

High-Temperature Infrared Emitters Based on HgCdTe Grown by Molecular-Beam Epitaxy

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Abstract Prospects of fabrication of high-temperature (up to 300K) infrared emitters based on HgCdTe alloys is discussed on the basis of the results of the study of photoluminescence of hetero-epitaxial structures. The structures were grown by molecular-beam epitaxy and emitted light with wavelength of 1.5 to 4.3 μm at room temperature. It is suggested that observation of photoluminescence of the narrow-gap semiconductor at high temperatures and the specific shape of photoluminescence spectra can be explained by taking into account HgCdTe alloy disorder as is the case, for example, in structures based on III-nitrides. Requirements for technology considerations for the optically-pumped high-temperature infrared emitters based on HgCdTe are discussed.

Keywords: HgCdTe, infrared emitters, photoluminescence, alloy disorder

1. Introduction

Hg_{1-x}Cd_xTe (MCT) alloy, which is one of the basic materials for infrared photodetectors, has been considered recently as a material for fabrication of light emitters used, for example, in optron pairs for the gas analyzers [1,2,3]. It is clear that the operation temperature of such emitters should be similar to that of photodetectors. At present, the working temperature of MCT detectors operating in the 3-5 μm wavelength range and functioning in the background-limited infrared photodetector (BLIP) regime, is as high as 180-200K [4]. In applications that are less demanding to sensitivity, MCT-based photodetectors can operate at temperatures up to 300K. However, emission from MCT in the same wavelength range has been believed to be limited to significantly lower temperatures. Typically, previous studies of emissive properties of MCT were carried out at temperatures $T=2-150\text{K}$. Difficulties with detecting radiation at higher temperatures were considered to be caused by fundamental limitations and, first of all, by Auger recombination [5,6,7]. At the same time, modern hetero-epitaxial structures (HES) based on MCT and fabricated with molecular-beam epitaxy (MBE), seem to be able to effectively emit infrared light at temperatures up to 300 K [3,8,9,10,11]. This is rather unexpected considering well-known effect of Auger recombination on the properties of narrow-bandgap semiconductors. At the same time, this effect makes prospects of manufacturing high-temperature infrared MCT-based emitters really optimistic.

In this paper, we make an attempt to understand the nature of high-temperature photoluminescence (HTPL) of narrow-bandgap MBE-grown HgCdTe and of the specific

shape of HTPL spectra observed in some cases. For that purpose, we analyze HTPL ($T=50-300\text{K}$), optical transmission and photoconductivity (PC) spectra of MCT HES, which emitted at $T=300\text{K}$ in the 1.5 to 4.3 μm wavelength range. As a result of the study performed on a large number of HES, we conclude that these structures can be considered as a promising material for fabrication of high-temperature short- and mid-wavelength infrared emitters operating under optical excitation, and discuss the prospects of this technology.

2. Experiment

The HES were grown on GaAs and Si substrates with ZnTe/CdTe buffer layers and had an active (light-emitting) layer of two types. The first type of the active layer was represented by a homogeneous film with the composition x_a ranging from 0.29 up to 0.64 and the thickness h ranging from 3.7 to 8.8 μm . The film was sandwiched between thin (less than 1 μm in thickness) vary-band protective layers. The second type of the active layer was a rather wide (50 to 200 nm) potential well with the composition in the well x_w ranging from 0.30 to 0.41 and that in the barrier layers x_b ranging from 0.50 to 0.74. The large width of the wells ensured that optical properties of the structures were not affected by quantum confinement effects [8]. Values of x_a , x_b and x_w , as well as the thickness of the layers within HES were monitored by *in situ* ellipsometric measurements; this technology has been described in detail elsewhere [8]. Temperature-dependent PL was studied under pulsed excitation with a semiconductor laser emitting at a wavelength of 1.03 μm . Some experiments at fixed temperature (300 K) were carried out using continuous excitation with a laser

emitting at $0.95\mu\text{m}$ with a possibility to tune the excitation power in a very wide range, up to thermal destruction of the samples. The PL spectra were recorded using an automated installation based on an MDR-23 grating monochromator. The PL signal was excited from the HES side, and detected with a Ge photodiode or cooled InSb photodiode from the side of the substrate. Optical transmission and PC spectra were recorded using infrared Fourier spectrometers Infracum-801 and Shimadzu 8400S. The aim of these experiments was to determine the optical absorption edge in the active layer and the corresponding value of the forbidden gap, E_g . The latter was estimated as the energy corresponding to the 50% decay of the transmission and/or PC signal.

3. Results and Discussion

Figure 1 shows PL, PC and optical transmission spectra of two HES, as recorded at $T=300\text{K}$ under pulsed excitation. As can be seen, both HTPL spectra were of clearly unsymmetrical shape. The spectra could be resolved into two Gaussian bands. The shape of the spectra did not depend on the excitation wavelength (0.95 or $1.03\mu\text{m}$) or excitation power up to powers causing thermal damage of the samples.

To reveal the nature of these two HTPL bands, we compared the PC and PL spectra. As can be seen in Figure 1, the energy at half-maximum for the PC and optical transmission curves was close to the maximum of the low-energy PL band. Thus, for sample #1215, E_g estimated using PC and transmission spectra was 0.710eV , which according to an empirical expression for $E_g(x, T)$ from [12], corresponds to chemical composition of the alloy $x=0.57$. PC measurements carried out at 77K (Figure 2) yielded similar x value. Thus, it could be considered that the low-energy PL band at $T=300\text{K}$ was caused by band-to-band recombination in the active layer of the HES. The full width at half maximum (FWHM) of this band was about 30meV .

The high-energy photoluminescence (HEPL) feature, which was represented for sample #1215 by a shoulder on the PL spectrum, when resolved into a band showed the FWHM of $\sim 70\text{meV}$ and blue-shift from the band-to-band maximum by the energy $\Delta E=46\text{meV}$ at 300K .

Figure 2 shows PL and PC spectra of the same HES recorded at 77K . Here, the PL spectra contain only one Gaussian band with the maximum located close to the point of 50% decay of the PC signal. A minor Stokes shift is caused by the presence of the tail states, which in MCT alloy may lead to the red-shift of the peak of the PL spectrum in relation to the nominal E_g value at temperatures up to $150\text{-}200\text{K}$ [8]. For HES #1215, all the PL spectra that were recorded in the temperature range $4.2\text{-}150\text{K}$ had the same shape. Some other structures had peculiarities in their spectra at $T < 50\text{K}$, caused by transitions to acceptor states, as described in [8].

Exemplary dependences of the PL peak position on the temperature are shown in Figure 3. Not all the HTPL spectra had the HEPL feature, but as can be seen in Figure 3, these features, when they were present, followed the temperature dependence of the low-energy PL bands, and not that of E_g . Curves 2 illustrate this effect more evidently, since temperature dependences of the energy of

both PL bands and that of E_g in this case had opposite signs.

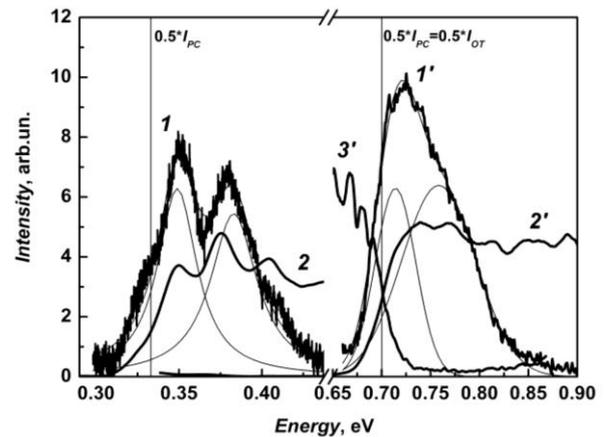


Figure 1. PL (1), PC (2) and optical transmission (3) spectra of HES #0117 ($x_w=0.34$, $x_b=0.69$, curves 1 and 2) and #1215 ($x_a=0.57$, curves 1', 2' and 3') at 300K under pulsed excitation. Thin lines demonstrate analytical fitting and decomposition of the spectra into Gaussian components. Vertical lines correspond to 50% of the intensity of optical transmission signal (I_{OT}) and/or that of PC signal (I_{PC}). Intensities cannot be compared.

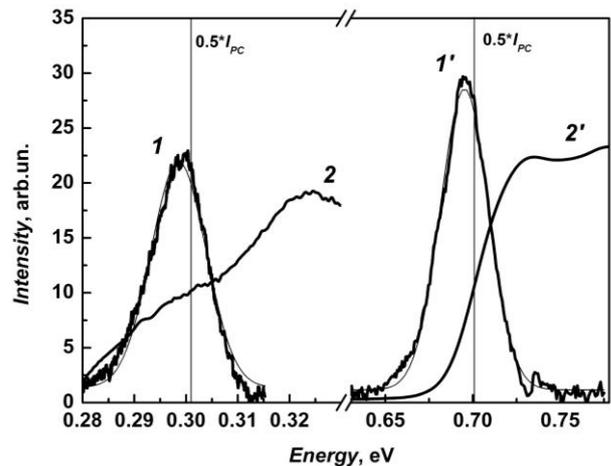


Figure 2. PL (1) and PC (2) spectra of HES #0117 (1 and 2) and #1215 (1' and 2') at 80K under pulsed excitation. Thin lines demonstrate analytical fitting of the spectra with a single Gaussian component. Vertical lines correspond to 50% of the intensity of PC signal (I_{PC}). Intensities cannot be compared.

All the HES with x_a down to 0.29 demonstrated PL at the room temperature. As to the HEPL feature, it began to appear in the spectra at temperatures higher than a certain threshold temperature T_c , which was greater than 127K . Statistically, the HEPL feature was found in the spectra of $\sim 20\%$ of HES with the active layer in the form of the homogeneous film (with a total number of studied samples equaling 20) and $\sim 80\%$ of HES with the active layer in the form of the potential well (11 samples). Our attempts to perform deconvolution of the spectra into separate bands showed that at 300K ΔE ranged from 27 to 56meV . No dependence of ΔE or T_c on HES parameters (in particular, x_a or x_w) could be revealed. However, it should be noted, that HTPL and, in some cases, the HEPL feature, were observed in HES without the wide-bandgap surface protective layer. Thus, neither HTPL nor HEPL feature could be associated with the presence of this layer and its contribution towards suppression of surface

recombination. For HES without the HEPL feature, the HTPL spectra at 300K could be fitted by a single Gaussian curve with a 35 to 45meV FWHM (see, for example, [13]).

It should be noted that high-temperature PL spectra with the HEPL feature have been already observed in recent studies of MBE MCT [3,9,10], but the origin of the feature remained unclear. The value of energy shift of HEPL bands in relation to the peaks associated with band-to-band transitions in the active layer does not allow for associating HEPL with radiation from wide-bandgap layers of HES. At the same time, the temperature dependence of the peak position of HEPL bands (Figure 3) makes it impossible to attribute them to radiation from the buffer layers or from the substrate either (for example, in Si, GaAs, ZnTe and CdTe $dE_g/dT < 0$ while in $Hg_{1-x}Cd_xTe$ with $x < 0.5$ $dE_g/dT > 0$). Therefore, the most probable assumption is that the shape of HTPL spectra in MBE MCT HES is affected by alloy disorder in the active layer itself. Indeed, as already mentioned, the PL studies of MBE MCT at $4.2 < T < 100$ K revealed the considerable disturbance of the long-range order in the crystalline lattice of the semiconductor, which resulted in both broadening of the PL band associated with recombination of localized exciton, and in the Stokes shift [8]. For example, in MBE HES with $x_a \sim 0.38-0.40$, FWHM of the exciton line at $T = 4.2$ K was about 12-17 meV, while that in the sample with similar composition grown by liquid-phase epitaxy (LPE) was about 5 meV. The latter value corresponds to the broadening caused by purely stochastic fluctuations of the alloy composition [14], and indicates high structural perfection of the LPE-grown films, yet PL signal from these films at $T > 150$ K was impossible to detect. Furthermore, in MCT bulk crystals and LPE films with, for example, $x \sim 0.4$, the Stokes shift disappeared at temperatures of 50 to 70 K [5,6]. This effect is caused by thermal delocalization of excitons; therefore, PL at higher temperatures, if any, resulted from recombination of free excitons or free carriers with photon energy close to the nominal value of E_g . For our HES and the MBE-grown structures studied in [8] and [9], the energy of the PL peak associated with the band-to-band recombination remained smaller than E_g for temperatures as high as $T > 200$ K (see Figure 3).

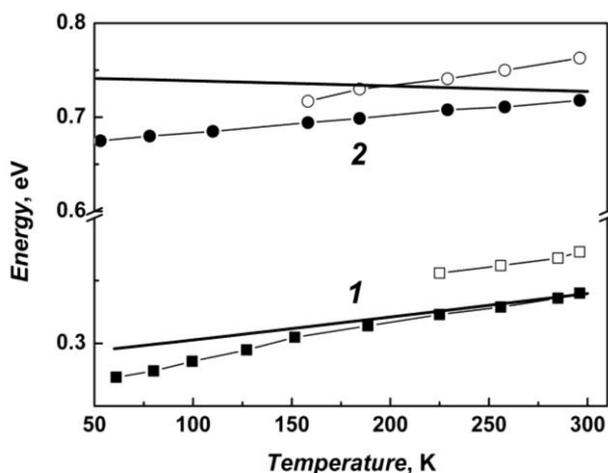


Figure 3. Temperature dependences of peak positions for “band-to-band” PL peaks (closed symbols), HEPL peaks (open symbols) and E_g of the HES active area (curves) calculated according to expressions from [12] for structures #1103 ($x_a = 0.33$, curves 1) and #1215 (curves 2)

The existence of strong disorder in MCT alloys in the form of compositional fluctuations has been studied for a long time. It has been shown by various authors that it was this effect that defined deviation of the energy of excitonic PL line from calculated $E_g(T)$ dependence at low temperatures [5,6,8,14,15]. Thus, it is quite natural to assume that the effect of compositional fluctuations on the optical properties of MCT also shows at high temperatures, provided the scale of the fluctuations is big enough.

Positive effect of compositional disorder in semiconductor alloys, even at the level of stochastic fluctuations, on carrier localization and increase of the PL intensity at high temperatures is already well-known (see, for example, [16]). Increasing the disorder beyond dimensions of such fluctuations can amplify the effect even more. For example, intensive PL of structures based on InGaN observed in samples even with very high density of non-uniformities, is explained by considerable composition inhomogeneities associated with instability of indium in the alloy [17]. Exciton localization at such inhomogeneities is considered to hinder diffusion of carriers to centers of non-radiative recombination and, therefore, stimulates radiative recombination. As to the HEPL-like feature in the HTPL spectra, it was repeatedly observed in various materials with essential disturbance of the long-range order, the latter showing itself in precipitation of nano-size clusters of the second phase (see, for example, [18]). Thus, it is of significant probability that the presence of HEPL feature in the PL spectra of MBE MCT is also associated with the fact that with increasing temperature conditions appear for recombination in the local areas with the composition other than that in the basic matrix of the alloy. Frequent observation of the HEPL feature in the HTPL spectra of HES with potential wells can be explained by the complexity of technological processes related to the growth of such structures with the strong dependence of their optical properties on growth regimes [8]. Also, it should be noticed that thermal annealing, while typically increasing the intensity of luminescence of HES at low temperatures, which was explained by ordering of the alloy structure [8], did not lead to increase in the intensity of HTPL. For some of the samples, the HTPL signal after annealing was weaker than that before the treatment. As to conditions necessary for the occurrence of the HEPL feature, they depend on mutual relation of the rate of the energy relaxation of photo-generated carriers, their lateral transport, and the rates of radiative and non-radiative recombination, and should be a subject of further study.

It has been long considered that alloy disorder is a serious drawback for the material used for fabrication of semiconductor devices: for example, the Stokes shift due to the presence of tail states makes the wavelength emitted by an alloy-based structure at low temperatures almost unpredictable (see, e.g., [8]). Apparently, if the object is to fabricate high-temperature light emitters, presence of such areas is not a drawback but a useful property of the material. For example, in light-emitting structures based on MBE AlGaN, composition inhomogeneities that cause localization of excitons are now specially introduced with the aim to increase the external quantum efficiency [19,20]. However, the situation with MCT shows that the technology of incorporation of inhomogeneities should be done in such a way as to provide at high temperatures the

maximal intensity of radiation, on the one hand, and the minimal FMHW of the spectra, on the other hand.

4. Conclusion

In conclusion, on the basis of observation and analysis of high-temperature ($T=50-300\text{K}$) photoluminescence, optical transmission and photoconductivity spectra of molecular beam epitaxy-grown HgCdTe hetero-epitaxial structures, which emitted in the 1.5 to 4.3 μm wavelength range, we suggest that the effect of alloy disorder, typical of these structures, actually makes them a promising material for fabrication of high-temperature short- and mid-wavelength infrared emitters with optical pumping. Though one cannot expect such devices to compete with those based on III-V materials as infrared emitters as such, they can be useful in applications based on HgCdTe photodetectors, as in this case both the detector and the emitter can be fabricated using the same technology. Simple emitters with optical pumping may represent a good alternative to injection HgCdTe emitters based on very complex heterostructures and operating in a non-equilibrium mode [21,22].

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