Abstract

Mid-infrared spectroscopy is an extremely useful and versatile technique to identify the chemical composition of gases, liquids, and solids via their unique absorption lines. The miniaturization of sensing systems is an important research topic, gaining momentum during the last couple of years. So far, all miniaturized concepts have been demonstrated with external optics, lasers or detectors. This thesis reports the realization of a monolithic approach, combining the source, the interaction region and the detector on a single chip. This work involved the full range and variety from the initial idea and concept development over the design and modelling to the device fabrication and experimental demonstration. Moving from the state-of-the-art to a single-chip solution required several important steps.

In a first step, a new class of intersubband devices was developed combining emission and detection capabilities with the very same semiconductor heterostructure. Simply by changing the applied bias, the quantum cascade device can be switched between laser and detector operation. Once the layer structure has been grown on a substrate, different parts of the chip can be used for lasers and others for detectors. With the introduction of a refined design approach, the horizontal-vertical extraction scheme led to high performance bi-functional quantum cascade laser and detectors with output power levels and efficiencies comparable to conventional lasers. Owing to direct coupling and the optimized quantum design, their photodetection capability provides a better performance than available discrete detectors operated at the same temperature.

In a second step, the lasers and detectors were connected with a surface plasmon polariton (SPP) waveguide. SPPs are optical surface waves that propagate along a metal/dielectric interface and are perfectly suited for on-chip sensing applications. Owning to their evanescent nature, 96% of the mode stays outside and interacts with substances, which are present on the waveguide surface. The introduction of the dielectric loading concept for mid-infrared plasmonics enabled to solve several fundamental problems that previously prohibited the exploitation of their full potential. The commonly weakly confined SPPs are squeezed, such that they are stronger bound to the interface and enable the direct coupling to and from the active devices. Furthermore, the elimination of the metal edges in narrow, laterally single mode waveguides leads to a reduction of the attenuation by one order of magnitude.

In a first prototype experiment, the entire device was submerged into a mixture of ethanol and water. A limit of detection of 0.06% over a wide range of concentrations from

0 to 60% clearly demonstrated the huge potential of the presented integration concept. In a second experiment, the device was extended to a multi-wavelength sensor combining multiple laser/waveguide/detector elements, each sensitive to another wavelength. Narrow mode laser emission at defined wavelengths was achieved by incorporating distributed feedback gratings on the laser waveguides. The additional spectral information, as well as the reduction of pulse-to-pulse and temperature induced noise provides the capability to detect single or multiple chemicals in a complex mixture of chemicals with ppm resolution.

The presented on-chip concept is now at a stage, where it can be adapted to particular applications. This thesis provides the required information and background of all electrical and optical parts and initializes a new class of miniaturized sensing devices.