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Extraction-controlled quantum cascade lasers

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A simple two-well design for terahertz quantum cascade lasers is proposed which is based on scattering injection and the efficient extraction of electrons from the lower laser level by resonant tunneling. In contrast to existing designs this extraction also controls the positive differential conductivity. The device is analyzed by calculations based on nonequilibrium Green's functions, which predict lasing operation well above 200 K at a frequency of 2.8 THz. © *2010 American Institute of Physics*. [doi:10.1063/1.3483764]

Since their first realization,[1] quantum cascade lasers (QCLs) have turned into versatile devices. While the first lasers operated in the infrared region above the optical phonon frequency (around 9 THz in the most common III/V semiconductor materials used), terahertz (THz)-QCLs, operating below this frequency, could be achieved later.[2] However, the operation of these THz-QCLs has only been established for temperatures up to 186 K yet.[3] The achievement of higher operation temperatures is of high significance for many technical applications, as one could apply simpler cooling techniques.

Based on a single concept QCLs operate over a range of almost two orders of magnitude in frequency from 1.2 THz (250 μm) (Ref. 4) to 114 THz (2.63 μm) (Ref. 5) except for a gap around the optical phonon frequency. The basic ideas, some of them essentially going back to Kazarinov and Suris[6] are as follows: (i) the use of *electronic subbands* in semiconductor heterostructures as *upper* (subscript u) and *lower* (subscript l) laser level allowing for the wide variation in the transition energy by properly chosen heterostructures. (ii) Electric pumping by a bias along the growth direction of the heterostructure. Here the flow of current through the structure feeds electrons into the upper laser level coming from the *injector level* (subscript i). While the further propagation from the upper laser level at energy E_u is essentially blocked by a gap in the energy spectrum of the heterostructure, efficient pathways are provided for the emptying of the lower level into an *extraction level* (subscript e). (iii) While a single intersubband transition is typically not sufficient to overcome the losses in the waveguide, a *cascade* of identical structures (called period) is realized, all contributing to the gain of the optical mode in the waveguide.

As an example the Wannier states for a recent THz QCL with high-temperature operation[3] have been displayed in Fig. 1(a). Here the current flows via resonant tunneling from the injector into the upper laser level and is extracted from the lower laser level by a further resonant tunneling processes, while this extraction level is emptied by optical phonon scattering. This *resonant phonon extraction* design[7] has been proven to be very effective for THz-QCLs as it selectively empties the lower laser level while the upper laser level is less affected due to the resonance condition.

An important issue for the operation of QCLs is the achievement of positive differential conductivity (PDC) for each period. Otherwise, for negative differential conductivity (NDC), the electric field distribution becomes inhomogeneous over the structure[9] and prevents from achieving the designed resonances in each period of the cascade. This phenomenon of domain formation is well known from the study of superlattices (see Ref. 10 and references cited therein) where it constitutes the main obstacle to observe the gain properties. Tunnel resonances exhibit commonly a current peak when the levels align. This provides PDC/NDC if the left level is located below/above the right level, respectively.[11,12] In particular, this relates to the gain transition in THz structures, where the energy separation is only slightly larger than the broadening and thus constitutes a source of NDC. This has to be compensated by PDC contributions in different parts of the current flow through each period which is typically achieved by a second tunneling transition just below resonance. In most cases this is the transition between the injector and the upper laser level, see also Fig. 1(a). Albeit establishing record temperature operation such a *tunneling injection* design has two shortcomings. (i) As the tunneling resonance should be an effective source of PDC the injector level must exhibit an occupation at least comparable to the upper laser level. This restricts the possible inversion for a given total carrier density. (ii) Tunneling from the injector to the lower laser level constitutes a second resonance which is a further source of NDC and thus of particular concern for low lasing frequencies, when it mixes with the tunneling resonance into the upper laser level. A

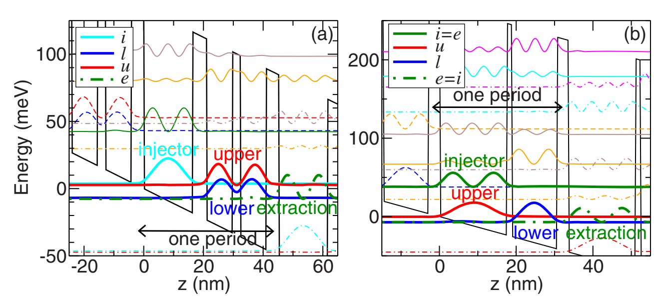

FIG. 1. (Color online) (a) Absolute square of the Wannier states of the QCL from Ref. 3 together with the heterostructure potential. (b) Same data for the device proposed here. The layer sequence is 17.5/**<u>1.5</u>**/11.5/**3** nm with effective masses of 0.067 in the wells and 0.0919 in the barriers (bold symbols). The conduction band offset is 0.27 eV, which relates to a GaAs/$Al_{0.3}Ga_{0.7}As$ structure. The underlined barrier is n-doped with $3\times10^{10}/cm^2$. [Note that Wannier states are not the commonly plotted eigenstates of the Hamiltonian but are better localized within the period (Ref. 8).]

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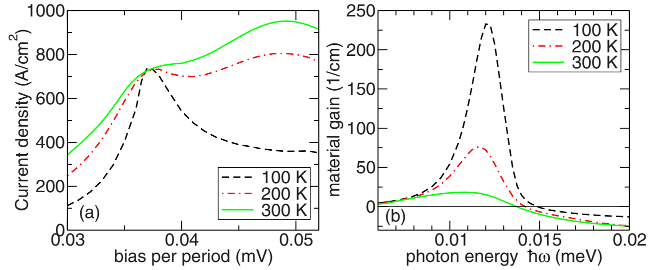

FIG. 2. (Color online) Simulation results for the proposed structure of Fig. 1(b) at different lattice temperatures. (a) Current vs bias per period. (b) Gain spectrum at a bias of 48 mV per period.

possible solution of this problem is the development of *scattering injection* designs.[13,14] Such a structure was recently shown to exhibit improved temperature performance in the THz region.[15] In these structures a tunneling resonance is included in the current flow before the electrons reach the injector state in order to guarantee PDC.

Here a design based on scattering injection is proposed where this tunneling resonance is skipped, see Fig. 1(b). Instead, the tunneling resonance from the lower laser level to the extraction level controls the current. The idea is that for biases below the designed operation point the carriers are essentially located in the lower laser level. At the design bias the extraction level removes these carriers effectively. Simultaneously, this level serves as the injection level for the upper laser level of the next period via phonon scattering. Thus this structure is a simplified combination between the resonant phonon extraction and the scattering injection scheme, where both features are provided by the same levels. This allows a design with only two wells per period and thereby increases the number of possible periods in the waveguide. (Two-well designs have been already established for the conventional tunneling injection design.[16,17])

The design of the structure was optimized by calculations within the nonequilibrium Green's function model described in Refs. 8, 18, and 19 using an improved treatment of acoustic phonon scattering and including alloy scattering, see Ref. 20 for details. This model allows for a consistent treatment of coherent evolution and scattering including level broadening, and has been recently used by other groups as well.[21,22] Here the following issues were found to be of relevance for the final design: (i) at the operating bias, the extraction level is in resonance with the lower laser level and located about one optical phonon energy above the upper laser level of the subsequent period. (ii) The higher levels do not provide further level spacings comparable to the lasing transitions in order to avoid reabsorption at higher temperatures, when they are partially filled. (iii) Increasing doping enhances the number of carriers in the gain transition but also strengthens impurity scattering associated with a larger linewidth and a shorter lifetime of the upper laser state. The chosen doping was found to provide the strongest gain. (iv) Compensation effects[18] reduce the width of the gain spectrum if the same doping atoms affect both laser levels. Thus, the placing of the doping in the barrier between the lasing states is advantageous.

Figure 2(a) shows the calculated current-voltage characteristics for different temperatures for the optimized structure. The currents are of the same magnitude as in the design in Ref. 3 and thus the same thermal management should

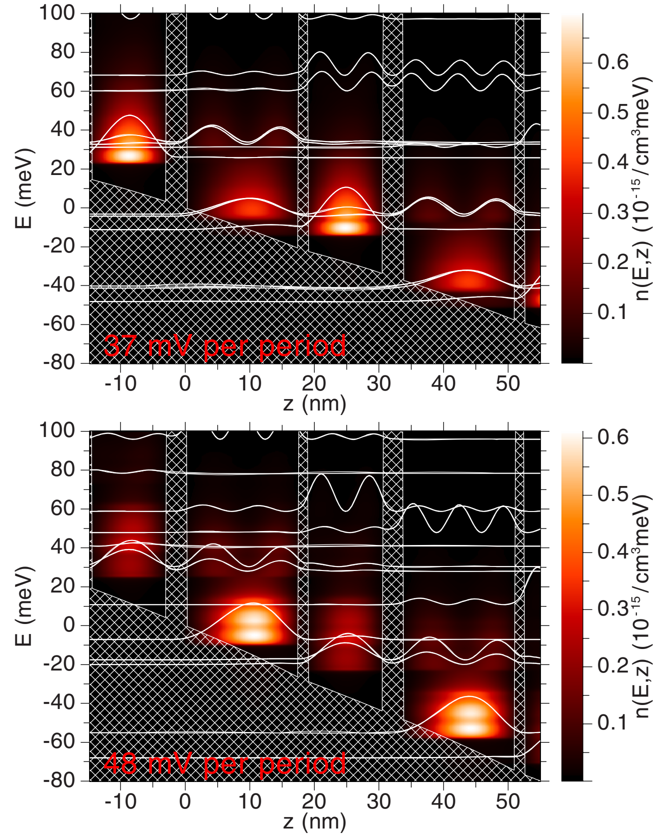

FIG. 3. (Color online) Electron density at 200 K for the first current peak at 37 mV per period (upper panel) and the lasing operation point at 48 mV per period (lower panel). In addition the electronic eigenstates are shown, which clearly show the mixing of the Wannier states at the respective resonances.

work. The gain spectrum, see Fig. 2(b), shows a peak around 12 meV (2.8 THz). At 200 K the gain maximum is 76/cm which is almost twice as large as the calculated value for the structure in Ref. 3 (42/cm at 17 meV for 200 K). Given the fact that the latter sample exhibited laser operation until 186 K, laser operation well above 200 K can be expected for the proposed design. At 300 K the peak gain is reduced to 22/cm, which is most likely not sufficient to overcome the waveguide losses.

In order to understand the operation, the energetically and spatially resolved carrier density[19] is shown in Fig. 3. At 37 mV per period, the extraction level is aligned with the upper laser level, which causes a pronounced current peak, while a significant part of the electrons is trapped in the lower laser level. Increasing the bias, the lower laser level is emptied at 48 mV due to its alignment with the extraction level. For low temperatures (e.g., 100 K) the scattering lifetime of the upper laser level is long and thus almost all electrons are collected in this level, see the data given in Table I. Thus the current is determined by the tunneling from the upper laser level into the extraction level which causes NDC at the bias of 48 mV per period. With increasing temperature, scattering becomes stronger leading to a higher occupation of the lower laser level, so that the contribution of the tunneling resonance between lower laser level and the extraction level is of larger importance. This provides PDC for each period as observed at 200 and 300 K and required for stable operation. Thus the scattering from the upper to the lower laser level, which reduces the inversion (see Ref. 23 for a detailed discussion), is actually required for the device

TABLE I. Calculated quantities for the gain transition at 48 mV per period. If the upper laser level were in thermal equilibrium with its injector level, one would expect $n_i = n_u e^{-\hbar\omega_{\rm opt}/k_B T}$, which is a lower bound for the population of the lower laser level, n_l, being in resonance with the injector level.

Temperature (K)	100	200	300
Upper n_u ($10^9/\mathrm{cm}^2$)	22.3	16.6	13.5
Lower n_l ($10^9/\mathrm{cm}^2$)	5.5	8.7	9.9
$n_u e^{-\hbar\omega_{\rm opt}/k_B T}$ ($10^9/\mathrm{cm}^2$)	0.3	2.1	3.4
Full width at half maximum of gain spectrum (meV)	2.2	2.9	3.9
Peak gain (1/cm)	233	76	21

operation in this design. A key feature is the efficient extraction, which maintains the inversion. Thus the design can be considered as extraction-dominated.

The reduction of gain with temperature can be attributed to a combination of increased broadening of the gain profile and reduced inversion, see Table I. The data indicates that thermal backfilling contributes to the increase in n_l with temperature but can only explain half the magnitude. The depopulation kinetics is of equal relevance. A principle advantage of the proposed design is that thermal backfilling cannot entirely destroy the inversion as the upper laser level plays the role of the reservoir, having the highest occupation at all temperatures. This is a common feature of properly designed scattering injection lasers.

The Green's function model used does not consider electron-electron scattering[22] and applies constant scattering matrix elements for simplicity. The impact of further scattering has been estimated by simulations using an increased elastic scattering. These resulted in slightly larger currents and reduced gain at 48 mV per period. If the additional scattering potential is located in the wider well a redshift in the gain is observed due to the real part of the self-energy. However the main results are unchanged.

In conclusion, a design for THz-QCLs has been proposed based on the efficient depopulation of the lower laser level, which also ensures the PDC. Lasing operation above 200 K is predicted.

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