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## High temperature operation of short wavelength InAs-based quantum cascade lasers

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InAs/AlSb quantum cascade lasers emitting at 3.06 and 3.22  $\mu\text{m}$  at room temperature has been studied. The lasers with high reflection coating on back facets operated in pulse mode up to 400 and 423 K, respectively. The obtained results showed no dramatic performance degradation of the InAs-based QCLs with decreasing emission wavelength down to 3  $\mu\text{m}$ . *Copyright 2012 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License.* [<http://dx.doi.org/10.1063/1.4714363>]

Quantum cascade lasers (QCL) are recognized now as universal light sources for the mid-infrared spectral range. Their performances in terms of output optical power and emission efficiency are especially impressive in the 4-5  $\mu\text{m}$  wavelength range.<sup>1,2</sup> Below 4  $\mu\text{m}$  performances of these InP-based QCLs degrade with decreasing emission wavelength because the conduction band offset between the GaInAs wells and AlInAs barriers is insufficient to host intersubband transitions of such high energies. Numerous efforts have been made last years to expand the QCL operation range towards short wavelengths below 3.5  $\mu\text{m}$ . InP-based QCLs with increased conduction band offsets emitting at 3.05  $\mu\text{m}$  at 80 K have been reported.<sup>3-5</sup> The lasers from ref. 5 could operate in pulsed mode up to room temperature with a threshold current density of 19  $\text{kA}/\text{cm}^2$ . High temperature operation of short wavelength InP-based QCLs has been reported recently.<sup>6</sup> These lasers emitting at 3.3  $\mu\text{m}$  at RT with a threshold current density of 3.6  $\text{kA}/\text{cm}^2$  for devices with high reflection (HR) coating operated in pulsed mode up to 350 K.

A series of short wavelength QCLs grown on InAs and emitting at 2.95  $\mu\text{m}$ ,<sup>7</sup> 2.75 and 2.88  $\mu\text{m}$ ,<sup>8</sup> and 2.63  $\mu\text{m}$ <sup>9</sup> at 80 K has been demonstrated in the InAs/AlSb material system. The 2.88  $\mu\text{m}$  lasers from ref. 8 operated in pulsed mode up to RT where their emission wavelength shifted to 2.97  $\mu\text{m}$  and the threshold current density increased up to 4.5  $\text{kA}/\text{cm}^2$ . The maximum operation temperature of InAs/AlSb QCLs emitting at 3.33  $\mu\text{m}$  at RT (3.22  $\mu\text{m}$  at 80 K) reaches 400K<sup>10</sup> but it decreases at shorter wavelengths down to 140 K in the 2.75  $\mu\text{m}$  lasers.<sup>8</sup> The drop in the maximum operation temperature in these lasers was accompanied with a decrease in the maximum available current from 9 to 3.5  $\text{kA}/\text{cm}^2$  despite nearly the same doping level in all the structures. The goal of this study was to reach high temperature operation of InAs/AlSb QCLs with  $\lambda_{\text{RT}}$  shorter than 3.3  $\mu\text{m}$ .

The evolution of the InAs-based QCL performances with decreasing emission wavelength was explained in ref. 8 by specific features of the used designs. The last injector level in the short wavelength QCLs was not sufficiently coupled with preceding injector states thus reducing the available current, which, in turn, limited the laser operation temperature. The electron leakage into the L-valley related states in the active InAs quantum wells which gets stronger in QCLs emitting at shorter wavelengths can also be responsible for such behavior. The L-valley effect on operation of the 2.88  $\mu\text{m}$  InAs-based QCLs mentioned above has been revealed in ref. 11, while performances of the 3.33  $\mu\text{m}$  QCLs were found to be not affected by the electron leakage into the indirect states. The L-valley leakage can be manifested in decreasing population of the upper level of the laser transition resulting in higher threshold but also in reduction of the laser current because of the long electron lifetime in the indirect valley. It is difficult to suppress the carrier leakage in short wavelength QCLs when the upper level of the lasing transition is close to the L-valley states. On the other hand, the



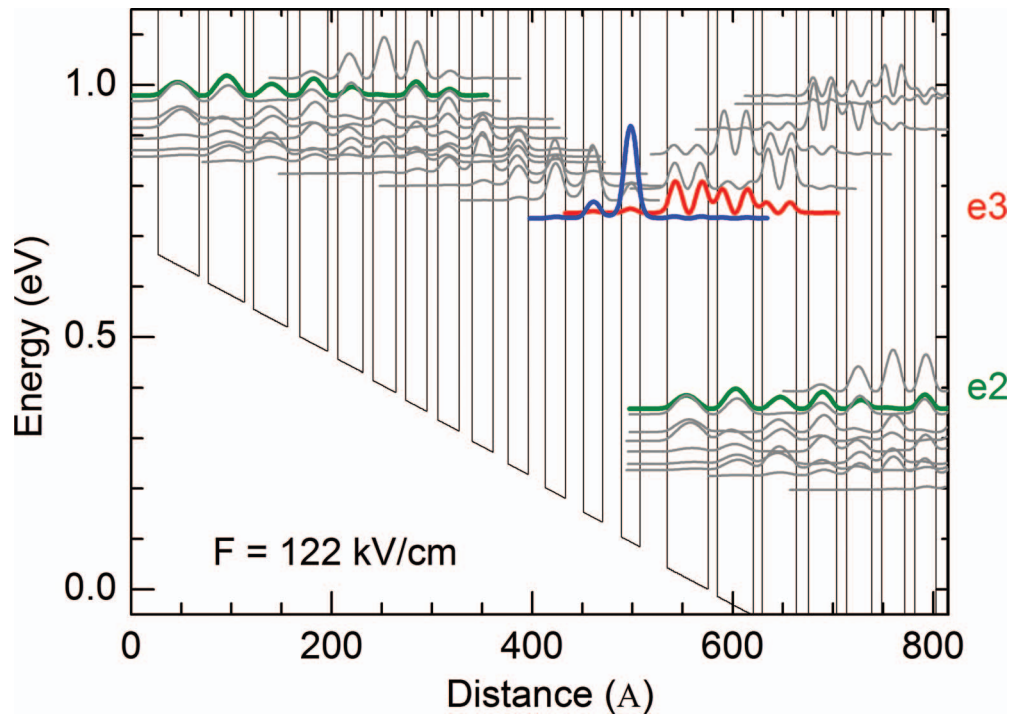


FIG. 1. Conduction band diagram of the active region of the QCL with nominal thicknesses of InAs layers at RT. Solid curves represent the moduli squared of the relevant electron wave functions.

weak coupling of the injector states, probably responsible for the small available current in lasers reported in ref. 8, can be avoided by optimization of the design. In this work we modified the QCL design to lift this limitation in order to improve the operation temperature of short wavelength QCLs.

Two QCLs structures targeted to emit at wavelengths between 3.0 and 3.3  $\mu\text{m}$  at RT have been grown by molecular beam epitaxy on n-InAs (100) substrates in a Riber Compact 21 solid source machine. In order to avoid critical modifications in the QCLs design leading to weak coupling of the injector states the laser emission wavelength was adjusted by deviating the InAs growth rate from its usual value of 1 Å/s. The QCL emission wavelength is nearly proportional to the thickness of InAs layers, that is to the InAs growth rate. The design of the QCLs is very close to that from ref. 10, as well as the intended doping level. The laser active zone is based on the bound-to-continuum scheme with vertical transitions and designed to emit at 3.18  $\mu\text{m}$  at RT when the InAs layers have the nominal thicknesses (Fig. 1). The design is characterized by a large injector miniband, which should reduce thermal backfilling and thus improve thermal stability of the laser. We tried to maximize the oscillator strength of the vertical lasing transition e3–e2 in order to weaken influence of interface scattering expected to be considerable in short wavelength QCLs with narrow quantum wells.<sup>12</sup> The high oscillator strength itself does not reduce the interface scattering but makes its impact less significant because of the faster e3–e2 transition. One period of the nominal design consists of the following layers (in Å and starting from the injection barrier): **27/41/9/36/9/34/12/28/10/25/10/23/10/21/11/21/13/21/15/20/17/20/18/19/19/18.5**, where AlSb layers are in bold and Si-doped layers ( $n = 4.10^{17} \text{ cm}^{-3}$ ) are underlined. The active zone of the lasers contains 24 repetitions of this layer sequence. The plasmon enhanced waveguide of the laser consisting of heavily doped n-InAs cladding layers and  $200 \times [2 \text{ nm InAs } (n = 1.10^{17} \text{ cm}^{-3}) + 2 \text{ nm AlSb}]$  superlattice spacers is similar to that used in our previous works.<sup>8–10</sup> Comparing periodicities related to the QCL active region and to the superlattice spacers obtained from X-ray diffraction measurements real thicknesses of the InAs and AlSb layers in the grown wafers could be calculated independently. The thickness of InAs layers was found to be 0.97 and 1.02 of its nominal value in the

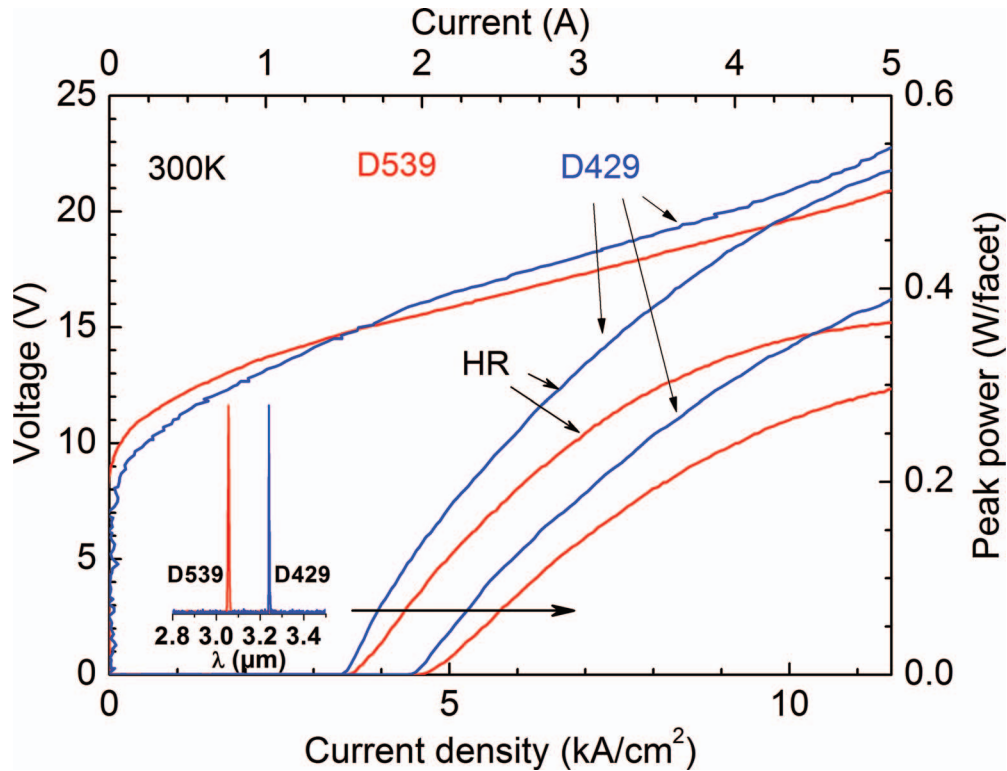


FIG. 2. Voltage-current and light-current characteristics of the studied QCLs at room temperature. Emission spectra of the lasers are shown in the inset. HR – lasers with high reflection coating on back facets.

grown wafers D539 and D429, respectively, while for the AlSb layers deviations from the nominal thickness were less than 1% in both structures.

The wafers were processed into deep mesa lasers with ridge width of  $12\ \mu\text{m}$  by conventional photolithography and wet chemical etching. Hard baked photoresist was used for electrical insulation. High reflection (HR) coating consisting of 500 nm of  $\text{SiO}_2$  and 100 nm of Cr was deposited on back facets of some lasers. The 3.5 mm long devices with cleaved Fabry-Perot resonators were soldered with In epi-side down onto copper heat sinks. The lasers were tested in pulsed mode at a repetition rate of 10 kHz and pulse duration of 100 ns. Emission spectra of the lasers were measured using a Bruker Vertex 70 Fourier transform spectrometer (FTIR) equipped with a pyroelectric detector in the rapid scan regime. This configuration was also used to measure the laser output power. For these measurements the setup was calibrated using a Melles-Griot 13P001 power meter.

Lasers fabricated from the wafer D539 grown at InAs growth rate of 0.97 A/s emitted at  $3.06\ \mu\text{m}$  at RT compared with  $3.22\ \mu\text{m}$  for lasers fabricated from the wafer D439 grown at the higher InAs rate. Fig. 2 displays voltage-current and light-current characteristics of these lasers, as well as their emission spectra. The threshold current density of the lasers with as-cleaved facets was 4.5 and 4.7  $\text{kA}/\text{cm}^2$  at 300K for devices fabricated from the wafers D429 and D539, respectively. The maximum available current was close to 12  $\text{kA}/\text{cm}^2$ , which is slightly higher than that in the reference devices from ref. 10. This difference can be explained by the insufficient precision of doping calibration in the structures doped with  $\text{Te}^{10}$  and in the Si-doped devices from this work. The HR coating on the back facets of the lasers allowed us to reduce threshold current densities down to 3.5  $\text{kA}/\text{cm}^2$  for the wafer D429 and to 3.6  $\text{kA}/\text{cm}^2$  for the D539 devices. Assuming that the reflectivity of HR coated and as-cleaved facets is 1 and 0.3, respectively, and using a classical balance of gain and loss at threshold the waveguide loss can be estimated to be 3.8 - 4.5  $\text{cm}^{-1}$  for both wafers from the data obtained on several typical devices. The waveguide loss can be also extracted from the light-current curves of the lasers comparing the slope efficiency of devices with as-cleaved

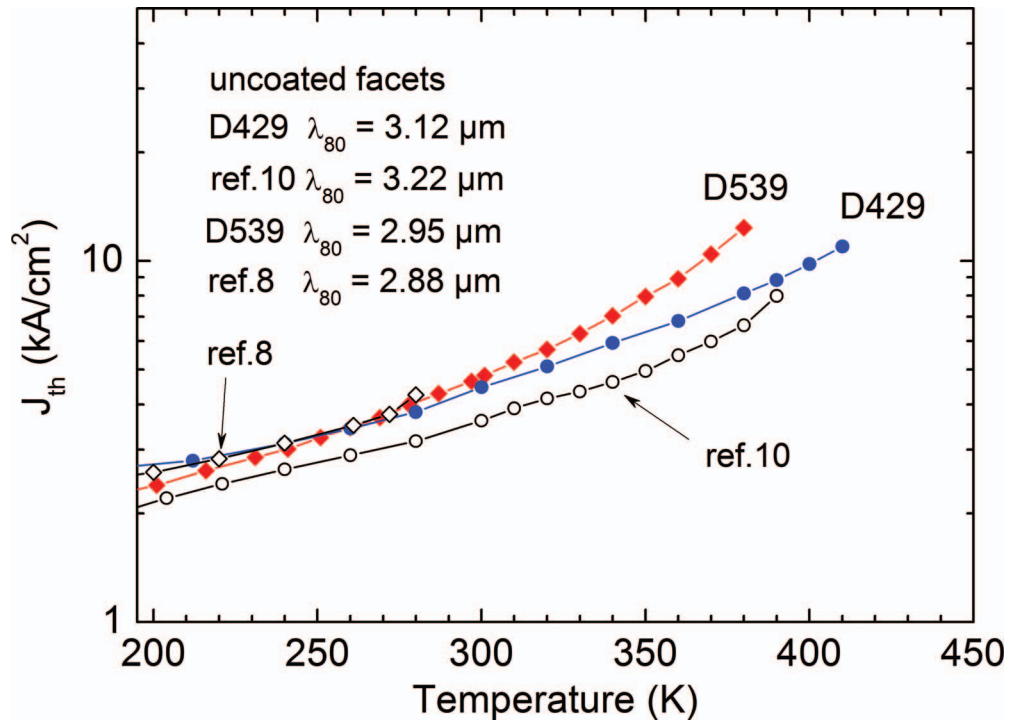


FIG. 3. Temperature dependence of the threshold current density of lasers with as-cleaved facets in comparison with previously reported results from refs. 8 and 10.

facets and with HR coating. The slope of light-current curves is proportional to the ratio of mirror loss to total loss of the laser. The initial slope efficiency of the lasers with HR coating was found to be 0.31 and 0.21 W/A for the wafers D429 and D539, respectively, compared with 0.5 W/A for the reference HR-coated lasers from ref. 10. Taking into account the slope efficiencies of total emitted power of the corresponding uncoated devices of 0.46 and 0.32 W/A the internal loss can be estimated to be  $3.2 - 3.8 \text{ cm}^{-1}$  for both wafers, in fair agreement with the values obtained from the data on the threshold current. It should be noted however that this analysis gives only a rough estimation of the internal loss because the used current pulses were not strictly rectangular, which deformed the shape of L-I curves.

Fig. 3 shows threshold current densities of the lasers with uncoated facets in comparison with previously reported InAs/AlSb QCLs emitting at close wavelengths.<sup>8,10</sup> Despite the 20% higher threshold current density of the D429 lasers their performances seem to be not strongly affected by the  $0.1 \mu\text{m}$  decrease in the emission wavelength compared with QCLs from ref. 10. The slope of the  $J_{\text{th}}(T)$  curve of D429 lasers is nearly the same and their maximum operation temperature of 410 K is even higher than that of the reference devices. With the further  $0.17 \mu\text{m}$  decrease in the emission wavelength in the D539 lasers the threshold grows faster at high temperatures, while below RT the characteristics of all lasers presented in Fig. 3 are comparable. The threshold current increase above RT in the lasers emitting at  $\lambda \leq 3 \mu\text{m}$  can be explained by the carrier leakage into the L-valley of active InAs quantum wells of the structure which should be stronger at high temperatures.<sup>11</sup> Nevertheless, the maximum operation temperature of D539 lasers reached 380 K. The temperature behavior of the D539 lasers and QCLs from ref. 8 is very similar up to RT, which can indicate that the operation temperature of the latter was limited near RT by the insufficient available current.

HR coating of the back facets of the lasers allowed further increasing of the QCL operation temperature. HR-coated D429 lasers were tested in pulsed mode at temperatures up to 423 K, only several degrees below the melting point of the used In solder. The temperature dependence of the threshold current density of these lasers did not exhibit faster growth at high temperatures (Fig. 4) showing that operation above 423 K was probably possible. D539 lasers with the HR-coating

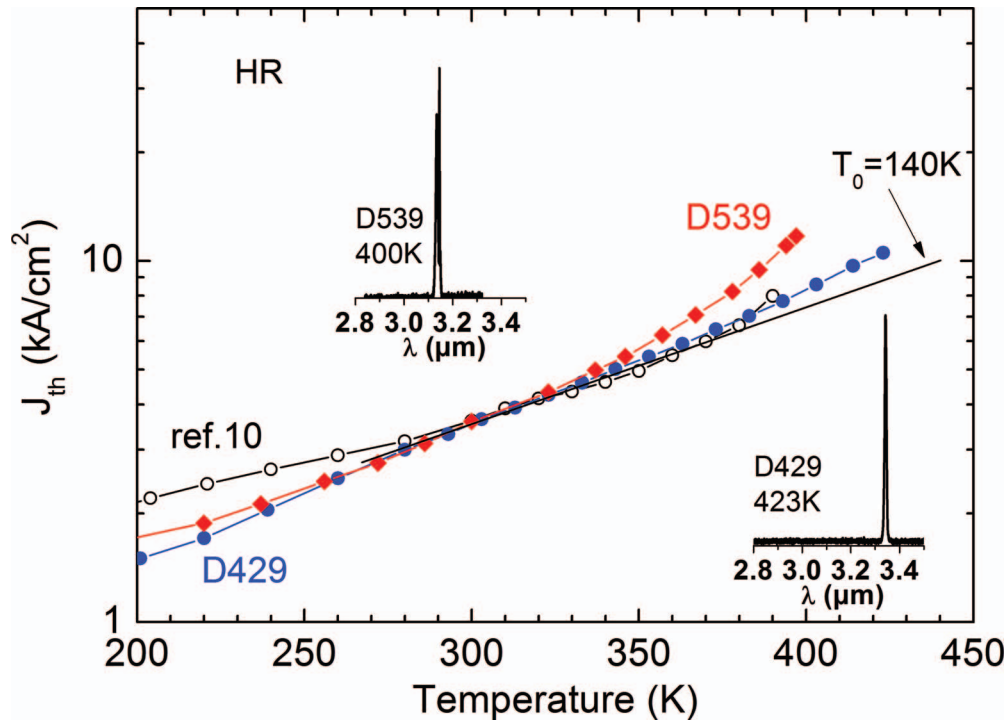


FIG. 4. Temperature dependence of the threshold current density of the lasers with HR-coated facets. Straight line corresponds to an exponential increase with a characteristic temperature of 140K.

operated up to 400 K. The characteristic temperature of the temperature dependence of the threshold current was similar for both wafers up to 350 K (Fig. 4) while for the lasers with uncoated facets these curves started to diverge already near RT. The stronger effect of HR coating in the D539 devices at high temperatures can be explained by lower waveguide loss due to weaker free carrier absorption at the shorter laser wavelength. The emission wavelength shifted to 3.13 and 3.33  $\mu\text{m}$  for the lasers D539 and D429, respectively, at their corresponding maximum operation temperatures (Fig. 4).

In summary, we have studied two sets of InAs/AlSb QCLs emitting at wavelengths shorter than 3.33  $\mu\text{m}$  at RT. It was expected that the QCL performances could degrade with decreasing emission wavelength because of electron leakage into the L-valley of InAs quantum wells.<sup>11</sup> The 3.33  $\mu\text{m}$  lasers from ref. 10 were considered as reference devices because their performances were previously shown to be not affected by this effect.<sup>11</sup> No dramatic change in QCL performances has been found with decreasing emission wavelength. The studied lasers demonstrated high temperature operation in pulse mode. HR-coated QCLs emitting at 3.22  $\mu\text{m}$  at RT operated up to 423 K. The lasers with  $\lambda_{\text{RT}} = 3.06 \mu\text{m}$  exhibited stronger  $J_{\text{th}}(T)$  dependence above RT, which can be attributed to the L-valley leakage increasing above RT, but their maximum operation temperature reached nevertheless 400K. The initial slope of light-current curves decreased from 0.5 W/A for HR-coated reference lasers to 0.31 and 0.21 W/A for QCLs with  $\lambda_{\text{RT}} = 3.22$  and 3.06  $\mu\text{m}$ , respectively. It should be noted that the observed slight degradation of some laser performances can be due just to the fact that the QCL design was not optimized for each particular case.

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