Dependence of structure and magnetic properties on magnetic field and temperature for Bi-Mn alloy

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The effects of magnetic field and temperature on structure and magnetic properties of *BiMn* compound were investigated. The microstructure showed that *MnBi* (low temperature phase, LTP) in *Bi*-wt.6%*Mn* alloys are all aligned, with the *c*-axis of the *MnBi* (LTP) crystal along the fabrication magnetic field $\boldsymbol{H_f}$. $\boldsymbol{H_f}$ explicitly improves the magnetic anisotropy. Magnetic measurements indicated that the *MnBi* (LTP) saturation magnetization M_s and its coercive field H_c change with the temperature. Most of all, the temperature of spin-reorientation increased with the increasing $\boldsymbol{H_f}$ but decreased with the increase of the measuring magnetic field $\boldsymbol{H_m}$.

INTRODUCTION

Owing to the high uniaxial magnetic anisotropy of its low-temperature phase (LTP) and the good magneto-optical properties of its quenched high-temperature phase (QHTP), the physical properties of the binary compound *MnBi* have been investigated extensively [1~6]. With the development of and the advance of superconducting magnet technologies, a high magnetic field has being operated in various academic fields such as material science and physics [7,8]. Currently, the physics of high field-induced transition is among the most interesting problems in condensed matter physics [9~11]. In order to investigate the effect of magnetic field and temperature on structure and magnetic properties of *MnBi* compound, we fabricated, in different fabrication magnetic field $\boldsymbol{H_f}$, *Bi*-wt.6%*Mn* alloys. Effects of $\boldsymbol{H_f}$ on structure of *Bi*-wt.6%*Mn* alloys have been reported elsewhere [12]. Here, we mainly report magnetization study of the alloy *Bi*-wt.6%*Mn*, of which *MnBi*(LTP) reveal a spin-reorientation transition (SRT) at about 90K. The research results show that the magnetic field $\boldsymbol{H_f}$ explicitly improves the specimen's magnetic anisotropy. Specifically, we find that dc magnetic fields, $\boldsymbol{H_f}$ and the measuring magnetic field $\boldsymbol{H_m}$, result in different temperatures of SRT.

EXPERIMENTAL PROCEDURE

Details of experimental techniques are in previous papers [12], and thus only a brief outline of this procedure is presented here. The sample was sealed in a graphite tube and inserted into a resistance furnace, which was placed between poles of the electromagnet. The intensity of the magnetic field between poles of the electromagnet can be adjusted and the temperature in the furnace chamber can be controlled automatically during the experiment. Since the liquidus temperature of *Bi*-6wt%*Mn* alloy is above 630K, the alloy is in a semi-solid state at 548K. The alloy was heated up to the temperature in the mushy zone without the magnetic field, held for 30min and then cooled to the temperature below 535K under various fabrication magnetic fields $\boldsymbol{H_f}$ of 0.0T, 0.3T and 0.5T, respectively. For characterizing the morphology of the *MnBi* phase, the samples obtained in the experiments were mechanically polished parallel and perpendicular to the $\boldsymbol{H_f}$ direction. The following *No*.1, *No*.2 and *No*.3 samples denote the samples solidified in the fabrication magnetic fields $\boldsymbol{H_f}$ of 0.0T, 0.3T and 0.5T, respectively. The samples were characterized for their structures by optical microscopy, SEM and XRD. Magnetic measurements were performed with $\boldsymbol{H_m}$ up to 9T in a temperature range from 1.9 K to 300K using PPMS.

RESULTS AND DISCUSSION

In the case of solidification with the field, the elongated *MnBi* crystals were oriented and grew preferentially along the applied field in the *Bi* matrix. The hexagonal sections of the crystals only appeared in the section perpendicular to the field. Furthermore, the XRD patterns showed that the *c*-axis of hexagonal *MnBi* crystal (easy magnetization axis) was aligned parallel to the $\boldsymbol{H_f}$ direction, and peaks for *Bi* and *MnBi*(LTP) could only be observed [12]. The XRD results and EDX analysis indicated the formation of *MnBi*(LTP) (approximately 28.656wt.%) and *Bi* phase. By comparison with magnetic powders aligned in a magnetic field in an epoxy resin to form a bonded magnet [5], our method has a prominent feature that *MnBi*(LTP) not only is aligned along the *c*-axis, but also grew preferentially and congregated along the $\boldsymbol{H_f}$ direction. Because *Bi* is diamagnetic, its effect has been ignored and only *MnBi*(LTP) has been considered in the magnetization measurement. The *MnBi* crystals observed in the microstructure micrographs were randomly oriented in the *Bi* matrix in the sample crystallized without the magnetic field (for the *No*.1 sample).

Figure 1 presents the magnetizations of the *No*.3 specimen parallel to and normal to *c*-axis direction at 150K and 300K for the *No*.3 specimen solidified in $\boldsymbol{H_f}$=0.5T. When the field is parallel to the *c*-axis, the saturation occurs much more easily compared with the field perpendicular to the *c*-axis. The anisotropy fields in *MnBi*(LTP) at 150K and 300K are about 2.5T and 5T, respectively. It can be assumed that there is a very strong anisotropy in the *MnBi*(LTP) compound and the anisotropy field of *MnBi*(LTP) increases with the increasing temperature. Shown in Figure 2 is saturation magnetization M_s and the coercive field H_c of *BiMn*(LTP) compound along the *c*-axis for the *No*.3 specimen at various temperatures. It is apparent from this graph that M_s decreases with the increase of temperature, and H_c decreases with the temperature less than 150K but increases with the temperature above 150K. M_s of *BiMn*(LTP) compound in the *No*.3

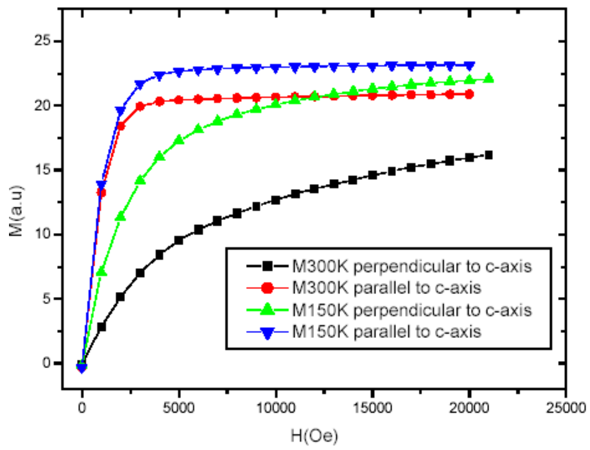

Figure 1 Magnetizations of *MnBi* (LTP) compound parallel to and perpendicular to *c*-axis direction at 150K and 300K for the *No*.3 sample.

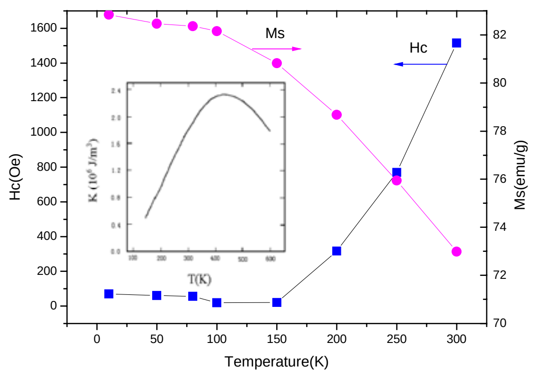

Figure 2 M_s and H_c of *MnBi* (LTP) along the *c*-axis at various temperatures for the *No*.3 sample. Inset: Anisotropy constant *K* vs. temperature in *MnBi*(LTP) [16].

specimen shows spin-wave behavior and holds fairly well the $T^{3/2}$ law especially at low temperature. The increase in coercivity with the increase in temperature is because of the increase in anisotropy energy in *MnBi*(LTP) (see inset in Figure 2.). Chen and Stutius also found that the uniaxial anisotropy energy increases with increasing temperature and reaches a maximum of 2.2×10^7erg/cm^3 at temperature 490K[3].

Figure 3 displays the thermomagnetic curves *M*(*T*) of *MnBi* (LTP) compounds in the *No*.1 *No*.2 and *No*.3 specimens at $\boldsymbol{H_m}$=0.1T. Under an applied dc field $\boldsymbol{H_m}$, the values of magnetization slowly increase and the shape of the anomaly in magnetization becomes non-peaklike (a peaklike profile indicates a spin reorientation of *MnBi* (LTP), see inset in Figure 5.) with $\boldsymbol{H_m}$ parallel to the *c*-axis. For each sample, the magnetization *M* decreases with the temperature less than the temperature of SRT, but increases with the temperature above the temperature of SRT. In the meanwhile, *M* increases with the $\boldsymbol{H_f}$ increasing when the temperature is above about 75K and decreases with the $\boldsymbol{H_f}$ increasing when the temperature is less than about 75K at a certain temperature. As a rule, the higher the H_f is, the better the alignment is and the less the obstacles that impede the spin-reorientation are. So the temperature of SRT increased with the increasing $\boldsymbol{H_f}$. The effect of the magnetic field $\boldsymbol{H_m}$ on the temperature of SRT can be seen from the

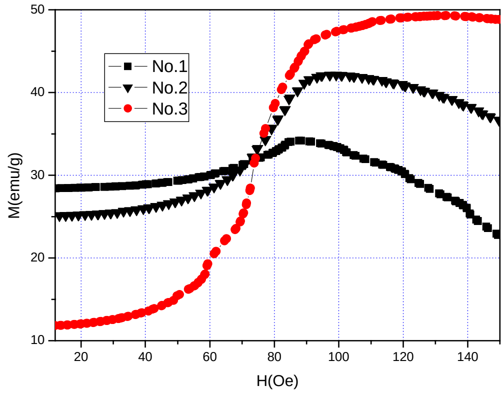

Figure 3 M vs. temperature measured on *MnBi* (LTP) in the different samples.

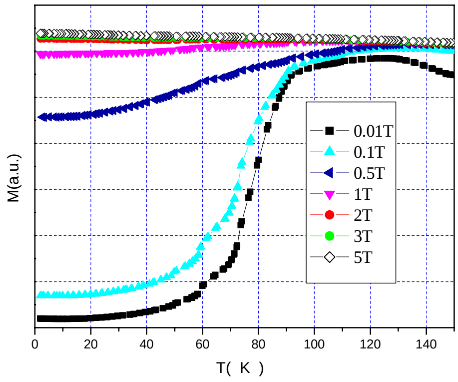

Figure 4 M vs. temperature measured on *MnBi* (LTP) for the *No*.3 sample when the different $\boldsymbol{H_m}$ is applied along the *c*-axis.

thermomagnetic curves $M(T)$ of *MnBi* (LTP) compound for the *No*.3 specimen shown in Figure 4. The $M(T)$ curves of *BiMn*(LTP) compound were obtained under different magnetic fields along the *c*-axis direction of *MnBi*(LTP) for the *No*.3 specimen. In Figure 4, the position of the bump in magnetization shifts to lower temperatures when $\boldsymbol{H_m}$ is applied along the *c*-axis direction. But with the increasing $\boldsymbol{H_m}$, the bump was not more visible, and the spin-reorientation was hardly observed even at H_m=5T. The thermomagnetic curves $M(T)$ of *MnBi* (LTP) compound in the *No*.2 specimen at the magnetic field $\boldsymbol{H_m}$=9T applied along *c*-axis is plotted in Figure 5. It is easy to see that the bump does not exist, and with the decreasing temperature, the magnetization increases and reaches saturation at about 10K. Those effects mean that although the Zeeman energy ($-\boldsymbol{M} \cdot \boldsymbol{H_m}$) produced by the applied external dc field keeps the magnetization parallel to the field direction, the application of an external dc field $\boldsymbol{H_m}$ modifies the temperature of SRT to some extent. This implies that the anisotropy energy is comparable to the Zeeman energy produced by a certain applied magnetic field.

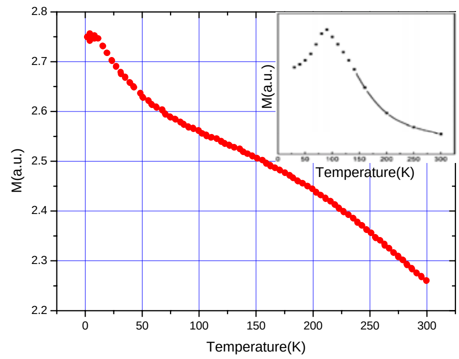

Figure 5 Thermomagnetic curve measured on *MnBi* (LTP) compound for the *No*.2 sample. Inset: M vs.Temperature for *MnBi* along the *c*-axis [4].

Generally, the magnetic moments rotated from along the *c*-axis into, or nearly into, the basal plane for *MnBi*(LTP) at about 90K, which is studied by many experiments[3,12,13]. By linear extrapolation of anisotropy constant $K=K_{u1}+2K_{u2}+3K_{u3}$ as a function of temperature (shown in inset in Figure 2.) [16] to temperature below 90K, K<0 will probably appear, then K_{u1} and K_{u2} (K_{u1} and K_{u2} are the first and second anisotropy constants) may meet the conditions of the plane anisotropy ($-K_{u2}>K_{u1}\geqslant 0$) or the easy cone ($2K_{u2}>-K_{u1}>0$). The Zeeman energy favors arrangement of the spins along *c*-axis. This competes with the plane anisotropy, causing a continuous rotation of the spins to the *c*-axis with increasing field strength. Finally, with field applied along the *c*-axis, a spin-reorientation transition occurs due to competition between Zeeman energy and the plane anisotropy, causing a slow rotation of the spins into the basal plane. The spin-orbit interaction causes the low-temperature magnetic anisotropy of *MnBi*(LTP) [15], so the effect of magnetic field on the temperature of SRT probably originates from the interaction between the magnetic field and spin-orbit coupling.

CONCLUSIONS

When Bi-wt.6%Mn alloys are solidified in the fabrication magnetic field $\boldsymbol{H_f}$, the primary phase *MnBi* (LTP) is aligned in the magnetic field, with the *c*-axis of the *MnBi* (LTP) crystal along the direction of $\boldsymbol{H_f}$. M_s of *MnBi* (LTP) decreases with the increase of temperature, and H_c of *MnBi* (LTP) increases with temperature above about 150K. $\boldsymbol{H_f}$ explicitly improves the magnetic anisotropy. The magnetic moment of *MnBi* gradually deviates from the *c*-axis at approximately 90K. It is interesting that, under a dc field applied $\boldsymbol{H_m}$ parallel to *c*-axis, the temperature of SRT decreases with the increase of magnetic field, and increases with the increasing $\boldsymbol{H_f}$.

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