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QCLs: 20 years of discoveries
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Monolithically integrated chemical sensor based on intersubband transitions and plasmonics

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1. Introduction

The miniaturization of mid-infrared sensing setups 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. In this work, we present a monolithic mid-infrared on-chip sensor, comprising the source, the interaction zone and the detector on the same substrate. In order to realize this, we combine two major technologies: intersubband transitions in quantum wells and surface plasmon polaritons.

2. Bi-functional quantum cascade laser/detector

Quantum cascade lasers are one of the most important compact coherent light sources in the mid-infrared, offering high power, engineerable emission wavelengths, room-temperature operation, etc. [1]. Such a quantum cascade laser can also act as a photovoltaic detector, but at a significant lower wavelength. This shift is because the detectors optical transition occurs between the upper laser level and an extraction level, not the lower laser level. Going one step further, QCLs can be designed in such a way, that they provide detection functionality at the same laser emission wavelength [2, 3]. Therefore, we use computational optimization utilizing an efficient semi-classical Monte-Carlo simulator. This design framework gives us the flexibility we need to develop bi-functional intersubband devices. We have compensated the intrinsic energy-shift by reducing the coupling of the lasers extraction levels and by down-shifting the upper level at zero bias via precise coupling adjustments. Additionally, we provide efficient electron injection/extraction to/from the upper level when used as laser/detector. Although wavelength matching limits the design freedom, our recently designed structure works at room temperature with a pulsed laser emission of 400 mW at 6.5 µm and a superior detection performance, compared to discrete quantum cascade detectors (one order of magnitude higher responsivity). The integrated detector has a responsivity of 45 mA/W at room temperature (30% of the theoretic maximum for 37 periods), extremely low noise and does not saturate at QCL power levels when a current amplifier is used.

3. Dielectric-loaded SPP waveguides

Surface plasmon polaritons (SPPs) are used to efficiently guide light from the laser to the detector. An SPP is an electromagnetic wave propagating along a metal/dielectric interface. Due to the evanescent nature of SPPs the mode is mainly located outside, which is beneficial to enhance the interaction with a surrounding chemical substance. In the mid-infrared, SPPs are commonly very weakly confined, as in this wavelength region metals have a large negative permittivity [4]. By applying a thin (200 nm thick) dielectric layer on top of an unpatterned metal surface, the propagation properties of the SPP can be modified in such a way, that it the SPP is strongly bound to the interface [5]. This increased confinement enables an efficient end-fire coupling to the dielectric waveguide of the laser and the detector via spatial mode matching. As a further advantage, the thin dielectric layer can be used to reduce the waveguide loss in narrow SPP waveguides. Commonly SPP waveguides are fabricated as metal stripes to provide lateral guiding. Due to scattering on the metal edges the propagation length drops with decreasing stripe width. The obvious solution is to eliminate this metal edges, which can be achieved by patterning the thin dielectric layer as a strip on top of unpatterned gold. With this structure, we report a coupling efficiency of up to 50% from the laser to the detector through a 50µm long SPP waveguide.

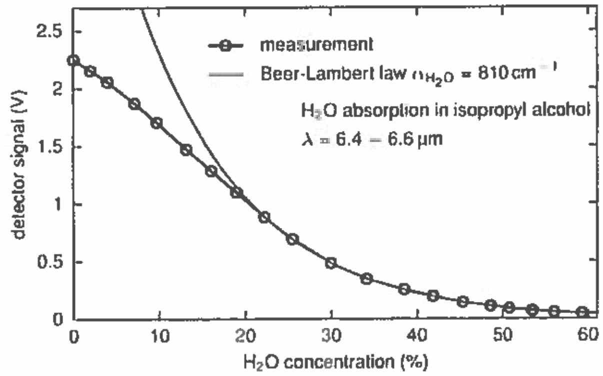

Figure 1: On-chip absorption measurement of a water in isopropyl alcohol. At low concentrations the detector saturations due to the high negative reverse bias. This effect is not present, when a current amplifier is used.

4. Chemical sensing

We demonstrate a fully integrated mid-infrared sensor for high dynamic range sensing. The bi-functional quantum cascade laser/detector structure is used to generate and detect the mid-infrared radiation. A 100 μm long dielectric loaded surface plasmon polariton waveguide acts as an interaction region and in parallel provide a high coupling efficiency. To prove the functionality of the sensor, we submerged the entire unpassivated device in a solution of isopropyl alcohol (low absorption) and water (high absorption). Figure 1 shows the detector signal versus the water concentration, which agrees with Beer-Lamberts law with $\alpha_{H_2O}(\lambda \approx 6.5\ \mu m) = 810\ cm^{-1}$. While longer waveguides are preferable to increase the sensitivity for low concentrations, short interaction length are beneficial if the background absorption is high, e.g. water containing liquids or high concentrations of the chemicals. Without any pulse-to-pulse normalization we achieve a resolution of 0.06% over a large dynamic range. A significant higher resolution can be achieved when normalizing pulse-to-pulse intensity, as well as temperature fluctuations with a second detector on the back facet of the laser.

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5. References

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