TEM Investigation of Defects in Arsenic Doped Layers Grown In-situ by MBE

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A study concerning the effect of growth condition on As incorporation and formation of defects using transmission electron microscopy (TEM) is presented. It is well known that devices in a narrow bandgap HgCdTe material system could suffer from tunneling currents and generation recombination processes, especially at cryogenic temperatures, due to material defects. For in-situ As doped p-on-n device structures grown by molecular beam epitaxy (MBE), extended defects and in particular twinning in a p-type layer grown under Hg-rich conditions is believed to reduce the zero bias dynamic impedance of devices and significantly impact recombination of carriers in the space charge region. Using TEM we have studied defects formed in As-doped layers grown under Hg- and Te-rich conditions. Samples grown under high II/VI flux ratio at growth temperature of 170°C have a high density of columnar twin defects, whereas no twin defects were seen for layers grown under optimal growth conditions at 190°C. A very high flux of As, however, was required to incorporate As into the layers at growth temperature of 190°C.

Key words: HgCdTe, TEM, MBE, As incorporation

INTRODUCTION

Growth of $Hg_{1-x}Cd_xTe$ by molecular beam epitaxy (MBE) in the past few years has shown both the control and reproducibility required for fabrication of state-of-the-art infrared detectors. Although n-type doping using In is well established in MBE growth, inherent flexibility of the MBE process can be fully utilized after as-grown in-situ p-type doping is developed.[1,2] MBE allows precise control over the doping profile and position of heterojunctions as well as structural properties of the $Hg_{1-x}Cd_xTe$ ternary alloy. Advanced device structures such as n-p-n dual band two-color and p-i-n double heterostructure detectors,[3] double heterostructure and multiple quantum well graded index separate confinement lasers,[4] and state-of-the-art focal plane arrays over a broad spectral range have been demonstrated using MBE material.[5] Elements such as Ag, Au, Sb, Bi, and P have been used previously for p-type doping.[1–7] However, the high diffusion coefficient and amphoteric behavior of these atoms in HgCdTe have restricted their use in heterojunction devices where control over doping profiles and carrier concentrations is needed.[1–9] Currently, As is used routinely to obtain extrinsic p-type conductivity in HgCdTe by various growth techniques, and several studies have reported on p-type doping of HgCdTe using As.[1,3] However, in-situ incorporation of As in the 10^{17} to 10^{19} cm^{-3} range in alloy of $Hg_{1-x}Cd_xTe$ ($0.2 < x < 0.4$) at ideal MBE growth temperature (i.e., 185–190°C) requires Hg-rich conditions or a very high flux of As. Growth using MBE Hg-rich conditions is known to promote defect formation and reduce the crystalline quality of the grown epilayer.[1,6,8] We report on transmission electron microscopy (TEM) investigation of defects introduced during in-situ doping with As in $Hg_{1-x}Cd_xTe$ using elemental As and growth conditions that promote defect formation.

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EXPERIMENTAL PROCEDURES

The epilayers were grown in a RIBER 2300 MBE system. See Refs. 1–6 for a detailed discussion of MBE HgCdTe growth procedures. The in-situ As doped P-on-n heterostructure is shown in Fig. 1. The indium doped n-type absorber layers were grown at 190°C on near lattice-matched (211)B $Cd_{0.96}Zn_{0.04}Te$ substrates to minimize the dislocation density. The p-type single

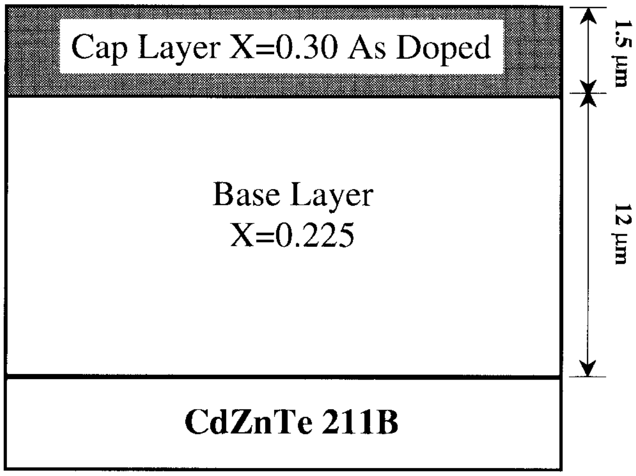


Fig. 1. Schematic diagram of an in-situ As doped p-on-n heterostructure.

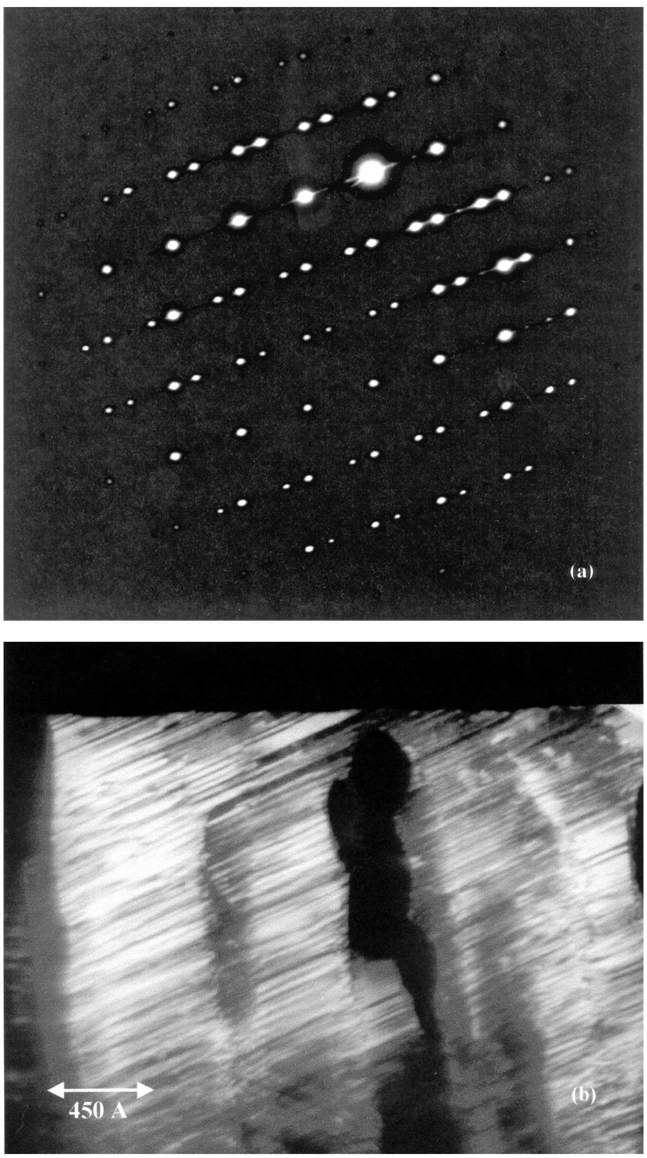


Fig. 2. (a) Electron diffraction pattern, and (b) electron diffraction contrast micrograph viewed from $[\bar{1}\bar{1}1]$ plane of an As doped layer grown at reduced growth temperature of 170°C under Hg-rich growth condition, showing high density of columnar twin defects. Layer 1-884.

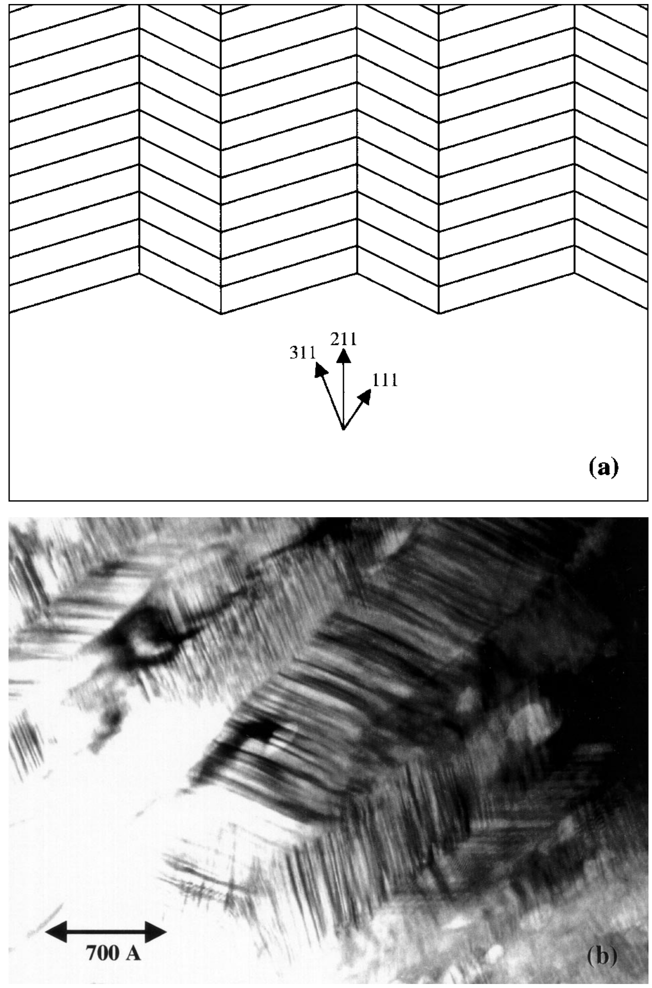


Fig. 3. Electron diffraction contrast micrograph viewed from $[\bar{1}\bar{1}1]$ plane of an As-doped layer grown at reduced growth temperature 170°C under very high II/VI flux ratio. Layer 1-883.

layers were grown at 170°C or 190°C and annealed at 300°C followed by an isothermal annealing at 250°C in Hg to annihilate Hg vacancies. Layers were characterized using a Nicolet Fourier transform infrared transmission system to determine the composition and layer thickness. Cross-sectional TEM specimens were prepared by thinning samples to 75 µm, and final thinning was achieved by using Ar^+ ion milling cooled with liquid nitrogen. Ion milling was performed using an incident angle of 12° with accelerating voltage of 5 KeV and beam current of 0.25 mA. Finally, 100 Å of polycrystalline carbon was evaporated on samples to reduce heating from electron irradiation. TEM investigations were performed using a Philips 420 transmission electron microscope.

RESULTS AND DISCUSSION

An electron diffraction contrast image of an As-doped layer grown at a reduced growth temperature of 170°C under high II/VI flux ratio (i.e., Hg rich growth) to promote incorporation of arsenic is shown in Fig. 2. Figure 2a shows near [011] zone axis electron diffraction pattern with $[\bar{1}\bar{1}1]$ twining. A high density of columnar twin defects is viewed from the

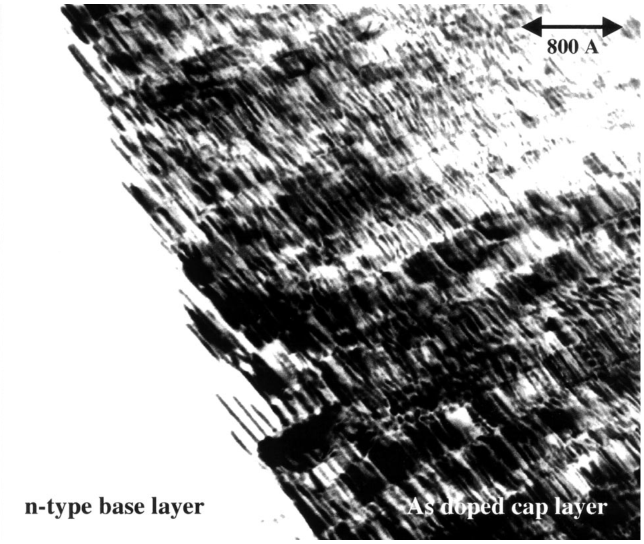
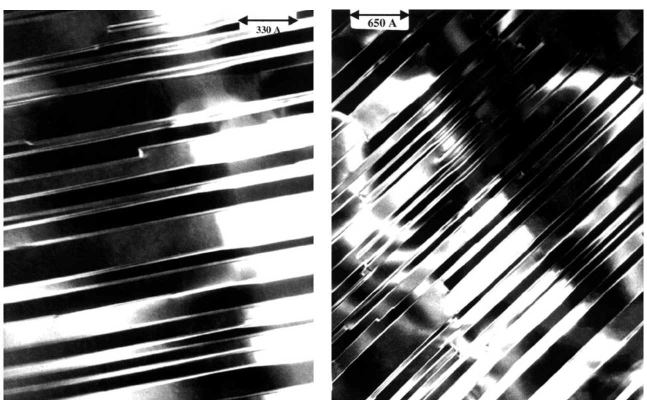


Fig. 4. TEM cross-section micrograph of an As-doped P-on-n double layer. Note that the cap As-doped layer was grown at 170°C under Hg-rich growth condition and shows high density of columnar twin defects, whereas n-type absorber layer grown under Te-rich condition is free of defects. Layer 1-884.



a b

Fig. 5. Cross-section image of an As-doped layer grown at reduced growth temperature of 170°C under Hg-rich growth condition. Viewed from [11$\bar{1}$] plane, (a) layer 1-884, and (b) layer 1-881.

[$\bar{1}\bar{1}$1] plane. At highest II/VI flux ratio used for growth of these samples, as shown in Fig. 3, layers exhibit double positioning (DP) twin defects, defined as a twin with the symmetry operator perpendicular to the twin boundary.[8] Notice that we have observed DP twining and faceting on both of two samples grown under very high II/VI flux ratios. Thus, double position twinning is the mode of growth under high II/VI flux ratio. However, the base layer absorber layer grown at 190°C under normal Te-rich growth conditions is free of twin defects as shown in Fig. 4. Cross section dark field TEM micrographs of the As doped region at higher magnifications are shown in Fig. 5a and b revealing the high density of twin defects. Preliminary analysis of partial dislocations for each twin boundary and their equilibrium separation indicates an average separation of about 180 Å. A surface study of As-doped layers grown at the low temperature of 170°C under high II/VI flux ratio revealed surface features oriented in one direction. Optical picture and scanning electron microscope (SEM) images of the needle shape defects are shown in Fig. 6a and b. These defects are related to a high density of twins in these layers. Densities in the range of 10^4 to 10^6 cm^{-2} of such defects were observed in all samples grown under high II/VI flux ratio. They are about 5 μm in length and less than 0.3 μm wide. They are all oriented in the same $<01\bar{1}>$ direction with a microcrack seen at higher magnifications at the center of each defect. The density of these microdefects is a very strong function of II/VI flux ratio and is inversely proportional to growth temperature as shown in Fig. 7.

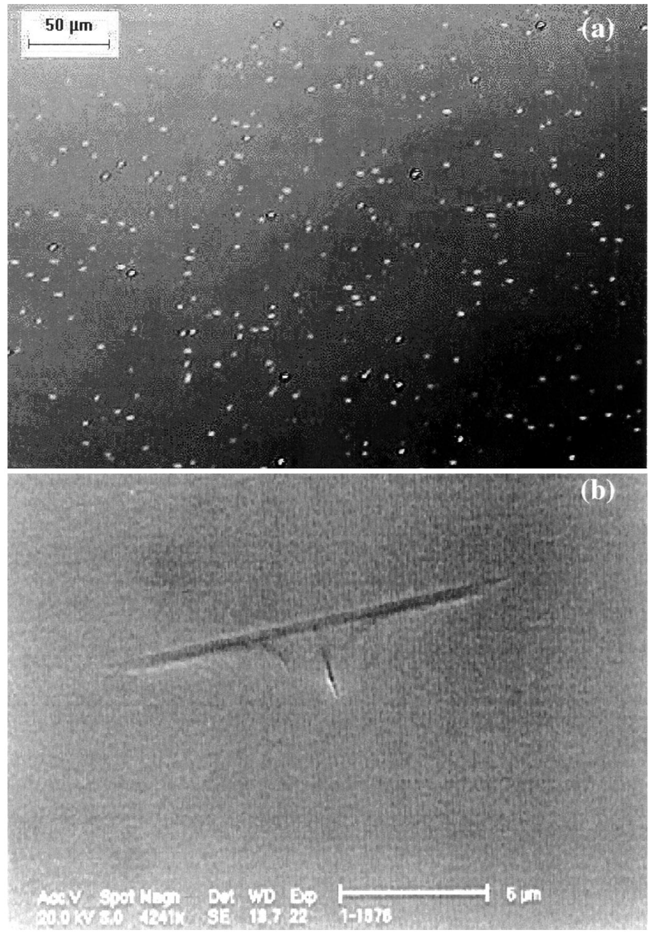


Fig. 6. (a) Normarski optical surface image of an As-doped layer grown at 170°C under Hg-rich growth condition showing high density of twin defects. (b) scanning electron microscope image of a needle shape defect. Layer 1-883.

To grow high quality As-doped alloy layers of HgCdTe free of twin defects we increased the growth temperature to 190°C and reduced the II/VI flux ratio and obtain twin free defect layers. However, to incorporate As into the alloy layers of HgCdTe and overcome very low sticking coefficient of As under Te-rich growth conditions, the As flux must be increased substantially.[1] We have previously published the details and results of growth and As activation for layers grown under Te-rich conditions.[1] Here we show TEM pictures of As-doped epilayers grown under Te-rich growth conditions at 190°C without growth interrup-

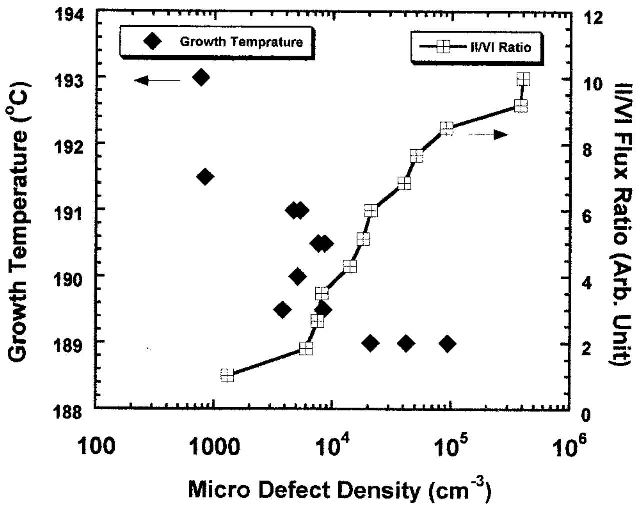


Fig. 7. Micro defect density as a function of growth temperature and II/VI flux ratio.

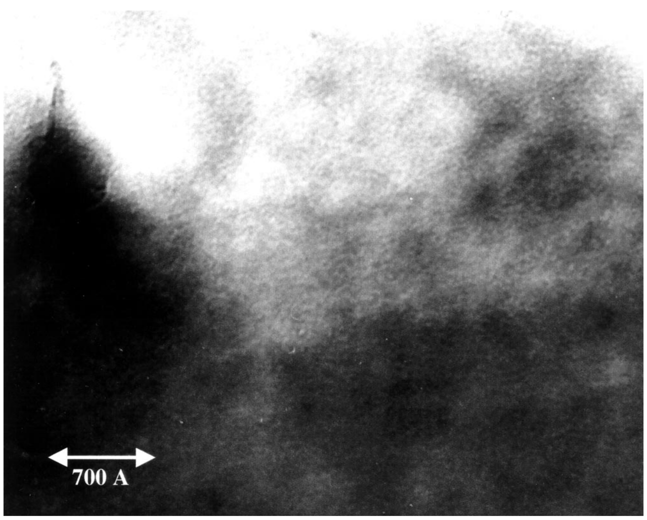


Fig. 8. Electron diffraction contrast micrograph of an As-doped layer grown at normal growth temperature of 190°C under Te-rich growth conditions. The sample is free of twin and other structural defects. Layer 1-965.

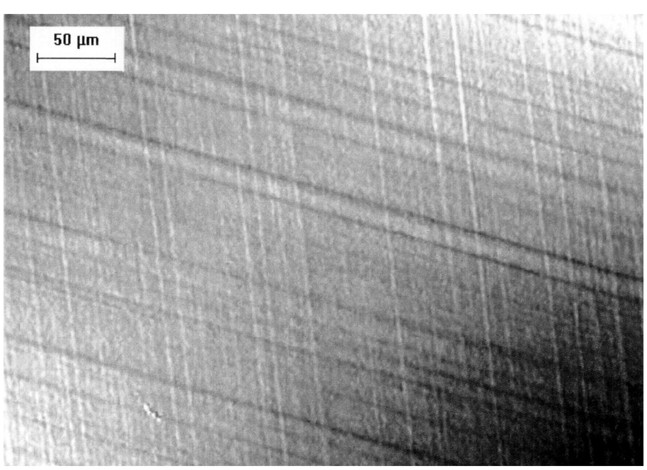


Fig. 9. Normarski optical surface image of an As-doped layer grown at normal growth temperature of 190°C under Te-rich growth conditions. Surface morphology is smooth and free of any surface feature. Layer 1-965.

tion between the base n-type layer and the cap p-type layer. An electron diffraction contrast image of an As-doped layer grown at a typical growth temperature of 190°C under low II/VI flux ratio (i.e., Te-rich growth) and a high flux of arsenic is shown in Fig. 8. TEM analysis was performed on [011] and [111] planes to observe twin defects directly, and no twin defects were observed in our analysis. Layers grown under Te-rich conditions exhibited high structural quality, as indicated also by low etch pit density values in the 10^4–10^5 cm^{-2} range. Surface study using optical microscopy shown in Fig. 9 reveals high structural quality, free of needle shapes and other defects. By increasing the As flux, high concentrations of As in the 10^{16} to 10^{18} cm^{-3} range can be readily incorporated into the layers, and for samples grown under Te-rich growth condition, full activation of As can be achieved by annealing at 300°C.[1]

SUMMARY

The growth of p-type layers doped with As at low temperatures requires optimization of II/VI flux ratio to reduce the density of columnar twin defects. It is possible, however, to incorporate As at a normal MBE growth temperature of 190°C, but very high flux of As is required to overcome lower sticking coefficient of As at high temperatures. No twinning was observed by TEM analysis for As doped layers grown under such conditions, and uninterrupted growth of p-on-n structures free of twins in p-type layer and interfacial defects due growth interruption is possible. For samples grown at low temperature and Hg-rich conditions high concentration of twin defects was observed by TEM analysis.

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REFERENCES

1. M. Zandian, A.C. Chen, D.D. Edwall, J.G. Pasko, and J.A. Arias, *Appl. Phys. Lett.* 71, 19 (1997).
2. O.K. Wu, D.N. Jamba, and G.S. Kamath, *J. Cryst. Growth* 127, 365 (1993).
3. C.H. Grein, J.W. Garland, S. Sivananthan, P.S. Wijewarnasuriya, F. Aqariden, and M. Fuchs, *J. Electron. Mater.* 28, 789 (1999).
4. M. Zandian, J.M. Arias, R. Zucca, R.V. Gil, and S.H. Shin, *Appl. Phys. Lett.* 59, 1022 (1991).
5. J.M. Arias, *Properties of Narrow Gap Cadmium-based Compounds*, ed. P. Capper (EMIS Data review Series No. 10, 1994), p. 30.
6. O.K. Wu, G.S. Kamath, W.A. Radford, P.R. Brat, and E.A. Patten, *J. Vac. Sci. Technol. A* 8, 1034 (1990).
7. S. Sivananthan, P.S. Wijewarnasuriya, F. Aqaridan, J.P. Faurie, H.R. Vydyanath, M. Zandian, D.D. Edwall, and J. M. Arias, *J. Electron. Mater.* 26, 621 (1997).
8. K. Shigenaka, L. Sugiura, F. Nakata, and K. Hirahara, *J. Electron. Mater.* 22, 865 (1993).
9. P.S. Wijewarnasuriya, I.K. Sou, J. Kim, K.K. Mahavadi, S. Sivananthan, M. Boukerche, and J.P. Faurie, *Appl. Phys. Lett.* 51, 2045 (1987).