Progress in Terahertz Quantum Cascade Lasers supporting clean n-level systems.

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Although Terahertz Quantum Cascade Lasers (THz-QCLs) have a lot of potential, since they were first demonstrated in 2002, their use has been restricted due to lack of portability due to the requirements of cooling machinery. Therefore, raising the T_{max} is the main goal in the field. In 2021, a new T_{max} of ~250 K was achieved and demonstrated [1], enabling the launch of the first high-power portable THz-QCL. Although portable, this device, still required thermoelectric cooling, and the T_{max} was reached in pulsed operation. Moreover, up to date, other groups did not report similar T_{max} values, indicating how big of a challenge this represents.

The design that reached the T_{max} of ~250 K [1] is a two-well (TW) design supporting a clean three-level system (meaning the electron transport occurs only within the laser´s active subbands and all thermally activated leakage paths for electrons were suppressed). This design is like the design demonstrated beforehand with small variations (Design HB2 in Ref. [2]), and it is not the only design with a clean n-level system. Other designs that showed to have successfully suppressed thermally activated leakage channels are a resonant-phonon design presented in 2016 [3], and a split-well direct-phonon (SWDP) proposed in 2019 [4]. However, it is not clear why designs with very similar characteristics show very different T_{max} values, hence, the investigation is still ongoing.

Within our study, we suggest two other novel designs with clean n-level system. The first one is a highly diagonal split-well resonant-phonon (SWRP) scheme [5] and the second is a two-well injector direct-phonon (TWI-DP) scheme. Just as the structures mentioned earlier, both these new designs support clean 4-level systems.

The focus of the research we are presenting is on investigating these designs and comparing their device performance with other designs supporting clean n-level systems. Considering that THz-QCL designs supporting clean n-level systems are not limited by thermal leakage, a detailed comparison of their temperature performance should be the key for improvements beyond the state-of-the-art.

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Supplementary Pages

To keep improving the temperature performance of THz-QCLs, we need to better understand the physics and obstacles that were overcome over the years to reach the developments that led to the T_{max} of ~250 K [1].

The thermally activated longitudinal optical (LO) phonon scattering from the upper lasing level (ULL) to the lower lasing level (LLL) is the main mechanism that limits the operation temperature of standard vertical-transition THz-QCLs [2]. This limitation was overcome by designing highly diagonal structures, which significantly reduce thermally activated LO phonon scattering [3, 4]. In highly diagonal THz-QCLs structures the main mechanism observed to limit the temperature performance, is the thermally activated leakage into the continuum [4], mainly when using barriers containing just 15% Al. Thermally activated leakage of charged carriers into excited bound states [5, 6] also proved to be harmful for the temperature performance, even with barriers containing 30% Al. Combining high barriers with thin wells proved to push the excited and continuum states to higher energies and suppress these leakage paths [6-8]. Carefully engineered devices, showed clear negative differential resistance (NDR) behavior in the current voltage (I-V) curves all the way up to room temperature [6–8]. A clear NDR region means that the electron transport occurs only within the laser´s active subbands, meaning all thermally activated leakage paths for electrons were suppressed. This way, a clean n-level system was obtained, n being the number of the laser's active subbands [6–8]. Taking this into account, the strategy has been to design THz-QCLs that have as close as possible to clean n-level systems, especially at elevated temperatures. This strategy of achieving a clean n-level system, led to the highest recorded T_{max} [1] and this is the strategy used in our research as well.

The design that reached the T_{max} of ~250 K [1] is a two-well (TW) design supporting a clean three-level system, like the design demonstrated beforehand with small variations (Design HB2 in Ref. [7]), and it is not the only design with a clean n-level system. Other designs that showed to have successfully suppressed thermally activated leakage channels are a resonant-phonon design presented in 2016 [5], and a split-well direct-phonon (SWDP) proposed in 2019 [8]. However, it is not clear why designs with very similar characteristics show very different T_{max} values, hence, the investigation is still ongoing.

Here, we suggest two other novel designs with clean n-level system. The first one is a highly diagonal split-well resonant-phonon (SWRP) scheme (Fig.1a) [9], based on the same design principles as the split-well direct-phonon (SWDP) design previously described in Refs. [8-10]. However, in the SWDP device there is a high overlap between the doped region and the active laser states [10] and in the new SWRP design, this overlap is reduced, and effects related to gain broadening should be lower. The second design is a two-well injector direct-phonon (TWI-DP) structure (Fig.2a), which combines both two-well injector and direct-phonon scattering schemes. The TWI-DP design keeps the direct-phonon scheme for the depopulation of the lower laser level (LLL), while overcoming its main disadvantages, such as the large overlap between the doped and active laser regions. Just as the structures mentioned earlier, both these new designs support clean 4-level systems, as shown by the NDR signature in their I-V curves all the way up to room temperature (Fig.1b and Fig.2b respectively).

The focus of the research we are presenting is on investigating these designs and comparing their device performance with other designs supporting clean n-level systems. Considering that THz-QCL designs supporting clean n-level systems are not limited by thermal leakage, a detailed comparison of their temperature performance should be the key for improvements beyond the state-of-the-art.

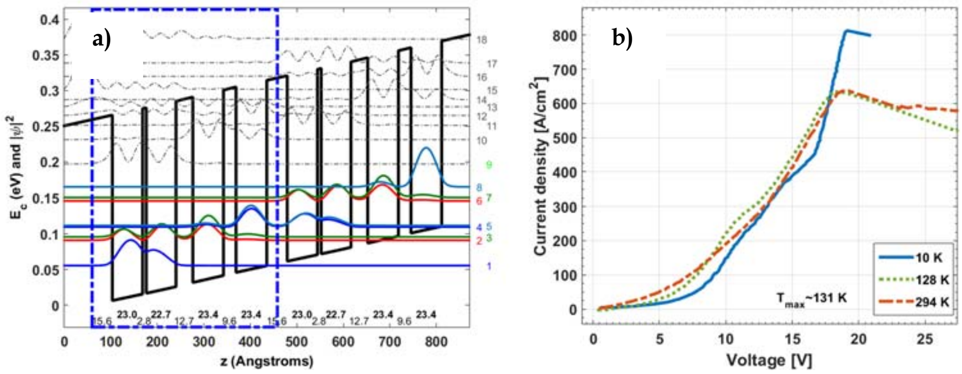

Fig. 1: a) Band diagram of two sequential periods termed *module i* (left, marked by dashed-dotted box) and *module i+1* (right) of the SWRP THz-QCLs with $Al_{0.3}Ga_{0.7}As$ barriers, corresponding to energy levels of the device. The doping is ~2.31×10^{16} cm^{-3} in the quantum wells by the sides of the thin barrier, an integral value of ~ 3×10^{10} cm^{-2} per module. b) Current-voltage (I-V) curves of the device at low, around maximum operating, and room temperatures. The maximum operating (lasing) temperature (~131 K) is indicated.

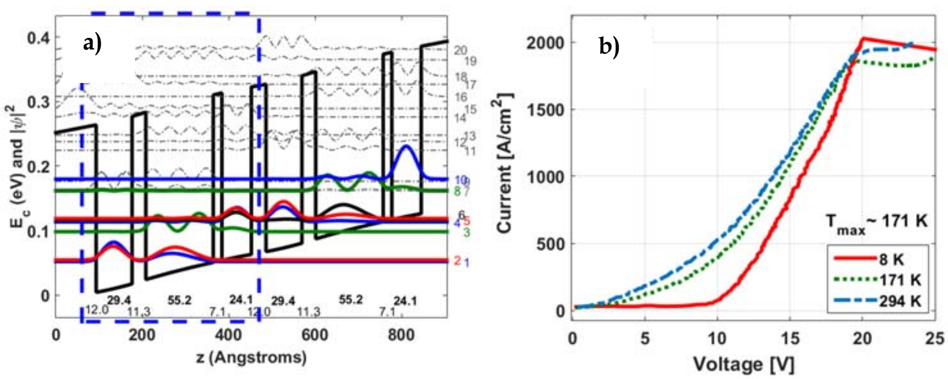

Fig. 2: a) Band diagram of two sequential periods termed *module i* (left, marked by dashed-dotted box) and *module i+1* (right) of the TWI-DP THz-QCL structure with $Al_{0.3}Ga_{0.7}As$ barriers, corresponding to energy levels of the device. The doping level is ~9.11×10^{16} cm^{3-} in the 24.9 monolayers (MLs) quantum well, an integral value of ~7.56×10^{10} cm^{-2}. b) Current-voltage (I-V) curves of the device at low, around maximum operating, and room temperatures. The maximum operating (lasing) temperature (~171 K) is indicated.

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