

Flipping of magnetic moments induced by the first-order phase transition in MnAs disks on GaAs(001)

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The relaxation of magnetization in MnAs nanomagnets fabricated on GaAs(001) substrates consists of three exponential decays that are associated with the first-order phase transition between the ferromagnetic and nonmagnetic phases of MnAs and fast and slow flipping processes of magnetic moments. Not only the phase-transition component but also the fast-relaxation component become appreciable in the narrow temperature range of the thermal hysteresis of the phase transition. The magnetic moments are suggested to be rotated by virtual phase-transition processes. A brief expansion of the lattice constants of MnAs through the magnetic-field-induced phase transition is found to generate a memory effect and permanently elongate the decay times.

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I. INTRODUCTION

Manganese arsenide is ferromagnetic at room temperature and possesses unusual magnetic characteristics around Curie temperature $T_C \approx 315$ K. The material undergoes a simultaneous magnetic and structural first-order phase transition at T_C and a second-order structural transition at $T_s \approx 395$ K. The magnetic phase transition is accompanied by a large magnetocaloric effect, which is useful for magnetic refrigeration.¹ Although the ferromagnetic order is lost at T_C , the magnetic susceptibility follows the Curie-Weiss law only at $T > T_s$.² In addition, the loss of the magnetic order at T_C is discontinuous. In typical ferromagnetic materials, the magnetization M changes with temperature T as

$$M(T) = M_0 B_S \left(\frac{S^2 J_0}{k_B T} \frac{M}{M_0} \right), \quad (1)$$

where M_0 is the magnetization at $T=0$, $B_S(x)$ is the Brillouin function, and J_0 is related to T_C as $k_B T_C = (1/3)S(S+1)J_0$. One obtains T_s as the extrapolated Curie temperature for MnAs if the temperature dependence of the magnetization for $T < T_C$ is fitted by Eq. (1).³ The peculiar magnetic properties have led to an unsettled debate whether the medium temperature phase, β -MnAs, is paramagnetic or antiferromagnetic.^{4,5}

In this paper, we investigate the magnetization reversal processes in nanometer-scale MnAs disks. The thermal fluctuations in the magnetization of small magnetic particles are one of the fundamental issues of modern micromagnetics. Due to the unusual magnetic properties around T_C , the magnetization relaxation in MnAs is anticipated to be different from that in ordinary ferromagnetic particles. We find that a certain relaxation process sets in dramatically in the narrow temperature range of the thermal hysteresis associated with the first-order phase transition, providing evidence that the phase transition can enhance the flipping of magnetic moments. We also demonstrate that the application of an external magnetic field modifies the relaxation behavior through the strain imposed by the substrates.

The thermal relaxation of magnetization is also of great importance for applications. Over nearly half a century, the density of bits in magnetic storage devices has increased

steadily at a rate of tenfold in six years. The so-called superparamagnetic limit resulting from thermal magnetization reversal is rapidly approaching as the magnetic energy to hold magnetic moments can no longer be much larger than the thermal energy $k_B T$.⁶ There are a number of proposals to extend the superparamagnetic limit, including, for instance, perpendicular recording and heat assisted magnetic recording (HAMR). In HAMR,⁷ a high-coercivity magnetic material is used to overcome thermal fluctuations. The material is heated during recording to “soften” it magnetically in order to reduce the external magnetic field required for the recording. Understanding the magnetization relaxation processes near the Curie temperature T_C is hence crucial for HAMR. There is also a practical issue. If one employs a ferromagnetic material having T_C not too far from room temperature in order to ease the heating task for HAMR, the magnetization is considerably reduced from M_0 at room temperature in accordance with Eq. (1).

The material properties of MnAs are intriguing from the viewpoint of magnetic storages and HAMR. The uniaxial magnetocrystalline anisotropy of MnAs is significantly large, giving rise to an almost square-shaped hysteresis in the magnetization curve and slow relaxation of magnetization in small disks.⁸ The abrupt disappearance of the ferromagnetic order at T_C means for HAMR that the remanent magnetization of MnAs remains substantial at room temperature even though the required heating is merely a few tens degree. If β -MnAs is antiferromagnetic, the exchange-biasing effect can be utilized^{9,10} to stabilize the magnetization of the ferromagnetic α phase.¹¹

II. EXPERIMENT

(1100)-oriented hexagonal MnAs films were grown on GaAs(001) substrates by molecular-beam epitaxy. MnAs disks were fabricated using electron-beam lithography and Ar ion milling.¹² In the inset of Fig. 1 we show a scanning electron micrograph of a typical sample. The MnAs disks were assembled in the form of a square array stretched along the cleavage directions of the GaAs substrates in order to strengthen the magnetization signal. The number of the disks

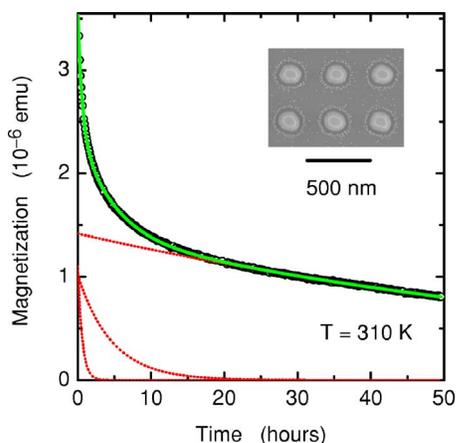


FIG. 1. (Color online) Decay of the remanent magnetization in MnAs disks No. 1 at a temperature $T=310$ K. The disks were magnetized at a magnetic field of 20 kOe prior to the time-dependence measurement. The solid curve shows a fit assuming three exponential decays with the decay times $\tau_p=0.59$ h, $\tau_f=4.65$ h, and $\tau_s=88.0$ h. The individual components are shown by the dotted curves. The inset shows a scanning electron micrograph of the MnAs disks. The diameter of the disks is 100 nm.

in a sample is on the order of 10^7 – 10^8 . The magnetic easy axis of the MnAs films is along the $[11\bar{2}0]$ direction, which is parallel to the $[110]$ direction of GaAs. The magnetization of the disks was measured using a superconducting-quantum-interference-device (SQUID) magnetometer (Quantum Design MPMS XL). We examined the relaxation of the remanent magnetization in samples processed from two 50-nm-thick films and one 37-nm-thick film grown under distinct growth conditions. All the samples exhibited qualitatively similar results, indicating that the phenomena we report here are generic for MnAs disks. Only the data obtained using the 50-nm-thick films are included in the present paper. In the microstructuring process, a Ti or NiCr mask was used for MnAs etching. For some samples the mask was removed at the completion of the ion milling using a HF solution, whereas, for the rest of the samples, the mask was left on the surface of the disks during the SQUID measurements. We emphasize that no essential difference was found among these different kinds of samples, indicating that the mask did not influence the magnetic properties of the MnAs disks.

III. RELAXATION OF REMANENT MAGNETIZATION

In Fig. 1, the time dependence of the magnetization at $T=310$ K in the sample shown in the inset (sample No. 1) is plotted by the circles. Prior to the measurement, the sample was magnetized in an external magnetic field of 20 kOe applied along the $[11\bar{2}0]$ direction of MnAs, i.e., the magnetic easy axis. The magnetic field was reduced to zero, at time $t=0$, at a rate of 8 kOe/min. Note that the remanence in the MnAs disks is fairly close to the saturation magnetization due to the strong uniaxial magnetocrystalline anisotropy.⁸ As shown by the solid curve, the experimental behavior is de-

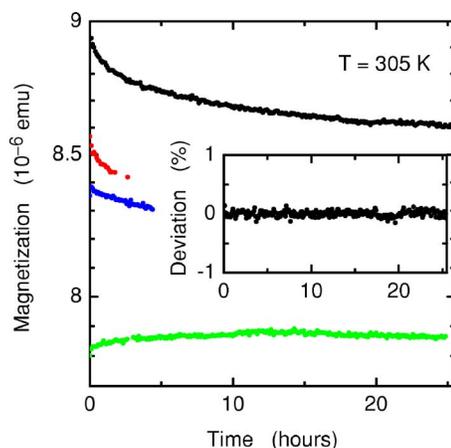


FIG. 2. (Color online) Time dependence of the remanent magnetization in MnAs disks No. 2 having a diameter of 100 nm after various thermal history. The disks were magnetized at a magnetic field of 20 kOe prior to each measurement run. The sample temperature before the measurements was higher and lower than the measurement temperature $T=305$ K for the top three and the bottom curves, respectively. The inset shows the difference between the experimental data (top-most curve) and a theoretical fit assuming $\tau_s=\infty$ ($\tau_p=0.87$ h, $\tau_f=10.5$ h, and M_p, M_f, M_s are 0.11, 0.24, 8.59×10^{-6} emu, respectively).

scribed by a superposition of three exponentially decaying components

$$M(t) = M_p e^{-t/\tau_p} + M_f e^{-t/\tau_f} + M_s e^{-t/\tau_s}, \quad (2)$$

where M_i and τ_i are the magnitude and the relaxation time of the component i ($\tau_p < \tau_f < \tau_s$), respectively. The individual components are shown by the dotted curves in Fig. 1. While the magnetic relaxation is given by an exponential decay if the underlying activation-energy processes are exactly similar, the relaxation is generally found to exhibit a $\ln t$ dependence due to a distribution in the activation energy.^{13,14} However, we have encountered that systematic analysis of our experimental data is possible only by assuming the three exponential decay components. We will return to this point in Sec. V.

With lowering temperature, the time dependence of the magnetization is drastically reduced. The variation at room temperature shrinks to the extent that it is barely detectable, as reported in Ref. 8. The temperatures at which the relaxation time can be evaluated are, as a consequence, in a narrow range just below T_C . As this range overlaps with that of the thermal hysteresis originating from the first-order phase transition at T_C , the relaxation characteristics critically depend on the thermal history of the samples. In Fig. 2 we show a number of the magnetization decay curves at $T=305$ K obtained from an identical sample (sample No. 2, which was fabricated from a MnAs film different from that of sample No. 1). The top three measurement runs were obtained under nominally the same thermal procedure but in different thermal cycles. The bottom curve was obtained under a thermal procedure fundamentally different from that for the top three curves. The variation in $M(t=0)$ for the differ-

ent measurement runs is a direct consequence of the thermal hysteresis. Notice that even the relaxation times change with thermal cycles. As the Néel-Brown law

$$\tau = \tau_0 \exp(E_B/k_B T) \quad (3)$$

implies that the relaxation time τ is determined by thermally activated processes over an energy barrier E_B , the latter indicates a fluctuation of E_B .

For the bottom curve in Fig. 2, the magnetization increased with t instead of a relaxation. The magnetization was maximized at $t \approx 13$ h and exhibited a slow decay afterwards. (Similar behavior at 293 K observed in the same sample was reported in Ref. 8, for which the maximum appeared at $t \approx 20$ h.) This qualitatively different behavior was reproducible under a specific thermal history. For the top three curves in Fig. 2, the sample temperature was lower than the measurement temperature of $T=305$ K prior to the measurement runs. To be specific, the sample was heated from 200 K to 305 K at a rate of 10 K/min, except when the sample temperature became less than 10 K below the measurement temperature, for which the heating rate was reduced to 1 K/min. On the contrary, the sample was cooled to the measurement temperature for the bottom curve, resulting in the distinctively small magnetization due to the thermal hysteresis. We have confirmed that solely the sample temperature immediately before the measurements determines the initial fate of the magnetization, i.e., an increase or a decrease. In addition, the magnetization decay for $t > 15$ h is a common feature regardless of the thermal history, i.e., the process associated with the component f universally reduces the magnetization. Therefore, the fastest decay when the sample was warmed to the measurement temperature (component p) and the initial increase when the sample was cooled to the measurement temperature are indicated to be associated with the first-order phase transition between the α and β phases of MnAs. In a first-order phase transition, the phase transition does not occur immediately. It takes place by surmounting a potential barrier separating the two phases, see Fig. 3, giving rise to a stochastic behavior.¹⁵

The initial increase of the magnetization takes place on a time scale which is considerably longer than τ_p . (We have not been able to extract the characteristic times when the magnetization initially increases.) The different time scales are ascribed to the fact that the transition from (magnetized) α -MnAs to β -MnAs always reduces the magnetization, whereas the transition from β -MnAs to α -MnAs does not have to change the magnetization. The direction of the magnetic moment in the α -MnAs disks emerged in the course of the phase transition is, in principle, random. The increase of the magnetization implies that the newly created α -MnAs disks are, at least partly, magnetized in the dominant magnetization direction of the surrounding disks, plausibly through the dipole-dipole interaction.¹⁶ The MnAs disks in our devices are assembled in the form of a square array having a period about one order of magnitude larger than the diameter of the disks. The stray fields from the surrounding disks can be large enough to influence the magnetization direction of the newly created ferromagnetic disks. For square arrays, the dipole-dipole interaction gives rise to a ferromagneticlike

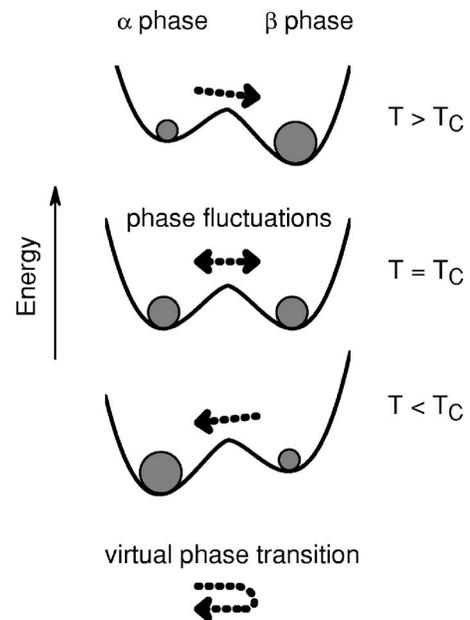


FIG. 3. Schematic energy diagram of the first-order phase transition between the α phase and the β phase of MnAs at temperatures around Curie temperature T_C . The arrows indicate the transition from the metastable state (the α phase for $T > T_C$ and the β phase for $T < T_C$) to the stable state (the β phase for $T > T_C$ and the α phase for $T < T_C$). The phase fluctuates between the α and β phases at temperature $T = T_C$. Such fluctuations may give rise to virtual phase transitions.

coupling between adjacent disks.¹⁷ The time scale of the magnetization increase is thus governed by the interdisk interaction.

The two components f and s correspond to the flipping of the magnetic moments in the disks. At present, the mechanism of the two relaxation processes has not been identified. The two distinct decays may originate from the fact that the sample contains two types of disks in terms of the magnetic-domain structure in individual disks. When the diameter of MnAs disks is reduced, the magnetic-domain structure undergoes a transition from a double-domain state to a single-domain state.¹⁵ In large disks, the double-domain state is favored as the closure flux arrangement reduces the magnetostatic energy originating from stray fields. Note that this double-domain state corresponds to the vortex state for ordinary magnetic materials. The strong uniaxial magnetocrystalline anisotropy of MnAs transforms the vortex state to the double-domain state. Below a critical diameter of the disks, the double-domain state becomes unfavorable as the cost of domain-wall energy exceeds the gain in the magnetostatic energy. The disks in the latter regime are of single magnetic domain even in the demagnetized state, the so-called nanomagnets. As the meandering of the local atomic magnetic moments along the disk boundary is fairly small, the magnetic relaxation in the two types of ferromagnetic MnAs disks can be treated as a thermodynamics of a single magnetic moment for the single-domain disks and of two magnetic moments arranged either in parallel or antiparallel configuration for the double-domain disks. (We do not refer a double-domain disk having parallel configuration as a single-

domain disk despite its effective single magnetic domain.) For the single-domain disks, the relaxation occurs by reversing the direction of the magnetic moment with respect to that of the rest of the disks. In contrast, the magnetization vanishes for the double-domain disks when the magnetic moments rearrange themselves from the parallel configuration to the antiparallel configuration, which is equivalent to a domain-wall formation. The relaxation in the double-domain disks will be faster than that in the single-domain disks, provided that all the disks have a comparable size, as only a half of the magnetic moments of the disks needs to be flipped for the former case.

Using magnetic force microscopy, we have established that the disks we examine in this paper are predominantly in the single-domain regime at room temperature.¹⁵ If the number of the double-domain disks increases at the high temperatures where the relaxation became appreciable, the two relaxation mechanisms will coexist. However, the component f is unlikely to be associated with the domain-wall formation in the double-domain disks. First, the competition between the domain-wall energy and the magnetostatic energy is hardly influenced by temperature, and so the temperature dependence of the critical size for the transition between the single- and double-domain regimes is expected to be weak.¹⁸ Second, the fractions of the two types of the disks will vary significantly with the mean disk diameter of the array when the disk size is comparable to the critical value. However, the three-component decay was observed generally in all the samples we examined having diameters of 70 ~ 120 nm.

We have found that the relaxation of magnetization reveals a strong and peculiar temperature dependence. Before we proceed to discuss the temperature dependence, we note a difficulty that we had to deal with in analyzing the experimental data. That is, due to the restricted measurement duration and the extremely slow relaxation for the component s , the experimental data could not be fitted using Eq. (2) unless $\tau_s = \infty$ was assumed, except for the measurement run shown in Fig. 1. For the analyses in the remainder of the paper, we assume that the magnetization associated with the component s is time independent. In the inset of Fig. 2, we show the deviation of the experimental data from the prediction by Eq. (2) assuming $\tau_s = \infty$ for the top curve in Fig. 2. The agreement between the theory and the experiment is still excellent, indicating that $\tau_s \gg 25$ h.

In Figs. 4(a) and 4(b) we show the temperature dependence of M_i and τ_i ($i=p, f$) from sample No. 2, respectively. The components p and f are found to exhibit similar temperature dependencies. Not only the phase-transition component p but also the fast relaxation of the magnetization emerges remarkably only in a narrow temperature range, $\Delta T \sim 15$ K, below T_C . This temperature range coincides with the range of thermal hysteresis in the disks, which was determined using x-ray diffraction.¹⁹ Moreover, the relaxation becomes appreciable not by decreasing τ_f but by increasing M_f , as highlighted by the dotted line in Fig. 4(a). As the relaxation time is expected to be given by Eq. (3), it would be roughly constant in such a narrow temperature range around room temperature, as we indeed find in Fig. 4(b).²⁰ (In our devices, τ_f is typically ten times longer than τ_p .) The

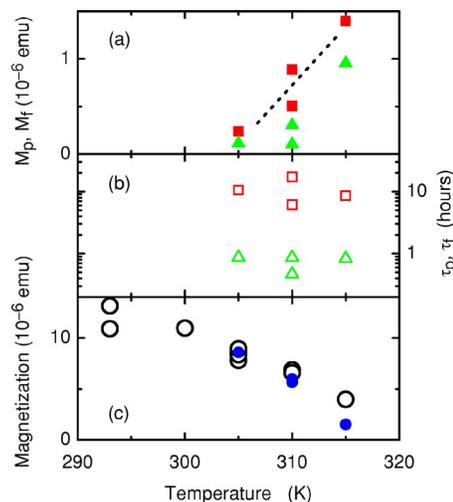


FIG. 4. (Color online) Temperature dependencies of (a) the magnitudes M_p and M_f , (b) the relaxation times τ_p and τ_f , and (c) the remanent magnetization at $t=0$ (open circles) and the magnitude M_s (filled circles) in MnAs disks No. 2. The triangles and squares correspond to the components p and f , respectively. The dotted line in (a) is a guide for the eyes.

similarity in the temperature dependence of M_f and M_p indicates that the fast relaxation of the magnetization is strongly associated with the phase transition. We emphasize that the component f cannot be due to a direct phase-transition process as the magnetization always decays regardless of the thermal history, i.e., even when the component p increases the magnetization. We propose that the fast relaxation may occur via temporally phase fluctuations from α -MnAs to β -MnAs.

Due to the nucleation initiation of the first-order phase transition, the array generally consists of those disks of α -MnAs and those of β -MnAs in the thermal hysteresis regime.¹⁵ That is, the disks of the metastable phase are transformed to the disks of the stable phase when nuclei of the stable phase are formed in the metastable phase by surmounting a potential barrier, see the top ($T > T_C$) and bottom ($T < T_C$) cases in Fig. 3. Once the nuclei are formed, they grow larger and convert the phase of the entire disk to the stable one. The energy barrier for the phase transition is responsible for the relaxation behavior in the phase transition manifested by the component p . When the two phases are comparably favored for $T \approx T_C$, as illustrated by the middle case in Fig. 3, the disks will fluctuate between being in the α and β phases. Similarly, even when MnAs disks remain nominally in the α phase, they may undergo virtual transitions to the β phase. In this circumstance, the information regarding the magnetization direction when the disks are in the ferromagnetic phase will be lost while MnAs is in the nonmagnetic phase for a very brief moment. Therefore, such virtual fluctuations from the α phase to the β phase will give rise to a randomization of the magnetic moment.

In Fig. 4(c) we show evidence that the disks responsible for the component f are rather extraordinary and ordinary disks do not seem to undergo the fast relaxation process. Here, the open circles show the remanence at $t=0$ ($=M_p$

$+M_f+M_s$) at various temperatures. The temperature dependence is nearly linear and the extrapolated temperature for vanishing magnetization ($T \sim 325$ K) is unusually large for T_C of MnAs. In contrast, M_s , plotted by the filled circles in Fig. 4(c), exhibits a temperature dependence similar to that of the saturation magnetization in MnAs films. The component s hence provides ordinary magnetization that obeys Eq. (1). This may suggest that the phase transition is unstable in some disks due, for instance, to defects. While stable disks yield the magnetization decay represented by the component s , the metastable α phase “pinned” in the unstable disks may undergo the virtual phase transitions, yielding the component f . The crystal imperfections can play an important role for the phase transition between α -MnAs and β -MnAs as the transition involves a discontinuous volume change.

Another possible explanation for the two relaxation processes is that they are associated with the two types of the phase distribution, rather than the magnetic-domain structure, in the disks. When the disk size is only slightly smaller than the period of the elastic domains of α -MnAs and β -MnAs in a film, the two phases can still coexist in a disk: the stress-free surface MnAs is in the α phase and the stress-stabilized β phase is buried at the vicinity of the MnAs-GaAs interface.¹⁵ Although most of the disks contain either α -MnAs or β -MnAs for the present disk diameter at room temperature,¹⁵ it is likely that the core-shell-type phase coexistence occurs in a small number of disks. The fast relaxation may then take place in the disks in which the α and β phases coexist. If β -MnAs is paramagnetic, the phase coexistence will not influence the magnetic relaxation. However, a magnetic interaction should occur between the segments of the α and β phases within a disk if β -MnAs contains an antiferromagnetic order.^{4,5} Unlike the magnetic-domain structure, the phase-domain structure will depend critically on temperature as it is determined by a competition between the elastic energy imposed by the substrate and the temperature-dependent free energy of the crystals. The fractions of the two types of the phase-domain structures will thus vary when the temperature is increased close to T_C . This could account for the strong temperature dependence of M_f in Fig. 4. However, besides the controversy over the existence of an antiferromagnetic order in β -MnAs,⁴ the coexistence is hardly expected to occur exactly in the same manner in a large number of disks to exhibit the well-defined relaxation time for the component f .

IV. STRAIN EFFECTS ON THE RELAXATION

Although M_i and τ_i remain constant as long as the sample temperature is kept unchanged, they are altered significantly with thermal cycles. The fluctuations of the decay parameters originate from the abrupt volume change of MnAs at the phase transition. The loss of the magnetic order accompanies a discontinuous expansion in the lattice constants in the C plane of MnAs by about 1%. The change in the strain between the MnAs films and the GaAs substrates when the fractions of α - and β -MnAs are varied has a memory effect as the phase transition is first order. The strain energy hence permanently modifies E_B . We have found that the decay

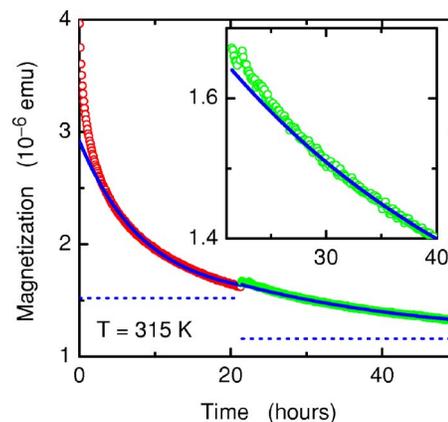


FIG. 5. (Color online) Decay of the remanent magnetization in MnAs disks No. 2 at a temperature $T=315$ K. The disks were briefly magnetized at time $t=21.4$ h in addition to the initial magnetization at $t<0$. The dotted lines show the component s . The solid curves show the contribution due to the components f and s ($\tau_p=0.84$ h, $\tau_f=8.58$ h for $t<21.4$ h and $\tau_p=0.87$ h, $\tau_f=2.66$ h for $t>26.6$ h). The decay after the remagnetization is shown with expanded scales in the inset.

properties of the magnetization are altered not only by thermal cycles but also by a temporary variation of an external magnetic field. Similarly, the remanence and its relaxation characteristics are permanently altered when a magnetic field is briefly applied.

In Fig. 5 the disks were magnetized again (at $t=21.4$ h) during the course of the relaxation characterization by briefly increasing the external magnetic field to 20 kOe. Although the magnetic field was applied well after the direct phase-transition contribution had vanished, the component p re-emerged when the magnetic field was quickly reduced to zero, as shown in the inset of Fig. 5. Here, the solid curves show the contribution of the components f and s of the theoretically fitted decay behavior. The deviation of the experimental data (circles) from the solid curves is equivalent to the component p . The excess α phase that exhibits the phase relaxation is produced by the magnetic-field-induced phase transition from β -MnAs to α -MnAs due to magnetostriction.^{21,22} In addition to the reemergence of the component p , the decay times τ_p and τ_f changed from 0.84 and 8.6 h, before the brief application of the magnetic field, to 2.7 and 27 h, after the application, respectively. The strain modification in the disks is responsible for the change of the decay times. It is noteworthy that the decay times were always elongated by applying the magnetic field, i.e., the strain modification leads to a “healing” effect. The magnitude of the component s decreased as shown by the dotted lines in Fig. 5. As the change in M_s is much larger than the magnitude of the reemerged component p , the slow-relaxation component is implied to be partly converted to the fast-relaxation component. However, at present, we cannot rule out the possibility that the reduction of M_s might be an artifact due to the necessary assumption of $\tau_s=\infty$.

V. IS THE DECAY EXPONENTIAL OR LOGARITHMIC?

As we stated earlier, magnetic materials generally exhibit a logarithmic decay of magnetization,¹⁴ reflecting a distribu-

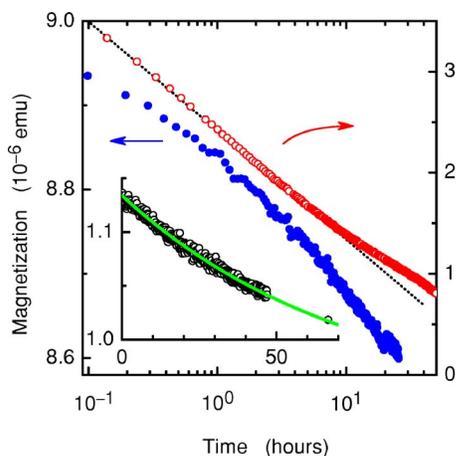


FIG. 6. (Color online) Magnetization versus the logarithm of time. The open circles are the experimental data plotted in Fig. 1. The filled circles are identical to the top curve in Fig. 2. Certain portions might be interpreted as demonstrating a logarithmic decay as shown by the dotted line. The inset shows the relaxation of the magnetization in MnAs disks No. 2 at a temperature $T=315$ K. Following an initial magnetization relaxation measurement, which dwelled about 50 h, the sample was temporarily heated to 335 K for about 10 min and re-magnetized briefly in a magnetic field of 20 kOe at 315 K. The decay obeys an exponential dependence superimposed on a constant background as shown by the solid curve.

tion of the activation energy in real devices.¹³ However, the whole of our experimental data can be analyzed systematically, apart from the cases where the magnetization initially increases with time after cooling of the sample, only if we assume a relaxation in the form of Eq. (2). As an example, we plot magnetization versus the logarithm of t in Fig. 6. Here, the open and filled circles show the experimental data identical to those plotted in Fig. 1 and in Fig. 2 as the top curve, respectively. Certain portions could be interpreted as exhibiting logarithmic decays, for instance, as indicated by the dotted line. However, it is apparent between these two examples that the decay behavior is not universal: the slope at large t is gentler than that at small t for the filled circles, whereas the logarithmic decay deviates in the opposite direction for the open circles. Moreover, the open circles in Fig. 6 clearly show an increase of the slope for $t > 30$ h, which corresponds to the regime where the component s becomes dominant in Fig. 1. Consequently, even a fit using a modified logarithmic decay $\ln(t+t_0)$ is unsatisfactory (not shown), in contrast to the excellent fit one finds in Fig. 1. In practice, the experimental data that were fitted assuming two exponential decays and a constant background could be fitted also using the modified logarithmic decay with comparable accuracies. However, the modified logarithmic decay cannot describe the experimental relaxation when it appears to consist of three exponential decays.

As an additional evidence for supporting our assumption of the exponential decays, we show in the inset of Fig. 6 a case in which the relaxation of magnetization exhibited a single exponential decay (plus a constant background). The experimental data were taken here at $T=315$ K following a procedure similar to that for Fig. 5: subsequent to an initial relaxation measurement, the sample was briefly heated to 335 K for about 10 min and then remagnetized by a magnetic field of 20 kOe at 315 K. The increase of the β phase by the heating and that of the α phase by the magnetic field in the component p presumably canceled each other, leaving only the exponential decay associated with the component f and the constant background associated with the component s . (The relaxation time for the fast-decay component increased and the constant magnetization value for the slow-decay component decreased after the remagnetization, similar to those shown in Fig. 5.)

We also emphasize that the magnetization deduced as corresponding to the component s using the interpretation based on the exponential decays, the filled circles in Fig. 4(c), is in reasonable agreement with the behavior of bulk MnAs. Nevertheless, as fluctuations in E_B are evidenced to be present in Fig. 2, which are the origin of the logarithmic decay observed in most of the magnetic materials,¹³ further studies are needed to clarify whether the relaxation follows the exponential decay or the logarithmic decay in our disk arrays.

VI. CONCLUSION

We have investigated the reversal processes of the magnetic moments in MnAs disks on GaAs substrates. Three exponentially decaying components are found to constitute the relaxation of magnetization. The contribution due to the stochastic nature of the first-order phase transition possesses the shortest characteristic time. The component having a medium relaxation time is not a direct consequence of the thermal hysteresis of the first-order phase transition although it is strongly related to the hysteresis. This relaxation may originate from the flipping of magnetic moments by virtual phase-transition processes. All the relaxation properties are altered permanently not only by thermal cycles but also by applying a magnetic field through the magnetic-field-induced phase transition.

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