Mid-Infrared (~2.8 µm to ~7.1 µm) Interband Cascade Lasers

Sven Höfling[1,2], Robert Weih[1], Matthias Dallner[1], Julian Scheuermann[3], Michael von Edlinger[3], Lars Nähle[3], Marc Fischer[3], Johannes Koeth[3], Martin Kamp[1]

[1]Technische Physik, Physikalisches Institut and Wilhelm Conrad Röntgen-Center for Complex Material Systems, Universität Würzburg, D-97074 Würzburg, Germany

[2]SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, KY16 9SS, United Kingdom

[3]nanoplus Nanosystems and Technologies GmbH, Oberer Kirschberg 4, Gerbrunn D-97218, Germany

ABSTRACT

20 years after their first reference interband cascade lasers (ICLs) have become a mature and competitive semiconductor laser source in the mid-infrared region. The carrier rebalancing concept that was introduced in 2011 drastically improved the performance. As a consequence the wavelength window that is accessible for ICLs operating at ambient temperatures could be extended. For GaSb based ICLs continuous wave (cw) emission at room temperature could be achieved up to a wavelength of 5.6 µm. As the need for thicker claddings at longer wavelengths makes the growth of the superlattice claddings increasingly difficult and limits the heat dissipation, a plasmon waveguide structure with highly doped InAs-layers grown on InAs-substrates is typically used for ICLs emitting up to ~7 µm in pulsed mode at room temperature. With regard to the short wavelength limit of ICLs, we present cw emission of a GaSb based ICL emitting at 2.8 µm and with regard to the long wavelength limit we present room temperature pulsed operation of an InAs based plasmonic waveguide ICL up to 7.1 µm. Furthermore, we show single mode emitting ICLs with distributed feedback gratings emitting between 2.8 and 5.2 µm.

1. INTRODUCTION

Based on the improvement in performance due to the introduction of the carrier rebalancing concept in 2011[1] interband cascade lasers (ICLs) have matured into a competitive, compact and low power consuming semiconductor mid infrared (MIR) laser source. Laser structures grown on GaSb substrates have shown continuous wave (cw) operation at room temperature up to a wavelength of 5.6 µm [2]. Up to now there has been no attempt to explore the ICL performance in their short wavelength limit. In order to do that a structure designed for emission at 2.8 µm was fabricated. Broad area devices measured under pulsed conditions at room temperature (20°C) showed a threshold current density (J_{th}) of 383 A/cm^2. Furthermore narrow ridges were processed and could be operated in cw-mode up to 50 °C. However the superlattice cladding used in the GaSb-based ICL devices features a rather low transversal thermal conductivity. The need for thicker cladding regions at longer wavelengths (> 6 µm) would make the heat dissipation increasingly difficult especially for wide ridge devices. In order to enhance the thermal conductivity of the waveguide region, the superlattice cladding can be replaced by highly doped bulk InAs-layers[3]. Due to the high doping with concentrations around $3*10^{19}$ cm^{-3} the plasmon frequency of these layers is lowered to values in range of the desired emission wavelengths, which in turn significantly lowers the refractive index of this material and hence provides the refractive index contrast required for proper mode confinement in the active region. The GaSb separate confinement layers located on both sides of the active region are replaced by thick undoped InAs-layers acting as the waveguide. By using only binary InAs for both, the waveguide and cladding layers, this region is intrinsically lattice matched to the InAs-substrates used for these structures. This significantly simplifies the growth of the whole structure in comparison to the several hundred layers that require careful strain compensation on GaSb-based ICLs. Wavelengths up to 10.4 µm have successfully been covered with this approach, with devices up to 7.1 µm operational at room temperature[4-6].

2. GROWTH AND PROCESSING

All structures were grown in an Eiko molecular beam epitaxy (MBE) system equipped with conventional effusion cells for the the group-III elements (Ga, Al, In) and valved cracker cells for the group-V elements (As, Sb). The GaSb-based ICL structures were grown on 2'' n-GaSb substrates. As a cladding region strain compensated short period InAs/AlSb superlattices were grown at a substrate temperature of 450 °C. For the GaSb separate confinement layers (SCLs) that surround the active region the substrate temperature was ramped up to 485°C. The cascades that comprise the typical W-quantum well (W-QW) again were grown at 450 °C. To extract basic parameters 150 µm wide broad area lasers were processed using optical lithography and dry etching. In order to avoid excessive current spreading the etch proceeded through the active cascades and the lower SCL. Right afterwards a Si_3N_4/SiO_2 passivation was deposited and subsequently etched back at the top of the ridge. After thinning of the substrate and contact evaporation 2 mm long laser bars were cleaved for electrical and optical characterization. In addition narrow ridge waveguide lasers were processed from the ICL material emitting at 2.8 µm in a similar fashion. To ensure sufficient heat dissipation a 5 µm thick gold layer was electroplated on top of the ridge. The InAs-based ICL structures were grown on n-type InAs wafers in the same MBE-chamber as the GaSb-based samples, hence using cracker cells for both, arsenic and antimony. The bulk InAs-layers in the waveguide region were grown at a temperature of 450 °C. This temperature was also used for the thin InAs-layers in the active region. Due to the short growth times of the individual layers (several seconds) in the active region no temperature adjustments were made for the AlSb, GaSb and GaInSb layers. As the AlSb, GaSb and GaInSb layers are all compressively strained with regards to the InAs substrate and no further tensile strained layer materials are used in the structure highly tensile strained AlAs interfaces are enforced by As soaks at the AlSb/InAs layer transitions to compensate this strain. After growth the wafers were processed into 45 µm wide RWG devices as described before and cleaved to laser bars of 2 mm length.

3. LASER RESULTS

Figure 1 features a map of threshold current densities measured in pulsed mode at room temperature in the wavelength range between 2.8 µm and 7.1 µm. The circles in the wavelength region below 6 µm were obtained on devices grown on GaSb substrates. The lowest J_{th} values can be found in the ICL sweet spot region between 3 and 4 µm with a record value of 98 A/cm² at 3.65 µm for a 10 stage device. Towards longer wavelengths J_{th} increases due to higher losses and lower oscillator strength of the lasing transition. At 5.70 µm a 2 mm long and 150 µm wide broad area device featuring 5 stages reached 731 A/cm². The device for emission at 2.80 µm showed a J_{th} of 383 A/cm² and a record characteristic temperature of $T_0 = 67$ K in the temperature range from 10 to 80 °C.
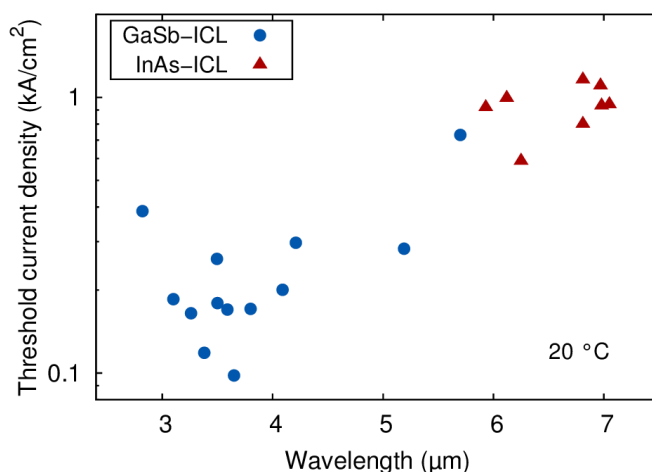

Figure 1: Threshold current densities of various ICL devices grown on GaSb (circle) and InAs (triangle) substrates in the 2.8-7.1 µm wavelength range. The devices were measured under pulsed conditions (250 ns, 1 kHz) at 20°C.
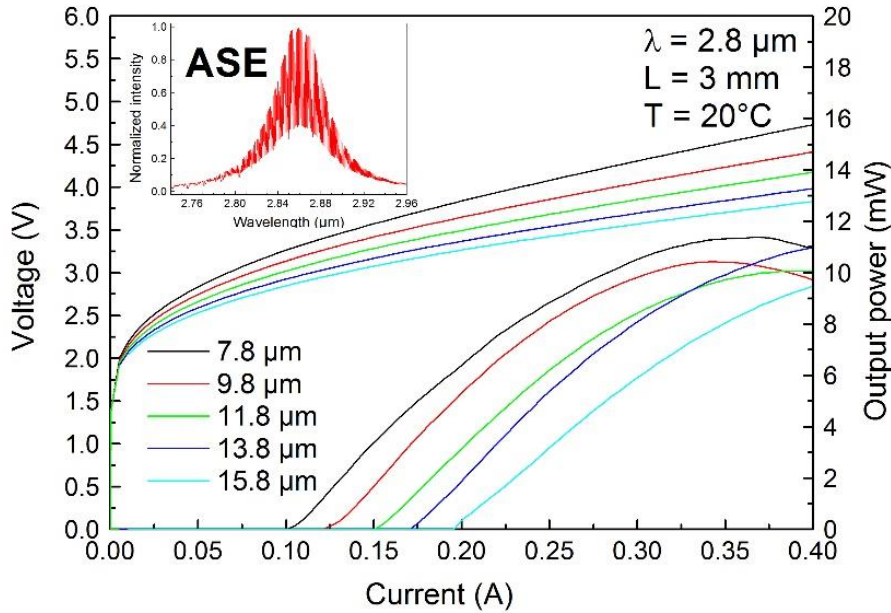
Figure 2: Electro optical characteristics of 3 mm long devices with varying ridge width. The measurements were taken in cw mode at 20 °C. The inset shows an amplified spontaneous emission spectrum of a 1.2 mm long laser just below threshold.

From this material RWG devices with varying ridge with were processed and mounted epi-side up on a copper heat sink. The facets were left as cleaved. As shown in Figure 2 the threshold current of the 3 mm long ICLs scales with the pumped area. All devices emit approximately 10 mW of output power at room temperature. From the IV-characteristics the change in differential resistance can be seen. While the value for the 15.8 μm wide ridge is 2.8 Ω it increases to 4.4 Ω for the 7.8 μm wide ridge. Nevertheless the narrowest ridge experiences superior heat dissipation and could be operated up to 50 °C in cw mode.

For longer wavelengths InAs-based ICLs were grown and examined (data shown as triangles in Figure 1). Here wavelengths up to 7.1 μm in pulsed operation at room temperature have been realized on a structure containing 22 cascades in the active region[7]. A threshold current density of 940 A/cm^2 was measured for this device at a temperature of 20 °C. Another structure featuring a slightly shorter electron injector with only two instead of three InAs QWs and 30 stages even showed a threshold current density at room temperature of only 800 A/cm^2 at an emission wavelength around 6.8 μm. Figure 3 shows the temperature dependent threshold current densities of another InAs-based device with 22 cascades in the active region, targeted for a shorter emission wavelength. The active region design of this device is similar to the one presented in [4], containing three InAs-QWs in the electron injector, with minor adjustments to tailor the emission wavelength around 6 μm. The emission wavelength of this device at a temperature of 20 °C, depicted in the inset of FFigure 3, is around 6,24 μm. For J_{th} a value of 588 A/cm^2 is obtained at this temperature. To our knowledge this is the lowest threshold current density achieved so far for InAs-based ICLs in this wavelength region. A T_0 value of 41 K can be extracted from a fit to the data at temperatures below 50 °C, while a steeper slope and hence lower T_0 value is observed above this point.
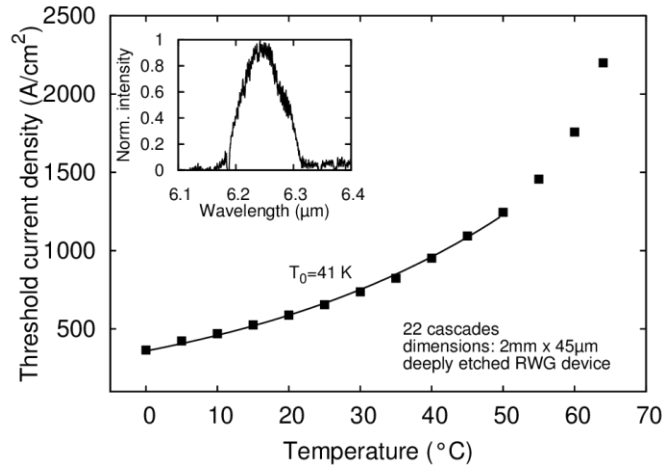
Figure 3: Temperature dependent threshold current densities of an InAs-based ICL with 22 cascades in the active region. At 20 °C a value of 588 A/cm^2 was achieved. The inset shows an emission spectrum of this device at a temperature of 20 °C.

4. DISTRIBUTED FEEDBACK LASER DEVICE RESULTS

Based on the fabrication techniques described in Ref 8[8], single mode GaSb based distributed feedback (DFB) ICLs have been developed in the wavelength range from below 2.8 to above 5.2 µm. Selected single chip devices were mounted epitaxial side up on TO-style headers with integrated thermoelectric coolers to allow for a broad wavelength tuning around ambient temperature. The headers were then hermetically sealed using antireflective coated windows. The electro-optical characteristics of these devices were examined in pulsed and cw mode with respect to their laser threshold, output power and spectral tuning behavior. For spectral characterization, a Fourier transform infrared spectrometer with a resolution of 0.125 cm^{-1} was used.

Figure 4 depicts a selection of cw emission spectra from different fabricated DFB ICLs including, to the best of our knowledge, the devices with longest[9] and shortest[10] reported emission wavelength for single mode ICLs, respectively. Setup limited signal to noise ratios of around 30 dB are observed, guaranteeing high gas species selectivity. Side mode suppression ratios (SMSR) are estimated to be significantly higher. Some gas species as potential candidates for related sensing applications are listed at the top of the spectra.
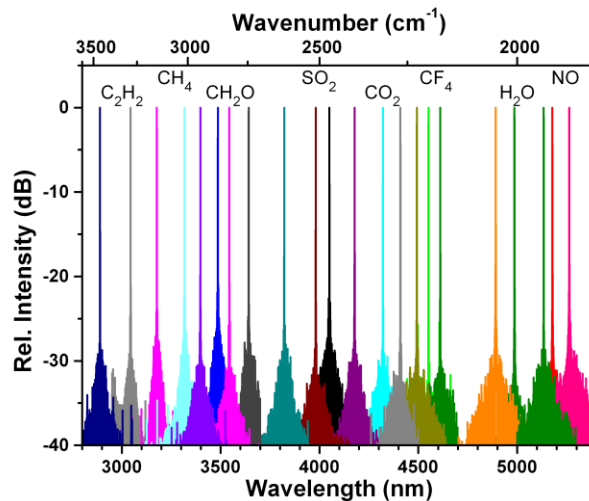

Figure 4: Emission spectra of selected single mode DFB ICL devices operating continuous wave in the 2.8 to 5.2 µm wavelength region. The gases listed at the top of the spectra represent potential candidates for TLAS applications.
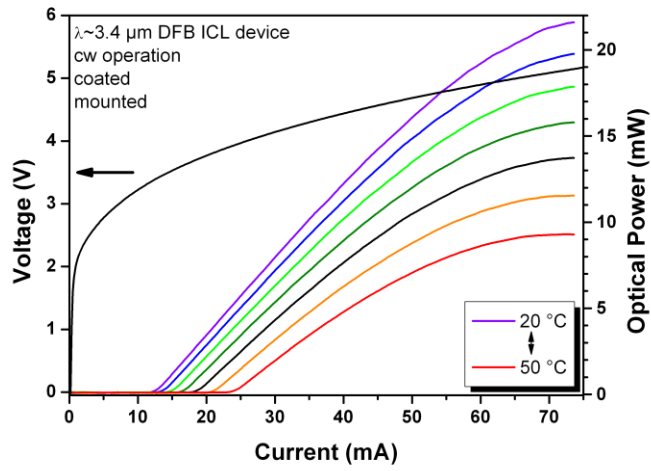
Figure 5: Voltage and temperature dependent light-current characteristics of a DFB ICL device operating in CW mode around 3.4 µm
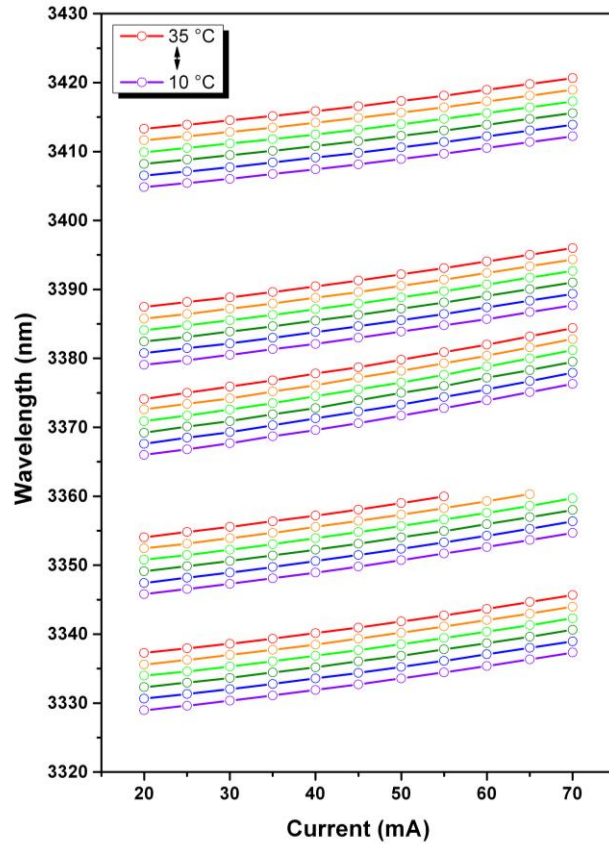

Figure 6: Several DFB ICL devices with different grating periods based on one epitaxial structure in the 3.3 µm wavelength range. Each block depicts single mode tuning behavior of a single device. Emission wavelength tuning is performed by a variation of operating current (x-axis) and temperature (color coded).

The threshold power densities of the fabricated DFB ICL devices in cw operation are around 1 kW/cm^2, which is more than an order of magnitude lower compared to the values of QCLs or diode lasers in this wavelength range. In Figure 5 temperature dependent light-current characteristics of a DFB ICL device operating around 3.4 μm are presented. With a laser threshold around 15 mA this device emits more than 20 mW single mode power in cw operation around room temperature (RT), which is perfectly suitable for most TLAS applications. Room temperature cw operation was achieved throughout the investigated wavelength range, while around 3.1 μm single mode operation with more than 1 mW of cw output power at 80 °C was observed[11].

The metal grating concept improves DFB coupling of the laser devices resulting, e.g., in increased DFB tuning ranges. As an example, the tuning behavior of several DFB ICL devices based on one epitaxial structure in the wavelength region from 3.3 μm to 3.4 μm is shown in Figure 6. By varying the grating period a spectral range of more than 90 nm is accessible for single mode DFB operation. Single devices exhibit an overall tuning range up to 18 nm by temperature and current variation. Typical current and temperature tuning ratios of around 0.2 nm/mA and 0.3 nm/K were obtained, respectively. Current tuning of more than 10 nm has been achieved, which makes these devices suitable for many spectroscopic sensing applications. In the wavelength range covered by the DFB ICL devices shown in this figure strong absorption features of, e.g., methane, ethane, hydrogen chloride and formaldehyde are located.

An example for a DFB ICL based sensor system is given in[12]. In this experiment two mobile sampling platforms, a ground vehicle and a small airplane have been used to measure ethane/methane enhancement ratios downwind of methane sources, providing ethane measurements with sub-ppb precision. Simultaneous field measurements of atmospheric ethane enable precise identification of the origin of methane traces, since the ethane concentration in methane background depends on the methane source. Large differences between biogenic and thermogenic sources are observed.

5. CONCLUSIONS

In conclusion low threshold ICLs have been realized on GaSb- and InAs-substrates. In the ICL sweet spot (3 − 4 μm) threshold current densities of below 100 A/cm^2 for broad area lasers operated in pulsed mode could be achieved. On GaSb substrates the lower limit for ICL emission has been pushed to 2.8 μm. RWG devices fabricated from the grown wafer achieved an ICL record characteristic temperature of 67 K and could be operated in cw mode up to 50 °C. For ICLs grown on InAs substrates a record low room temperature J_{th} of 588 A/cm^2 could be measured. Furthermore the wavelength for pulsed operation at room temperature could be extended to 7.1 μm. From the GaSb based wafers DFB lasers based on a loss coupled metal grating were fabricated throughout the entire wavelength range between 2.8 and 5.2 μm. At 3.4 μm a device emitted more than 20 mW of single mode output power at room temperature. By changing the grating period a wavelength window of 90 nm could be covered by DFB devices made from one wafer.

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