Probing quantum efficiency by laser-induced hot-electron cooling

Miriam S. Vitiello,1,a Gaetano Scamarcio,1,b Jerome Faist,2 Giacomo Scalari,2 Christophe Walther,2 Harvey E. Beere,3 and David A. Ritchie3

1CNR-INFN Regional Laboratory LIT and Dipartimento Interateneo di Fisica “M. Merlin” Università degli Studi di Bari, Via Amendola 173, 70126 Bari, Italy
2Zurich Physics Department, Institute of Quantum Electronics, ETH Hönggerberg, HPT H 6 Wolfgang-Pauli-Str. 16, CH-8093 Zürich, Switzerland
3Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

(Received 13 November 2008; accepted 2 December 2008; published online 15 January 2009)

Experimental evidence of a physical phenomenon characteristic of semiconductor lasers, i.e., cooling of the electrons above the threshold for stimulated emission, is reported. We show that this effect is directly related with the internal quantum efficiency (\(\eta_{\text{int}}\)), which is one of the central physical quantities in the theory of semiconductor lasers. As a model system we selected the terahertz quantum-cascade laser that is particularly suitable for the investigation of nonequilibrium electronic ensembles. The reported procedure for the assessment of \(\eta_{\text{int}}\) can be easily extended to other model systems, enlightening the relevance of including hot-electron distributions in semiconductor laser modeling. © 2009 American Institute of Physics. [DOI: 10.1063/1.3054644]

In electronic and photonic devices such as transistors or lasers, electrons release the excess energy gained from the applied electric field by exciting other electrons and emitting phonons or photons. The equilibrium between the input power and the energy loss rate is reached at average electron energies larger than the crystal lattice one, eventually giving rise to hot-electron populations. At large electron densities (>\(10^{10}\) cm\(^{-2}\)), the associated distributions of carriers are Fermi–Dirac functions characterized by temperatures significantly larger than the lattice one.2

Quantum-cascade lasers (QCLs) with the large electrical input power, the inherently high thermal resistance3 and the limited c-lattice relaxation efficiency4–2 are ideal to study hot-electron populations. In QCLs the electron energy distribution arises from the balance between the input power associated with tunnelling injection5 and several energy relaxation channels, i.e., inter- and intrasubband e-e, e-phonon, e-impurity, and interface-roughness scattering. The interplay between the above processes can lead to different temperatures (\(T_{P}\)) for the electronic subbands.2

In this letter, by using a terahertz QCL as a prototype, we show that the quantum efficiency\(^6\) of a semiconductor laser is correlated with the hot-electron cooling associated with photon emission. These findings enlighten the relevance of including the hot-electron distribution in the general theory of semiconductor lasers, with important implications relevant for the rapidly developing field of long-wavelength QCLs. In the latter system, hot-electron effects must be fully understood to explore the device physical limits in terms of maximum temperature, wavelength, and quantum efficiencies.

We selected a recently reported terahertz QCL based on a bound-to-continuum quantum design combined with a doublet injection/depletion scheme7 [Fig. 1(a)]. Two electronic subsystems can be identified: (i) the active region, including the upper laser level (8) and the depletion miniband (mb); (ii) the injector, constituted by a doublet (1,2) of closely spaced lowest energy levels.

---

*aElectronic mail: vitiello@fisica.uniba.it.

bElectronic mail: scamarcio@fisica.uniba.it.

---

FIG. 1. (a) Conduction band structure of one period of the active region calculated using a self-consistent Schrödinger–Poisson solver with a voltage drop of 25 mV per period, corresponding to the laser threshold. Starting from the injection barrier, the layer thickness in nanometers are (from right to left): 5.9/15.3/1.0/17.7/1.3/16.6/1.7/13.9/3.9/26.8/3.5/21.4. Values in bold correspond to Al\(_{0.1}\)Ga\(_{0.9}\)As layers. The underlined GaAs wells are \(n\)-doped to 1.0\times\(10^{18}\) cm\(^{-3}\). The wavefunction square moduli of the upper and lower laser levels are labled as 8 and 6, respectively, while those of the injector doublet are marked as 1,2. The shaded areas identify the active and lower laser levels and the depletion miniband (mb); (b) Representative PL spectra measured in a 50 μm wide-1 mm long QCL at the current densities \(J=70\) A/cm\(^2\) (1), \(J=93\) A/cm\(^2\) (2), \(J=118\) A/cm\(^2\) (3), \(J=140\) A/cm\(^2\) (4), each plotted as a function of the energy difference \(\Delta E\) with respect to the corresponding energy \(E_p\) of the low energy peak of the doublet. The vertical lines, labeled 1.2→k and 8→k mark transition energies between conduction and valence (k) subbands. The heat sink temperature is \(T_S=50\) K.
correlated with features in the transport measurements [Figs. 2(b) and 2(d)], can be identified. At the low $P$ values corresponding to region I, band structure calculations show that the energy of the injector doublet remains more than 6 meV lower than level 8 and transport proceeds via injection into the mb. Under these conditions, the injector doublet is always close to resonance with one of the four subbands in the miniband. Since the $e-e$ scattering time $\tau_{ee}$ is proportional to the energy separation between the initial and final states, the energy redistribution process between the injector and the mb is so efficient ($\tau_{ee} \approx 100$ s) that a common temperature between the injector and active region subbands is reached ($T_{inj} \approx T_{active}$). Following the approach pioneered by Luryi\cite{1}, we assume that the exchange rate of the excess energy $E_J$ of a subband population $n_j$ at a temperature $T_j$ can be written as $dE_J/dt = -n_j/k \tau_{ee} (T_{active} - T_j)$, where $P$ is the power density and $\tau_{ee}$ the energy loss lifetime between the system and the lattice which is expected to be roughly independent from the level energy. The above equation fits well the linear increase in the electronic temperature observed in region I [Figs. 2(a) and 2(c)] and gives $\tau_{ee}=0.22–0.25$ ps. These sub-ps values reflect an efficient electron-lattice coupling typically found when the dominant energy relaxation mechanism is the emission of polar optical phonons. Hence, we presume that in our structure hot electrons can perform phonon-assisted intersubband transitions (e.g., $6^* \rightarrow 1$).

The electronic temperature in region II corresponds to the active region one ($T_{active}$) which is shared by all electrons populating level 8 and the mb. These notions are supported by the following facts: (i) electrons are progressively injected into level 8, as shown by the appearance of the high energy PL peaks [Fig. 1(b)] and the flattening of the differential resistance [Figs. 2(b) and 2(d)];\cite{3} (ii) ultrafast measurements show that the subband populations in the same quantum wells equilibrate to a common temperature on a very fast time scale of about 100–200 fs;\cite{12} (iii) previous experiments performed in bound-to-continuum QCLs have shown that the bound state and the mb share the same electronic temperature.\cite{4} $T_{active}$ increases with $P$ with a much larger slope than in region I. In fact, band structure calculations show that the injector doublet lies in the minigap between the mb and level 8. Cold electrons progressively populate level 8 and are scattered elastically or quasielastically with a large excess energy to a lower state in the active region. These electrons will then thermalize within their respective subbands at a temperature $T_{active}>T_{active}$. This is a consequence of the fact that while a comparable amount of $P$ is distributed between the two subsystems, $n_{active}$ is always one order of magnitude smaller than $n_{inj}$. This picture explains analogous observations in resonant-phonon QCLs.\cite{2,3,4}

The large negative discontinuity in the differential resistance at the onset of region III [Figs. 2(b) and 2(d)] indicates that the laser threshold is reached while the population inversion $\Delta n$ becomes clamped at the onset for stimulated emission.\cite{2,5} Correspondingly, the electron heating rate decreases meaning that the photon emission extracts part of the input power, efficiently cooling the electrons. A further proof of the optical origin of the latter effect is the fact that the change in the electronic temperature slope disappears when the same measurements are performed on a nonlasing mesa device as shown in Fig. 3. In region IV lasing ceases, as revealed by the sudden jump in the differential resistance,\cite{3} [Figs. 2(b) and 2(d)]. In this transport regime, the voltage drop in each stage, the associated subband structure and the assignment of PL spectral features become ambiguous.

A simple rate equation model describes well our data and gives further meaning to the temperature measurements. We assume that (i) the average excess energy of the active region (injector) is the difference between the energy carried by the incoming and the outgoing electrons, that leave the active region (injector) with an average energy $kT_{active} (kT_{inj})$, (ii) far from resonance the $e-e$ energy relaxation terms coupling the injector and active region subsystems can be neglected with respect to the $e$-lattice ones. Accordingly:

$$\frac{dE_{inj}}{dt} = \frac{J}{q} \frac{(kT_{active} - kT_{inj} + \Delta_E - \Delta T_e)}{T_{inj} - T_e},$$

$$\frac{dE_{active}}{dt} = \frac{J}{q} \frac{(kT_{inj} - kT_{active} - \Delta_E + \Delta_{mb})}{T_{active} - T_e} - \frac{n_{active} k}{T_{active} - T_e} - g \Delta n S h \nu,$$

where $J$ is the current density, $\Delta$ is the energy separation...
between the bottom of the miniband and level 1, $\Delta_{mb}$ the miniband width, $\Delta E_{60}$ the energy separation between the upper and lower (6) laser levels, $S$ is the photon flux, $h v$ is the photon energy, and $g = \alpha_{int}/\Delta n$ is the gain cross section, related with the total losses ($\alpha_{tot}$) in the laser cavity.\(^5\) In the present case, the energy difference $kT_{act}^{int} - kT_{act}^{int} = kT_L = 5.5$ meV and thus $kT_{act}^{int} - kT_L$ can be neglected in Eqs. (1) and (2). This approximation is even more valid for midinfrared semiconductor lasers.

Combining the experimental measurement of the electronic temperatures with the derivative of Eq. (2) in steady state, below ($L=0$) and above ($L=1$) the laser threshold, provides a self-calibrated way to determine the internal quantum efficiency\(^6\) ($\eta_{int}$) of a laser via the equation:

$$d(T_{act}^{int} - T_L) / dJ = \frac{\tau_{act}}{q n_{act} k} (h v + \Delta_{mb} - h v L \eta_{int}),$$

where we exploit the fact that in the semiconductor laser theory $\eta_{int}$ depends from the level lifetimes ($\tau_8, \tau_6$) and the total nonradiative scattering rate ($\tau_{act}^0$) that are related in turn, with the derivative of the photon flux in the laser cavity\(^5\) as $\eta_{int} = \tau_8 (1 - \tau_6 / \tau_8) / [\tau_6 (1 - \tau_6 / \tau_8) + \tau_8] = \alpha_{off} dS / dJ$. The proportionality between $\eta_{int}$ and the derivative $d(T_{act}^{int} - T_L) / dJ$ is nicely reflected from the electronic temperature measurements at different heat sink temperatures ($T_H$). At increasing $T_H$ [Figs. 4(a)–4(d)] the slope $d(T_{act}^{int} - T_L) / dJ$ above lasing threshold progressively increases, meaning that the laser cooling becomes less effective. As a consequence $\eta_{int}$ decreases with $T_H$ [Fig. 4(e)].

The internal quantum efficiency is directly related with other physical parameters, central in the theory of lasers sources such as the differential external quantum efficiency ($\eta_e$) and the slope efficiency $dP_0 / dI$. In the present semiconductor source at $T_H = 40$ K we found $\eta_e = \eta_{int} \alpha_{int} / \alpha_{tot} \approx 3\%$ and $dP_0 / dI = \eta_{int} \alpha_{int} / \alpha_{tot} (h v / e) = 24$ mW/A, where $\eta_{int}$ and $\eta_e$ refer to a single QCL period, $N$ is the number of periods, and $\alpha_{int}$ the mirror losses. The above efficiencies values are a factor of $\approx 4.5$ larger than those obtained by conventional optical measurements,\(^7,\(^8\) which are inherently limited by the small collection efficiencies of the optical setups and the optical beam divergence.\(^9\) Alternative approaches commonly used in electrically pumped laser sources and based on the relative change in the differential resistance above and below threshold,\(^10\) ($\eta_{int} = 1 - \Delta R/R$), gives $\eta_{int}$ values underestimated by $\approx 40\%$ because of the residual resistances.

Furthermore, alternatively to recent approaches\(^11,\(^12\) which exploits $T_L$ as a probe of the wall-plug efficiency of a laser $\eta_w$, here we employ the electronic temperature [Fig. 4(f)] via the relation $\eta_w = \eta_{int} (\alpha_{int} / \alpha_{tot}) (h v / e) (1/V) [1 - (I_{th} / J_{th})]$, where $J_{th}$ is the threshold current density for lasing. This assures an inherently higher sensitivity, particularly useful in the characterization of terahertz sources with highly diverging beams or double-metal QCLs.\(^13\)

The processes observed and described in the present terahertz QCLs are quite general and can be conveniently extended also to other gain media. For example, in doubleres. heterostructure interband lasers where carrier heating by Auger recombination plays a very fundamental role, the hot carrier cooling rate may be much slower than the energy loss rate by phonon emission ($>1$ ps$^{-1}$). This may cause the increase in the excited level temperature well above the one of the lattice or the carrier reservoir, although a less abrupt change in the heating rate at threshold is expected since a significant amount of power is extracted from the laser via spontaneous emission processes even below threshold.

---