Molecular-beam epitaxy growth and magnetic properties of BeTe with Cr doping

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We report the growth and magnetic properties of BeTe with Cr doping grown on GaAs(001) substrate at Te-rich condition by solid-source molecular-beam epitaxy. Ferromagnetisms were observed for films with high Cr concentration, x. The Curie temperatures $T_C$ for $x=0.13$ and $x=0.17$ are $175\pm5$ K, while the $T_C$ for $x=0.27$ is $250\pm5$ K. Structural properties were studied by in situ reflection high-energy electron diffraction, atomic force microscopy, and x-ray diffraction. Be$_{1-x}$Mn$_x$Te and Cr$_{1-x}$Te films were also grown and compared with the Be(Cr)Te films. We show that the ferromagnetic ordering of Be(Cr)Te films can be attributed to precipitations of NiAs Cr$_{1-x}$Te. © 2006 American Institute of Physics. [DOI: 10.1063/1.2168434]
become modulated in intensity [see Fig. 1(a)]. When \( x > 0.05 \), a bright \((1 \times 1)\) spotty pattern was observed immediately after the Cr shutter was opened. The stacking fault lines were also observed at high \( x \), as shown by the crosses observed in Fig. 1(b). However, for Be\(_{1-x}\)Mn\(_x\)Te, \((2 \times 1)\) streaky patterns were still clearly observed when \( x = 0.03 \) (not shown here).

No hysteresis was observed in the field-dependent magnetization \((M-H)\) curves obtained at 5 K for Be(Cr)Te films with \( x < 0.13 \). Hysteresis curves were observed only for films with \( x = 0.13, 0.17, \) and 0.27, as shown in the insets of Fig. 2, which indicates clearly the FM ordering. From the temperature-dependent magnetization \((M-T)\) curves shown in Fig. 2, \( T_c \approx 175 \pm 5 \) K was obtained for films with \( x = 0.13 \) and 0.17. For \( x = 0.27 \), we obtained a hysteresis loop with large coercive field at 5 K and the \( T_c \approx 250 \pm 5 \) K. We notice that the coercive field and \( T_c \) for the samples with different Cr compositions (\( x = 0.13 \) and 0.17) have very close values. This in principle indicates the presence of secondary phases with the same composition in both samples. The increase of magnetization with increasing temperature below 25 K in Figs. 2(b) and 2(c) suggests the presence of the antiferromagnetic ordering as well. This behavior can be explained by a change from a canted FM structure to a collinear FM structure, which had also been observed in Cr\(_{1-x}\)Te.\(^7\)

Atomic force microscopy images (not shown here) reveal that the Cr doping roughened the surface. The root-mean-square (rms) roughness increases from 0.65 nm (\( x = 0 \)) to 4.30 nm (\( x = 0.27 \)) with increasing \( x \), which correlates well with the RHEED observations. Films with rms > 1.5 nm are all FM. Based on Vegard’s law [using the lattice constants, \( a = 5.6269 \) Å for BeTe (Ref. 8) and \( a = 6.2920 \) Å for hypothetical zinc-blende CrTe (Ref. 9)], the full lattice match with GaAs(001) is found to be at \( x \approx 0.04 \). We would thus expect the crystal quality to become better with increasing \( x \) up to 0.04. Figure 3 shows the (002) diffraction peaks of Be(Cr)Te as well as GaAs substrates. Unlike the Be\(_{1-x}\)Mn\(_x\)Te film, where the peak shift indicates that substitutional Mn was observed, there is almost a negligible peak shift with \( x = 0.035 \) in Be(Cr)Te film (see Fig. 3 and the inset). When \( x > 0.035 \), the (002) peak in \( \theta-2\theta \) HRXRD scan decreases in intensity and the peak broadens. This suggests that the solubility limit of Cr in BeTe is very low and the Cr atoms were not able to be incorporated substitutionally. Thus the Cr atoms may have gone into interstitial sites or precipitated out. But the \( \theta-2\theta \) scan did not reveal any secondary phases except BeTe within the detectable limits. We note that HRXRD may not be sensitive enough to detect the precipitates when the amount is very little or when they are amorphous.

As shown in the \( M-T \) curves in Fig. 4, Cr\(_{1-x}\)Te films grown with different Cr/Te flux ratios are FM. The \( T_c \) in-
from Cr$^{1-\delta}$Te films with a metal-deficient NiAs structure are ferromagnets with $T_C$ ranging from 175 to 340 K with increasing Cr/Te flux ratio. Cr$_{1-\delta}$Te films with Cr/Te flux ratios of 0.10, 0.45, and 1.08 give $T_C$ of about 175, 265, and 340 K, respectively. The $T_C$ of ~175 K obtained from the Cr$_{1-\delta}$Te films with a flux ratio of 0.10 is almost the same as that obtained from our samples with $x=0.13$ and 0.17, while the $T_C$ of ~265 K obtained from Cr$_{1-\delta}$Te films with a flux ratio of 0.45 is very close to that of our sample with $x=0.27$. It is known that Cr$_{1-\delta}$Te with a metal-deficient NiAs structure are ferromagnets with metallic conductivity, with $T_C$ ranging from 170 to 360 K.$^{10-12}$ Among these, only Cr$_3$Te$_3$ ($\delta=0.333$) has $T_C$ from 170 to 180 K,$^{11}$ and Cr$_5$Te$_8$ ($\delta=0.375$) is known to have a $T_C$ of 245 K.$^{12}$ Therefore, the FM properties observed in the Be(Cr)Te films are very likely due to the formation of these FM Cr$_{1-\delta}$Te NiAs phases, namely, Cr$_2$Te$_3$ for $x=0.13$ as well as $x=0.17$, and Cr$_3$Te$_8$ for $x=0.27$. The fact that the $T_C$ of Cr$_{1-\delta}$Te films strongly depends on the Cr composition shows that a scaling of $T_C$ vs $x$ may not be a conclusive piece of evidence for a pure DMS, particularly for highly Cr-doped ZnTe.

**IV. CONCLUSIONS**

In conclusion, BeTe with Cr doping were grown by MBE on GaAs(001) and the effect of Cr doping on the structural and magnetic properties was studied. We have also compared its properties with Be$_{1-\delta}$Mn$_x$Te and Cr$_{1-\delta}$Te films grown by MBE. For BeTe with low Cr concentration ($x < 0.13$), no ferromagnetism was observed. Films with $x=0.13$ and 0.17 are FM with $T_C=175 \pm 5$ K, while films with $x=0.27$ are FM with $T_C$ of 250 $\pm 5$ K. Be(Cr)Te and Cr$_{1-\delta}$Te films show similar behaviors in our magnetization results. This result together with the degraded crystal quality observed suggested the formation of FM Cr$_{1-\delta}$Te secondary phases. This also calls into question the origin of ferromagnetism reported in Zn$_{1-\delta}$Te. We also found that, unlike Mn, Cr atoms were difficult to be incorporated substitutionally into BeTe lattices and thus its solubility limit in BeTe is very low.

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