HgCdTe based quantum well heterostructures for long-wavelength lasers operating in 5 - 15 THz range

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Abstract. Stimulated emission (SE) at wavelengths up to 20.3 μm (14.7 THz) is demonstrated from HgCdTe based quantum well heterostructures. The mitigation of Auger processes resulting from «graphene-like» energy spectrum in structures under study is exemplified. By studying the carrier lifetime via time resolved photoconductivity and transmission pump-probe measurements we show that further increase in SE wavelength is feasible and discuss the promising routes towards the 5 – 15 THz frequency domain, where quantum cascade lasers are scarce and HgCdTe lasers may be competitive to the prominent emitters.

1. Introduction

The problem of developing terahertz (THz)/long-wavelength emitters is one of the hottest topics in the applied physics. For many spectroscopy related applications, it would be favorable to employ compact semiconductor lasers as the sources of long wavelength radiation. Quantum cascade lasers (QCLs) demonstrate remarkable performance in the spectral range from 1 THz to 5THz and above 15 THz [1]. However, the majority of the QCLs exploit GaAs and InP semiconductors, in which lattice absorption becomes too strong at frequencies lower than 15 THz. GaN QCL are tackling the 5 – 15 THz “gap” from the low-frequency side, but their figures of merit are yet to be improved [2]. The interband lasers are a straightforward alternative, but it requires narrow-gap materials, in which the non-radiative Auger recombination is expected to be very effective. The spectral range 5 – 15 THz is now partly covered only with the lead salt diode lasers, which provide emission wavelengths up to 46 μm [3]. The factor that mitigates the Auger recombination in PbSnSe(Te) is the symmetry between the dispersion laws in the conduction band and in the valence band. It can be shown that for the energy-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 $E_{th}$ [4] that depends on carrier energy spectra. For the certain types of carrier spectra, e.g. for the Dirac relativistic energy spectrum, it is not possible to fulfill the energy-momentum conservation laws in Auger process at all, i.e. $E_{th}$ is infinite. Note that the particular case of massless Dirac fermions is realized in graphene, which has been studied intensively as a promising candidate for THz lasers and sensors. However, there is still some debate concerning the effectiveness of the Auger recombination in graphene structures because the marginal case of relativistic spectrum with zero bandgap and linear dispersion law requires rigorous consideration [5]. As for lead salt lasers, their figures of merit are limited by the growth technology: there are formidable problems in manufacturing quantum well (QW) structures for PbSnSe(Te) solid solutions, and the residual carrier density remains high $\sim 10^{17}$ cm$^{-3}$ [3].

There are alternative semiconductor systems that allow one to come close to the “graphene-like” energy-momentum law, but leave a finite bandgap. As it has been shown in Ref. [6] one of such systems is HgTe/CdHgTe QW heterostructures. Unlike graphene, HgCdTe based QW allow tailoring the bandgap by changing the QW width and Cd content in it. Modern molecular beam epitaxy (MBE) delivers high quality HgCdTe epitaxial structures not only for native CdZnTe substrates, but for “alternative” GaAs substrates as well. HgCdTe epitaxial structures grown on GaAs(013) substrates have demonstrated remarkable figures of merit during our previous studies of photoconductivity (PC) and photoluminescence (PL) in the very long wavelength infrared ($\lambda = 15 \sim 30$ µm) range [7, 8]. In HgCdTe QW structures with bandgap $\sim 60 \sim 80$ 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 [7]. However, previously lasing in HgCdTe has been studied only in the short-wavelength part of the mid-infrared range ($2 \sim 5$ µm) [9]. In 1993, Arias et al. achieved the emission wavelength of 5.3 µm at 45K in diode laser that did not exploit QWs in its design [10]. As for the HgCdTe lasers with QWs, only emission near $\lambda \sim 2$ µm and $\lambda \sim 3$ µm was demonstrated [9] under optical pumping. In this work, we report stimulated emission (SE) from HgCdTe structures at wavelengths up to $\lambda \sim 20$ µm, and discuss the underlying physics that controls the Auger recombination in such structures. We demonstrate that there is a considerable reserve for HgCdTe based lasers to enter the $5 \sim 15$ THz frequency domain, where no QCLs are available yet, and HgCdTe emitters might appear as a better alternative than the lead salt lasers.

2. Results and discussion

Structures under study were MBE-grown on semi-insulating GaAs(013) substrates with ZnTe and CdTe buffers using in situ ellipsometric control of the layer content and thickness [11]. Ex situ characterization of structures was performed by measuring interband photoconductivity (PC) and photoluminescence (PL) spectra at different temperatures. The temperature dependence of the bandgap was extracted from the PC and PL spectra and then compared to the energy spectra, calculated in the framework of Kane 8x8 Hamiltonian axial model, allowing us to determine the width and Cd content for each QW.

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$_{0.65}$Hg$_{0.35}$Te QWs. The structures were not intentionally doped; the residual carrier density obtained from the Hall measurements is several $10^{10}$ cm$^{-2}$ and the typical dislocation density determined from the etch pits density was of $\sim 10^6$ cm$^{-2}$. The structures were designed so as to effectively confine light to in-plane direction, therefore the “active” region (5 -- 10 QWs) was grown inside a thick (several micron) waveguide. Due to a quite specific growth direction (013), naturally cleaved facets do not form the Fabri-Perot resonator: the angle between the sample’s surface and the lateral edge planes is far from 90º. Thus, the SE studied in this work results from single-pass amplification.
Fig. 1 Stimulated emission spectra for structures under study at different temperatures (solid curves). SE was obtained under pulsed pumping with 2300 nm wavelength and 10 kW/cm$^2$ intensity for Structure#1 ($T = 8K$, $T = 50K$) and 65 kW/cm$^2$ for Structure#2 at 175K. SE at cw excitation with 7W/cm$^2$ intensity at 900 nm wavelength is presented for Structure#2 at 8K. Dash curves show PL spectra obtained with the same cw pumping source at 5 W/cm$^2$ intensity for Structure#1 ($T = 8K$, $T = 50K$) and 1 W/cm$^2$ for Structure#2 at 8 K. Fig. 2 Calculated energy spectrum of Structure#1 (solid lines) and HgTe/CdHgTe QW with the same bandgap and much less than typical width of PL from single HgCdTe QWs under pulsed excitation with the same intensity, which is < 10 meV [7].

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). However, these values are obtained for “below barrier” excitation, when the wavelength of the pumping radiation is longer than the cutoff wavelength of the interband transitions in the waveguide material and QW barriers. In this case one can presume that non-equilibrium carriers are generated only in QWs. Taking for estimation the QW absorption as 1 % one can find that corresponding carrier density in each QW should be $n_{th} = 1.4 \times 10^{11} \text{cm}^{-2}$ for $\lambda_{th} = 2.3 \mu\text{m}$ and $I_{th} = 0.12 \text{kW/cm}^2$ pumping intensity. This $n_{th}$ value agrees well with our previous calculations: in Ref. [12] the possibility of radiation amplification in narrow gap HgTe QWs was stated for excess carrier densities above $1 \times 10^{11} \text{cm}^{-2}$. It also allows one to estimate the equivalent threshold current density for the same $N_{well} = 5$ QWs placed into a $p$-$n$ junction as $J_{th} = eN_{well}n_{th}/\tau_{pulse}$ ($e$ is the elementary charge), which for $\tau_{pulse} = 10$ ns gives $J_{th} = 11 \text{A/cm}^2$. This value is at least the order of magnitude less than that of lead salt lasers operating at the same temperature and emission wavelength and practically equal to threshold current density of InAs-based interband QCL emitting near 10.4 µm at 80 K [13]. In particular, the threshold is low enough to obtain SE under cw excitation: Fig 1. shows the corresponding spectrum, measured with cw pumping at 900 nm wavelength. In this case, pumping radiation generates electron-hole pairs in the barriers and as a result, the threshold is as low as 5 W/cm$^2$ and the SE line FWHM is only 0.5 meV ($\Delta\lambda/\lambda \sim 0.004$).

Obviously, the threshold grows with increase in the SE wavelength and the maximum “operating” temperature $T_{max}$ gets lower. To understand the energetic scale that determines the critical temperature $T_{max}$ consider the energy spectrum of Structure#1, presented in Fig.2. As can be seen from Fig. 2, for
large k-vectors the hole effective mass increases dramatically 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. Indeed, 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 the most important) and Fig. 2 shows the corresponding configuration of carriers for Auger process at the threshold. When compared to the critical temperature $T_{max}$, observed in the experiment, for Structure#2 under study we get $T_{c} \approx E_{th}/2$ (the same relation appears to be valid for all structures under study), corresponding to $\sim 25\%$ of holes having kinetic energy above the threshold in case of Boltzmann distribution law (as can be seen the portion of electron kinetic energy is the threshold energy in negligible). However, the detrimental impact of side maxima in the valence band can be reduced in QW from pure HgTe. Figure 2 shows the energy spectrum for HgTe/CdHgTe QW with the same bandgap as Structure#1. It can be seen that larger-mass region in the valence band shifts to lower energies, increasing the threshold energy dramatically. As it will be shown elsewhere, changing the sign of the QW strain (by adding Zn to barrier layers, for instance) can additionally suppress the Auger recombination.

Carrier lifetime measurements agree well with the abovementioned experimental data. In particular, the calculated threshold energy $E_{th}$ is 29 meV for Structure #2, which gives $T_{max} \sim E_{th}/2 \sim 168$ K, close to experimental value. Indeed, calculations demonstrate that radiative lifetime dependence on carrier density is enough to describe well the experimental PC and PL dynamics at 77K, showing that Auger recombination is of minor importance. For Structure#1 the PC decay measurements at 77K give carrier lifetime of $\sim 60$ ns for carrier density $\sim 10^{11}$ cm$^{-2}$, while the calculated radiative lifetime is an order of magnitude higher, explaining the absence of SE at 77K. Obviously, 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 a free electron laser [14]. For HgCdTe QW with 20 meV, corresponding to 4.8 THz frequency, the carrier lifetime is no less than 100 ps for carrier density of $10^{11}$ cm$^{-2}$ that is sufficient to achieve 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 in $5-15$ THz range as well.

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References

1. M.S. Vitiello et al., Opt Express, 2015. 23(4): p. 5167-82.
2. M.F. Anwar et al., Proc. SPIE, 2015. 9483: p. 948304.
3. K.V. Maremyanin et al., Semiconductors, 2016. 50(12): p. 1669-1672.
4. V.N. Abakumov et al., Nonradiative Recombination in Semiconductors. 1991, North-Holland: Elsevier Science Publishers.
5. G. Alymov et al., arXiv 2018: p. 1709.09015.
6. B.A. Bernevig et al., Science, 2006. 314(5806): p. 1757-61.
7. S.V. Morozov et al., Applied Physics Letters, 2014. 105(2): p. 022102.
8. V.V. Rumyantsev et al., Semiconductors, 2013. 47(11): p. 1438-1441.
9. J. Bleuse et al., Journal of Crystal Growth, 1999. 197(3): p. 529-536.
10. J.M. Arias et al., Semiconductor Science and Technology, 1993. 8(1S): p. S255.
11. S. Dvoretsky et al., Journal of Electronic Materials, 2010. 39(7): p. 918-923.
12. S.V. Morozov et al., Semiconductors, 2012. 46(11): p. 1362-1366.
13. Z. Tian et al., Electronics Letters, 2012. 48(2): p. 113-114.
14. S. Ruffenach et al., APL Materials, 2017. 5(3): p. 035503.