Influence of annealing conditions on impurity species in arsenic-doped HgCdTe grown by molecular beam epitaxy*

Yue Fang-Yu(越方禹)[a)b)†], Chen Lu(陈 璐)[c)], Li Ya-Wei(李亚巍)[a)], Hu Zhi-Gao(胡志高)[a)], Sun Lin(孙 琳)[a)], Yang Ping-Xiong(杨平雄)[a)], and Chu Jun-Hao(褚君浩)[a)b)]

[a)] *Key Laboratory of Polar Materials and Devices, Ministry of Education, East China Normal University, Shanghai* 200241, *China*
[b)] *National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai* 200083, *China*
[c)] *Research Center for Advanced Materials and Devices, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai* 200083, *China*

(Received 22 April 2010; revised manuscript received 21 June 2010)

Based on our previous work, the influence of annealing conditions on impurity species in *in-situ* arsenic (As)-doped $Hg_{1-x}Cd_xTe$ ($x \approx 0.3$) grown by molecular beam epitaxy has been systematically investigated by modulated photoluminescence spectra. The results show that (i) the doped-As acting as undesirable shallow/deep levels in as-grown can be optimized under proper annealing conditions and the physical mechanism of the disadvantage of high activation temperature, commonly assumed to be more favourable for As activation, has been discussed as compared with the reports in the As-implanted HgCdTe epilayers ($x \approx 0.39$), (ii) the density of V_{Hg} has an evident effect on the determination of bandgap (or composition) of epilayers and the excessive introduction of V_{Hg} will lead to a short-wavelength shift of epilayers, and (iii) the V_{Hg} prefers forming the V_{Hg}–As_{Hg} complex when the inactivated-As (As_{Hg} or related) coexists in a certain density, which makes it difficult to annihilate V_{Hg} in As-doped epilayers. As a result, the bandedge electronic structures of epilayers under different conditions have been drawn as a brief guideline for preparing extrinsic p-type epilayers or related devices.

Keywords: As-doped HgCdTe, annealing influence, extrinsic/intrinsic impurities, modulated photoluminescence spectra

PACC: 7155G, 7855D, 7155E, 8140T

1. Introduction

Narrow-gap mercury cadmium telluride (HgCdTe) semiconductor has found wide applications in infrared detection. The p-type doping is a key issue in the molecular beam epitaxial (MBE) growth of HgCdTe for improving the performance of infrared (IR) heterojunction detectors, as well as multi-colour detectors.[1] Metallic vacancies are usually employed as acceptors in HgCdTe, but they are known to act as Shockley–Read–Hall combination centres for minority carriers, shorten the carrier lifetime, and hence decrease the quantum efficiency of detectors with the p-type photon absorption layers. Thus, to fabricate large scale high performance infrared detector focal plane arrays, extrinsic p-type doping by *in-situ* growth is crucial, of which the column V element arsenic (As) is the most favourite dopant for its stability and low diffusivity.[2]

However, the amphoteric As in HgCdTe can be incorporated as acceptors (As_{Te}) under Hg-rich conditions while as donors (As_{Hg}) under Te-rich conditions, which normally occurs in the growth of MBE to avoid high Hg pressures and lattice imperfections. Therefore, a feasible post-growth annealing process, especially a two-stage annealing process, has been proposed to realize extrinsic p-type conductivity by transferring the As from occupying Hg-sublattice sites to Te-sublattice sites under low activation temperature (e.g. < 300 °C) for preserving the intrinsic advantages of low growth temperature of MBE.[3,4] To our knowledge, different activation anneals on *in-situ* As-

*Project supported by the National Basic Research Program of China (Grant No. 2007CB924901), Shanghai Leading Academic Discipline Project (Grant No. B411), National Natural Science Foundation of China (Grant No. 60906043), Shanghai Municipal Commission of Science and Technology Project (Grant Nos. 09ZR1409200 and 10ZR1409800), Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20090076120010), and the Fundamental Research Funds for the Central Universities (Grant No. 09ECNU).

†Corresponding author. E-mail: fyyue@ee.ecnu.edu.cn

© 2010 Chinese Physical Society and IOP Publishing Ltd

doped HgCdTe have been investigated by theoretical calculations[5,6] and electrical measurements,[7,8] but few reports can be systematically accessed by optical measurements about the influence of annealing conditions on the impurity species and the optimized activation conditions as well as the physical mechanism of the advantage of low activation temperature, although the energy positions of As-related impurity levels have been discussed in our previous works by modulated photoluminescence (PL) spectra[9] and photoreflectance (PR) spectra on as-grown As-doped HgCdTe epilayers,[10] respectively, such as the inactivated-As (As_{Hg}) of ∼8.5 meV below the conduction band, the activated-As (As_{Te}) at 10.5±1.0 meV and the V_{Hg}–As_{Hg} complex at about 25 meV above the valence band, as well as the other levels including the intrinsic mercury vacancy (V_{Hg}) at 14.0–15.0 meV above the valence band and the tellurium antisite (Te_{Hg}) at ∼20 meV below the conduction band.

In this work, the influence of annealing conditions on impurity species in *in-situ* As-doped $Hg_{1-x}Cd_xTe$ ($x \approx 0.3$) epilayers have been investigated by modulated PL spectra. The results show that low activation temperatures during the two-stage annealing process are of benefit to the As-activation because higher activation temperatures at the first-stage can deteriorate the quality of epilayers possibly due to producing excessive intrinsic defects (V_{Hg}), and the density of V_{Hg} has an evident effect on the determination of the composition of epilayers. Meanwhile, we find that it is more difficult to completely eliminate V_{Hg} by n-type anneals in As-doped epilayers than in unintentionally (or V_{Hg})-doped epilayers, because the V_{Hg} prefers forming the V_{Hg}–As_{Hg} complex when the inactived As (e.g., As_{Hg} or related) coexists in a certain density. Finally, the bandedge electronic structures of As-doped HgCdTe epilayers have been separately represented under different conditions, which can be used as a guideline for preparing extrinsic p-type epilayers or related devices.

2. Experimental details

The HgCdTe epilayers were grown in a Riber 32P MBE system on undoped semi-insulating GaAs (211)B substrates at a normal growth temperature. To avoid As out-diffusion from GaAs substrates, a CdTe buffer layer of thicker than 3 μm was grown prior to the HgCdTe nucleation.[11] The doping source was from As_4 dopant. The epilayers were followed by different post-growth annealing processes including n-type anneals, p-type anneals and vacuum anneals. The n-type anneals meant the annealing at 240 °C for 48 h under Hg-saturated pressure for annihilating V_{Hg} created either during the growth or during other annealing processes. The p-type anneals represented the annealing in a temperature range of 285 °C–440 °C for 0.5 h–30 h at different Hg pressures in an attempt to transfer As atoms probably originally occupying Hg sublattice sites in as-grown to Te sublattice sites.[12] The vacuum anneals were performed at 230 °C for 24 h without the participation of Hg in order to confirm the role of intrinsic V_{Hg} during the course of As activation. Note that the n-type anneals could annihilate the density of V_{Hg} while the p-type anneals and the vacuum anneals could create additional V_{Hg}. For comparison, the unintentionally (or V_{Hg})-doped HgCdTe epilayers have been prepared under different annealing conditions.

The carrier density and mobility were measured by temperature-dependent Hall measurements. The doping level was determined by the second ion mass spectrometry (SIMS), as described in detail elsewhere.[13] For p-type activation, epilayers have been succeeded by the two-stage annealing process of 285 °C for 16 h and 240 °C for 48 h. In order to avoid the problem of reproducibility, pieces of epilayers have been grown and annealed to make a comparison. Typical samples are listed in Table 1 together with other parameters. From the table we can see that the as-grown M1 shows p-type conductivity and then is converted to n-type (M2) by n-type anneals, while maintains p-type (M3, M4) after different two-stage annealing processes. It should be pointed out that the undoped M5 and M6 show p-type and n-type conductivities under vacuum anneals and two-stage anneals, respectively.

The modulated PL measurements were performed on a step-scan-based Fourier transform infrared (FTIR) spectrometer. The spectral resolution was set to 6 cm^{-1} (∼ 0.7 meV). Before the experiment the samples were treated with a quick etch for avoiding the influence from surface smear, and then mounted on a cold finger of an Oxford cycling-cryostat (OptistatAC-V), of which the temperature can be continuously adjusted from 4 K to 300 K. The thickness and composition of epilayers were evaluated from transmission spectra at a low temperature of about 10 K.[14] During the experiment, the emission optical path has been purged with high-pure nitrogen to eliminate the disturbance of the atmosphere absorption.

Table 1. Parameters of samples including composition x, thickness d/μm, doping, annealing conditions, carrier density N_c/cm^{-3} and mobility $M_c/(\text{cm}^2/(\text{V·s}))$ at 77 K, as well as major levels.

	x	d	doping	anneal/(°C/h)	N_c	[a]M_c	major levels
M1	0.300	6.0	As-doped	–	1.2×10^{16}	259	V_{Hg}, [b]As^D, V_{Hg}–As_{Hg}, Te_{Hg}
M2	0.304	6.5	As-doped	240/48 (Hg-sat.)	-1.0×10^{15}	–2800	As_{Hg}, V_{Hg}, V_{Hg}–As_{Hg}
M3	0.300	5.9	As-doped	[c]285/16+240/48	3.3×10^{16}	295	As_{Te}
M4	0.305	6.1	As-doped	[d]400/0.5+240/48	3.6×10^{16}	292	As_{Te}, V_{Hg}
M5	0.300	11.0	–	[e]360/16	1.0×10^{16}	261	V_{Hg}
M6	0.304	6.0	–	[d]400/0.5+240/48	-6.0×10^{14}	–24500	–

[a] '–' representing the carrier of electrons.
[b] As-related donors including shallows and deeps.
[c] With the Hg pressure of 0.016 atm (1 atm=1.013×10^5 Pa).
[d] With the Hg pressure of 0.07 atm
[e] Vacuum without Hg atoms.

3. Results and discussions

Figure 1 typically shows the modulated PL spectra of all samples at low temperature of 10 K (4 K for M1) and low excitation power of 10 mW (30 mW for M4). In order to determine the peak energy, curve-fitting procedures and second-order derivative operations have been performed on the PL spectra, respectively.[15] The scattering of less than ±0.5 meV between them represents that they both are reliable to determine the peak position. It should be stated that no mathematical smoothing has been performed on experimental data, and the band tail effect (or band filling effect) at high energy side should be considered under higher temperatures or higher excitation powers when curve-fitting procedures are operated on the PL lineshapes.[16] For clarity, the curve-fitting results have been shown on the corresponding curves. From Fig. 1 we can see that all samples show more than two evident PL peaks, especially M1 in Fig. 1(a) with about seven peaks and M2 in Fig. 1(b) with about four peaks.

In order to confirm the evolutive mechanism of peaks in Fig. 1, the modulated PL spectra have been performed at different temperatures and different excitation powers. Figure 2 summarizes the temperature dependence of the peak energy of all samples. For comparison, the calculated results of the well-accepted $E_g - T$ empirical relation of Chu *et al.* (abbreviated as CXT)[17] have been depicted with solid-line in Fig. 2(a). From Fig. 2 we can see that the peaks almost show superlinearity against temperature, except that some of them disappear gradually as temperature increases, especially over 50 K.

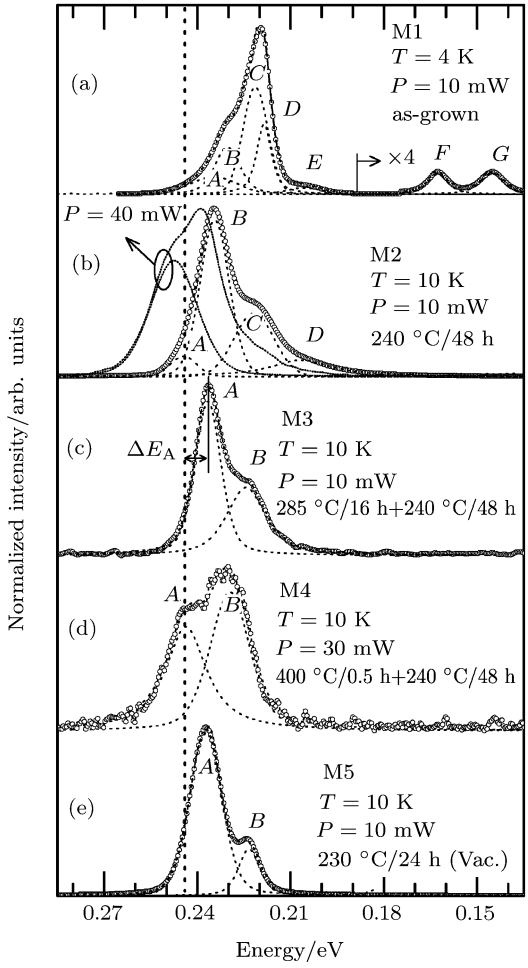


Fig. 1. Normalized PL spectra of all samples. The partial spectrum at low energy side in Fig. 1(a) has been amplified by 4 times for clarity. The annealing process and experimental condition are correspondingly shown on the curves. The dotted curves give the curve-fitting results. The vertical dashed is used to guide the eyes.

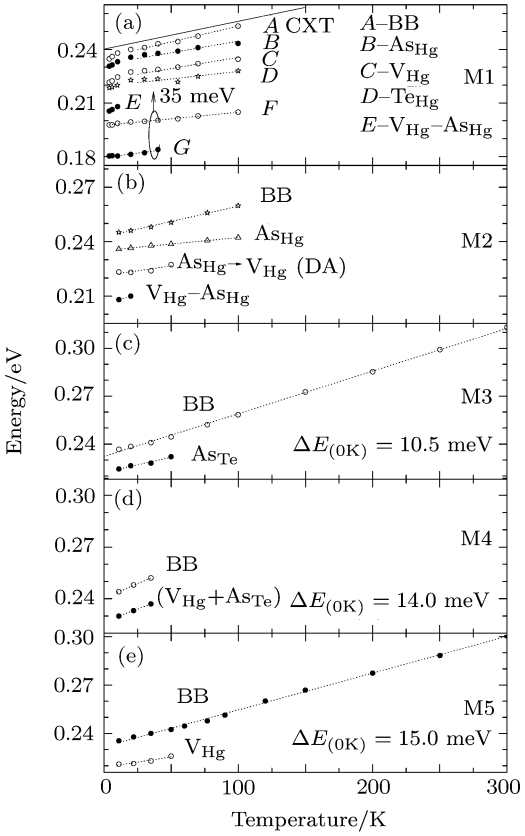


Fig. 2. Temperature dependence of the peak energy of all samples in Fig. 1. In figure (a) the solid line gives the calculated result of CXT, and the data of F and G are upshifted by 35 meV for the sake of making the temperature dependence clear. $\Delta E_{(0K)}$ in figures (c)–(e) shows the peak energy separation at 0 K, respectively.

For the complicated peaks of as-grown M1 (As-inactivated) in Fig. 1(a), they have been systematically discussed in our previous work in the Ref. [18], where the highest energy peak A was attributed to the band-to-band (BB) transition and the middle peaks B–E were assigned to the shallow-related transitions of As_{Hg}, V_{Hg}, Te_{Hg} and V_{Hg}–As_{Hg} (complex) with an ionization energy of $\sim$ 8.5 meV, 15.0 meV, 20.0 meV and 25.0 meV, respectively, while peaks F–G at low energy side with an ionization energy of about 70–100 meV were identified as deep donors related to the defects like As_4 tetramers and clusters by considering the As_4 dopant source (even a As_2 cracker oven used),[19] as shown in Fig. 2(a). Close results have also been reported elsewhere.[10,20]

Figure 1(b) shows the spectra of M2 (single n-type annealing). The peak A in it can be definitely ascribed to the BB transition by referring to the calculated result of CXT and the interpretation of the line originating in a band-to-band transition.[21,22] In view of its weak intensity under the excitation power of 10 mW, Fig. 1(b) shows the scaled PL spectrum of 40 mW at the same temperature and the fitting-curve of peak A with dashes to reveal its BB transition characteristic. In fact, peak A of other samples shown in Figs. 2(c)–2(e) has also been attributed to the BB-related transition according to these discussions.

As shown in Table 1, M2 was obtained from as-grown M1 by n-type anneals. According to the relationship that the SIMS result of the doped-As is much higher than the carrier density of Hall measurements, it can be figured out that a certain density of impurities providing holes should exist in M2. As a result, the V_{Hg}, reported as intrinsic acceptor, should be imaged to be subsistent in M2 in large numbers of density. Therefore, the net n-type in M2 should sum over the main As_{Hg} (or related) and the residual V_{Hg} as well as the possibly formed V_{Hg}–As_{Hg} complex (theoretically predicted). Correspondingly, peaks B–D in Fig. 2(b) can be tentatively ascribed to the transitions of As_{Hg}-to-band (DB), As_{Hg}-to-V_{Hg} (DA) and the V_{Hg}–As_{Hg} complex (BA), respectively, and their ionization energies can be determined to be about 8.5 meV (As_{Hg}), 14.5 meV (V_{Hg}) and 25.0 meV (V_{Hg}–As_{Hg} complex) by extrapolating the temperature dependence of peak energy to 0 K, which are well consistent with the results in as-grown M1. At this point, it seems to be apparent that V_{Hg} can not be fully annihilated in As-doped HgCdTe epilayers by n-type anneals even if the n-type anneal (under the participation of Hg-saturated atmosphere) has been commonly assumed as a matter of fact to fully annihilate the intrinsic impurities including V_{Hg} and Te_{Hg} without activating the doped-As as acceptors!

Figure 1(c) gives the spectrum of M3 (two-stage activation annealing) at 10 K. As mentioned and discussed above, the As in it have been fully activated as extrinsic acceptors. Thus peak B in Fig. 1(c) should be attributed to the transition of As_{Te} with an ionization energy of about 10.5 meV (see Fig. 2(c)). It should be noted that this value of As_{Te} ($\sim$ 10.5 meV) is almost triple that ($\sim$ 31.5 meV) of As-implanted $Hg_{0.61}Cd_{0.39}Te$ by traditional PL spectra in our previous Refs. [23] and [24], where another viewpoint has also been mentioned that only the high activation temperature over 400 °C (at the first-stage) could activate the implanted-As as acceptors while the low temperature of 300 °C could be invalid. However, there are essential differences between them as follows, (i) the evident difference of composition, which influences the ionization energy of shallow levels;[25,26] moreover, the

bigger composition (∼0.39) in the As-implanted epilayer can be investigated by traditional PL spectra while the current composition of about 0.3 should be quantitatively analysed by modulated PL spectra, (ii) the different doping technique, As-implantation and *in-situ* As-doping, of which the latter has been taken as the ideal growth method and the former could affect the electronic structure of epilayers, (iii) most important is the activation ratio of As, which was not measured in the As-implanted epilayers (largely, partially-activated) and as a result the ionization energy of As_{Te} could be deduced roughly by fitting the complicated PL spectra since the related theoretical calculation reports could not be available at that moment. Instead, the doped-As in M3 in this work has been definitely activated as acceptors according to the Hall/SIMS measurements, based on which the ionization energy can be obtained correctly. In this case, the deduced value of As_{Te} ($x \approx 0.3$) here is more convincing by combining with the results of temperature-dependent absorption spectra and the reports (3.0–10.0 meV) of As_{Te} from electrical measurements.[8,27,28] Pay attention to the results of As_{Te} and V_{Hg}, and we can find that the ionization energy of As_{Te} is slightly smaller than that of V_{Hg} ($\sim$ 14.5 meV), implying that it is difficult to separate from each other in PL spectra if they individually coexist in a certain density in epilayers. This will be vital for analyzing the spectra below in Fig. 1(d).

Comparing M3 with M2, we can observe an interesting phenomenon that the intrinsic V_{Hg} can be fully eliminated in M3 by the second-stage annealing process (like n-type anneals), while can not be effectively annihilated in M2 (see Fig. 2(b)) by the single n-type anneal. By taking into account the facts that (i) the second-stage during the two-stage annealing process can annihilate V_{Hg} completely in M3 when the As has been completely activated by p-type anneals (see Fig. 2(c)), (ii) the n-type anneal can reverse the conductivity of undoped epilayers from intrinsic p-type to n-type, and (iii) the two-stage annealing process can result in the n-type conductivity in unintentionally (or V_{Hg})-doped epilayers (see M6 in Table 1), representing that V_{Hg} in undoped epilayers can be eliminated completely by n-type anneals, the reason can be ascribed to that the V_{Hg} prefers forming the V_{Hg}–As_{Hg} complex when the inactivated-As (As_{Hg} or related) coexists in enough density, which makes it difficult to fully eliminate V_{Hg}. Thereby, it may suggest that the duration of the single n-type annealing process (M2) should be prolonged for effectively eliminating the excessive V_{Hg}.

The emphasis may be paid on Fig. 1(d), the result of M4, which has been annealed at a high activation temperature of 400 °C (or 440 °C for others) to make a comparison with M3 (285 °C). The doped As in it have also been completely activated as acceptors by higher activation temperature. However, the spectral signal-to-noise ratio (SNR) was worsened rapidly as temperature increases so that the curve-fitting procedures could not be accurately performed, especially over 35 K. More important are the differences of the peak position and its energy separation between M4 and M3, namely, (i) peak A of M4 shows an evident blue-shift (ΔE_A in Fig. 1(d)), (ii) the FWHM (full wave at half maximum) of peak A in M4 is broadened as compared to M3, and (iii) the peak separation of M4 at 0 K ($\sim$ 14.0 meV, see Fig. 2(d)) appears to be noticeably different from that of As_{Te} ($\sim$ 10.5 meV in Fig. 2(c)) but close to that of V_{Hg} ($\sim$ 15.0 meV,[29] as shown in M5 in Fig. 2(e), which gives the exact ionization energy of V_{Hg} in undoped epilayers under the same measure condition). Similar results have also been observed in As-doped epilayers with a higher activation temperature of 440 °C. Note that M4 and M3 were cut from the same piece but with a different activation temperature at the first-stage. Thus it can be taken for granted that the peak energy separation of M4 should be around $\sim$ 10.5 meV if there only exists the activated-As (As_{Te}), and that the high energy peak A (roughly corresponding to composition) should also be close to that of M3. Reversely, it is conclusive that the high activation temperature has equivalently largened the composition x of epilayers by decreasing the concentration of Hg atoms (excessive V_{Hg} produced), which results in the main contribution of peak B in M4 not only from the transition of extrinsic acceptor As_{Te}, but also from the residual intrinsic V_{Hg} possibly produced by the high activation temperature. Actually, a double peaks close to each other can be observed in the original peak B in Fig. 1(d), which can nearly not be separated by curve-fitting operations for their tiny energy difference of $\sim$ 3.0 meV. Simultaneously, the worse spectral SNR of M4 even under a much higher excitation power of 30 mW also represents the bad quality of M4, potentially due to the excessive introduction of intrinsic defects (e.g. V_{Hg}).

It should be pointed out that the temperature-dependent Hall measurement showed that the interface curve between the buffer layer and the epilayer

is very sharp, which suggests that the bigger density of carriers in M4 than that in M3 can not be caused by As out-diffusion from substrate though the buffer layer of CdTe is only about 3 μm, but by excessively produced V_{Hg}. Of course, it may be more suitable to exclude the issue of As out-diffusion by performing the experiments on HgCdTe epilayers grown on Si substrate.

Focus on the peak position in Figs. 2(b), 2(c) and 2(d), and we can find that peak A (E_A, corresponding to E_g or x) of M2 and M4 is almost equal to each other but bigger than that of M3 at the same temperature. Here, a preliminary conclusion can be reached that the density of V_{Hg} indeed influences the composition of epilayers, and a high density of V_{Hg} (created or residual) in the annealed epilayers induces a big E_A (or large x value), which may be understood from the decrease of Hg ratio in $Hg_{1-x}Cd_xTe$ when V_{Hg} increases in density. This will further make us stick to our previous reports on the important role of intrinsic absorption spectra of low temperatures in the determination of composition of narrow-gap semiconductors, because the influences of impurities on the absorption-edge can be avoided at low temperature.[14]

Based on the above discussions, Fig. 3 summarizes the bandedge electronic structures of As-doped epilayers under different conditions. Note that the complicated levels in as-grown (a) can be optimized as the desirable levels (c) under a suitable annealing condition, while a high activation temperature (e.g. 400 °C or higher) will be unfavourable for As-activation and deteriorate the epilayer's quality by producing excessive intrinsic defects (see V_{Hg}(HT) in Fig. 3(c)). The value of As_{Te} reported by traditional PL spectra in As-implanted HgCdTe ($x \approx 0.39$, activated under 450 °C) has also been depicted in figure (c) to make a comparison. The levels in dashes (V_{Hg}–As_{Hg} and V_{Hg}) in figure (b) represent that they can be eliminated by prolonging the second-stage duration of the two-stage annealing process (or n-type anneals) while exist under the annealing condition in this work. In addition, it is clear that the deep levels in as-grown (D^{d1} and D^{d2}, also see Fig. 1(a)) disappear after n- or p-type anneals (also see Figs. 1(b)–1(d)), regardless of whether the As is activated or not.

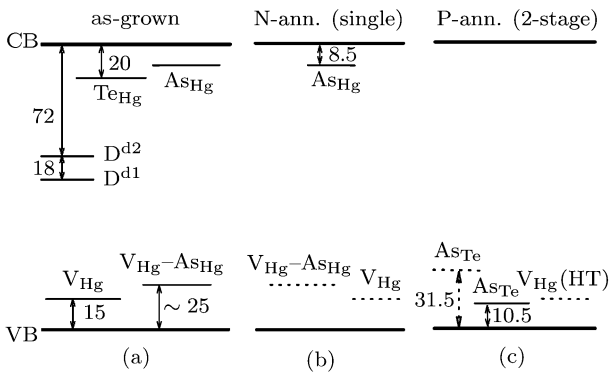


Fig. 3. Schematic of electronic structures in *in-situ* As-doped HgCdTe ($x \approx 0.3$) under different conditions including as-grown (a), single n-type anneals (b) and two-stage anneals (c), respectively. The values in the figure are in the unit of meV.

4. Conclusion

In summary, the influence of annealing conditions on impurity species in As-doped $Hg_{1-x}Cd_xTe$ ($x \approx 0.3$) grown by MBE have been investigated by modulated PL spectra. The experiments represent that the doped-As mainly acting as shallow/deep donors in as-grown can be combined in different forms under different annealing conditions. For p-type activation, the mechanism of the advantage of low activation temperature has been discussed by comparing with the reports in As-implanted epilayers. The intrinsic V_{Hg}, which can be excessively produced by higher activation temperature and as a result 'increases' the composition of epilayers, can not be eliminated completely by n-type anneals (or the second-stage annealing process) for preferring forming the V_{Hg}–As_{Hg} complex when the inactivated-As (As_{Hg}) coexists in enough density. This can be used as a brief guideline for preparing extrinsic p-type epilayers or related devices.

Acknowledgments

Thanks are due to Prof. J. Shao, Prof. X. D. Tang, Prof. Z. Tang and Prof. C. G. Duan for their helpful discussions.

References

[1] Sivananthan S, Wijewarnasuriya P S, Aqariden F, Vydyanath H R, Zandian M, Edwall D D and Arias J M 1997 *J. Electron. Mater.* **26** 621
[2] Wu O K, Kamath G S, Redford W A, Bratt P R and Pattern E A 1990 *J. Vac. Sci. Technol.* A **8** 1034
[3] Berding M A and Sher A 1999 *Appl. Phys. Lett.* **74** 685

[4] Boieriu P, Chen Y and Nathan V 2002 *J. Electron. Mater.* **31** 694
[5] Shaw D and Capper P 2008 *J. Mater. Sci.: Mater. Electon.* **19** 67
[6] Schaake H F 2001 *J. Electron. Mater.* **30** 789
[7] Tsen G K O, Sewell R H, Atanacio A J, Prince K E, Musca C A, Dell J M and Faraone L 2008 *Semicond. Sci. Technol.* **23** 015014
[8] Selamet Y, Grein C H, Lee T S and Sivananthan S 2001 *J. Vac. Sci. Technol.* B **19** 1488
[9] Yue F Y, Chu J H, Wu J, Hu Z G, Li Y W and Yang P X 2008 *Appl. Phys. Lett.* **92** 121916
[10] Shao J, Lv X, Guo S L, Lu W, Chen L, Wei Y F, Yang J R, He L and Chu J H 2009 *Phys. Rev.* B **80** 155125
[11] He L, Yang J R, Wang S L, Guo S P, Yu M F, Chen X Q, Fang W Z, Qiao Y M, Zhang Y, Ding R J and Xin T L 1997 *J. Cryst. Growth* **175/176** 677
[12] Monterrat E, Ulmer L, Mallard R, Magnea N and Pautrat J L 1992 *J. Appl. Phys.* **71** 1774
[13] Wu J, Xu F, Wu Y, Chen L, Wang Y, Yu M and He L 2005 *SPIE* **5640** 637
[14] Yue F Y, Shao J, Lü X, Huang W, Chu J H, Wu J , Lin X C and He L 2006 *Appl. Phys. Lett.* **89** 021912
[15] Yue F Y, Chen L, Wu J, Hu Z G, Li Y W, Yang P X and Chu J H 2009 *Chinese Phys. Lett.* **26** 047804
[16] Herrmann K H, Mollmann K P and Tomm J W 1992 *J. Cryst. Growth* **117** 758
[17] Chu J H, Xu S C and Tang D Y 1983 *Appl. Phys. Lett.* **43** 1064
[18] Yue F Y, Wu J and Chu J H 2008 *Appl. Phys. Lett.* **93** 131909
[19] Grein C H, Garland J W, Sivananthan S, Wijewarnasuriya P S, Aqariden F and Fuchs M 1999 *J. Electron. Mater.* **28** 789
[20] Sun L Z, Chen X S, Zhao J J, Wang J B, Zhou Y C and Lu W 2007 *Phys. Rev.* B **76** 045219
[21] Elliott R J 1957 *Phys. Rev.* **108** 1384
[22] Hunter A T, Smith D L and McGill T C 1980 *Appl. Phys. Lett.* **37** 200
[23] Chang Y, Chu J H, Tang W G, Shen W Z, Li Z Y and Tang D Y 1995 *Acta Phys. Sin.* (Oversea Edition) **4** 606
[24] Dai N, Chang Y, Wang X G, Li B and Chu J H 2002 *Current Appl. Phys.* **2** 365
[25] Vydyanath H R and Hiner C H 1989 *J. Appl. Phys.* **65** 3080
[26] Ravid A and Zussman A 1990 *J. Appl. Phys.* **67** 4260
[27] Shi X H, Rujirawat S, Ashokan R, Grein C H and Sivananthan S 1998 *Appl. Phys. Lett.* **73** 638
[28] Wu J, Xu F F, Wu Y, Chen L,Yu M F and He L 2005 *J. Infrared Millim. Waves* **24** 81
[29] Kenworthy I, Capper P, Jones C L, Gosney J J G and Coates W G 1990 *Semicond. Sci. Technol.* **5** 854