EPJ Web of Conferences **195**, 02001 (2018) https://doi.org/10.1051/epjconf/201819502001
TERA-2018

THz stimulated emission at interband transitions in HgTe/CdHgTe quantum wells

V.I.Gavrilenko[1], V.V.Rumyantsev[1], A.A.Dubinov[1], S.V.Morozov[1], N.N.Mikhailov[2], S.A.Dvoretsky[2], F.Teppe[3], C.Sirtori[4]

[1]Institute for Physics of Microstructures, Nizhny Novgorod, Russia, gavr@ipmras.ru
[2]A.V.Rzhanov Institute of Semiconductor Physics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia
[3]Charles Coulomb Laboratory, University of Montpellier & CNRS, Montpellier, France
[4]Laboratory of Materials and Quantum Phenomena, University Paris-Diderot, Paris, France

Terahertz (THz) spectral range still lacks compact and efficient radiation sources. Quantum cascade lasers (QCLs) based on GaAs and InP demonstrate remarkable performance in the spectral range from 1 THz to 5THz and above 15 THz[1] the "gap" resulting from strong two-phonon absorption. The interband lasers are a straightforward alternative, but in narrow-gap materials the non-radiative Auger recombination is expected to be very effective. Lead salt diode lasers are known to operate up to 50 μm[2]. (though their figures of merit are very limited). The factor that mitigates the Auger recombination in PbSnSe is the symmetry between electron and hole dispersion laws. For energy and momentum conservation laws to be fulfilled, the summarized kinetic energy of the three particles involved in the Auger process has to be over a certain threshold energy E_{th}[3] that decreases if there are heavy mass carries, e.g. heavy holes.

Symmetric energy-momentum laws are realized in HgTe/CdTe based quantum wells (QWs). In HgCdTe QW structures with bandgap 60 - 80 meV we observed the increase of carrier lifetimes with the pumping intensity up to several microseconds due to saturation of Shockley-Read-Hall (SRH) recombination centers, inferring that optical gain can be obtained under reasonable pumping intensity[4]. Earlier the longest wavelength of 5.3 μm was obtained in HgCdTe-based lasers that did not exploit QWs in its design[5]. In this work, we report stimulated emission (SE) from HgCdTe structures at wavelengths up to λ ~ 20 μm, and demonstrate possibilities for HgCdTe based lasers to enter 5 – 15 THz frequency domain.

Structures under study were grown by molecular beam epitaxy on semi-insulating GaAs(013)[6]. Energy spectra were calculated in the framework of Kane 8x8 model. Structure #1 contains ten 12 nm thick $Hg_{0.87}Cd_{0.13}Te/Cd_{0.65}Hg_{0.35}Te$ QWs and structure #2 - five 5.4 nm thick $Hg_{0.91}Cd_{0.09}Te/Cd_{0.6}Hg_{0.4}Te$ QWs. The structures were designed so as to effectively confine light to in-plane direction, therefore the "active" region (5 - 12 QWs) was placed at the antinode position of TE_0 mode in a thick (several micrometers) dielectric waveguide. Due to a quite specific growth direction (013), naturally cleaved facets do not form the Fabri-Perot resonator. Thus, the stimulated emission (SE) studied in this work results from single-pass amplification.

SE spectra for two samples under study at 8K and a "critical" temperature $T_{\max}$, above which no SE is observed, are given in Fig. 1. The emission intensity demonstrates clear threshold dependence on pumping power, typical for the onset of SE. Another telltale sign of the SE is photoluminescence (PL) line narrowing.

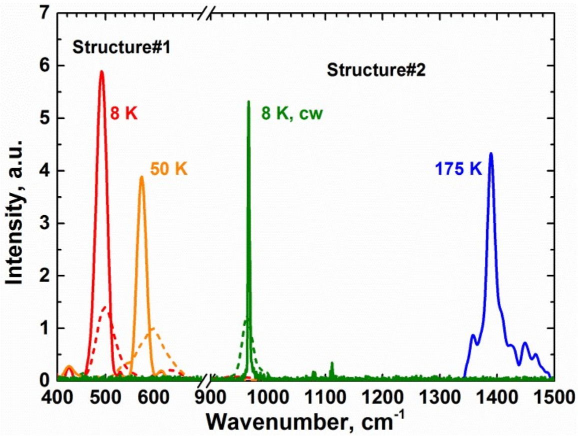

Fig. 1. SE spectra at different temperatures (solid curves) obtained under pulsed pumping with 2.3 μm wavelength and 10 kW/cm^2 intensity for Structure #1 (at both temperatures) and 65 kW/cm^2 for Structure #2 at 175K. SE for Structure #2 at T = 8K was obtained at cw excitation with 0.9 μm wavelength 7 W/cm^2 intensity. Dash curves show PL spectra obtained with the same cw pumping source at 5 W/cm^2 intensity for Structure #1 and 1 W/cm^2 for Structure #2 at 8 K.

The corresponding thresholds are 5 kW/cm^2 and 120 W/cm^2 for SE wavelength ~20 μm (15 THz) and ~10 μm (30 THz) at low temperatures. However, these values are obtained for "below barrier" excitation ($\hbar\omega < E_g$ in barriers), i.e. when non-equilibrium carriers are generated in QWs only. Taking for estimation the QW absorption as 1% one can find the corresponding carrier density in each QW $n_{\text{th}} = 1.4\times10^{11}$ cm^{-2} for $\lambda_p = 2.3$ μm and $I_{\text{th}} = 0.12$ kW/cm^2 pumping intensity. This n_{th} value agrees fairly well with our previous calculations[7]. It also allows estimating the equivalent threshold current density for 5 QWs placed into a *p-n* junction as $j_{\text{th}} = 5en_{\text{th}}/\tau_{\text{pulse}}$ (e is the elementary charge), that for $\tau_{\text{pulse}} = 10$ ns gives $j_{\text{th}} = 11$ A/cm^2. This threshold is low enough to obtain SE under cw excitation: Fig 1. shows the corresponding spectrum, measured with cw pumping at 0.9 μm wavelength.

Obviously, the threshold grows with the SE wavelength and the maximum "operating" temperature $T_{\max}$ gets lower. To understand the energetic scale that determines $T_{\max}$ let us consider the energy spectrum of Structure #1, presented in Fig.2. One can see that the hole effective mass increases dramatically with k and the dispersion laws in the valence band and the conduction band are no longer quasi-symmetrical. When holes reach larger-mass region the Auger recombination becomes efficient. We have calculated the threshold energies E_{th} for CCHC Auger process (the energetic threshold for CHHH process is high compared to CCHC process, therefore the latter is less important) given in Fig. 2. For both structures under study we get $k_B T_{max} \approx E_{th}/2$. In Fig. 2 one can see also that the detrimental impact of side maxima in the valence band can be reduced in QW of pure HgTe with the same bandgap as in Structure #1. As easy to see in this case the threshold energy increases significantly.

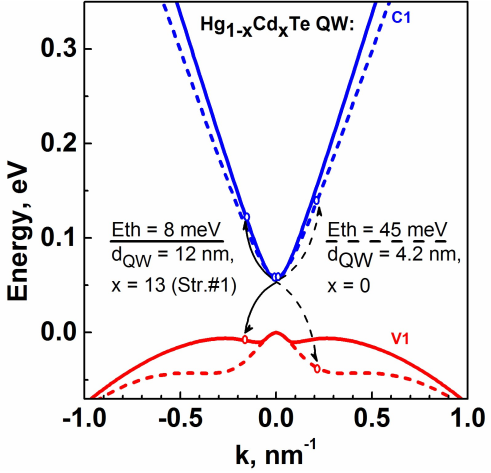

Fig. 2. Calculated energy spectrum of Structure #1 (solid lines) and HgTe/CdHgTe QW with the same bandgap (dash lines), $T = 0$. Threshold energies and carrier configuration are shown for Auger CCHC process.

Effective carrier temperature is affected by their heating by the pumping radiation. At the excitation with radiation wavelength 2.3 µm the carrier heating effect is noticeable already in QW structures emitting at wavelengths µm about 14 µm. For the Structure #1 emitting at λ ~ 20 µm the SE quenching with the increase of pumping power takes place just after the SE arising. We have demonstrated that the pumping with CO_2-laser (λ = 10.6 µm) drastically decrease the carrier heating and the SE intensity monotonously grows with pump power. Thus, the effect of SE quenching with the pump power, observed in Ref.8 is not fundamental but results from using the short wavelength excitation.

Carrier lifetimes are expected to decrease for QW structures with narrower bandgap. The sub-nanosecond carrier lifetimes have been explored via the pump-probe measurements of a sample's transmission using THz free electron laser FELBE at Helmholtz-Zentrum Dresden-Rossendorf[9]. For HgCdTe QW with $E_g = 20$ meV ($f \sim 4.8$ THz) the carrier lifetime proved to be about 100 ps for carrier density 10^{11} cm^{-2} that is sufficient to achieve the population inversion. One can estimate a threshold pumping intensity of 10 kW/cm^2 for an optically pumped laser exploiting such QWs as an active media. Thus, HgCdTe QWs should be able to provide amplification of radiation at interband transitions down to 5 THz (λ = 60 µm).

In conclusion, we demonstrated stimulated emission at wavelengths up to 20.3 µm (14.7 THz) from HgCdTe based waveguide quantum well heterostructures. Nonradiative Auger recombination is shown to be suppressed compared to bulk HgCdTe solid solutions due to the "symmetry" of electron and hole energy-momentum laws. Results of time-resolved pave the way to obtain stimulated emission in wide THz range down to 5 THz.

This work was financially supported by the Russian Foundation for Basic Research (Grants #16-32-60172, #18-52- 16013) and Ministry of Education and Science of the Russian Federation (Grant MK-4399.2018.2). The work was done using equipment of Common Research Center "Physics and technology of micro- and nanostructures" at IPM RAS.

References

1. *Vitiello, M. S., Scalari, G., Williams, B., De Natale, P.* Quantum cascade lasers: 20 years of challenges // Opt. Express. 2015. V.23, No. 4. P. 5167-5182.
2. *Maremyanin, K. V., Ikonnikov, A. V., Bovkun, L. S., Rumyantsev, V. V., Chizhevskii, E. G., Zasavitskii, I.,I., Gavrilenko, V. I.* Terahertz injection lasers based on the PbSnSe solid solution with emission wavelength up to 50 µm and their use for magnetospectroscopy of semiconductors // Semiconductors. 2018. V. 52, No 11 (in press).
3. *Abakumov, V. N., Perel, V. I., Yassievich, I. N.* Nonradiative Recombination in Semiconductors. North-Holland: Elsevier Science Publishers. 1991.
4. *Morozov, S. V., Rumyantsev, V. V., Antonov, A. V., Kadykov, A. M., Maremyanin, K. V., Kudryavtsev, K. E., Mikhailov, N. N., Dvoretskii, S. A., Gavrilenko, V. I.* Time resolved photoluminescence spectroscopy of narrow gap $Hg_{1-x}Cd_xTe/Cd_yHg_{1-y}Te$ quantum well heterostructures // Appl. Phys. Lett. 2014. V. 105, No 2. P. 022102.
5. *Arias, J. M., Zandian, M., Zucca, R., Singh, J.* HgCdTe infrared diode lasers grown by MBE // Semicond. Sci. Technol. 1993. V. 8, No 1S. P. S255-S260.
6. *Dvoretsky, S., Mikhailov, N., Sidorov, Yu. Shvets, V., Danilov, S., Wittman, B., Ganichev, S.* Growth of HgTe Quantum Wells for IR to THz Detectors // J. Electronic Mater. 2010. V. 39, No. 7. P. 918-923.
7. *Morozov, S. V., Joludev, M. S., Antonov, A. V., Rumyantsev V. V., Gavrilenko, V. I., Aleshkin, V. Ya., Dubinov, A. A., Mikhailov, N. N., Dvoretskiy, S. A., Drachenko, O., Winnerl, S., Schneider, H., Helm, M.* Study of lifetimes and photoconductivity relaxation in heterostructures with $Hg_xCd_{1-x}Te/Cd_yHg_{1-y}Te$ quantum wells // Semiconductors. 2012. V. 46, No 11. P. 1362-1366.
8. *Morozov, S. V., Rumyantsev, V. V., Fadeev, M. A., Zholudev, M. S., Kudryavtsev, K. E., Antonov, A. V., Kadykov, A. M., Dubinov, A. A., Mikhailov, N. N., Dvoretsky, S. A., Gavrilenko, V. I.* Stimulated emission from HgCdTe quantum well heterostructures at wavelengths up to 19.5 µm // Appl. Phys. Lett. 2017. V. 111, No 19. P. 192101.
9. *Ruffenach, S., Kadykov, A., Rumyantsev, V. V., Torres, J., Coquillat, D., But, D., Krishtopenko, S.S., Consejo, C., Knap, W., Winnerl, S., Helm, M., Fadeev, M. A., Mikhailov, N. N., Dvoretskii, S. A., Gavrilenko, V. I., Morozov, S. V., Teppe, F.* HgCdTe-based heterostructures for terahertz photonics // APL Materials. 2017. V. 5, No. 3. P. 035503.