Investigating the effect of doping concentration on the performance of Terahertz Quantum Cascade Lasers

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Abstract:

In this poster we present the impact of doping on the temperature performance of a split-well (SW) direct-phonon (DP) terahertz (THz) quantum-cascade laser (QCL) scheme supporting a clean three-level system.

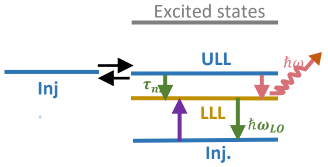
Clean 3-level system

Most of the electrons occupy the active laser levels, with thermally activated leakage channels being suppressed almost entirely up to room temperature.

Motivation

To date, no room temperature THz-QCLs have been reported. The study towards realization of operating THz-QCLs at room temperature is of high importance and can make this technology available for industrial use and allows this technology to be used for widespread applications.

Limiting mechanisms:

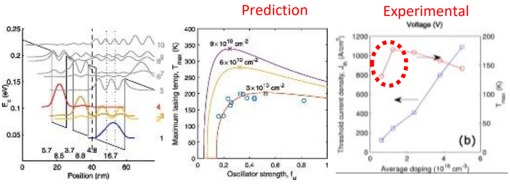


Already addressed:

- ✓ Non-radiative LO-phonon scattering from ULL to LLL
- ✓ Leakage into the continuum
- ✓ Leakage into excited states

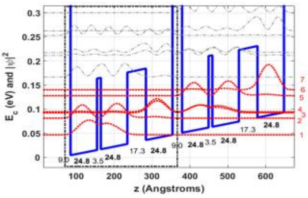
The effect of doping in resonant phonon designs

- Doping: $3\times10^{10}\mathrm{cm}^{-2}$ → $6\times10^{10}\mathrm{cm}^{-2}$
- T_{max}: 135 K → 177 K



Chan, C.W.I.; Albo, A.; Hu, Q.; Reno, J.L. Appl. Phys. Lett. 2016, 109, 201104.

SWDP scheme



- SW-DP THz QCLs
- Mixed potential barriers
- f~0.2
- $Al_{0.55}Ga_{0.45}As$ injection barriers
- $Al_{0.15}Ga_{0.85}As$ remaining barriers
- Doping: $3\times10^{10}cm^{-2}$

- Clean 3-level system
- T_{max}=170 K

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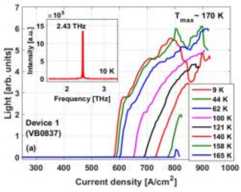
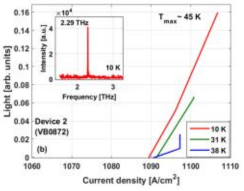
Pulsed light current measurements

Device 1 – $3\times10^{10}cm^{-2}$



T_{max} – 170 K

Device 2 – $6\times10^{10}cm^{-2}$



T_{max} – 45 K

- T_{max} decreased when increasing the doping.

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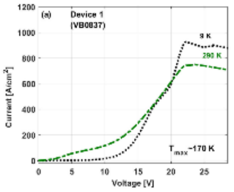
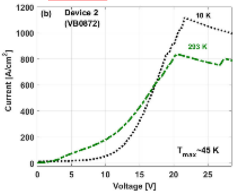
I-V curves for different doping

Device 1 – $3\times10^{10}cm^{-2}$



T_{max} – 170 K

Device 2 – $6\times10^{10}cm^{-2}$



T_{max} – 45 K

- Clear NDR signature up to room temperature.
- Flattening of I-V curves with temperature.
- Current increased with doping as expected.

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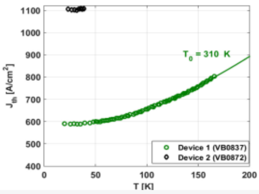
Threshold current



Device 1 – $3\times10^{10}cm^{-2}$

Device 2 – $6\times10^{10}cm^{-2}$

- Threshold current increased with doping as expected.
- Current dynamic range decreased with doping.

Table 2. Device parameters and performance.

Device (Wafer, Scheme)	Injection Coupling ($2\hbar\Omega_{ij}$) [meV]	Design Electric Field [kV/cm]	τ^0_{ul} [ps] *	τ^0_{21} [ps] **	IFR Gain Broadening [meV] ***	Lasing Energy [meV]	Expected Activation Energy [meV]	J_{th} (10 K) [A/cm^2]	J_{max} (10 K) [A/cm^2]	Dynamic Range (10 K) [A/cm^2]	J_{max} (290 K) [A/cm^2]	T_{max} [K]
Device 1 (VB0837)	2.08	16.5	1.21	0.18	4.37	10.05	25.5	578	928	350	750	170
Device 2 (VB0872)	2.09	16.8	1.32	0.18	4.37	9.5	26.5	1089	1118	29	840	45

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Resonant tunnelling

Kazarinov–Suris expression

$$J = eN \times \frac{2\Omega^2\tau_\parallel}{4\Omega^2\tau\tau_\parallel + \omega_{21}^2\tau_\parallel^2 + 1}$$

Strong coupling regime: $\tau \gg \frac{1}{4\Omega^2\tau_\parallel}$

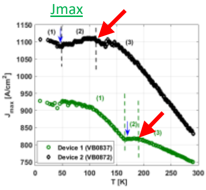
- Region 1: strong coupling regime when lasing (T < Tmax) → $J_{max} \sim \frac{1}{\tau}$
- Region 2: strong coupling regime when not lasing (T > Tmax) → $J_{max} \sim \frac{1}{\tau} \approx \frac{1}{\tau_{nr}}$

Weak coupling regime: $\tau \ll \frac{1}{4\Omega^2\tau_\parallel}$

- Region 3: weak coupling regime → $J_{max} \sim \tau_\parallel$

Kazarinov, R.F.; Suris, R.A. Sov. Phys. Semicond. 1971, 5, 707.

Jmax



Device 1 – $3\times10^{10}cm^{-2}$

Device 2 – $6\times10^{10}cm^{-2}$

- Experimental observation of dephasing time decrease with doping (Region 3).

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Conclusions:

- We experimentally observed the effect of doping on dephasing times and line broadening.
- Strategy to improve the temperature performance of THz-QCLs: Engineering the doping profile and its spatial location by minimizing the overlap between the doped regime and the active level region.