Electronic temperatures and electron-lattice relaxation in THz QCLs

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- **MOTIVATION:** The detailed knowledge on the nature of the electronic distribution in THz QCLs is of paramount importance as a guide for the design of improved structures aiming at high temperature operation.

- **TECHNIQUE:** $\mu$-photoluminescence spectroscopy as a function of voltage/current → probe of:
  - Conduction subband electronic temperatures ($T_{e_j}$)
  - Local lattice temperature ($T_L$)
  - Electron-lattice energy relaxation rates
  - Population inversion
  - Leakage channels
Features of electronic distribution in THz QCLs:

- Many energy relaxation channels:
  - e-LO phonons
  - e-e
  - e-impurity
  - interface roughness
- Thermally induced electron leakage in the continuum due to the small band offset of GaAs/AlGaAs (x = 0.10-0.15)

Electronic temperature $T_E$ → critical to validate theoretical models for optical gain:

- *Is $T_E$ the same for all the subbands?*
- *How “hot” is the electronic distribution?*
Main results

- Assessment of the electronic temperature of individual subbands
- Electronic temperature of the upper laser level → non-radiative scattering time
- Simultaneous determination of the power dependence of the lattice and electronic temperatures → electron - lattice energy relaxation rate
- Population inversion
- Comparison between quantum designs: BTC, RP, interlaced design
- Role of the conduction band offset

Study of cw operating QCLs both below and well above laser threshold
**Set-up schematics**

- **Lattice temperature** → PL shift
- **Electronic Temperature** → high energy slope analysis
- Features of µ-PL spectra in THz QCLs
  - both ground and excited subbands (not observable in mid-ir)
  - band-to-band and/or excitonic transitions

**Features of µ-PL spectra in THz QCLs**

\[
I_{PL}(E) \propto \sum_{j=1}^{5} \sum_{k=1}^{4} A_{jk} E_{jk}^2 |\langle \psi_j | \psi_k \rangle|^2 L(E)
\]

\[
\Delta E = (E-E_p) \text{ (eV)}
\]

**He-flow micro-cryostat**

**Kr+ Laser**

**Objective**

**Notch filter**

**Si CCD**

**X-Y control (100nm)**

**PL Intensity (arb. units)**

**Energy (eV)**

**Lattice temperature**

**Electronic Temperature**

**PL shift**

**High energy slope analysis**

**Features of µ-PL spectra in THz QCLs**

- both ground and excited subbands (not observable in mid-ir)
- band-to-band and/or excitonic transitions
Bound-to-continuum THz QCLs - Excitons

![Diagram of PL Intensity vs. Energy Level Calculations]

**Excitons**
- Energy level calculations
- $b_{HH} - b_{LH} \sim 6$ meV coincident with the HH-LH splitting of excitons in large (170-180 Å) GaAs QWs
- Lorentzian lineshape
- Small linewidth (1.3-1.6 meV)

**Equations**

\[ \Delta E = (E - E_p) \] (eV)

\[ \lambda_D = \frac{\epsilon k_b T}{e^2 n} \]
Subband Electronic Temperatures

Resonant - phonon (2.8 THz)

- $R_L = 25.3 \text{ K/W}$
- $R_E = 28 \text{ K/W}$

Bound-to-continuum (2.9 THz)

- $R_L = 23.2 \text{ K/W}$
- $R_E = 17.3 \text{ K/W}$

$T_E > T_L$, both linear w/electric power

- $R_E \sim R_L \rightarrow$ efficient electron-lattice coupling

- $T_e^5 >> T_L$ of $\sim 100K \rightarrow$ fast non-radiative relaxation times $\tau_{5\rightarrow4,3} \approx 1.3$ ps $\rightarrow$ key limiting factor for THz QCL high temperature operation

- $R_E > R_L \rightarrow$ electron-lattice coupling not strong

- The electrons in the active region share the same $T_e$
Subband Electronic Temperatures II
toward low frequencies

Resonant - phonon with one well injector
(1.9 THz)

BTC with phonon extraction
(1.7 THz)

\[ R_L = 24.5 \text{ K/W} \]
\[ R_E = 28.1 \text{ K/W} \]

\[ R_L = 15.4 \text{ K/W} \]
\[ R_E = 18.9 \text{ K/W} \]

\[ T_e^4 >> T_L \text{ of } \sim 90K \rightarrow \text{still fast non-rad. relaxation rate } \tau^5 \rightarrow 4.3 \approx 1.9 \text{ ps} \]

\[ T_e^b > T_L \text{ but of } \sim 50K \rightarrow \text{estimated thermally activated LO phonon scattering times } \approx 4.8 \text{ ps} \]
**e\(^-\) - lattice energy relaxation rate**

\[
N_e \cdot k_B \cdot \frac{dT_E}{dt} = P - \frac{N_e \cdot N \cdot k_B}{\tau_E} (T_E - T_L)
\]

\[
\tau_E^{-1} = [N_e N k_B (R_e - R_L)]^{-1}
\]

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\nu) (THz)</th>
<th>Design</th>
<th>(\tau_E^{-1}) (ps(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>1,2,3</td>
<td>2.9</td>
<td>btc</td>
<td>&lt;0.28&gt;</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>btc</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>btc</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>2.8</td>
<td>rp</td>
<td>4.90</td>
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<td>7</td>
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<td>rp</td>
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<tr>
<td>9</td>
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<td>rp-1w</td>
<td>1.25</td>
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<tr>
<td>10</td>
<td>1.7</td>
<td>btc+rp stage</td>
<td>2.68</td>
</tr>
</tbody>
</table>
Electron cooling

**Bound-to-continuum**

- e-e scattering → dominant channel for carrier thermalization
- cooling via e- LO-phonon scattering only for electrons that acquire sufficient energy by e-e or e-interface roughness scattering
- most of the electrons dissipate excess energy via the low efficient acoustic phonons assisted transitions

**Resonant-phonon**

Main depletion mechanism → LO-phonon assisted transitions → efficient cooling of the electronic ensemble.
Electronic Temperature influence of the band offset

Compare two “similar” btc THz QCLs with different barrier materials: $Al_xGa_{1-x}As$

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\nu$ (THz)</th>
<th>Waveguide</th>
<th>$\tau_E^{-1}$ (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.9</td>
<td>sp</td>
<td>0.27</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>sp</td>
<td>0.17</td>
</tr>
</tbody>
</table>

$\tau_E^{-1}$ (B) $< \tau_E^{-1}$ (A):

- reduced band-offset in sample B
- The energy separation between the ground state level of the miniband $M'$, and the top of the tunnel-injection barrier is $\sim 2$ times lower in sample B

- Increase of the thermally activated electrons leaking in the continuum
- Additional increase of the electronic temperature.
Relative laser level population in resonant-phonon THz QCLs

- \( n_5/n_4 > 1 @ P > 1W \)
- \( n_5/n_4 \sim \text{constant} \) during laser operation → clamping of the gain (expected)
- \( P > 2W \) → negative differential resistance → lasing ceases → \( n_5/n_4 \) reduced

![Diagram showing the relationship between \( n_5/n_4 \), electrical power, and Lasing]
Future development

• Assessment of the optimum active region → comparison of micro-PL spectra of mesa devices preliminary to laser fabrication
• Local probe of the uniformity of the electronic distribution in different stages of the active region both below and above the designed bias
• Exploiting pulsed I-CCD detection to fully separate the electronic and lattice contributions

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