity exceeding 90%, opening new possibilities for their application in vertical-cavity structures emitting in the mid-infrared range.

FTIR (Fourier Tansform Infrared Spectroscopy) measurements conducted as part of this research, combined with ellipsometry measurements and microscopic imaging, additionally

enabled the determination of refractive indices for semiconductor materials used in modeling and designing optoelectronic devices in the mid- and long-wavelength infrared range. The temperature dependence of the refractive indices for InP, InGaAs, AlAs, and GaAs was determined in the 10–300 K range. This knowledge allowed for reducing the number of unknown parameters used in the simulation of reflection spectra for DBRs designed for this spectral range.

In summary, the conducted studies enabled the optimization of Bragg reflectors and HCGs and provided a deeper understanding of their optical properties. The results presented in this dissertation open new possibilities for designing VCSEL components intended for emission in the mid- and long-wavelength infrared range, representing a significant contribution to the development of optoelectronic technology, particularly in the context of next-generation lasers used for applications such as precise gas detection. Finally, the research results have been published in renowned scientific journals such as Optics Express, Physical Review Applied, and Opto-Electronics Review.