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Growth of novel InAs sources and detectors

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14. ABSTRACT

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The InAs/AlAsSb QCD was grown lattice-matched on unintentionally doped InAs substrates with a Riber Compact 21 molecular beam epitaxy (MBE) chamber. The active region was designed using an 8-band k â‹… p-method formalism. The electron transport includes scattering mechanisms, such as longitudinal optical (LO)- and acoustic phonon scattering, interface roughness scattering, and alloy
scattering. The designed wavelength is 2.7 µm, which is in the center of a CO2 absorption band. A surface diffraction grating was simulated and fabricated to allow top-side illumination of this short wavelength QCD that is additionally detecting above the bandgap energy of the InAs substrate. The electrical and optical characterization was performed in ambient conditions and in a cryostat, cooled in
temperature-steps to 80 K, with a Bruker Vertex 70v Fourier-transform infrared spectrometer (FTIR) and a broadband mid-infrared (MIR) Globar source.

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Final Report for EOARD Grant FA9550-17-1-0340

"**Develop the Molecular Beam Epitaxy Growth and Design of InAs-based Mid-infrared Quantum Cascade Detectors**"

November 25, 2021

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Abstract:

The growth conditions for the molecular beam epitaxy (MBE) of lattice-matched InAs/$AlAs_{0.16}Sb_{0.84}$ on InAs substrates were developed. Using experimental techniques such as high-resolution X-ray diffraction (HR_XRD), atomic force microscopy (AFM), and reflection high-energy electron diffraction (RHEED), the quality of the grown films and heterostructures was investigated and improved. This was done by taking shutter effects into account and interface engineering with shutter sequences.

A quantum cascade detector (QCD) designed for the wavelength of 2.7 µm was grown. HR-XRD shows sharp superlattice peaks for this device, indicating low interface roughness supported by AFM measurements. The QCD was designed for top-side illumination, and diffraction gratings were simulated using COMSOL and fabricated using electron beam lithography and dry-etching.

The QCD was optically characterized with surface-normal illumination using a Fourier transform infrared spectrometer (FTIR) with a Globar light source in ambient conditions and inside a cryostat cooled down to 80 K. A room temperature peak responsivity of 5.63 mA/W was found; from this and the current-voltage measurements, a specific detectivity of 1.37×10^8 Jones was calculated.

Accomplishments

Research Objectives:

There are three goals of the research in this 3-year project: 1) improve AlAsSb epitaxy lattice-matched to InAs substrates, 2) design and realize a short-wavelength above-bandgap quantum cascade detector (QCD), 3) design and realize a light coupling mechanism for surface-normal illumination.

The InAs/AlAsSb QCD was grown lattice-matched on unintentionally doped InAs substrates with a Riber Compact 21 molecular beam epitaxy (MBE) chamber. The active region was designed using an 8-band $k \cdot p$-method formalism. The electron transport includes scattering mechanisms, such as longitudinal optical (LO)- and acoustic phonon scattering, interface roughness scattering, and alloy scattering. The designed wavelength is 2.7 µm, which is in the center of a CO_2 absorption band. A surface diffraction grating was simulated and fabricated to allow top-side illumination of this short wavelength QCD that is additionally detecting above the bandgap energy of the InAs substrate. The electrical and optical characterization was performed in ambient conditions and in a cryostat, cooled in temperature-steps to 80 K, with a Bruker Vertex 70v Fourier-transform infrared spectrometer (FTIR) and a broadband mid-infrared (MIR) Globar source.

This research was conducted at the Technische Universität Wien (TU Wien) in the Institute of Solid-State Electronics (FKE) and the cleanroom located in the Center for Micro- and Nanostructures (ZMNS).

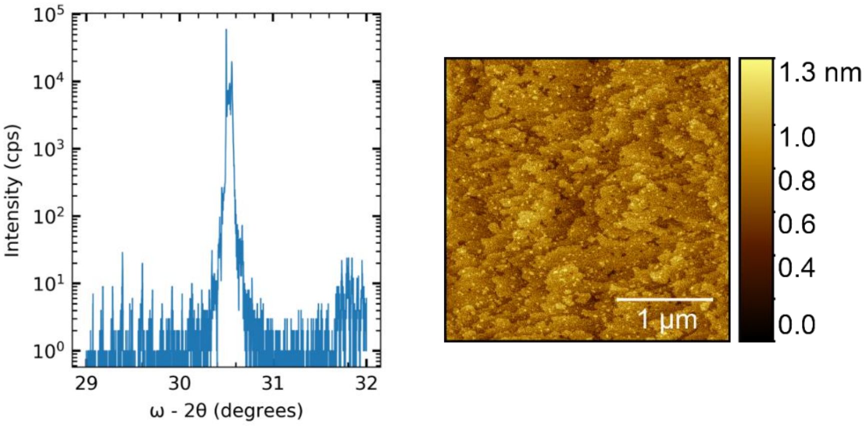

Figure 1: a) HR-XRD (004) ω-2θ scan of the grown 2.7 µm QCD. **b)** 3×3 µm AFM scan, whereas the 10×10 µm AFM scan shows an RMS surface roughness of 0.228 nm.
Taken from M. Giparakis et al. (*submitted to APL*).

Details of accomplishments:

Figure 1 a) shows the high-resolution X-ray diffractogram (HR-XRD) (004) ω-2θ scan of the grown QCD detecting at a wavelength of 2.7 µm. Sharp superlattice peaks indicate low interface roughness. The growth of high-quality films is supported by the atomic force microscope (AFM), see Figure 1 b), where a 10×10 µm scan shows a root mean squared (RMS) roughness of 0.228 nm. This is not much rougher than a commercially available InAs substrate with an RMS of approximately 0.2 nm.

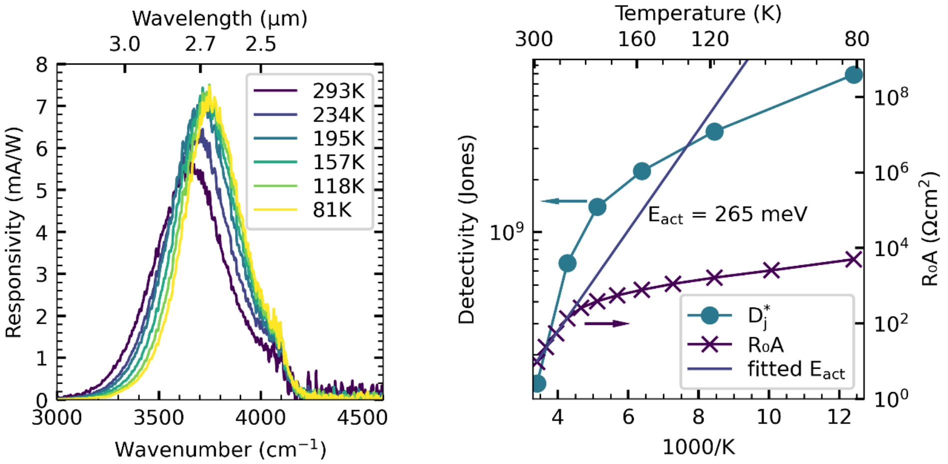

Figure 2: a) Measured responsivity of the 2.7 µm QCD at different temperatures of the 200×200 µm surface grating. **b)** Specific detectivity at different temperatures to the left and the differential resistance at zero voltage times the electrical area product to the right.
Taken from M. Giparakis et al. (*submitted to APL*).

The final process of the QCD detecting at 2.7 µm includes for three different grating periods (0.97 µm, 1.24 µm, and 1.98 µm) 4 different surface grating sizes: 50×50 µm, 100×100 µm, 150×150 µm, 200×200 µm. Each grating has a 20-µm-wide Ti/Au contact around the perimeter, making the mesa 40 µm longer per side than the surface grating, see Fig. 8.

In Figure 2, the responsivity of the 200×200 µm surface grating at different temperatures is plotted. Note that there is minimal temperature dependence in the responsivity at temperatures from 200-80 K while a blue shift still occurs. The responsivity at room temperature is 5.63 mA/W at 2.73 µm (3650 1/cm) and it increases to 7.49 mA/W at 80 K. The measurements inside the cryostat were scaled according to a measurement of the same device at ambient conditions to compensate for the reduced transmission of the cryostat window and the shadowing effects of the window.

From the responsivity and the current-voltage (IV) characteristics, the specific detectivity can be calculated to be 1.37×10^8 Jones at room temperature, see Fig.2 b). For this purpose, the differential resistance at zero voltage was extracted from the IV curves. From the differential resistance, electrical area product plotted over the temperature, the activation energy can be fitted/calculated to be 265 meV.

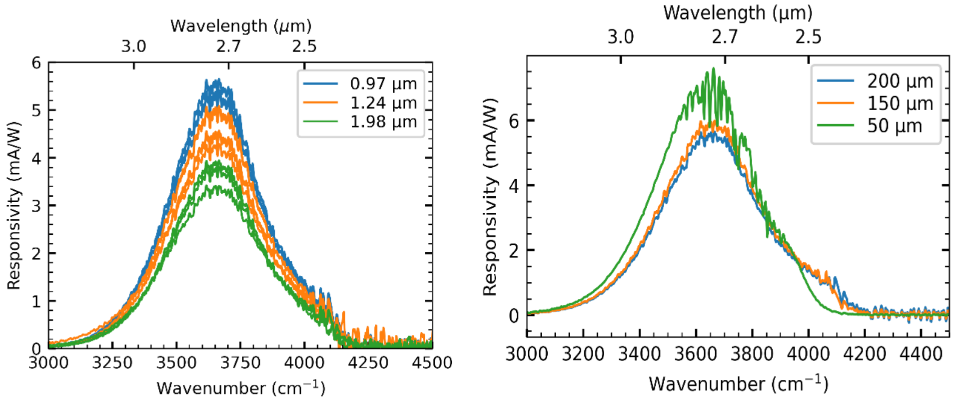

Figure 3: a) Responsivity measurements of 200×200 µm surface grating with different grating periods at ambient conditions. **b)** Responsivity of different sized surface gratings with a grating period of 0.97 µm at ambient conditions.

Figure 3 a) shows the comparison of responsivity measurements for different grating periods. Whereas the grating period of 0.97 µm performed the best, followed by the 1.24 µm and the 1.98 µm. This agrees with the COMSOL simulation for the etched depth of 980 nm, red line in Figure 6. Comparing the different surface grating sizes, whereas no data for the 100×100 µm devices exists, the 50×50 µm devices showed the highest responsivity, see Figure 3 b).

Figure 4 shows the IV curves of the different surface grating sizes divided by a) their area and b) their circumference. At least for the 200 µm and the 150 µm surface gratings, the leakage current scales with the circumference and not the area. These results suggest surface leakage. In future work, leakage paths will be analyzed and processing will be adapted to suppress any leakage current.

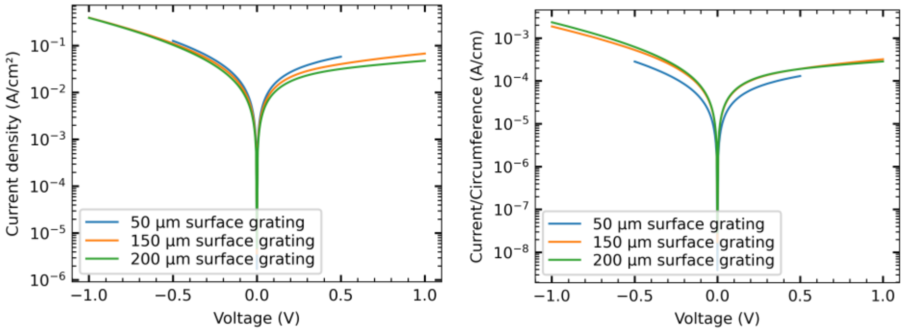

Figure 4: IV measurements of differently grating sizes at ambient conditions.

Dissemination of the results:

The results were disseminated by presentations at conferences and papers published in peer-reviewed journals. As a public institution, the TU Wien encourages Open Access publishing when possible. Please see the List of Publications and Presentations at the end for details.

Impacts

Development of the principal discipline(s) of the project:

QCDs are a unique classification of MIR photodetectors. They are room-temperature photovoltaic detectors that use band structure engineering to design the energy levels and electron lifetimes in an active region. The individual active regions are repeated and stacked into a cascading structure. Unlike classic semiconductor photodetectors, the energy transitions are not determined by the inherent material bandgap, instead, by the intersubband (ISB) transitions between quantized energy levels in the conduction band. The conduction band offset (CBO) of the quantum well and barrier materials determines the energy range that can be utilized to form a QCD. InAs and AlAsSb have the largest CBO of conventional III-V semiconductors and InAs has one of the lowest electron effective masses m_e^*. These two characteristics make this material system a good candidate for high-performance QCDs that could cover a broad range of energies.

Since QCDs are based on intersubband transitions with lifetimes around a ps ($\sim 1 \times 10^{-12}$ s), they are high-speed detectors too (>20 GHz). However, intersubband transitions are not sensitive to surface-normal incident light, due to the intersubband selection rule. This means that you cannot just shine light on them and measure a photoresponse. The light must be coupled into the structure and propagate perpendicularly to the surface to be detected. The incoupling can be achieved by a photonic crystal, diffraction grating, or rotating the sample.

In this project, growth techniques were adapted and refined to improve the crystal quality and interface quality of AlAsSb lattice-matched to InAs. The growth of mixed group V compounds is complicated by the As-for-Sb exchange that occurs at high growth temperatures and under high As flux. Several QCD active regions were designed, grown, and characterized. These allowed us to modify our material parameters, improve our modeling software, and adjust the growth parameters further. Finally, a 2.7 µm QCD was designed and grown. This structure was used to study different grating periods and compare them to the COMSOL simulations. A room-temperature surface-normal illuminated responsivity of 5.63 mA/W was measured for the 200×200 µm surface grating.

Other disciplines:

The developments in the design and MBE of Sb-compounds apply to other ISB optoelectronics, including quantum cascade lasers (QCLs) and interband cascade lasers (ICLs), MIR sensors, and high-speed electronics. The realization of the first surface-normal illuminated InAs/AlAsSb QCD, with a room temperature responsivity >5 mA/W, demonstrates the potential of this material system to be used in MIR detector applications ranging from imaging and chemical sensing to high-speed communication.

Development of human resources:

This project provided the resources for three different Ph.D. students, two women, to learn ISB device design, sample growth by MBE, cleanroom processing, and device characterization. These students have been able to collaborate with fellow graduate students and postdocs on a wide variety of research topics, as demonstrated in the List of Publications.

Over the past three years, we were able to recruit more female students than male students. We believe that this is due to the research topics, group dynamic and reputation, state-of-the-art facilities, and being located in a major cultural capital of Europe.

Impact on teaching and educational experiences:

The topics and discoveries made in this research project have been incorporated into lectures on nanostructure epitaxy, semiconductor physics, active region design, and the ZMNS presentation for student and visiting scientists.

Impact on society beyond science and technology:

We believe the major impact of MIR photodetectors will be in future smart products, chemical sensing for safety and security, and high-speed communication. The QCDs are an important building block for these applications.

Changes

Changes in approach

The original idea was to remove the InAs substrate from the QCD to form a free-standing membrane, to solve the issue of strong light absorption by the substrate and to use a photonic crystal for surface normal light coupling. After promising results from COMSOL modeling, we changed to a top grating that would result in most of the light being absorbed by the active region.

The original test structures utilized a contact superlattice on the bottom and top of the active region. Later designs removed the superlattice and were replaced with more periods of the active region.

Problems or delays

In the first year of the project, we had a failure in the Sb cracker and were not able to grow samples with Sb for the rest of the growth campaign. We proceeded with the growth and modeling of other QCD and QCL structures.

During this project there were two major delays: The first was known before the start of the project. The FKE and ZMNS moved to a newly renovated TU Wien building with a new cleanroom, MBE Lab, lab space, and offices. The second was due to the Coronavirus pandemic, the resulting lockdowns, and parts and service delays.

A no-cost extension was granted for one year.

Expenditure Impacts

As stated, the FKE and ZMNS moved during the project. This resulted in a delay of almost a year.

Changes to the primary place of performance from that originally proposed

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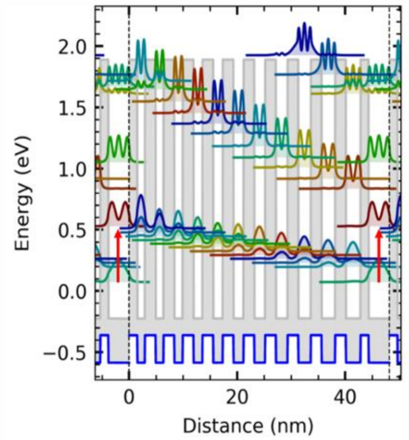

Figure 5: Band diagram of the InAs/AlAsSb QCD detecting at 2.7 μm. The layer thicknesses in nm are as follows: **1.50**, 1.38, **2.00**, 1.43, **2.00**, 1.55, **2.00**, 1.65, **2.00**, 1.75, **2.00**, 1.85, **2.00**, 2.00, **2.00**, 2.15, **2.00**, 2.30, **2.00**, 2.50, **2.00**, 2.70, **1.50**, 3.85. The underlined layer is doped at n= 1.09×10^{12} 1/cm². The bold printed layers are the barriers.
Taken from M. Giparakis et al. (*submitted to APL*).

Technical Updates

As mentioned above, the QCD was designed using an 8-band k·p -method formalism. The electron transport includes scattering mechanisms, such as longitudinal optical (LO)- and acoustic phonon scattering, interface roughness scattering and alloy scattering. High optical transition energies, as it is the case for this design, yield a high extraction efficiency and decreased absorption efficiency. For this reason, a design with a vertical absorption was implemented. Figure 5 shows the active region design of the QCD. The conduction band is drawn in grey and the valence band in blue. The optical transition is marked with a red arrow and is followed by an efficient LO-phonon extractor. To benefit the absorption efficiency, the lowest LO-phonon extractor state has an energy difference to the ground state of the optical transition of approximately 120 meV, this is in order to reduce backfilling and increase the electron lifetime in the ground level.

A challenge of this material system is making ohmic contacts to the active region as the narrow bandgap of InAs of 0.34 eV absorbs wavelengths below 3.5 μm. A method that was implemented in the first generation of this QCD is short period superlattice InAs/AlAsSb contacts. For the second generation the active region was contacted with a 50 nm thick highly Si-doped (2.5×10^{19} 1/cm³) InAs layer (the diffraction grating was planned to be etched through), because it was suspected that interband absorptions occurred from the valence band to the lower miniband of the superlattice contact. The narrow type-II band alignment of the InAs/AlAsSb material system between the valence band edge of the barrier material and the conduction band edge of the well material of approximately 0.14 eV is apparent (see Fig.5). Still, the ground state is lifted by the narrow wells needed for the absorption wavelength of 2.7 μm and thus the bandgap is effectively increased.

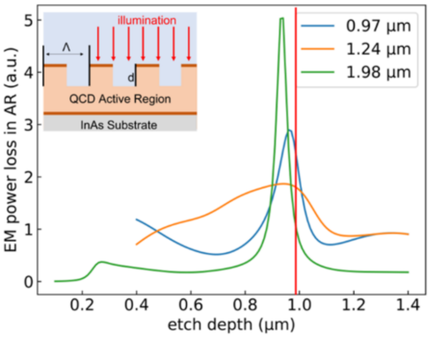

Figure 6: COMSOL simulation for the absorption in the active region of the QCD, plotted over the etch depth for three grating periods: 0.97 µm, 1.24 µm, and 1.98 µm. The red line indicates the real etch depth of the 2.7 µm QCD. The inset depicts a sketch of the grating that is etched into the active region of the QCD.

COMSOL simulations were performed for diffraction gratings to be able to top-side illuminate the QCD. This was done using the Electromagnetic Waves, Frequency Domain interface in the Optics module. Periodic boundary conditions and a periodic input port were implemented. The active region was then probed for electromagnetic power loss, which equals the absorption. Parametric sweeps were performed for vertical incidence light sweeping over the grating period, the duty cycle and the grating depth. Like this, three grating periods were selected for a duty of 0.5 that yielded high absorptions in the simulations, namely 0.97 µm, 1.24 µm, and 1.98 µm see Fig.6, where the absorption is plotted over the etch depth. One can see that the high absorption bandwidth at full width at half maximum (FWHM) over the etch depth is only about 50 – 90 nm. As it is difficult to etch structures of this size with the accuracy needed the three different grating periods were selected to have maxima at different etch depths, whereas the 1.24 µm grating period has a broad absorption bandwidth.

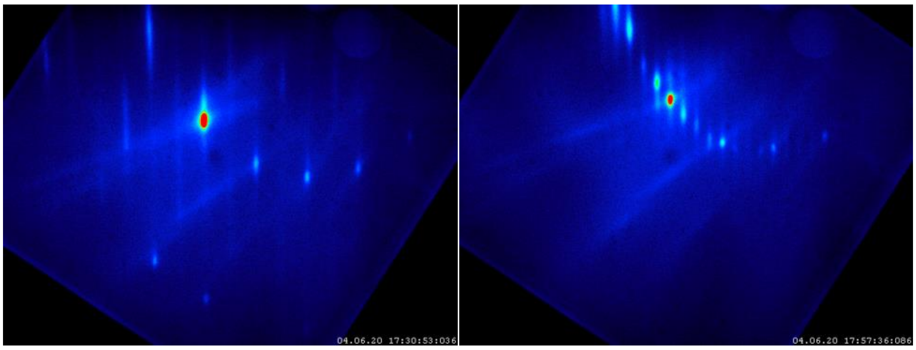

Figure 7: RHEED patterns of InAs growth **a)** As rich conditions showing a 2×4 reconstruction and **b)** In rich conditions showing a 4×2 reconstruction.

The QCD was grown in a Riber C21 MBE system on undoped InAs substrates. The growth was in-situ monitored by reflection high-energy electron diffraction (RHEED) and analyzed by HR-XRD and AFM.

A major objective was to grow AlAsSb lattice-matched to the InAs substrate and to advance the growth techniques. To do this, first the minimum As flux at different growth temperatures to grow InAs on an InAs substrate was investigated. This was done by in-situ monitoring the RHEED reconstructions of the growing InAs film. Figure 7 shows that for As-rich conditions 2×4 reconstructions form, while for In-rich conditions 4×2 reconstructions form. In the next step, $AlAs_{0.16}Sb_{0.84}$ bulk layers were grown on InAs to obtain the correct lattice matching conditions. During this process, factors like growth temperature and flux ratios were varied and analyzed with HR-XRD and AFM to obtain optimized parameters.

When growing with mixed group-V materials, as it is the case here, grown layers are suspected of intermixing at the interfaces due to the As-for-Sb exchange. This has detrimental effects to the grown structure, because grown layer thicknesses would not be nominal, and interfaces would show roughness. To avoid this effect, we implemented new shutter sequences. When analyzing the grown structures with HR-XRD, effects on the interfaces can be observed by looking at the FWHM of superlattice peaks, as a larger FWHM is usually a sign of rougher interfaces.

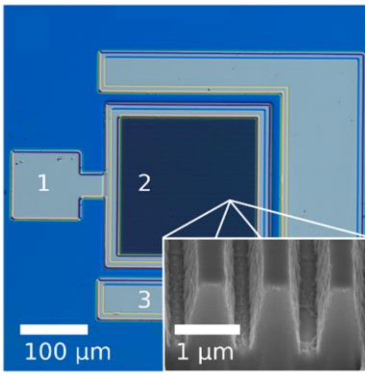

Figure 8: Optical microscopy image of a 200×200 µm surface grating. (1) is the extended top contact that also frames the mesa with diffraction grating (2). Surrounding the mesa on three sides is the bottom contact (3). In the inset a focused ion beam cut through the grating is shown.
Taken from M. Giparakis et al. (*submitted to APL*).

Because of high absorption energies in short-wavelength mid-infrared QCDs, the InAs wells now become significantly thinner. This puts higher importance on accurate growth rates to match the nominal structure as closely as possible. Therefore, the effects of shutter operations on the growth rate were investigated. For this, double superlattices were grown with decreasing InAs wells. The effect on the InAs growth rate (closed shutter time) of the $AlAs_{0.16}Sb_{0.84}$ growth time could be extracted. As expected, this study showed a higher InAs growth rate for thinner wells corresponding to the well-known phenomenon of an overshoot of the In cell flux when the shutter opens. With this, the final grown QCD analyzed with HR-XRD corresponds to the nominal structure.

Mesas were fabricated using a dry etching Cl/Ar process with an inductively coupled plasma process, see Figure 8. This process results in smooth slightly positive sloped sidewalls. In the inset of Fig.8, a focused ion beam cut through the grating is shown. Electron beam lithography was employed for the grating, and it is etched about 980 nm deep. This is very close to the desired etch depth of 960 nm, which would yield the highest absorption according to the COMSOL simulations, see Fig.6. The grating spans over a 200×200 µm surface on the mesa, plus a 20-µm-wide top contact around the perimeter, which is 240×240 µm in total. The mesa is surrounded on three sides by the bottom contact. Top and bottom contact (10/300 nm Ti/Au respectively) are separated and insulated by a 240 nm thick Si_3N_4 passivation layer.

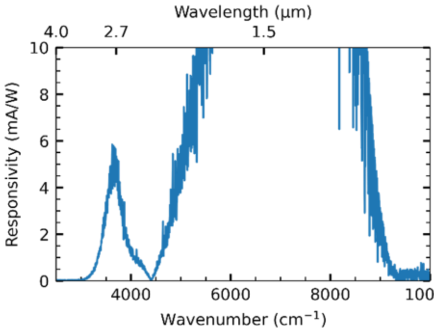

Figure 9: Responsivity measurement of the 2.7 µm QCD without the lowpass filter. The signal ranging from 440 – 8500 1/cm is attributed to an interband absorption from the valence band to the conduction band of the QCD.

The optical measurements were performed using an FTIR with a broadband mid-infrared Globar light source. A longpass filter with a specified cut-on wavelength of 2.4 µm, 4166 1/cm (or cut off at 2.5 µm, 4000 1/cm) was utilized. The measurements were conducted at ambient conditions. A selected 200×200 µm surface grating device was also measured in a cryostat that was cooled down from room temperature to 80 K. To confirm the intersubband nature of the absorption signal at 2.7 µm, mesas processed without a diffraction grating and the bottom contact on the backside of the substrate were side illuminated using a polarizer. Whereas the signal at 2.7 µm is polarization dependent, the absorption signal ranging from 4400–8500 1/cm is not. This indicates an intersubband absorption. The responsivity measurement without the lowpass filter of the diffraction grating mesa design at ambient conditions is shown in figure 9.

For the different grating periods, 35 devices of the 200×200 µm were measured respectively. For the 0.97 µm grating period 35 devices of the different sizes were measured respectively. These measurements were conducted at room temperature. For the 200×200 µm surface grating with a period of 0.97 µm, temperature-dependent measurements were conducted.

List of Publications and Significant Collaborations that resulted from your AOARD supported project:

a) papers published in peer-reviewed journals

1. J. Hillbrand, A. M. Andrews, H. Detz, G. Strasser, and B. Schwarz. "Coherent injection locking of quantum cascade laser frequency combs". Nature Photonics 13, 101 (2019). doi:10.1038/s41566-018-0320-3.
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3. J. Hillbrand, M. Beiser, A. M. Andrews, H. Detz, R. Weih, A. Schade, S. Höfling, G. Strasser, and B. Schwarz. "Picosecond pulses from a mid-infrared interband cascade laser". Optica 6(10), 1334 (2019). doi:10.1364/optica.6.001334.
4. M. Kainz, M. Semtsiv, G. Tsianos, S. Kurlov, W. Masselink, S. Schönhuber, H. Detz, W. W. Schrenk, K. Unterrainer, G. G. Strasser, and A. A.M. Andrews. "Thermoelectric-cooled terahertz quantum cascade lasers". Opt. Exp. 27(15), 20688 (2019). doi:10.1364/OE.27.020688.
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b) papers published in peer-reviewed conference proceedings

c) papers published in non-peer-reviewed journals and conference proceedings

d) conference presentations without papers

1. J. Hillbrand, H. Detz, A. M. Andrews, H. Schneider, R. Weih, F. Capasso, S. Höfling, G. Strasser, B. Schwarz: "Semiconductor Laser Frequency Combs: From Fundamentals Towards Applications"; Talk: SCIX 2019, Palm Springs (invited); 2019-10-13 - 2019-10-18; in: "SciX 2019", (2019), Paper ID IR-06.4, 1 pages.
2. M Beiser, J. Hillbrand, A. M. Andrews, R. Weih, S. Höfling, G. Strasser, B. Schwarz: "Monolithic Frequency Comb Generation and High-speed Detection based on Interband Cascade Structures"; Talk: German Molecular Beam Epitaxy 2019 (DEMBE2019), Würzburg; 2019-10-07 - 2019-10-08.
3. H. Detz, S. Lancaster, M. Potocek, D. MacFarland, T. Zederbauer, W. Schrenk, A. M. Andrews, G. Strasser: "Boron Incorporation into BGaAs for Strain Engineering"; Poster: German MBE Workshop, Würzburg; 2019-10-07 - 2019-10-08.
4. M Giparakis, M. A. Kainz, S. Schönhuber, B. Limbacher, H. Detz, M Beiser, W. Schrenk, A. M. Andrews, G. Strasser, G. Bastard, K. Unterrainer: "Selective Emission of a THz QCL using a Magnetic Field"; Talk: German Molecular Beam Epitaxy 2019 (DEMBE2019), Würzburg; 2019-10-07 - 2019-10-08.
5. M. Jaidl, M. A. Kainz, S. Schönhuber, C. Deutsch, D. Bachmann, M. Brandstetter, M. Krall, J. Darmo, A. M. Andrews, W. Schrenk, G. Strasser, K. Unterrainer: "Double-metal waveguide fabrication for high performance THz Quantum Cascade Lasers"; Talk: Workshop on Dry Processing for Nanoelectronics and Micromechanics Deposition and Etching, Wien; 2019-09-17 - 2019-09-18.
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7. M.A. Kainz, M. Semtsiv, G. Tsianos, S. Kurlov, W.T. Masselink, S. Schönhuber, B. Limbacher, H. Detz, W. Schrenk, K. Unterrainer, G. Strasser, A.M. Andrews: "Thermoelectrically Cooled Terahertz Quantum Cascade Laser", Talk: Infrared Terahertz Quantum Workshop (ITQW) 2019, Ojai, California, USA, 15.09.2019 - 20.09.2019.
8. M.A. Kainz, Aaron Maxwell Andrews, S. Schönhuber, B. Limbacher, M. Jaidl, D. Theiner, H. Detz, G. Strasser, G. Bastard, K. Unterrainer: "Mode Switching of a Dual-color Terahertz Quantum Cascade Laser", Talk: Infrared Terahertz Quantum Workshop (ITQW) 2019, Ojai, California, USA, 15.09.2019 - 20.09.2019. 37
9. S. Schönhuber, M.A. Kainz, B. Limbacher, D. Theiner, M. Jaidl, A.M. Andrews, H. Detz, G. Strasser, J. Darmo and K. Unterrainer: "Optical Tuning of Terahertz Quantum Cascade Random Lasers", Poster: Infrared Terahertz Quantum Workshop (ITQW) 2019, Ojai, California, USA, 15.09.2019 - 20.09.2019.
10. M. Wenclawiak, B. Limbacher, C.G. Derntl, A.M. Andrews, G. Strasser, K. Unterrainer and J. Darmo: "Superradiant meta-atoms strongly coupled to intersubband transitions",

11. F. Pilat, B. Schwarz, H. Detz, A.M. Andrews, B. Baumgartner, B. Lendl, G. Strasser, B. Hinkov: "QCLD-based lab-on-a-chip for µ-fluidic sensing", Talk: Infrared Terahertz Quantum Workshop (ITQW) 2019, Ojai, California, USA, 15.09.2019 - 20.09.2019.
12. B. Schwarz, J. Hillbrand, M. Beiser, N. Opačak, A.M. Andrews, H. Detz, G. Strasser, A. Schade, R. Weih, S. Höfling: "Towards monolithic and battery driven mid-infrared dual-comb spectrometers", Talk: (Invited) Infrared Terahertz Quantum Workshop (ITQW) 2019, Ojai, California, USA, 15.09.2019 - 20.09.2019.
13. J. Hillbrand, A.M. Andrews, H. Detz, H. Schneider, G. Strasser, F. Capasso, B. Schwarz: "Actively mode-locked mid-infrared quantum cascade laser", Talk: Infrared Terahertz Quantum Workshop (ITQW) 2019, Ojai, California, USA, 15.09.2019 - 20.09.2019.
14. J. Hillbrand, S. Dal Cin, A.M. Andrews, H. Detz, E. Gornik, B. Schwarz, G. Strasser: "High bandwidth quantum cascade detectors" Talk: Infrared Terahertz Quantum Workshop (ITQW) 2019, Ojai, California, USA, 15.09.2019 - 20.09.2019.
15. A.M. Andrews, M.A. Kainz, S. Schönhuber, B. Limbacher, H. Detz, M. Beiser, M. Giparakis, W. Schrenk, G. Strasser, G. Bastard, K. Unterrainer, “Laser Level Selection in Terahertz Quantum Cascade Lasers”, Talk: IEEE Research, Applications of Photonics in Defense (RAPID) 2019, Miramar Beach (Invited), Florida, USA, 19.08.2019-21.08.2019.
16. H. Detz, S. Lancaster, H. Groiss, J. Zeininger, A.M. Andrews, W. Schrenk, G. Strasser: "Elucidating the impact of B incorporation in GaAs through nanowire growth"; Talk: Gemeinsame Jahrestagung in Zürich ÖPG, SPS, Zürich; 2019-08-26 - 2019-08-30; in: "Gemeinsame Jahrestagung in Zürich ÖPS, SPS", (2019), 5.
17. J. Hillbrand, A.M. Andrews, H. Detz, H. Schneider, G. Strasser, F. Capasso, B. Schwarz: "Picosecond pulses from mid-infrared quantum cascade lasers"; Talk: Gemeinsame Jahrestagung in Zürich ÖPG, SPS, Zürich; 2019-08-26 - 2019-08-30.
18. S. Lancaster, M. Schinnerl, A.M. Andrews, M. Sistani, A. Lugstein, W. Schrenk, G. Strasser, H. Detz: "Optically active nanowires nucleated via a novel focused ion beam implantation method"; Talk: Gemeinsame Jahrestagung in Zürich ÖPG, SPS, Zürich; 2019-08-26 - 2019-08-30; in: "Gemeinsame Jahrestagung in Zürich ÖPS, SPS", (2019), 4.
19. F. Pilat, B. Schwarz, H. Detz, A.M. Andrews, B. Baumgartner, B. Lendl, G. Strasser, B. Hinkov: "µ-fluidic sensing with a quantum cascade lab-on-a-chip"; Talk: Gemeinsame Jahrestagung in Zürich ÖPG, SPS, Zürich; 2019-08-26 - 2019-08-30; in: "Gemeinsame Jahrestagung in Zürich ÖPG, SPS", (2019), 4.
20. B. Schwarz, J. Hillbrand, M Beiser, N Opačak, A.M. Andrews, H. Detz, A. Schade, R. Weih, S. Höfling: "Interband and quantum cascade laser frequency combs: From fundamentals toward monolithic spectrometers"; Talk: Gemeinsame Jahrestagung in Zürich ÖPG, SPS, Zürich; 2019-08- 26 - 2019-08-30.
21. E. Gornik, J. Hillbrand, A.M. Andrews, R. Weih, S. Höfling, G. Strasser, B. Schwarz: "Monolithic Frequency Comb Generation and High-speed Detection based on Interband Cascade Structures"; Talk: EDISON 21, Buffalo; 2019-07-14 - 2019-07-19; in: "EDISON 21", (2019), 87.
22. J. Hillbrand, A.M. Andrews, H. Detz, G. Strasser, B. Schwarz: "Coherent control of quantum cascade laser frequency combs via electrical locking"; Talk: CLEO/Europe-EQEC 2019, München; 2019-06-23 - 2019-06-27; in: "CLEO/Europe-EQEC 2019", (2019), 187. 38
23. M.A. Kainz, S. Schönhuber, B. Limbacher, A.M. Andrews, H. Detz, G. Strasser, K. Unterrainer: "Dual-lasing Channel of a High-Temperature Terahertz Quantum Cascade Laser"; Poster: CLEO/Europe-EQEC 2019, München; 2019-06-23 - 2019-06-27; in: "CLEO/Europe-EQEC 2019", (2019), ISBN: 978-1-7281-0469-0; 1 - 2.
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30. J. Hillbrand, B. Schwarz, H. Detz, A.M. Andrews, G. Strasser: "High-speed mid-infrared detectors" Talk: Photonics West 2019, San Francisco (invited); 2019-02-02 - 2019-02-07; in: "Proceedings of SPIE", (2019), Paper ID 10934-102, 1 pages.
31. B. Schwarz, J. Hillbrand, M Beiser, A. Schade, H. Detz, A.M. Andrews, R. Weih, S. Höfling: "Repulsive intermode beat synchronization in interband cascade laser frequency combs"; Talk: Photonics West 2019, San Francisco; 2019-02-02 - 2019-02-07; in: "Proceedings of SPIE", (2019), Paper ID 10939-45, 1 pages.
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33. S. Schönhuber, M. A. Kainz, B. Limbacher, M. Wenclawiak, A. M. Andrews, G. Strasser, J. Darmo, K. Unterrainer: "Controlling and shaping the THz emission from Quantum Cascade Lasers"; Keynote Lecture: IRMMW-THz 2020, New York, USA (invited); 2020-11-08 - 2020-11-13; in: "45th International Conference on Infrared, Millimeter, and Terahertz Waves", (2020), 3 pages.
34. B. Hinkov, F. Pilat, L. Lux, B. Schwarz, H. Detz, A. M. Andrews, B. Baumgartner, B. Lendl, G. Strasser: "Towards In-situ Measurements Of The Protein Secondary Structure Based On Mid- IR Lab-on-a-chip Quantum Cascade Technology"; Talk: Online Conference SCIX 2020, Sparx (invited); 2020-10-12 - 2020-12-15; in: "SCIX2020", (2020), Paper ID MOLEC-OD1.2, 1 pages.
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40. M. Wenclawiak, J. Darmo, K. Unterrainer, A. M. Andrews, G. Strasser: "cQED in Ensembles of Polaritonic Meta-Atoms"; Poster: Online Conference - International Quantum Cascade Laser School and Workshop (IQCLSW 2020), Zürich; 2020-09-07 - 2020-09-10; in: "Proc. International Quantum Cascade Lasers School and Workshop", (2020).
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43. A. M. Andrews, M. A. Kainz, S. Schönhuber, B. Limbacher, H. Detz, M Beiser, M Giparakis, W. Schrenk, G. Strasser, G. Bastard, K. Unterrainer: "Laser level Selection in Terahertz Quantum Cascade Lasers using a Magnetic Field"; Poster: 21st International Winterschool New Developments in Solid State Physics, Mauterndorf; 2020-02-23 - 2020-02-28; in: "21st International Winterschool New Developments in Solid State Physics", (2020), 97.
44. M Beiser, J. Hillbrand, A. M. Andrews, R. Weih, S. Höfling, G. Strasser, B. Schwarz: "Interband Cascade Laser Frequency Comb generation and high-speed detection"; Poster: 21st International Winterschool New Developments in Solid State Physics, Mauterndorf; 2020-02-23 - 2020-02-28; in: "21st International Winterschool New Developments in Solid State Physics", (2020), 92.
45. M. David, J. Hillbrand, S. Dal Cin, A. M. Andrews, H. Detz, E. Gornik, B. Schwarz, G. Strasser: "High speed and high bandwidth quantum cascade detectors"; Poster: 21st International Winterschool New Developments in Solid State Physics, Mauterndorf; 2020-02-23 - 2020-02-28; in: "21st International Winterschool New Developments in Solid State Physics", (2020), 83.
46. M Giparakis, M. A. Kainz, M Beiser, K. Unterrainer, G. Strasser, A. M. Andrews: "Investigation of the optimum phonon depopulation energy separation in a GaAs/AlGaAs superlattice"; Poster: 21st International Winterschool New Developments in Solid State Physics, Mauterndorf; 2020-02-23 - 2020-02-28; in: "21st International Winterschool New Developments in Solid State Physics", (2020), 87.
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52. B. Schwarz, J. Hillbrand, M Beiser, A. M. Andrews, H. Detz, R. Weih, A. Schade, S. Höfling, G. Strasser: "Interband cascade laser frequency combs"; Talk: SPIE Photonics West 2020, San Francisco (invited); 2020-02-01 - 2020-02-06; in: "Proceedings Volume 11284, Smart Photonic and Optoelectronic Integrated Circuits XXII", (2020), Paper ID 11284-40.
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1. M. Giparakis et al., “2.7 µm Quantum Cascade Detector: Above Band Gap Energy Intersubband Detection”, *submitted (October 2021)*.
2. M. Jaidl et al., “Silicon Integrated Terahertz Quantum Cascade Ring Laser Frequency Comb”, *submitted (November 2021)*.
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f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.