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Magnetic force microscopic study of the magnetic field induced antiferro to ferrimagnetic transition in $Mn_{1.85}Co_{0.15}Sb$

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ABSTRACT

Magnetic field induced first order antiferromagnetic (AFM) to ferrimagnetic (FRI) transition in polycrystalline $Mn_{1.85}Co_{0.15}Sb$ has been studied using magnetic force microscopy (MFM) at 60 K and up to 8 T magnetic fields. Our MFM studies provide real space visualization of AFM to FRI transition. It shows growth (decay) of FRI phase with increasing (decreasing) magnetic field. The hysteretic behavior and co-existing FRI and AFM phases across the critical field required for FRI–AFM transition in $Mn_{1.85}Co_{0.15}Sb$ are highlighted. This study demonstrates the potential of MFM for studying phase co-existence at high field and low temperatures.

1. Introduction

Hysteresis is the characteristic property of first order phase transition, which can be seen on varying either temperature or magnetic field. A discontinuous jump in the order parameter is identified as the first order transition. A large number of first order transitions show thermal hysteresis where the transition during cooling occurs at the temperature lower than during heating, due to supercooling/superheating. In between these temperatures the material is said to exhibit a metastable state [1,2].

Mn_2Sb is a ferrimagnetic material with $T_C \sim 550$ K. A first order ferrimagnetic (FRI) to antiferromagnetic (AFM) transition is induced with the doping of transition metals like Cr, Co, Cu, V, etc. on Mn site [3–5]. This AFM–FRI transition shows many interesting and anomalous behaviors and transition temperature varies with transition element concentration. The resistivity, magnetization and magnetostriction show a large change near the transition temperature (TN) [6,7,11]. We have recently studied magnetic field induced AFM–FRI phase transition and metastability in Cobalt doped Mn_2Sb [7]. The Neel temperature of $Mn_{1.85}Co_{0.15}Sb$ sample is ~120 K. Below 120 K, the application of magnetic field also induces a first order AFM–FRI transition, showing a large magnetoresistance. These magnetic field induced first order transitions in various functional materials are of great technological interest due to large magnetoresistance, giant magnetocaloric effect and magnetic shape memory alloys. They are of great fundamental interest as well, e.g. in the understanding of phase separation, metastability and co-existence of competing phases. In the recent past magnetic imaging has been used to visualize thermo magnetic irreversibility in magnetically disordered materials [8–11]. In this paper we present the visual evidence of field induced hysteretic behavior and metastable states in Mn_2Sb at 60 K by MFM study.

2. Experimental

The sample $Mn_{1.85}Co_{0.15}Sb$ for present study is taken from the same ingot, which was used, in the previous study [7]. Resistivity and magnetoresistance measurements are done by standard four-probe method using home made resistivity setup along with cryostat/magnet system from Oxford Instruments, UK in the temperature range of 5–300 K and up to 8 T magnetic field. For in-field measurements magnetic field is applied parallel to current direction.

Magnetic imaging at sample surfaces as a function of magnetic fields (up to 8 T) at 60 K is carried out by magnetic force microscope (MFM) from Nanomagnetic Instruments, UK with a cryostat/magnet system from American Magnetics, USA.

Sample was mirror polished for MFM imaging. Magnetically coated tips from NanoSensors of the size <50 nm on a cantilever of the width ~30 μm size is used for scanning the sample surface. The microscope uses a fiber interferometer for tuning/alignment of the tip over sample surface. Forward scan is used to get the topographic image. During reverse scan, tip is lifted by few hundreds of nanometer (~700 nm in the present study). Sample to sensor distance is maintained constant during reverse scan. The frequency shift during reverse scan provides information about the sample surface magnetic profile.

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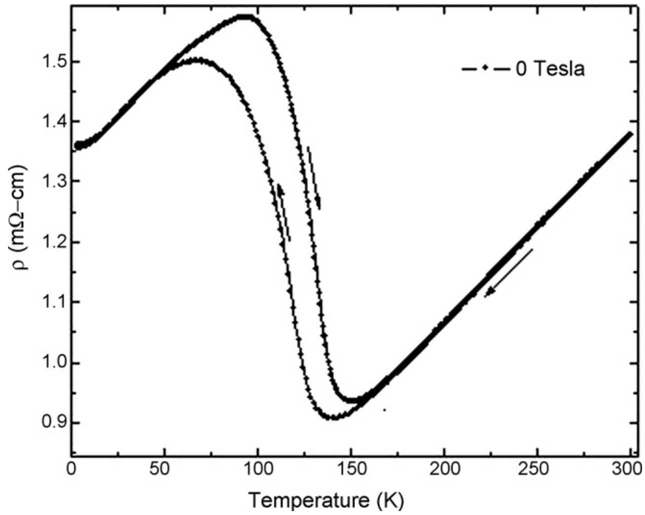

Fig. 1. Resistivity vs temperature for $Mn_{1.85}Co_{0.15}Sb$ in zero field during cooling and heating cycles.

3. Results and discussions

Fig. 1 shows the temperature dependence of zero field resistivity with decreasing and increasing temperature. Antiferro to ferrimagnetic transition is seen as sharp drop in resistivity with increasing temperature which starts around 90 K. Transition temperature, which is taken as the inflection point of the resistivity is found to be ∼120 K. During cooling reverse transformation occurs at lower temperature compared to warming cycle resulting in a hysteresis of ∼10 K around transition region. Besides hysteresis transition is broad with the width of ∼50 K. Such a broadening of transition region is a result of disorder inherent in substitutional alloys. This broadening of transition region gives rise to co-existing AFM and FRI phases, the field dependence of which has been studied recently by us, using Scanning Hall Microscopy [11]. In this study it has been shown that state of the system depends on the path followed to reach the measurement temperature. Earlier we have demonstrated by macroscopic measurements that difference in initial state persists only within the supercooling and superheating spinodal and vanish beyond it. This is shown in Fig. 2, by ρ–H measurement at 60 K, where zero field resistivity is same before and after the application of magnetic field. Therefore, we obtain completely homogeneous state after complete cycle of magnetic field at this temperature (below 120 K).

MFM images at various constant magnetic fields are shown in Fig. 2. Measurement protocol was identical to that used in R–H measurement. Each MFM image labeled by alphabets (A–O) corresponds to the points on R–H curve represented by the stars. All the images while decreasing and increasing magnetic field are plotted on the same scale. Image A and B in the presence of 1 and 2 T magnetic field shows almost homogeneous AFM state represented by light color. With further increase in magnetic field system tends to become FRI (represented by dark color) and starts getting inhomogeneous as seen in image C taken at 3 T, where both AFM and FRI phases co-exist. On increasing the field while going from A to H system tends to become ferrimagnetic and turn completely ferrimagnetic at 8 T. In between fields at 4, 5 and 6 T both FRI and AFM phases co-exist with increase in FRI phase, respectively. Similarly while decreasing field from 8 to 0 T system tends to AFM state with more FRI phase fraction in comparison to

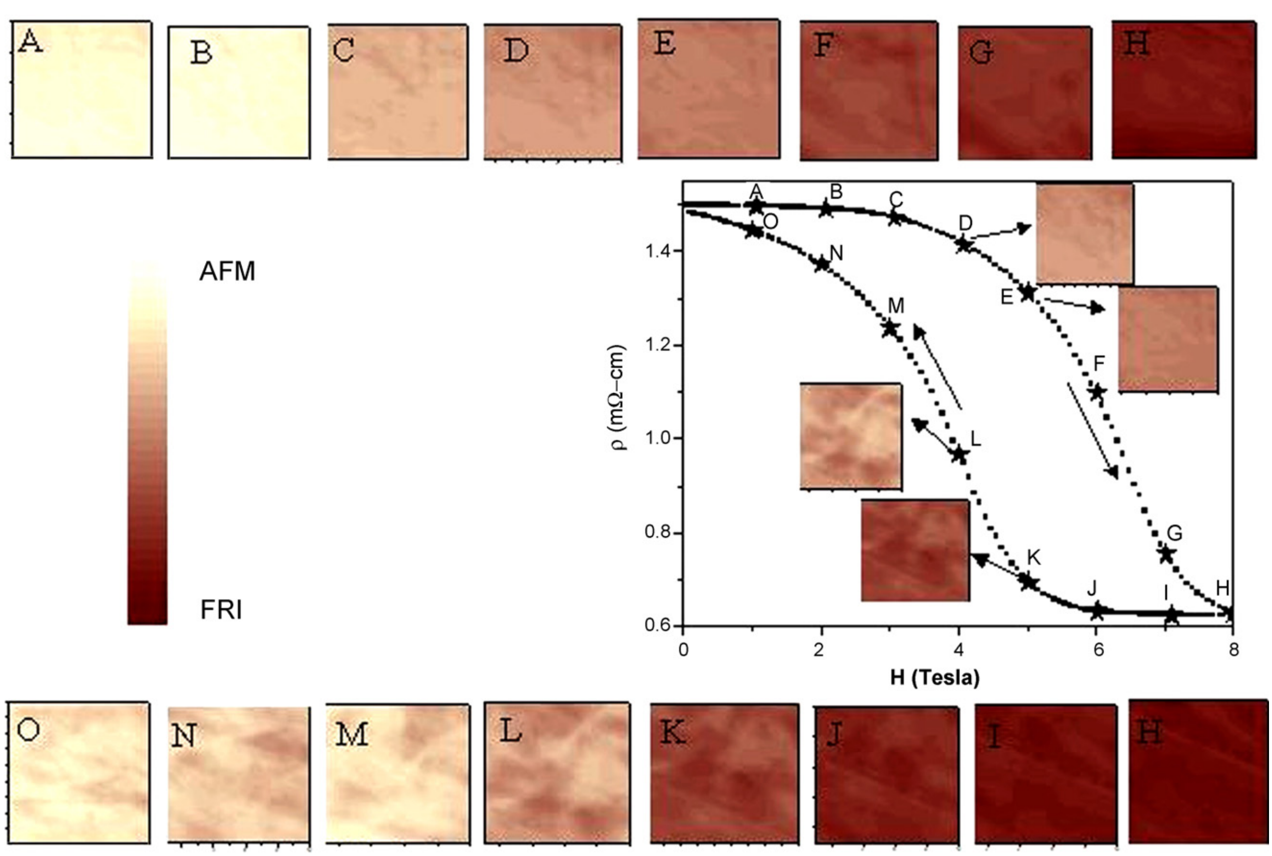

Fig. 2. (A–O) Magnetic force microcopy images (17.8 μm × 17.8 μm) of $Mn_{1.85}Co_{0.15}Sb$ in presence of various constant magnetic fields with increasing and decreasing field. Each point indicated by alphabets (A–O) in ρ–H at 60 K reached by warming represents the corresponding MFM image.

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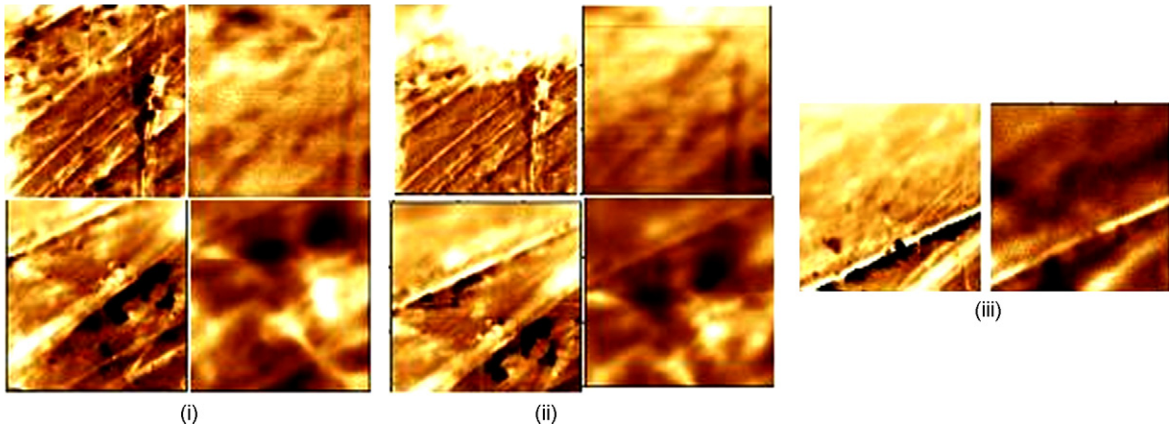

Fig. 3. Topographic (left) and magnetic (right) images at (i) 4 T, (ii) 5 T and (iii) 8 T. Top and bottom images in figure (i) and (ii) are the images taken with increasing and decreasing field cycles, respectively.

increasing field cycle at all corresponding field values. This difference between the two field cycles in MFM images provides the mesoscopic origin of hysteretic behavior in ρ–H curve.

Some of the representative MFM images along with corresponding topography across the magnetic field induced AFM–FRI transition are shown in Fig. 3. Fig. 3(i) taken during field increasing cycle at 4 T shows almost AFM state with few dark regions showing the growth of FRI phase. While during field decreasing cycle it shows co-existing FRI (dark region) and AFM (light region). The fact that the dark regions are not a result of topography is evident from the comparison of topographic and magnetic images. The regions studied during field increasing and decreasing cycle seems to be different from topographic images. However, magnetic images clearly show higher FRI phase fraction during field reducing cycle. Similar inference can be drawn from 5 T images shown in Fig. 3(ii). These results provide origin of hysteretic behavior in magnetoresistance. At 8 T almost entire sample is homogeneous FRI. Small bright features observed in MFM images seem to be correlated with topography as shown in Fig. 3(iii).

4. Conclusions

Magnetic force microscopy (MFM) has been used to study the field induced AFM to FRI transition in $Mn_{1.85}Co_{0.15}Sb$. These images show nucleation and growth of FRI phase with increasing magnetic field on mesoscopic length scales. It provides the mesoscopic origin of hysteretic magnetic field induced transition in magnetoresistance studies. Different phase fractions are confirmed during decreasing and increasing field cycles consistent with our magnetoresistance studies. This study shows the potential of MFM in studying field induced magnetic transitions and phase co-existence at high magnetic field and low temperature.

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