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

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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 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 µm². (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 $E_{th}$ that decreases if there are heavy mass carriers, 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. Earlier the longest wavelength of 5.3 µm was obtained in HgCdTe-based lasers that did not exploit QWs in its design. In this work, we report simulated 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). Energy spectra were calculated in the framework of Kane 8x8 model. Structure #1 contains ten 12 nm thick Hg0.87Cd0.13Te/Cd0.06Hg0.94Te QWs and structure #2 - five 5.4 nm thick Hg0.87Cd0.13Te/Cd0.06Hg0.94Te QWs. The structures were designed so as to effectively confine light in-plane direction, therefore the “active” region (5 - 12 QWs) was placed at the antinode position of TE0 mode in a thick (several micrometers) dielectric waveguide. Due to a quite specific growth direction (013), naturally cleaved facets do not form the Fabry-Perot resonator. Thus, the simulated 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/cm² intensity for Structure #1 (at both temperatures) and 65 kW/cm² for Structure #2 at 175K. SE for Structure #2 at $T = 8K$ was obtained at cw excitation with 0.9 µm wavelength 7 W/cm² intensity. Dash curves show PL spectra obtained with the same cw pumping source at 5 W/cm² intensity for Structure #1 and 1 W/cm² for Structure #2 at 8 K.](https://doi.org/10.1051/epjconf/201819502001)

The corresponding thresholds are 5 kW/cm² and 120 W/cm² 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 $n_{th} = 1.4 \times 10^{11}$ cm⁻² for $\lambda_p = 2.3$ µm and $I_{th} = 0.12$ kW/cm² pumping intensity. This $n_{th}$ value agrees fairly well with our previous calculations. It also allows estimating the equivalent threshold current density for 5 QWs placed into a p-n junction as $j_{th} = 5 e n_{th}/\tau_{pulse}$ ($e$ is the elementary charge), that for $\tau_{pulse} = 10$ ns gives $j_{th} = 11$ A/cm². 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 struc-
ter structures under study we get $h_\nu T_{\text{max}} \approx E_0/2$. 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.

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 ($\lambda = 10.6 \mu$m) 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. For HgCdTe QW with $E_g = 20$ meV ($\lambda \sim 48 \text{ THz}$) 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 ($\lambda \sim 60 \mu$m).

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.

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