Far-infrared ($\lambda = 88 \, \mu m$) electroluminescence in a quantum cascade structure

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Intersubband electroluminescence has been investigated in a quantum cascade structure based on vertical transition designed for far-infrared ($\lambda = 88 \, \mu m$) emission. A narrow luminescence peak with a full width at half maximum of 0.7 meV is measured at low excitation currents (30 A/cm$^2$) and low temperature ($T = 5$ K). The electroluminescence efficiency exhibits a strong temperature and current dependence, consistent with an interplay between electron–electron and optical phonon scattering. © 1998 American Institute of Physics.

Quantum cascade lasers based on intersubband transitions\(^1\) have now demonstrated a very high level of performance in the mid infrared.\(^2\) It is hoped that the same technology could also be applied in the far infrared, where the lack of convenient sources is especially strong. Intersubband electroluminescence has been observed in the far infrared (FIR) using a periodic superlattice,\(^3\) and, more recently, broadband FIR emission has been observed in a quantum cascade structure based on diagonal transitions.\(^4\) FIR electroluminescence was also observed in structures where the electron temperature was raised by applying a current in the plane of the layers.\(^5\)–\(^7\)

At the FIR wavelengths, because the photon energy is lower than the optical phonon energy ($\hbar \omega_{LO} = 36$ meV in GaAs), optical phonon emission is not always the dominant intersubband nonradiative channel. Indeed, a large spread in the values reported in the literature for the intersubband nonradiative lifetime (between 0.5 ps\(^8\) and 1 ns\(^9\)) reflects the complex interplay between various nonradiative channels. Our results are consistent with an effective upper subband lifetime around 10 ps, depending on the injection current and temperature. This lifetime is determined by a combination of electron–electron scattering and optical phonon emission from electrons which have an excess kinetic energy larger than the optical phonon energy.

Our structure was grown by molecular beam epitaxy on an n-doped GaAs substrate and consists of 35 periods. As shown in Fig. 1(a), one period of our structure consists of four GaAs quantum wells separated by thin Al$_{0.15}$Ga$_{0.85}$As tunnel barriers. As in mid-infrared quantum cascade structures, each period consists of an undoped active region, in which the spontaneous emission occurs, and a graded-gap injector. The active region consists of a 28 nm GaAs quantum well coupled through a 2.5 nm Al$_{0.15}$Ga$_{0.85}$As barrier to an 18 nm GaAs well. The emission occurs in the 28 nm well through a vertical transitions, i.e., the optical transition proceeds between two states with a strong spatial overlap. Compared to diagonal transitions, the vertical transition has the advantage of a large oscillator strength and a narrower linewidth since it is less influenced by interface roughness. To minimize space-charge effects due to injection, the center well of the injector is doped with Si to $n = 8 \times 10^{15}$ cm$^{-3}$.

For the experiments, the samples were processed into 420 $\mu$m×420 $\mu$m mesas and Au/Ge ohmic contacts were provided to the $n^+$ contact layers on the periphery of the mesa. In order to couple the light out from the structure, we also evaporated a Cr/Au metal grating with a 15 $\mu$m periodicity. Gratings with a 10 $\mu$m periodicity gave us similar spectral results, but with a lower efficiency. The samples were mounted on the cold finger of a He flow cryostat.

![FIG. 1. (a) Self-consistent computation of the energy band diagram of two periods of the structure under an average applied electric field of 2.7 kV/cm. Shown are the moduli squared of the relevant wave functions. The wavy line corresponds to the radiative transition. The dashed lines show the energy of the optical phonon, measured from the ground state of the active region and corresponds to the radiative transition. The dashed lines show the energy of the optical phonon, measured from the ground state of the active region and of the injector. The layer sequence of one period of the structure left to right and finishing with the injection barrier is 28/2.5/16/4/16/2.5/15.5/6. The thickness is in nanometers, and the thickness of the Al$_{0.15}$Ga$_{0.85}$As layers is indicated in boldface. (b) Experimental setup.](https://www.aip.org/aplo/aplcr.jsp)
Trains of 600 1.7 μs long current pulses at 2.1 μs intervals were injected into the device, providing an overall duty factor of 40% at a frequency of 413 Hz, in order to match the frequency response of the bolometer detector while minimizing the heating of the device. The light was then collected by an off-axis parabolic mirror with an f/1.5 aperture and sent through a Fourier transform infrared (FTIR) spectrometer on a liquid-helium cooled Si bolometer detector [Fig. 1(b)]. The entire optical path was purged by dry air to minimize water vapor absorption.

Spectral measurements of the luminescence were performed using the FTIR in the step-scan mode, the signal being detected with a lock-in amplifier. A few representative spectra taken for increasing injected currents at $T = 5$ K are displayed in Fig. 2. They show that the luminescence spectrum mainly consists of one narrow peak centered at a wavelength of $\lambda = 88 \mu$m. This peak is easily identified to correspond to the $n=2 \rightarrow n=1$ transition in the 28 nm well, since its measured photon energy of $h\nu = 14.1$ meV corresponds very well to the calculated value of the $n=2 \rightarrow n=1$ transition energy $h\nu = 13.9$ meV using the thickness measured by x-ray diffraction. Working with a resolution of 0.12 meV between adjacent points, the FTIR allows us to spectrally resolve the luminescence peak and we measure a full width at half maximum of 0.7 meV. This value is larger than the one predicted from the calculated value of the intersubband lifetime ($\Delta \nu \sim 0.1$ meV), which implies that some additional in-plane dephasing mechanism or inhomogenous broadening is responsible for the line broadening. As the current is lowered to $I = 20$ mA, a broad shoulder appears on the high-energy side of the main luminescence peak. We identify this feature, present on all the spectra measured at this current, as the transition from the $n=2 \rightarrow n=1$ transition of the adjacent well. The calculated splitting between the state $n=1$ and $n=1'$ is 1.4 meV, and corresponds approximately to the measured separation between this broad feature and the luminescence peak. The high energy shoulder decreases with increasing current, and has essentially vanished at $I = 75$ mA. This is expected because the $n=2 \rightarrow n=1'$ optical matrix element decreases abruptly with increasing applied electric field as the states $n=1$ and $n=1'$ anticross.

In Fig. 3, simultaneous measurements of the voltage and optical output power versus injection current performed on the same device are reported for temperatures of $T = 5$ K (upper curve) and 80 K (lower curve). In contrast to measurements performed on mid-infrared devices, the luminescence efficiency is not constant. At $T = 5$ K, the optical power rises sublinearly to a current of $I = 80$ mA. The characteristic is more linear, with a lower efficiency, at $T = 80$ K. The spectral measurements show that the abrupt change in optical power above $I = 80$ mA (for $T = 5$ K) and 100 mA (for $T = 80$ K), which is correlated with an abrupt increase of the applied voltage, arises when the ground state $g$ of the injector is not resonant anymore with the upper state $n=2$ of the optical transition and a negative differential resistance (NDR) occurs. The optical spectrum (inset of Fig. 2) in the region of negative differential resistance is extremely broad (>30 meV) and features many additional peaks. The spectrum is consistent with a broad injection in many energy levels from electron population with a broad energy distribution. This very good correlation between the electrical and spectral characteristics in the same device is a proof that the electroluminescence arises from a resonant tunneling injection into the $n=2$ state and not from a heating of the electron gas.

The spectrum of Fig. 2 exhibits some additional small features at 24, 30, and 40 meV. The lack of clear current dependence of their peak intensity, and the small signal to noise prevents us from making unambiguous assignment. These features are most likely spurious artifacts from the grating.

The shape of the optical output power versus injection current characteristic provides some insight into the scattering mechanism. As has been shown in previous measurements of the electron lifetime in quantum wells, the nonradiative scattering at $T = 80$ K is dominated by optical phonon scattering by electrons with a thermal energy allowing the
emission of optical phonons. Indeed, at this temperature, we observe a fairly linear relationship between emitted power and injected current [see the linear fit in Fig. 3(a)], indicating a scattering process with a constant lifetime. The total non-radiative rate \( w_{nr} \) is then

\[
w_{nr} = w_{ish} \exp \left( -\frac{\hbar \omega_{LO} - E_{21}}{kT} \right).
\]

Using the calculated value of the optical phonon scattering rate \( w_{ish} = 2.35 \, \text{ps}^{-1} \) for electrons with an excess kinetic energy of \( \hbar \omega_{LO} + kT = 42 \, \text{meV} \), we find a total nonradiative rate corresponding to a lifetime \( \tau_{nr} = 10 \, \text{ps} \). From a \( n = 2 \) to \( n = 1 \) optical matrix element of 6.0 nm, we derive a radiative lifetime of 10 \( \mu \text{s} \) and a radiative efficiency \( \eta_{rad} = 10^{-6} \). The optical power is related to the injected current \( I \) by

\[
P_{opt} = \eta_{coll} \eta_{rad} N_{per} \frac{I}{q_0} h \nu,
\]

where \( \eta_{coll} \) is the collection efficiency, \( N_{per} = 35 \) the number of repeated periods of the structure, and \( h \nu \) the photon energy. For an injected current of \( I = 50 \, \text{mA} \), we measure an optical power of 0.6 \( \text{pW} \). This value is about a factor of 4 lower than our estimate (2.4 \( \text{pW} \)) using a collection efficiency \( \eta_{coll} \sim 10^{-4} \) (including a coupling efficiency of the grating of \( \sim 10\% \)). A possible explanation for the discrepancy is the presence of large optical losses induced by the highly doped substrate.

At low temperature, and in the limit of low injection current to prevent significant electron heating, optical phonon emission is forbidden. It has been shown in the literature both experimentally and theoretically that for electron sheet densities larger than \( \sim 10^6 \, \text{cm}^{-2} \), electron–electron scattering is an efficient scattering mechanism. Our measurements are in very good agreement with this picture. Hyldgaard and Wilkins\(^{13} \) gave a simplified expression for the electron–electron scattering rate, showing that this rate is in good approximation proportional to the electron density in the upper subband. Therefore the population (and the optical power) has a square root dependence on the injected current. As shown by the fit (dotted lines in Fig. 3), this is very well observed in our data. The lifetime now depends on the injected current. Using the measured optical power and the calculated value of the lifetime at \( T = 80 \, \text{K} \) as a reference, we find a lifetime \( \tau = 30 \, \text{ps} \) at \( I = 50 \, \text{mA} \) and \( \tau = 44 \, \text{ps} \) at \( I = 20 \, \text{mA} \), still much shorter than the calculated acoustic phonon emission time of \( \tau = 400 \, \text{ps} \). These lifetimes are only estimates. The actual values will be somewhat shorter, because electron–electron scattering and self-heating effects have been neglected in our calculations at \( T = 80 \, \text{K} \).

Our luminescence measurements do not directly indicate whether a population inversion was obtained in our structure. From the calculated lifetime values, we obtain a maximum upper state density of \( \sim 5 \times 10^5 \, \text{cm}^{-2} \) at \( I = 50 \, \text{mA} \), which would translate into a material gain of 150 \( \text{cm}^{-1} \) if one could assume a negligible ground state population. However, the latter hypothesis is overly optimistic since one should expect some electron heating which will induce some population in the \( n = 1 \) state. However, this effect could be suppressed and the population inversion be maintained in a structure based on a photon-assisted transition.\(^{14} \)

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