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A new aluminum-free material system for intersubband emitters and detectors

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Abstract. We report on the InGaAs/GaAsSb material system lattice-matched to InP for intersubband devices. Due to the much lower electron effective mass in the GaAsSb barrier material, this system is very promising for the realization of high performance intersubband devices, like quantum-cascade lasers and quantum well infrared photodetectors. Type I intersubband absorption in InGaAs/GaAsSb multi-quantum wells samples has been studied experimentally and the conduction band offset at the InGaAs/GaAsSb hetero-interface has been determined to be 360 meV. Additionally, we realized the first Al-free QCL based on the same material system, emitting at a wavelength of 11.3 μm.

1. Introduction
Modern mid-infrared and far-infrared optoelectronic devices, such as quantum cascade lasers (QCLs) [1] and quantum well infrared photodetectors (QWIPs) [2], exploit intersubband (ISB) transitions in semiconductor quantum wells (QWs). High power and high temperature performance QCLs have been demonstrated in InP-based [3, 4] and GaAs-based materials system [5, 6]. For the shorter wavelengths (2.75-4 μm), strain compensated InGaAs/AlGaAs and InAs/AlSb based QCLs have been reported [7, 8], while GaAs/AlGaAs QCLs have been shown for the terahertz range (60-300 μm) [9]. An aluminum-free material system, where the effective mass of the electrons in the barrier acting layers is much lower, would be desirable. Higher optical gain and improved device performance are expected to be the consequence of this [10, 11]. Besides the development of II-VI materials in recent years [12], a very promising candidate to this aim is the InGaAs/GaAsSb material system lattice-matched to InP, which shows a type II alignment, with the InGaAs being the well for the electrons and the GaAsSb for the holes [13, 14]. We report on ISB absorption in InGaAs/GaAsSb multiple quantum wells, where the transitions between the quantized states within the conduction band are investigated. Using the measured CBO we designed and fabricated the first aluminum-free QCL.

2. Intersubband Absorption
The samples consisting of 30 periods of In0.53Ga0.47As/GaAs0.51Sb0.49 QWs were grown lattice-matched to InP substrates by solid-source molecular beam epitaxy (MBE) [15]. The thicknesses of the InGaAs
wells range between 4.5 and 12 nm. In order to supply electrons in the wells, the wells were Si doped in the center to a sheet density of $5 \times 10^{11}$ cm$^{-2}$. The thickness of the GaAsSb barriers is 50 nm.

For the ISB absorption measurements, the samples have been cleaved into 3x10 mm$^2$ pieces and the facets have been 45° polished in order to allow multi-pass waveguide geometry [16]. The light from a broadband source is focused onto one of the polished facets and the light coming out from the opposite facet is refocused on a liquid-nitrogen cooled HgCdTe detector. The signal of the detector is then dispersed in a Fourier-transform infrared (FTIR) spectrometer. The incoming beam was prepared in the TM-polarization (the electric field of the optical wave is along the growth axis) and TE-polarization (the electric field of the optical wave is in the plane of the wells) and all measurements have been performed at room temperature.

The ISB absorption spectrum is obtained by taking the negative natural logarithm (-ln) of the transmission ratio TTM/TTE. Very clear ISB absorption peaks are observed in a broad spectral region, where the transition energy decreases from 214-107 meV (5.8-11.6 µm) by increasing the well width from 4.5-12 nm. In addition, the ISB absorption peaks show a full-width at half-maximum (FWHM) of $\sim 17$ meV, which is very close to the value obtained for state-of-the-art bound-to-bound transitions in InGaAs/InAlAs QWs [15, 16].

The ISB transition energies have been modeled using the envelope function approximation considering the nonparabolicity of the conduction band [16]. Since the sheet electron density is quite high in the QWs, we solved Schrödinger’s and Poisson’s equations self-consistently, including the exchange-correlation potential. The collective shift of the ISB resonance peak due to depolarization and excitonic shift has also been considered. Since the wells are decoupled because of the thick GaAsSb barriers (50 nm), the calculations have been performed assuming a single QW only. The
values of the electron effective mass used in the calculations are $0.043m_0$ and $0.045m_0$ for the InGaAs wells and GaAsSb barriers respectively [17, 18]. By performing a least squares fitting between the theoretically calculated transition energies and the experimental ISB resonances, we obtain a CBO at the InGaAs/GaAsSb hetero-interface of 360 meV, in agreement with Hu et al. [13]. An excellent agreement is obtained between the theoretical calculation and the experimental results over the whole range of well thicknesses, as shown in Figure 1.

3. Quantum Cascade Laser

The QCL samples have been grown lattice-matched on an n-doped ($2\times10^{17} \text{ cm}^{-3}$) InP substrate by MBE. The QCL active region has been designed following a 3-well scheme [5] and consists of 40 repetitions of an injector/active cell superlattice. The layer thicknesses in angstroms are as follows: $81/27/13/67/22/59/70/50/19/12/19/38/27/38/28/32$. The GaAs$_{0.51}$Sb$_{0.49}$ barrier layers are in bold, while the underlined layers are Si doped ($4\times10^{17} \text{ cm}^{-3}$). As shown in Figure 2, the ground state of the injector (g) and the upper laser level (3) align at a field of 30 kV/cm. The calculated energy separation between the levels 3 and 2 is 114 meV, which corresponds to an emission wavelength of 10.9 µm. The active region is placed between upper and lower In$_{0.53}$Ga$_{0.47}$As layers, 600 and 100 nm respectively, doped $1\times10^{17} \text{ cm}^{-3}$. The growth is completed by a heavily doped contact layer.

![Figure 3](image3.png)

**Figure 3.** Light-current-voltage curve of a 60µm-wide, 2mm-long ridge InGaAs/GaAsSb quantum cascade laser at a temperature of 78K.

The samples have been processed into 60 µm-wide ridges by reactive ion etching. Afterwards, a 300 nm-thick SiN layer and a Ti/Au top ohmic contact were deposited in a way that an aperture is left on the top of the ridges, in order to form a low-loss air-waveguide. The back contact of the lasers is a standard Ge/Au/Ni/Au ohmic contact.

![Figure 4](image4.png)

**Figure 4.** Spectrum of the light emitted by a 60 µm-wide ridge InGaAs/GaAsSb quantum cascade laser. The spectrum has been taken at a current density of 3.6 kA/cm², corresponding to the maximum optical output power in the light-current curve.
For the optical measurements, the lasers were cleaved into 2 mm-long bars and mounted on the copper cold finger of a cryostat equipped with ZnSe windows, kept at a temperature of 78K. The lasers are operated in pulsed mode, with a pulse width of 100 ns and a repetition frequency of 5 kHz. The light-current-voltage (LIV) curves and the spectra of the emitted light are recorded by a deuterated triglycine sulfate (DTGS) detector and a Fourier transform infrared (FTIR) spectrometer. In Figure 3, the LIV of a 60µm-wide ridge InGaAs/GaAsSb QCL is presented. The threshold current density and the maximum optical output power are 1.7 kA/cm² and 20 mW, respectively, at a temperature of 78 K. In Figure 4, the spectrum of the light emitted is shown.

4. Conclusions
We observed room temperature ISB absorption in InGaAs/GaAsSb MQWs lattice-matched to InP. The ISB absorption of five samples with different well widths covers a broad spectral region (5.8 - 11.6 µm). By using a value for the CBO at the InGaAs/GaAsSb hetero-interface of 360 meV, the experimental results are in excellent agreement with the theoretical calculations. Furthermore, we demonstrated the first aluminum-free QCL, realized in the InGaAs/GaAsSb material system lattice-matched to InP. A threshold current density and maximum optical output power of 1.7 kA/cm² and 20 mW respectively at 11.3 µm emission wavelength are reported at a temperature of 78K.

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References