Photoluminescence characteristics of ZnTe bulk crystal and ZnTe epilayer grown on GaAs substrate by MOVPE*

Lü Hai-Yan(吕海燕)[a], Mu Qi(牟 奇)[a], Zhang Lei(张 磊)[a], Lü Yuan-Jie(吕元杰)[b], Ji Zi-Wu(冀子武)[a]†, Feng Zhi-Hong(冯志红)[b], Xu Xian-Gang(徐现刚)[c], and Guo Qi-Xin(郭其新)[d]‡

[a] *School of Physics, Shandong University, Jinan* 250100, *China*
[b] *National Key Laboratory of Application Specific Integrated Circuit (ASIC), Hebei Semiconductor Research Institute, Shijiazhuang* 050051, *China*
[c] *Key Laboratory of Functional Crystal Materials and Device (Ministry of Education), Shandong University, Jinan* 250100, *China*
[d] *Department of Electrical and Electronic Engineering, Synchrotron Light Application Center, Saga University, Saga* 840-8502, *Japan*

(Received 22 May 2015; revised manuscript received 7 July 2015; published online 20 October 2015)

Excitation power and temperature-dependent photoluminescence (PL) spectra of the ZnTe epilayer grown on (100) GaAs substrate and ZnTe bulk crystal are investigated. The measurement results show that both the structures are of good structural quality due to their sharp bound excitonic emissions and absence of the deep level structural defect-related emissions. Furthermore, in contrast to the ZnTe bulk crystal, although excitonic emissions for the ZnTe epilayer are somewhat weak, perhaps due to As atoms diffusing from the GaAs substrate into the ZnTe epilayer and/or because of the strain-induced degradation of the crystalline quality of the ZnTe epilayer, neither the donor–acceptor pair (DAP) nor conduction band-acceptor (e–A) emissions are observed in the ZnTe epilayer. This indicates that by further optimizing the growth process it is possible to obtain a high-crystalline quality ZnTe heteroepitaxial layer that is comparable to the ZnTe bulk crystal.

Keywords: photoluminescence, ZnTe bulk crystal, ZnTe epilayer, defect or impurity-related emissions

PACS: 42.70.–a, 61.50.–f, 68.55.–a, 61.72.–y **DOI:** 10.1088/1674-1056/24/12/124207

1. Introduction

ZnTe is a semiconductor of the II–VI family with a zinc-blende structure and a direct energy gap E_g of 2.26 eV at room temperature, and has attracted growing attention because of its applications in green light emitting devices, THz detectors, wave guides, solar cells, and modulators.[1–5] The epitaxial growth of ZnTe on GaAs has aroused considerable interest because GaAs is a desirable substrate due to its important role in the optoelectronic industry. If ZnTe could be grown epitaxially on GaAs, device integration would be possible.[5] However, the lattice mismatch and the difference in thermal expansion coefficient between the GaAs substrate and the ZnTe epilayer are considered to lead to strain and structural defects.[6,7] Hence, to improve the structural quality of the ZnTe epilayer, various growth techniques concerning ZnTe/GaAs heterostructures have been explored,[8–10] and some work has been done on the ZnTe epilayers grown on GaAs substrates by molecular beam epitaxy (MBE) and metal–organic vapor phase epitaxy (MOVPE).[5,11,12] Despite all that, compared with the study of homoepitaxial growth of ZnTe, the investigation of the heteroepitaxial growth of ZnTe on GaAs is still in its infancy. Therefore, more researches are needed before obtaining a high-quality ZnTe epilayer to meet the requirements for optoelectronic device applications.

MOVPE is a promising growth technique for obtaining epitaxial layers, and is suitable for mass production. Here, to obtain a high-quality ZnTe heteroepitaxial layer, a ZnTe epilayer grown on (100) GaAs substrate is prepared by using the MOVPE system under suitable growth conditions,[5,13] while a ZnTe bulk crystal grown by the vertical Bridgman growth method is also presented for comparison. Photoluminescence (PL) measurement results from these two samples indicate that it is possible to fabricate a high-crystalline quality ZnTe heteroepitaxial layer by the MOVPE growth technique.

2. Experiment

The ZnTe epilayer was grown by the home-made MOVPE at atmospheric pressure and a substrate temperature of 420 °C. The details of this system have been described elsewhere.[5,13] Briefly, DMZn and DETe were used as source materials and H_2 as the carrier gas. Polished (100) GaAs substrates were chemically cleaned, degreased in or-

*Project supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20120131110006), the Key Science and Technology Program of Shandong Province, China (Grant No. 2013GGX10221), the Key Laboratory of Functional Crystal Materials and Device (Shandong University, Ministry of Education), China (Grant No. JG1401), the National Natural Science Foundation of China (Grant No. 61306113), the Major Research Plan of the National Natural Science Foundation of China (Grant No. 91433112), and the Partnership Project for Fundamental Technology Researches of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

†Corresponding author. E-mail: jiziwu@sdu.edu.cn
‡Corresponding author. E-mail: guoq@cc.saga-u.ac.jp

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ganic solvents, and then etched in a solution composed of $H_2SO_4 + H_2O_2 + H_2O$ (5:1:1) for about 20 s at 60 °C followed by deionized water rinse. The growth system was evacuated to a pressure on the order of 10^{-7} Torr (1 Torr = 1.33322×10^2 Pa) with a turbomolecular pump before the source materials and the carrier gas were brought into the chamber. To remove the native oxide from the surface of the GaAs substrate, it was cleaned by thermal annealing at 580 °C for 30 min before the growth. The transport rates of DMZn and DETe were kept at 15 μmol/min. The thickness of the ZnTe epilayer was approximately 10 μm. In addition, a ZnTe bulk crystal grown by the vertical Bridgman growth method was also prepared.

The PL measurements of the ZnTe epilayer and ZnTe bulk crystal were performed in a closed-cycle He cryostat and the temperature was controlled to vary from 6 K to 300 K. The 442-nm line of an He–Cd laser was used as an excitation light source with a spot size of *c*. 250 μm, and the excitation power was changed from 2 μW to 40 mW. The PL signal was dispersed through a monochromator (JOBIN YVON iHR320) with a grating groove density of 1200 line/mm, and detected by using a semiconductor cooled charge coupled device (CCD) array of 256×1024 pixels.

3. Results and discussion

Figure 1(a) shows the PL spectra of the ZnTe epilayer in a range of 1.90 eV–2.41 eV, measured at 6 K and 2 μW. As seen from Fig. 1(a), the PL spectrum of the ZnTe epilayer is dominated by a sharp excitonic emission peak I_a at around 2.371 eV with a very narrow full-width at half maximum (FWHM) of about 1.5 meV. The spectrum is similar to that obtained from the ZnTe homoepitaxial layer on (100) ZnTe substrate.[14] The sharp emission peak I_a is attributed to the recombination transition of an exciton bound to the neutral-shallow-acceptors such as Li, Na, and Cu.[1,5,15] The peak (denoted as I_a-LO) on the low-energy side of the peak I_a by 26 meV, is a phonon replica of the peak I_a. It is worth noting that neither both the Y lines usually at 2.188 eV and 2.147 eV which are known to arise from extended structural defects,[16,17] nor the oxygen-bound-exciton (OBE) emission band at around 1.986 eV[18,19] appears here. Likewise, neither the donor–acceptor pair (DAP) emission at around 2.329 eV which is due to the recombination transition between the Zn vacancy (V_{Zn}) acceptor and Te vacancy (V_{Te}) donor or between the Zn interstitial (Zn_i) donor and the Te interstitial (Te_i) acceptor,[20] nor V_{Zn}-related emission at around 2.355 eV,[21] is observed. The results indicate that the ZnTe epilayer structure is of good quality in terms of its crystallinity.

In order to observe clearly the main peak I_a and its excitation power-dependent behavior, figure 1(b) shows the enlarged PL spectra of the I_a peak shown in Fig. 1(a) at different excitation powers, and figure 2 shows the plots of the energy position and intensity of the peak I_a as a function of excitation power. With excitation power increasing from 2 μW to 40 mW, it is seen from Figs. 1(b) and 2, that the I_a peak intensity increases due to the effective capture of the photo-generated carriers by the neutral-shallow-acceptors below the excitation power of about 10 mW, and then becomes gradually saturated. At the same time, the energy position of the peak I_a exhibits a slight red-shift with increasing excitation power. The energy red-shift could be attributed to the increase in strain with the increase of the effective excited depth in the ZnTe epilayer.[22,23] In fact, in previous work,[5] it has been found that the energy of the I_a peak increases monotonically with increasing ZnTe epilayer thickness, suggesting that a tensile strain existing in ZnTe/GaAs epilayer can be gradually relaxed with increasing the ZnTe epilayer thickness.

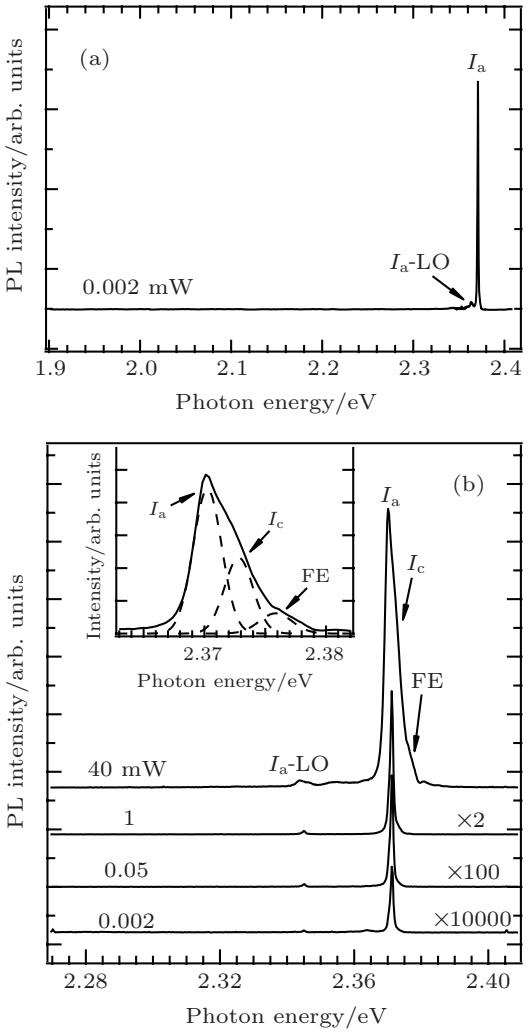


Fig. 1. (a) PL spectrum of the ZnTe epilayer in a photon energy range of 1.90 eV–2.41 eV measured at 2 μW. (b) Excitation power-dependent PL spectra of the ZnTe epilayer in a range of 2.27 eV–2.41 eV. The inset shows the further enlarged PL spectrum including the I_a, I_c, and FE peaks at 40 mW. $T = 6$ K.

Figure 1(b) shows that on the high-energy side of the main peak I_a, a new emission peak (denoted by I_c) appears at a high excitation power. The peak I_c is considered as the

transition of the excitons bound to the As atoms (or As-related complex) diffusing from the GaAs substrate into the epilayer during the growth of the epilayer, due to the high growth temperatures.[5] With increasing excitation power, the peak I_c markedly increases in intensity relative to the I_a peak, while a new free excitonic (FE) emission peak appears on the high-energy side of the I_c peak. In order to observe clearly the emission components at around 2.371 eV, the inset in Fig. 1(b) gives the further enlarged PL spectrum including the I_a, I_c, and FE peaks at 40 mW. The aforementioned behavior for the FE emission peak is due to the energy level filling of the ZnTe epilayer with the increase of the number of the photo-generated carriers. In contrast, however, the marked increase in the I_c peak intensity is mainly attributed to the rapidly increasing density of the As atom in the ZnTe epilayer with increasing effective excited depth. This is because the As atoms diffusing into the ZnTe epilayer are mainly distributed near the epilayer/substrate interface,[5,24] and figure 1 shows the absence of the emission peak I_c in the low excitation range below 1 mW. This is also consistent with the result previously reported by the authors, i.e., the intensity of the I_c peak drastically decreases with increasing the epilayer thickness.[5] Therefore, it is believed that this problem could be solved by appropriately increasing the epilayer thickness.

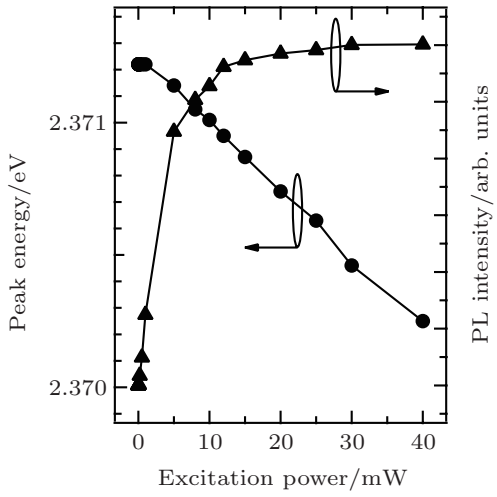


Fig. 2. Excitation power dependences of the I_a peak energy and intensity shown in Fig. 1. $T = 6$ K.

Figure 3 shows the excitation power-dependent PL spectra of the ZnTe bulk crystal measured at 6 K. The PL spectra are dominated by an emission band (denoted by I_b) at around 2.340 eV in the low excitation range. In fact, as seen from Fig. 3 the emission band I_b contains two emission components: a low-energy component located at around 2.335 meV (denoted by I_{bl}) and a high-energy component at around 2.344 meV (I_{bh}). In addition, a weak emission band (denoted by I_b-LO) at around 2.314 eV is the phonon replica of the emission band I_b, and the weak peak at around 2.375 eV originates from the contribution of the emission I_a that may be due to the V_{Zn}.[20] Here, it should be pointed out that although the PL spectra of the ZnTe bulk crystal are dominated by the I_b emission in the low excitation range, the I_a emission from the ZnTe bulk crystal is stronger than that observed in the ZnTe epilayer in the same measurement conditions. The weaker I_a emission for the ZnTe epilayer may be due to the aforementioned As atoms diffusing from the GaAs substrate into the ZnTe epilayer, and/or because of the strain-induced degradation of the crystalline quality of the ZnTe epilayer. With the increase of excitation power in our measurement range, the emission peak I_a together with the well-resolved emission lines of the ground state FE(1S) and excited state FE(2S) of the free excitons,[25] shows a rapid increase in intensity compared with the emission band I_b, as expected. At the same time, the low-energy emission component I_{bl} shows a slower increase in intensity than the high-energy emission component I_{bh} (see inset, Fig. 3), while it gradually shifts towards the higher-energy side and partially merges into the high-energy emission I_{bh}. This is a typical characteristic of donor–acceptor pair (DAP) emission often observed in the spectra of the ZnTe bulks and ZnTe homoepitaxial epilayers.[26,27] Consequently, the low-energy emission component I_{bl} is considered to be a DAP emission, which may result from the carrier transition between the Zn vacancy (V_{Zn}) acceptor and the Te vacancy (V_{Te}) donor or between the Zn interstitial (Zn_i) donor and the Te interstitial (Te_i) acceptor.[20] The aforementioned slower intensity increase and the clear peak blue-shift for the emission peak I_{bl} with increasing excitation power, are due to the gradual saturation of the PL components from distant pairs emitting in the low-energy part of the emission band I_{bl}.[28,29] On the other hand, for the high-energy emission component I_{bh}, the peak blue-shift with increasing excitation power is less obvious. The aforementioned characteristics show that the emission component I_{bh} may originate from the conduction band-acceptor (e–A) emission.[28,30] This less obvious peak blue-shift for the emission I_{bh} with increasing excitation power, is due to the large state density for the conduction electron. For the type of emission component I_{bh}, this will be discussed later.

Figures 4 and 5 show the temperature-dependent PL spectra of the ZnTe epilayer and ZnTe bulk crystal measured at 1 mW, respectively. As seen from Figs. 4 and 5, the I_a emissions in both the structures have similar behaviors. That is, with increasing temperature, the intensity of the emission I_a rapidly decreases compared with those of the FE and I_{bh} emissions, reflecting the thermal dissociation process of the bound excitons from the neutral-shallow-acceptors. At the same time, the emission I_{bl} (i.e. the DAP emission) is rapidly quenched with increasing temperature (Fig. 5), due to the thermal release of electrons from the shallow donor to the conduction band.[28,29]

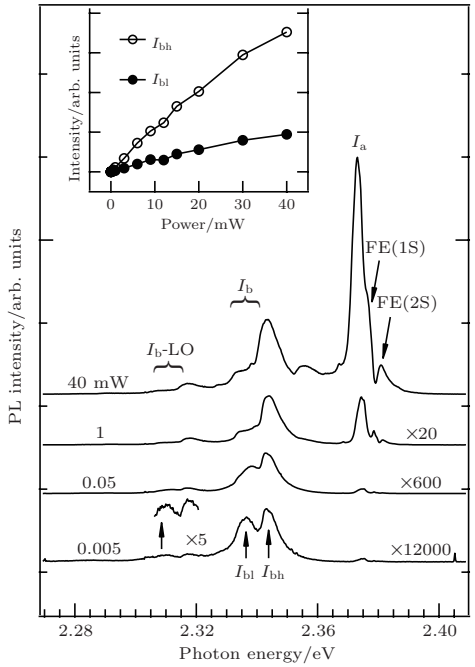


Fig. 3. Excitation power-dependent PL spectra of the ZnTe bulk crystal. The inset shows the PL intensities of the emissions I_{bl} and I_{bh} versus excitation power. $T = 6$ K.

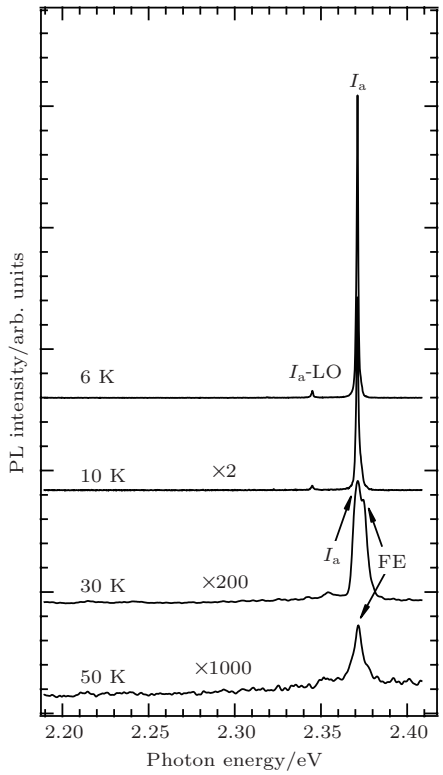


Fig. 4. Temperature-dependent PL spectra of the ZnTe epilayer. $P =$ 1 mW.

Figure 5 also shows that, with increasing temperature, the peak position of the I_{bh} emission shows a blue-shift relative to those of the I_a and FE emissions. Figure 6(a) shows the typical temperature dependences of the peak energies of the emissions I_{bh} and FE(2S). The FE(2S) peak energy is associated with the band-gap energy, and can be found by subtracting its binding energy from the band-gap energy. That is, the variation of the FE(2S) peak energy is equal to that of the band-gap energy. The dashed curve in Fig. 6(a) represents a fit to the FE(2S) experimental data by using the Varshni equation[31]

$$E(T) = E(0) - \frac{\alpha T^2}{\beta + T}, \tag{1}$$

with the following parameters: $E(0) = 2.382$ eV, $\alpha =$ 0.545 meV/K, and $\beta = 203$ K, where $E(T)$ and $E(0)$ are the FE(2S) emission energy at T and 0 K, respectively, and α and β are the Varshni coefficients. Figure 6(a) shows that the temperature dependence of the FE(2S) energy closely follows the Varshni equation. In contrast, however, the peak energy of the emission I_{bh} shows a slight blue-shift relative to the Varshni curve with increasing temperature.

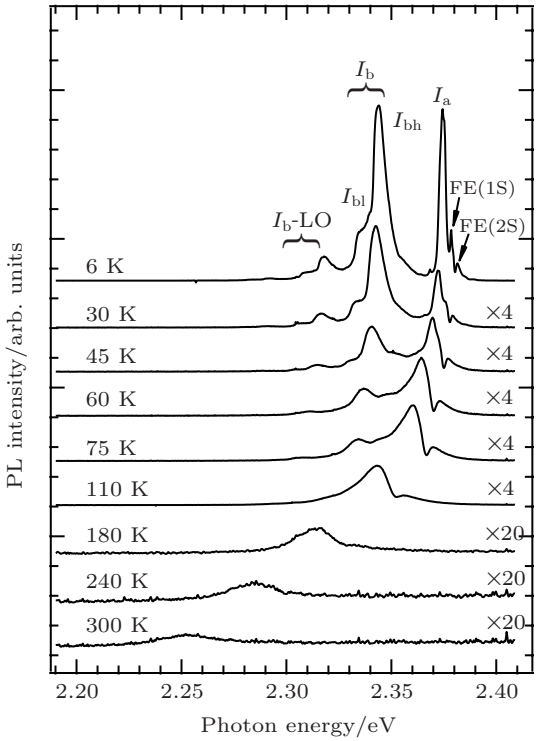


Fig. 5. Temperature-dependent PL spectra of the ZnTe bulk crystal. $P = 1$ mW.

As is well known, the peak energy of the FE transition is[30]

$$E(\mathrm{FE}) = E_G - E_x, \tag{2}$$

where E_G and E_x are energy gap and binding energy of the free exciton, respectively. While the temperature dependence of the peak energy of the e–A transition can be written as

$$E(\mathrm{e-A}) = E_G - E_A + \gamma kT, \tag{3}$$

where E_A is the acceptor binding energy, γ is a constant relating to the dimension of free electron motion in the ZnTe epilayer, k is the Boltzman constant, and kT is due to the kinetic energy and the energy dependence of the transition probability

of free electrons.[30] Thus from Eqs. (2) and (3), the temperature dependence of the spectral peak separation between the FE and e–A transition lines, ΔE, can be written as

$$\Delta E = E(\mathrm{FE}) - E(\mathrm{e}-\mathrm{A}) = E_\mathrm{A} - E_\mathrm{x} - \gamma kT, \qquad (4)$$

which shows that ΔE decreases linearly with temperature with the slope being γk since E_A and E_x are independent of temperature.

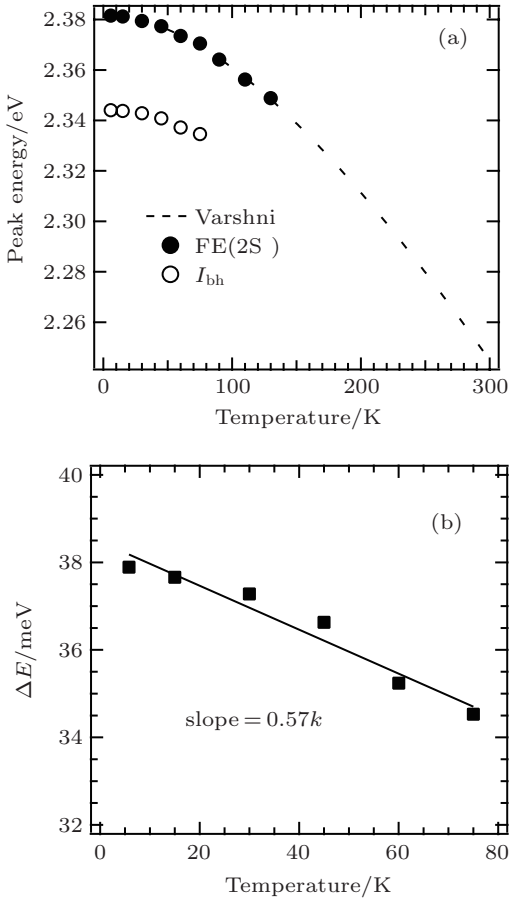


Fig. 6. (a) Temperature dependences of the FE(2S) (•) and I_{bh} (○) peak energies shown in Fig. 4. The dashed line represents the theoretical fit by Eq. (1). (b) Temperature dependence of the energy separation (ΔE) between the FE(2S) and the I_{bh} emission peaks. The solid line is the least-squares fit of data with Eq. (4).

To identify the type of emission I_{bh}, i.e., whether the emission I_{bh} originates from the e–A emission, figure 6(b) shows the temperature dependence of the spectral peak separation (ΔE) between the FE(2S) and the I_{bh} transition lines. The slope obtained from the least-square fit between data points in Fig. 6(b) and Eq. (4) is about $0.57k$ (i.e. $\gamma = 0.57$). That is, with increasing temperature the emission component I_{bh} shifts towards the FE(2S) emission at a rate of $0.57k$. This is a typical characteristic of the e–A emission often observed in GaN or GaN-based materials.[28–30] Together with the observed excitation power dependence shown in Fig. 3, the emission component I_{bh} is considered to be of an e–A emission. The e–A emission may be due to the Zn vacancy (V_Zn), and/or Te interstitial ($\mathrm{Te_i}$). Figures 1–5 also show that the emission I_a for the ZnTe epilayer has a lower peak energy of about 4 meV than that for the ZnTe bulk crystal. The reason for this is not clear now, but it may be due to the different acceptors for these two structures, or due to the tensile strain in the ZnTe epilayer induced by the lattice mismatch and the difference in thermal expansion coefficient between the GaAs substrate and the ZnTe epilayer.[5,23]

All of these results show that both the ZnTe epilayer and the ZnTe bulk crystal used in this work are of good structural quality, due to the sharp bound excitonic emission I_a and the absence of deep structural defect-related Y lines. Furthermore, although the excitonic emissions (I_a and FE) from the ZnTe epilayer are somewhat weaker than that from the ZnTe bulk crystal, which may be due to As atoms diffusing into the ZnTe epilayer and/or because of the strain-induced degradation of crystalline quality of the ZnTe epilayer, the DAP and e–A emissions, which are observed in the ZnTe bulk crystal in this work or are often observed in the ZnTe bulk crystal and ZnTe homoepitaxial layers in other studies,[26,27] do not appear in the ZnTe epilayer, indicating that the ZnTe epilayer grown on its GaAs substrate is a promising material or structure for applications in future optoelectronic devices. It is believed that by further optimizing the growth process, such as using the patterned substrates and low-temperature nucleation layers, introducing the strain release layers, and optimizing the growth parameters (temperature, reactor pressure, and transport rate), these unfavorable factors (the tensile strain and the diffusion of the As atom from the GaAs substrate) affecting the quality of the crystallinity of the ZnTe epilayer could be rendered less harmful. Therefore, it is possible to obtain a high-quality ZnTe heteroepitaxial layer by using the MOVPE system, which is comparable to the ZnTe bulk crystal or ZnTe homoepitaxial layer.

4. Conclusions

In this work, we investigate the excitation power and temperature-dependent PL spectra of the ZnTe epilayer grown on (100) GaAs substrate and ZnTe bulk crystal over the excitation power range of 2 μW to 40 mW and the temperature range of 6 K to 300 K. The sharp bound excitonic emission peak (I_a) and the absence of deep structural defect-related emissions (Y lines) indicate that both the structures are of good structural quality. Furthermore, in contrast to the ZnTe bulk crystal, although the ZnTe epilayer shows a weaker emission peak I_a (possibly due to As atoms diffusing from the GaAs substrate into the ZnTe epilayer and/or because of the strain-induced degradation of crystalline quality of the ZnTe epilayer), neither the DAP emission nor e–A emission is observed in the ZnTe epilayer. All of the results indicate that by further optimizing the growth process, it is possible to obtain a high-quality ZnTe

heteroepitaxial layer, which is comparable to the ZnTe bulk crystal or ZnTe homoepitaxial layer.

References

[1] Garica A, Remon A, Munoz V and Triboulet R 1998 *J. Crystal Growth* **191** 685
[2] Wu S, Shen W Z, Ogawa H and Guo Q X 2003 *Chin. Phys.* **12** 1026
[3] Shao J 2003 *Acta Phys. Sin.* **52** 1743 (in Chinese)
[4] He L R, Gu C M, Shen W Z, Cao J C, Qgawa H and Guo Q X 2005 *Acta Phys. Sin.* **54** 4938 (in Chinese)
[5] Guo Q X, Sueyasu Y, Ding Y L, Tanaka T and Nishio M 2009 *J. Crystal Growth* **311** 970
[6] Naumov A, Wolf K, Reisinger T, Stanzl H and Gebhardt W 1988 *J. Appl. Phys.* **64** 3210
[7] Wolf K, Naumov A, Reisinger T, Kastner M, Stanzl H, Kuhn W and Gebhardt W 1994 *J. Crystal Growth* **135** 113
[8] Jang M S, Oh S H, Lee K H, Bahng J H, Choi J C, Jeong K H, Park H L, Choo D C, Lee D U and Kim T W 2003 *J. Phys. Chem. Sol.* **64** 357
[9] Longo M, Lovergine N, Mancini A M, Leo G and Berti M 1998 *J. Vac. Sci. Technol. B* **16** 2650
[10] Zozime A, Seibt M, Ertel J, Tromson-Carli A, Druilhe R, Grattepain C and Triboulet R 2003 *J. Crystal Growth* **249** 15
[11] Kuhn W S, Lusson A, Quō Hen B, Grattepain C, Dumont H, Gorochov O, Bauer S, Wolf K, Worz M, Reisinger T, Rosenauer A, Wagner H P, Stanzl H P and Gebhardt W 1995 *Prog. Crystal Growth Charact. Mater.* **31** 119
[12] Shigaura G, Ohashi M, Ichinohe Y, Kanamori M, Kimura Na, Kimura No, Sawada T, Suzuki K and Imai K 2007 *J. Crystal Growth* **301–302** 297
[13] Kume Y, Guo Q X, Fukuhara Y, Tanaka T, Nishio M and Ogawa H 2007 *J. Crystal Growth* **298** 445
[14] Tanaka T, Hayashida K, Wang S, Guo Q X, Nishio M and Ogawa H 2003 *Nucl. Instrum. Method Phys. Res. B* **199** 356
[15] Dean P J, Venghaus H, Pfister J C, Schaub B and Marine J 1978 *J. Luminescence* **16** 363
[16] Naumov A, Wolf K, Reisinger T, Stanzl H, Wagne H P and Gebhardt W 1993 *Physica B* **185** 250
[17] Naumov A, Wolf K, Reisinger T, Stanzl H and Gebhardt W 1993 *J. Appl. Phys.* **73** 2581
[18] Ekawa M and Taguchi T 1989 *Jpn. J. Appl. Phys.* **28** L1341
[19] Zhang Y, Skromme B J and Turco-Sandroff F S 1992 *Phys. Rev. B* **46** 3872
[20] Yoshino K, Yoneta M, Ohmori K, Saito H, Ohishi M and Yabe T 2004 *J. Electron. Mater.* **33** 579
[21] Tu R C, Su Y K, Chen H J, Huang Y S, Chou S T, Lan W H and Tu S T 1998 *J. Appl. Phys.* **84** 2866
[22] Ekawa M and Taguchi T 1989 *Jpn. J. Appl. Phys.* **28** L1341
[23] Zhang L, Ji Z W, Huang S L, Wang H N, Xiao H D, Zheng Y J, Xu X G, Lu Y and Guo Q X 2013 *Thin Solid Films* **536** 240
[24] Huang S L, Ji Z W, Zhao M W, Zhang L, Guo H Y, Liu B L, Xu X G and Guo Q X 2012 *Phys. Status Solidi A* **209** 2041
[25] Tanaka T, Hayashida K, Wang S L, Guo Q X, Nishio M and Ogawa H 2003 *J. Crystal Growth* **248** 43
[26] Nishio M, Guo Q X and Ogawa H 1999 *Thin Solid Films* **343–344** 512
[27] Traversa M, Lovergine N, Prete P, Yoshino K and Di Luccio T 2004 *J. Appl. Phys.* **96** 1230
[28] Reshchikov M A and Morkoç H 2005 *J. Appl. Phys.* **97** 061301
[29] Ursaki V V, Tiginyanu I M, Zalamai V V, Hubbard S M and Pavlidis D 2003 *J. Appl. Phys.* **94** 4813
[30] Chen G D, Smith M, Lin J Y, Jiang H X, Salvador A, Sverdlov B N, Botchkarv A and Morkoc H 1996 *J. Appl. Phys.* **79** 2675
[31] Varshni Y P 1967 *Physica* **34** 149