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Studies of electroluminescence spectra of HgCdTe quantum well structures under lateral current pumping

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We study a HgCdTe heterostructure with multiple quantum wells as a possible source for NDIR spectroscopy. It is shown that during lateral current pumping, as a result of injection of hot carriers from contacts, interband spontaneous emission is observed at temperatures up to room one. We investigate the current voltage characteristics for the structures and determine the dominant mechanism of generation of nonequilibrium carriers under conditions of lateral current pumping.

Keywords: HgCdTe, NDIR, quantum well, IR.

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Current studies into solid solutions $\mathrm{Hg}_{1-x}\mathrm{Cd}_x\mathrm{Te}$ have at least two well-known applied aspects. The first one concerns the development of night vision devices, thermal imagers, and other similar receivers of electromagnetic radiation in the infrared (IR) range [1]. The second aspect is the use of thin films and quantum wells (QWs) based on HgCdTe with a Dirac energy spectrum for production of emitters of electromagnetic waves covering the range from terahertz frequencies [2] to the short-wave part of the mid-IR range [3]. However, current pumping is preferable for a compact device. It should be emphasized that interband spontaneous electroluminescence in HgCdTe under impact ionization or hot carrier injection from contacts with lateral current pumping has not been reported in literature yet. The present study is focused on spontaneous emission upon interband recombination of nonequilibrium carriers in HgCdTe structures under lateral current pumping.

Similar IR radiation sources with lateral current pumping (with the same form factor as LEDs, but without diode characteristics) may find practical applications primarily in non-dispersive IR spectroscopy (NDIR spectroscopy) in the atmospheric transparency windows of 3−5 and 8−13 μm. NDIR spectroscopy is used widely in industrial gas analyzers [4,5] (among other things, for the analysis of multicomponent gas mixtures [6,7]). Since HgCdTe is the leading material for receivers in these wavelength regions, it appears possible to design an integrated planar optocoupler for gas mixture analysis. What is actually referred to here is the possibility of fabrication of a radiation source and a photoelectric receiver (photoresistor) on the same chip within a single technological process. It is noteworthy that this optocoupler design implements a resonant detection mechanism: the emitter emission spectrum lies near the interband transition energy of the receiver (in the region of its maximum sensitivity), and since detection occurs near the edges of bands, threshold Auger recombination is not activated and does not reduce the concentration of carriers involved in the formation of the photocurrent signal.

Nonradiative Auger recombination in heterostructures with thin HgCdTe/CdHgTe quantum wells is suppressed due to the Dirac energy spectrum [8]. This suppression of the nonradiative recombination channel holds promise of only a slight reduction in integrated radiation intensity of HgCdTe heterostructures with increasing temperature and ensures better sensitivity of receivers based on such structures in the high-temperature region. In addition, the density of states for a two-dimensional carrier gas in a QW is characterized by a Heaviside staircase function with a sharp energy edge. The indicated properties of HgCdTe heterostructures allow one to use them as both emitters and receivers in the proposed optocoupler design. On the one hand, the emitting part of the optocoupler should ensure efficient emission at room temperature, which implies suppression of non-radiative recombination channels. On the other hand, the detecting part of the optocoupler should have a sharp edge of the absorption spectrum (density of states), since the maximum of the spectrum of the emitting part will lie near the band gap energy in the semiconductor. In the present study, the photo- and electroluminescence (PL and EL, respectively) spectra of HgCdTe structures with QWs are examined experimentally at different temperatures.

All the heterostructures with HgCdTe/CdHgTe quantum wells studied here were grown by molecular beam epitaxy with *in situ* ellipsometry on a semi-insulating

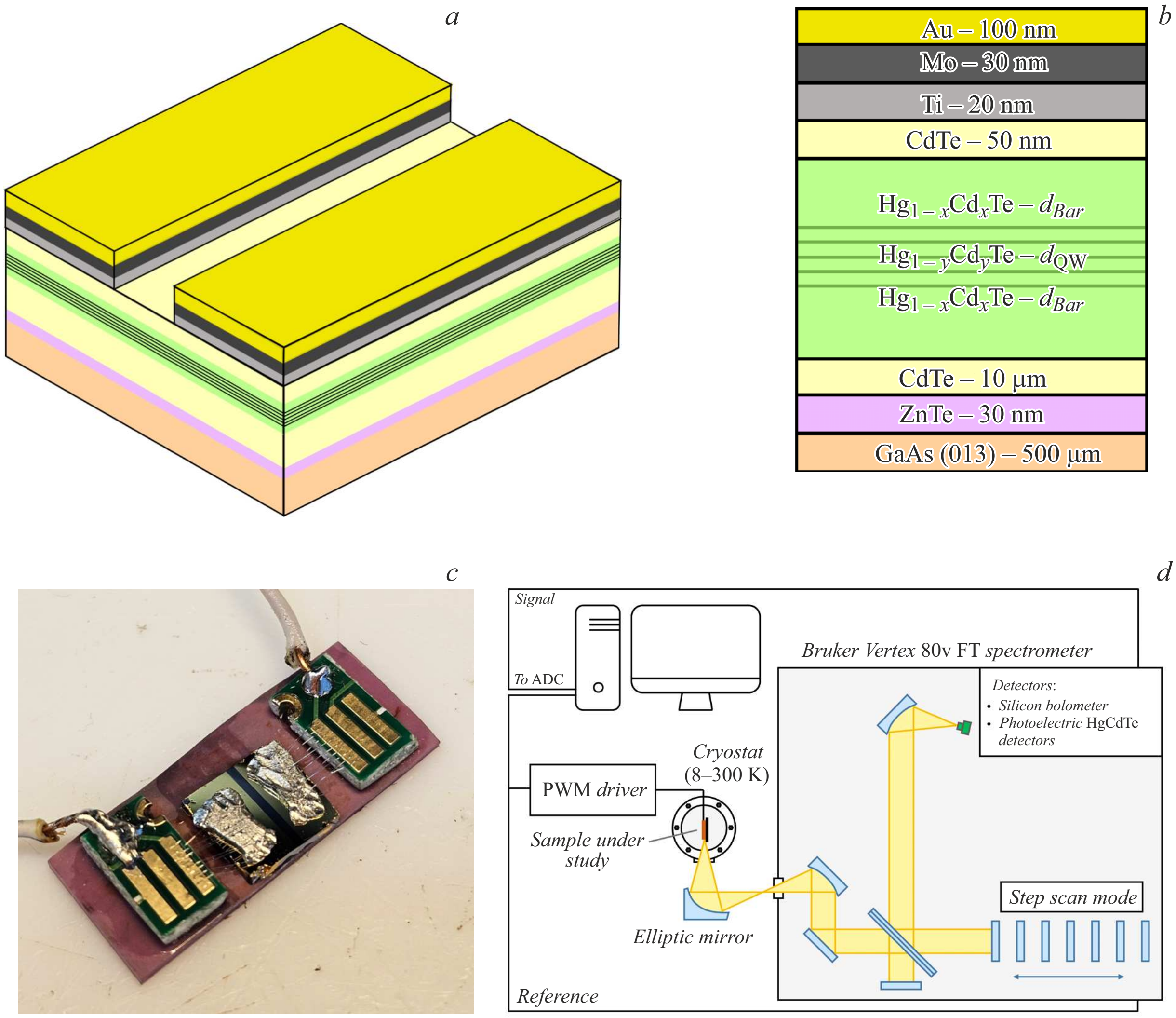

Figure 1. *a* — General view of the studied samples; *b* — diagram of their structural layers (not to scale); *c* — photographic image of the structure with soldered contacts; *d* — diagram of the experimental setup for recording EL spectra (PWM *driver* — pulsed power supply). PL spectra were recorded in a similar geometry with the current excitation source replaced by a thulium laser.

GaAs (013) substrate. The examined structure contained five $Hg_{0.98}Cd_{0.02}Te/Cd_{0.6}Hg_{0.4}Te$ QWs 3.2 nm in thickness that were positioned at a depth of 750 nm within the structure. Prior to the deposition of multilayer metal contacts, the sample surface was subjected to short-term ion etching. Multilayer metal contacts were then applied (Figs. 1, *a*–*c*): gold electrodes were secured through an indium layer to layers of Ti (20 nm), Mo (30 nm), and Au (100 nm). The distance between contacts (the intercontact area width) was 200 μm. The samples with applied contacts were mounted on the cold finger of a closed-loop helium cryostat with a temperature range of 8–300 K (Fig. 1, *d*). The PL and EL spectra were recorded in the same geometry with radiation collected from the end of the sample; the focus of the optical radiation collection system was set to the intercontact gap.

A continuous-wave thulium laser (1.91 μm, 200 mW) was used as an excitation source for PL spectroscopy; excitation radiation was introduced from the side of the grown HgCdTe structure into the intercontact region. In experiments on EL, voltage ranging from 0 to 200 V was applied in pulses 800 ns in length with a repetition rate of 111 Hz to the samples in lateral geometry. A current-limiting resistor with a nominal value of 7.5 Ω was connected in series with the sample under study. Both EL and PL spectra were recorded by a Bruker Vertex 80v Fourier spectrometer in the step-by-step scanning mode.

Current–voltage curves (CVCs) were studied using the two-point method: current flowing in the sample–resistor circuit was measured using a current transformer. The total voltage drop in the sample–resistor circuit was monitored using a Keithley 2400 voltage source; to determine the voltage drop across the sample, the voltage drop across the current-limiting resistor was subtracted from the total voltage. To identify the interband nature of EL, interband PL spectra were recorded in advance at different temperatures

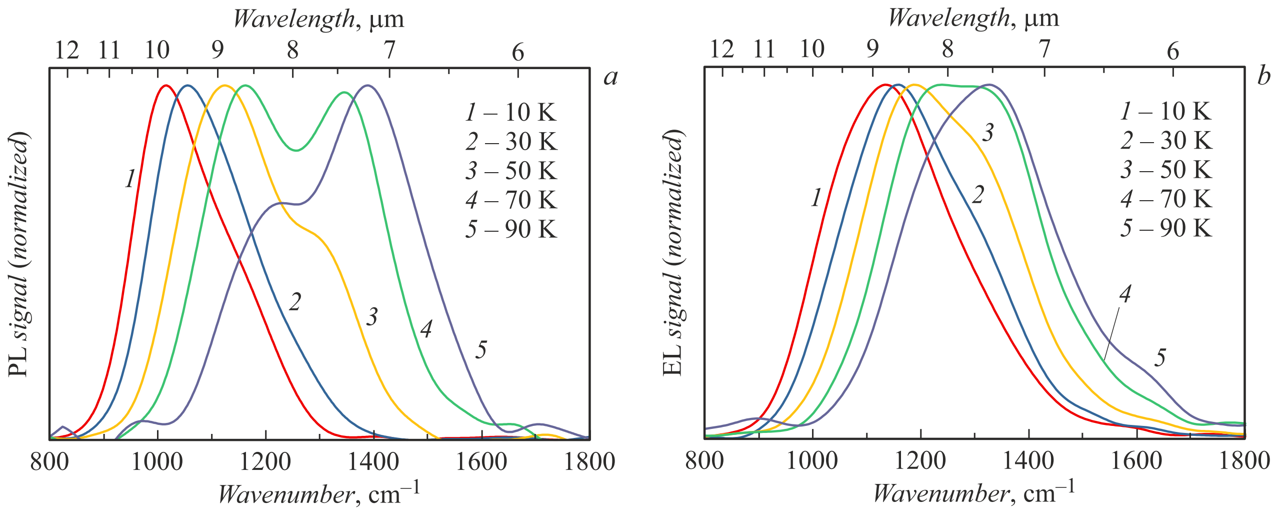

Figure 2. PL (*a*) and EL (*b*) spectra of the studied structure under optical excitation by a thulium laser (*a*) and under excitation by current pulses with an intercontact potential difference of ~ 45 V (*b*) at temperatures of 10–90 K.

and compared with the EL spectra at the same temperatures. Figure 2, *a* shows the PL spectra of the studied structure within the temperature range of 10–90 K. It is evident that the interband PL line at 10 K lies in the vicinity of 10 μm and shifts toward shorter waves with increasing temperature, which is consistent with the temperature variation of the band gap in HgCdTe. The PL spectrum at 90 K lies near the wavelength of 7 μm. The full width of the spectrum at half maximum (FWHM) is $\sim 210\,\text{cm}^{-1}$ at 10 K and increases smoothly to $\sim 360-370\,\text{cm}^{-1}$ as the temperature grows to 90 K (see the table). Note that the PL spectra of all structures with contacts and their quenching with increasing temperature corresponded to those for structures without contacts. Therefore, the fabrication of contacts did not affect the optical properties of the active region of structures (the quantum well array).

Figure 2, *b* shows the EL spectra of the studied structure within the same temperature range. It is evident that the positions of EL lines and their shift with temperature are qualitatively consistent with the overall behavior of PL lines. At a temperature of 10 K, the maximum of the spectrum is at 9 μm, shifting to 7.5 μm at high temperatures. At low temperatures, the spectrum FWHM is $\sim 290\,\text{cm}^{-1}$; at higher temperatures, it is $\sim 320\,\text{cm}^{-1}$. It can be seen that the FWHM of the EL spectra has a less pronounced temperature dependence, which is coupled with a smaller temperature shift of the spectra. The observed result indicates that the effective temperature of carriers depends only weakly on the lattice temperature during EL in the low-temperature region, and their distribution function is shaped largely by the conditions of current excitation.

Full width at half maximum (in cm^{-1}) of PL and EL spectra at different temperatures

Luminescence type	*T*, K				
	10	30	50	70	90
PL	209	219	306	368	360
EL	292	304	323	330	324

As for the study of EL within a wide temperature range, spontaneous emission was observed at all temperatures up to room one (Fig. 3). The integral quenching of EL in transition from a temperature of 10 K to room temperature did not exceed one order of magnitude; notably, the quenching effect was mostly confined to the temperature range of 10–100 K, and the integral emission intensity at a temperature of 90 K differed from the intensity at room temperature by a factor of just 1.5. This relatively small reduction in emission intensity is indicative of suppression of non-radiative mechanisms of carrier recombination (especially Auger recombination, since its rate depends exponentially on temperature) in the examined structures. At the same time, the FWHM of the EL spectra increases smoothly as the temperature grows closer to room levels and becomes comparable with the FWHM of the PL spectra, which is $\sim 450\,\text{cm}^{-1}$ for the structure in question.

The probable key mechanisms for generating nonequilibrium carriers in such a system with lateral contacts are impact ionization in an electric field and the injection of minority carriers associated with the metal–semiconductor contact. Since it appears difficult to estimate theoretically the contribution of each of them to the overall rate of carrier generation, it was important to identify the dominant mechanism of carrier generation in experiments. CVCs were examined for this purpose.

Impact ionization is an interband process, and the activation energy of impact ionization grows higher as the band gap of a QW increases with increasing temperature. Therefore, the characteristic CVC inflection point (the moment of activation of impact ionization) should shift to the right (toward stronger fields) at higher temperatures.

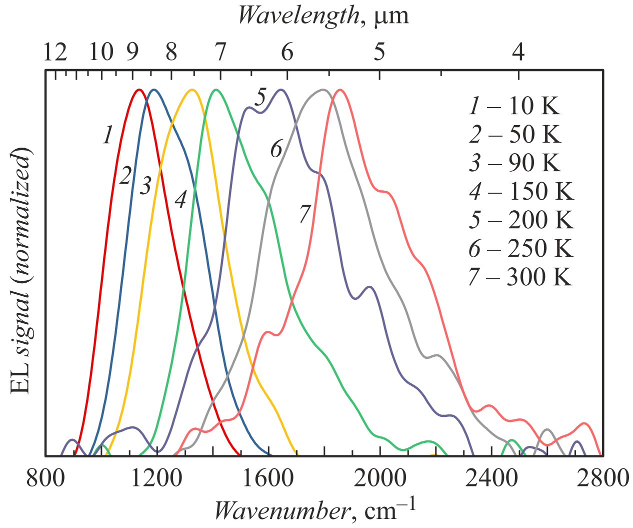

Figure 3. Electroluminescence spectra of the studied structure excited by current pulses 800 ns in length with a voltage of ∼ 40−45 V at temperatures varying from 10 to 300 K.

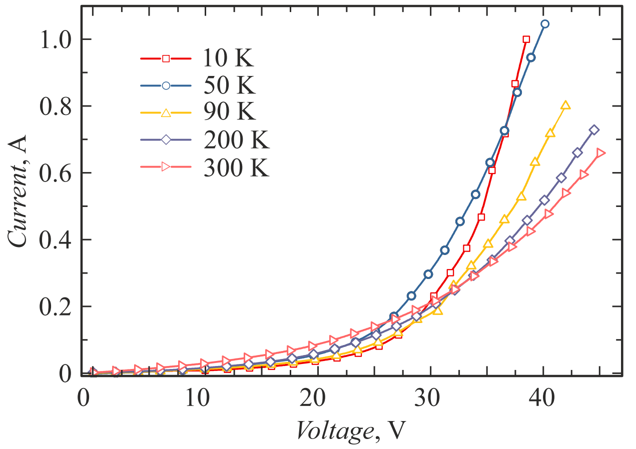

Figure 4. CVC of the studied structure at temperatures of 10−300 K.

At the same time, since the injection of minority carriers is governed by the properties of the semiconductor/metal interface and should depend weakly on temperature, the CVC inflection point should not undergo a significant shift with a change in sample temperature.

Figure 4, *a* shows the CVCs of the structure at different temperatures within the range of 10−300 K. The measured CVCs do not reveal any signs of a shift to the right in proportion to the E_g change, which is what is expected of impact ionization. Thus, the main mechanism of carrier generation in the studied structure is the injection of minority carriers in the contact region.

Mid-IR emission is possible in HgCdTe structures in the pulsed mode at room temperature under current pumping; notably, the overall reduction in radiation intensity in transition from 10 to 300 K did not exceed one order of magnitude. It was demonstrated that nonequilibrium carriers in the studied structure are generated via injection of hot carriers from contacts. Combined on a single chip with a photodetector based on the same HgCdTe structure, such emitters may find application in gas analyzers relying on NDIR spectroscopy both in the atmospheric transparency window of 3−5 μm and in the transparency window of 8−13 μm, where the production of interband emitters based on traditional IR semiconductors with a larger band gap is infeasible.

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Conflict of interest

The authors declare that they have no conflict of interest.

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