Annealing effects on the microstructural and optical properties of $Hg_{0.7}Cd_{0.3}Te$ epilayers grown on CdTe buffer layers

Y. S. RYU, T. W. KANG*
Quantum-Functional Semiconductor Research Center and Department of Physics, Dongguk University, 3-26, Pildong, Chungku, Seoul 100-715, Korea
E-mail: twkang@donguk.edu

T. W. KIM
Advanced Semiconductor Research Center, Division of Electrical and Computer Engineering, Hanyang University,17 Haengdang-dong, Seongdong-gu, Seoul 133-791, Korea

n- and *p*-type $Hg_xCd_{1-x}Te$ epilayers have many potential applications, such as infrared detectors, infrared photovoltaic detectors, and infrared focal-plane technologies [1–3]. Even though $Hg_xCd_{1-x}Te$ epitaxial films at high temperatures have been grown by using liquid-phase epitaxy and metalorganic chemical vapor deposition methods for many years [4, 5], interdiffusion or intermixing problems have occurred due to possible cross-doping effect. Recently, *p*-type $Hg_xCd_{1-x}Te$ epitaxial films were grown at low temperature by using an *in-situ* doping process utilizing molecular beam epitaxy [6]. However, high carrier concentrations have not been consistently achieved in *p*-type $Hg_xCd_{1-x}Te$ epilayers grown by using *in-situ* doping [7]. Even though some work concerning the formation of *p*-type $Hg_xCd_{1-x}Te$ epilayers through *in-situ* annealing has been performed [8, 9], ZnTe or ZnSe capping layers were used to avoid surface degradation. Since the growth of capping layers on $Hg_xCd_{1-x}Te$ epilayers is a complicated process, the formation of *p*-type $Hg_xCd_{1-x}Te$ epilayers of high quality and without any capping layer by using *in-situ* annealing is still necessary. Since the electrical, microstructural, and optical properties of $Hg_xCd_{1-x}Te$ epilayers significantly affect the quality of high efficiency devices, studies of the physical properties of $Hg_xCd_{1-x}Te$ epilayers are indispensable when attempting to understand the performance of optoelectric devices based on $Hg_xCd_{1-x}Te$ epilayers. Furthermore, since thermal treatment is necessary for the fabrication of optoelectronic devices utilizing $Hg_xCd_{1-x}Te$ epilayers, the role of the thermal annealing is very important in achieving high-performance devices [9]. Therefore, studies of *in-situ* annealing effects on the electrical, microstructural, optical properties play a very important role in enhancing efficiency.

This letter reports the effect of *in-situ* annealing on the electrical, microstructural, and optical properties of $Hg_xCd_{1-x}Te$ thin films which were grown by using molecular beam epitaxy (MBE), utilizing CdTe buffer layers on GaAs substrates. The carrier concentration and the mobility of the as-grown and the *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers were investigated by using Hall-effect measurements. Selected area electron diffraction pattern (SADP) and transmission electron microscopy (TEM) measurements were performed to characterize the microstructural properties of the as-grown and the *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ thin films. Fourier transform infrared (FTIR) measurements were carried out in order to investigate the optical properties.

The samples used in this study were grown on undoped semi-insulating GaAs (211) B-oriented substrates by using MBE in a facility with a Riber 32P MBE chamber for the growth of $Hg_xCd_{1-x}Te$ active layers and CdTe buffer layers. The GaAs substrates were degreased in warm trichloroethylene (TCE), etched in a mixture of H_2SO_4, H_2O_2, and H_2O (5:1:1) at 40 °C for 1 min, and rinsed in deionized water thoroughly. As soon as the chemical cleaning process was finished, the GaAs substrates were mounted onto a molybdenum holder. After the GaAs substrates had been thermally cleaned at 200 °C for 2 h in the introduction chamber, they were transferred into the growth chamber. The deposition of a 12-μm-thick $Hg_{0.7}Cd_{0.3}Te$ active layer onto a 5-μm-thick CdTe buffer layer, which had been grown at 200 °C, was carried out at a substrate temperature of 190 °C, and its growth rate was approximately 8.3 Å/s. After intentionally doped *n*-type $Hg_xCd_{1-x}Te$ epilayers had been grown, *in-situ* annealing was performed in the MBE growth chamber. The thermal annealing process was performed in a Hg atmosphere at a pressure of 8.5×10^{-4} Torr for 60 min at a temperature of 250 °C.

The Hall-effect measurements were performed at a temperature of 77 K in a magnetic field of 3200 G by using a Keithley 181 nanovoltmeter. Ohmic contacts to the samples for the Hall-effect measurements were made by diffusing a small amount of indium through the $Hg_{0.7}Cd_{0.3}Te$ layer at 150 °C in a hydrogen atmosphere for approximately 10 min. TEM measurements were performed using a JEOL JEM 3010 transmission electron microscope operating at 300 keV. The samples for cross-sectional TEM measurements were prepared by cutting and polishing with diamond paper to a thickness of approximately 30 μm and then argon-ion milling at liquid-nitrogen temperature to electron

* Author to whom all correspondence should be addressed.

DOI: 10.1007/s10853-005-4393-2

TABLE I Carrier types, carrier concentrations, and mobilities for as-grown and annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers grown on CdTe buffer layers at 77 K

Sample condition			Electronic parameter		
Annealing temperature ( )	Hg-cell flux pressure (Torr)	Annealing time (min)	Carrier type	Carrier concentration (cm^{-3})	Mobility (cm^2/V.s)
As-grown			*n*	-2×10^{15}	30,100
350	8.5×10^{-4}	60	*p*	$+8 \times 10^{15}$	488

transparency. The FTIR measurements were performed with a Bio-Rad far-infrared spectrometer.

The carrier types, carrier concentrations, and mobilities obtained from the Hall-effect measurements at 77 K on as-grown and annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers are summarized in Table I. The as-grown *n*-$Hg_{0.7}Cd_{0.3}Te$ epilayers were converted to *p*-$Hg_{0.7}Cd_{0.3}Te$ epilayers by *in-situ* annealing.

The bright-field TEM image of as-grown and *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers grown on CdTe buffer layers showed that each layer had no microcracks and defects and that the $Hg_{0.7}Cd_{0.3}Te$/CdTe heterointerface had an relatively interfacial abruptness. The SADPs from the TEM measurements on (a) as-grown and (b) *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers grown on CdTe buffer layers are shown in Fig. 1. While regular strong spots, together with irregular and diffused spots, were observed for the as-grown $Hg_{0.7}Cd_{0.3}Te$ epilayers, as shown in Fig. 1a, only regular strong spots with a single pattern occurred in the *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayer, as shown in Fig. 1b. The SADP of the Fig. 1a shows that the as-grown $Hg_{0.7}Cd_{0.3}Te$ epilayers contains stacking faults or misfit dislocations. However, the SADP for the *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers depicts that there are no stacking faults and misfit dislocations in the *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers. Since the structural property of the *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epitaxial layer grown on the CdTe buffer layer is improved by thermal annealing, only regular spots around (000) with perfect circles occurs.

Fig. 2 shows a high-resolution TEM (HRTEM) image of the (a) as-grown and the (b) *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ thin films. The HRTEM image of the as-grown $Hg_{0.7}Cd_{0.3}Te$ thin film indicates the presence of misfit dislocations resulting from the lattice mismatch between the $Hg_{0.7}Cd_{0.3}Te$ epilayer and the CdTe buffer layers. The appearance of stacking faults in the $Hg_{0.7}Cd_{0.3}Te$ thin film might originate from the exis-

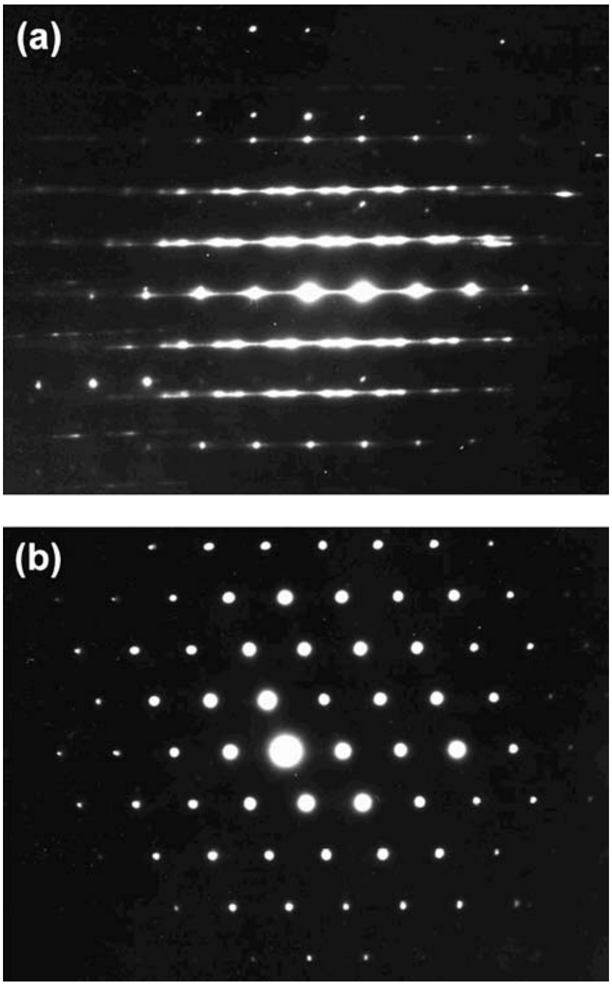

Figure 1 Electron diffraction pattern from transmission electron microscopy of the (a) as-grown and (b) *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers grown on CdTe buffer layers.

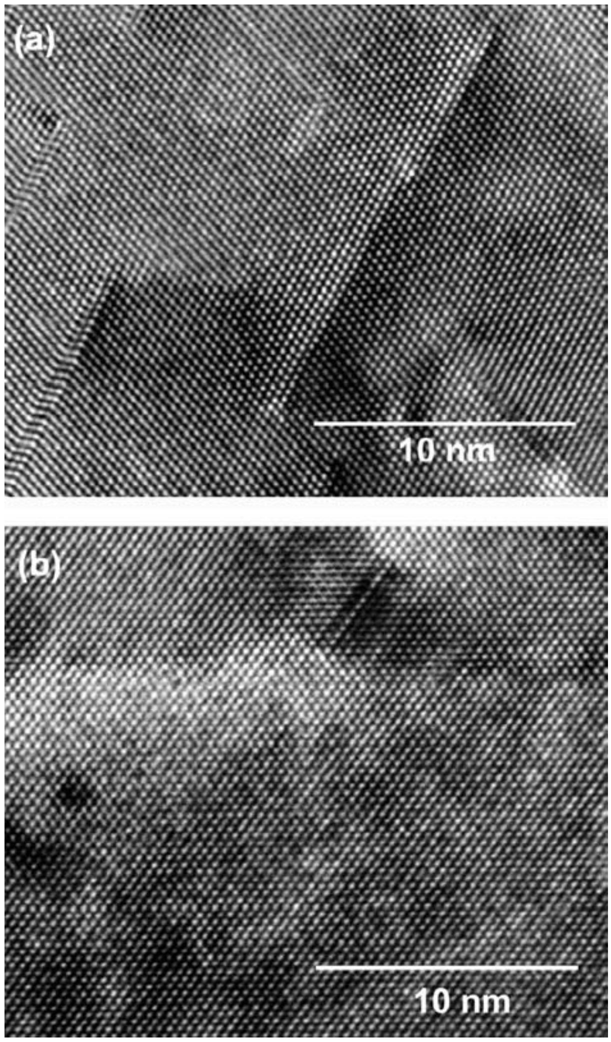

Figure 2 High-resolution transmission electron microscopy of the (a) as-grown and the (b) *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ thins film grown on CdTe buffer layers.

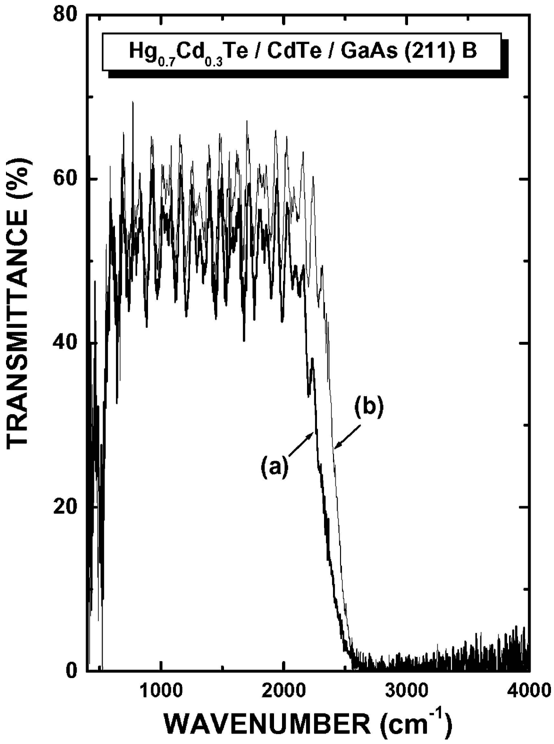

Figure 3 Fourier transform infrared transmission spectra for the (a) as-grown and the (b) *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers grown on CdTe buffer layers.

tence of a large number of Hg vacancies. The number of misfit dislocations and stacking faults in *in-situ* annealed $Hg_{0.7}Cd_{0.3}Te$ is much smaller than it is in the as-grown $Hg_{0.7}Cd_{0.3}Te$. The SADP and the high-resolution TEM images indicate that the microstructural qualities of the $Hg_{0.7}Cd_{0.3}Te$ epilayers are improved by thermal annealing.

Fig. 3 shows the results of the FTIR spectra for (a) as-grown and (b) annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers. After thermal treatment, the transmittance intensity of the FTIR spectrum is increased. The increase in the transmission intensity is due to an increase in the number of Hg vacancies being passivated by the Hg atoms. Since the cutoff region in the spectrum of the annealed $Hg_xCd_{1-x}Te$ epilayers is more abrupt than it is in the spectrum of the as-grown epilayer, the variation with the composition Hg is expected to be small, which was verified by energy-dispersive X-ray fluorescence measurements.

In summary, the results of Hall-effect measurements showed that as-grown *n*-type $Hg_{0.7}Cd_{0.3}Te$ epilayers were converted to *p*-type $Hg_{0.7}Cd_{0.3}Te$ epilayers by *in-situ* annealing. The results of the TEM measurements on annealed $Hg_{0.7}Cd_{0.3}Te$ epilayers grown on CdTe buffer layers in a Hg atmosphere flux of 8.5×10^{-4} Torr at 250 °C for 1 h showed that the microstructural quality of the $Hg_{0.7}Cd_{0.3}Te$ films was improved by *in-situ* thermal annealing. The results of the FTIR measurements showed that the transmittance intensity at the absorption edge increased after annealing. These results can help improve understanding of *in-situ* thermal effects on the electrical, the microstructural, and the optical properties of $Hg_{0.7}Cd_{0.3}Te$ thin films grown on CdTe buffer layer.

Acknowledgement

This work was supported by the Korea Science and Engineering Foundation through the Quantum-functional Semiconductor Research Center at Dongguk University.

References

1. M. D. LANGE. S. SIVANATHAN, X. CHU and J. P. FAURIE, *Appl. Phys. Lett.* **52** (1988) 978 .
2. T. SASAKI and N. ODA, *J. Appl. Phys.* **78** (1995) 3121.
3. T. J. DE LYON, D. R. RAJAVEL, J. A. VIGIL, J. E. JENSEN, O. K. WU, C. A. COCKUM, S. M. JOHNSON, G. M. VENZOR, S. L. BAILEY, I. KASAI, W. L. AHIGREN and M. S. SMITH, *J. Electron. Mater.* **27** (1998) 550.
4. M. S. HAN, T. W. KANG, M. D. KIM, Y. T. JEOUNG, H. K. KIM, J. M. KIM, H. J. WOO and T. W. KIM, *Appl. Surf. Sci.* **120** (1997) 287.
5. J. S. GOUGH, M. R. HOULTON, S. J. C. IRVINE, N. SHAW, M. L. YOUNG, and M. G. ASTLES, *J. Vac. Sci. Technol.* B **9** (1991) 687.
6. M. S. HAN, T. W. KANG and T. W. KIM, *J. Mater. Res.* **14** (1998) 2778.
7. T. C. HARMAN, *J. Electron. Mater.* **8** (1989) 191.
8. G. L. DESTEFANIS, J. CRYSTAL GROWTH **86** (1998) 700.
9. L. HE, S. L. WANG, J. R. YANG, M. F. YU, Y. WU, X. Q. CHEN, W. Z. FANG, Y. M. QIAO, YONGSHENG GUI and JUNHAO CHU, *J. Crystal Growth* **201/202** (1999) 524.
10. S. M. SZE, "VLSI Technology" (McGraw-Hill, New York, 1988).

Received 18 November 2003
and accepted 10 February 2005