# Split-well resonant-phonon terahertz quantum cascade laser


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## Abstract

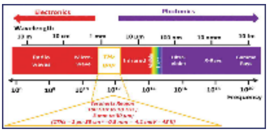
We present a novel GaAs/$Al_{0.3}Ga_{0.7}$As split-well resonant-phonon (SWRP) terahertz quantum cascade laser (THz QCLs). This scheme allows efficient isolation of the carriers from the continuum and excited states and decreases the overlap between the active region and the doped area. This design has potential to improve temperature performance of THz QCLs .

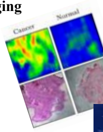

## Motivation

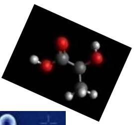
The 1~10 THz range is called the THz gap.
The invention of THz QCLs can bridge this gap.
To date, no room temperature THz-QCLs have been reported. The study towards realization of operating THz-QCLs at room temperature is of high importance and can make this technology available for industrial use and allows this technology to be used for widespread applications.

## THz applications

- ✓ Biochemistry
- ✓ Astrophysics
- ✓ Spectroscopy
- ✓ Security
- ✓ Medicine
- ✓ Real-time imaging

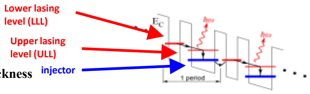


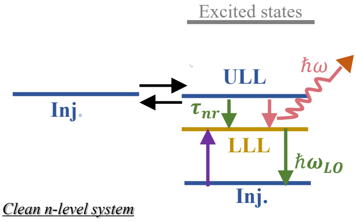



## THz QCLs Operating principle

- Intersubband transition in quantum well
- A single electron generate multiple photons
- The wavelength is determined by the layers thickness




## THz QCLs limiting mechanisms




**Already addressed:**

- ✓ Non-radiative LO-phonon scattering from ULL to LLL[1]
- ✓ Leakage into the continuum[2]
- ✓ Leakage into excited states[3]

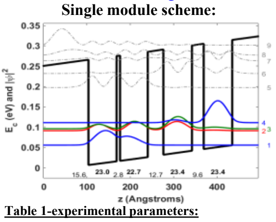
*Clean n-level system*

Most of the electrons occupy the active laser levels, with thermally activated leakage channels being suppressed almost entirely up to room temperature[4].


1. Appl. Phys. Lett. 106(13), 131108 (2015).
2. Appl. Phys. Lett. 107(24), 241101 (2015).
3. Appl. Phys. Lett.109(8) , 081102.(2016).
4. Appl. Phys. Lett. 111(11), 111107 (2017).


## THz QCL SWRP scheme

**Single module scheme:**



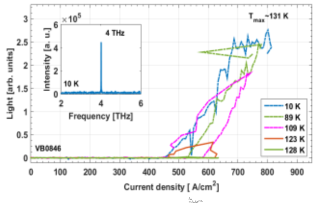

- SWRP THz QCLs
- Oscillator strength for the radiative transitions $f$~0.22
- GaAs/AlGaAs barriers containing 30% aluminium
- Doping per module: 3 $\times 10^{10} cm^{-2}$
- The relevant excited state, level 6 in the scheme is 120 meV above the ULL

**Table 1-experimental parameters:**

**Clean 4 level system**

| Device (Wafer, Scheme) | Lasing Energy [meV] | Expected Activation Energy [meV] | $J_{th}$(10K) [A/cm2] | $J_{max}$(10K) [A/cm$^2$] | Dynamic Range (10K) [A/cm$^2$] | $J_{max}$(290K) [A/cm$^2$] | $T_{max}$ [K] |
|---|---|---|---|---|---|---|---|
| Device VB0846 | 16.5 | 19.5 | 449 | 809 | 360 | 637 | 131 |

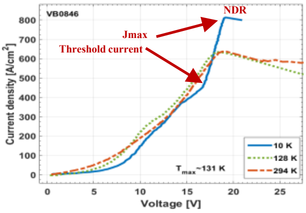
## Pulsed light current and spectrum measurements




$T_{max}$ =131K

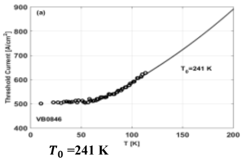
- Lasing frequency of ~4 THz as expected.
- We attribute the noisy curves to the instability of the laser.
- A strong drop at temperatures above 109 K.

## I-V curves




- Clear NDR signature up to room temperature, this indicates that no leakage channels were activated, and the active laser levels are isolated (clean 4-level system).
- Below the threshold current, there is no lasing (parasitic injection). Above threshold current there is a sharp rise and than NDR region.

## Threshold current

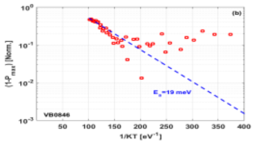



$T_0$ =241 K

- The threshold current rises exponentially and its behavior can be well characterized by the standard model[5]


5. Appl. Phys. Lett. 107 (24), 241101 (2015).


## Output power analysis




- The activation energy extracted is ~19 meV, indicating the thermally activated LO-phonon relaxation[6].


6. Appl. Phys. Lett. 106(13) 131108 (2015).


## Resonant tunnelling

**Kazarinov–Suris expression[7]**

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

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

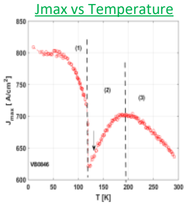
- **Region 1:** strong coupling regime when lasing
- (T < Tmax)→ $J_{max} \sim \frac{1}{\tau}$

- **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 → $J_{max} \sim \tau_\parallel$

**Jmax vs Temperature**





7. Phys.-Semicond. 5.4 707-709 (1971).


## Conclusions:

- We experimentally demonstrated a novel SWRP scheme for THz QCLs that has a potential for high temperature operation.
- This scheme allows efficient isolation of the carriers from the continuum and excited states and decreases the overlap between the active region and the doped area.
- Strategy to improve the temperature performance of THz QCLs: an increased doping level