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AC susceptibility of current-carrying iron whiskers: Effect of current variation

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The ac magnetic susceptibility of {100} iron whiskers as a function of currents is studied with and without external field. The ac susceptibility depends on the magnitude and the direction of the applied dc current when a small external field is applied along the magnetization of the central domain of the whisker. Variation of the central domain size accounts for the current-dependent response. The measured magnetic responses are explained, using a micromagnetic calculation based on a simple model, as a function of applied currents over a wide range except critical values.

I. Introduction

A well-grown {100} iron whisker is bound by {100} planes and has the Landau structure of two long domains separated by a 180° domain wall with closure domains on each end. Applied dc current transforms the Landau structure of the {100} whisker into the rotated structure, which has been suggested by Shumate *et al*[1]. Their predicted structure is based on a surface observation and it consists of six domains. Four of them near surfaces surround two domains at the center separated by a 180° wall. The structure is designed to accommodate both the field from the current and the need to decrease the demagnetizing energy. But the surface observation can not give detailed information on the principal domain walls concealed inside the whisker.

The information of the internal domain structure can be provided from the ac susceptibility measurement using two different external fields, dc and small ac fields along the principal axis of the whisker. The dc magnetic field changes the domain structure of the {100} whisker and the small ac driving field vibrates domain walls. The change in the magnetic flux is measured with the pickup coil around the mid-plane of the whisker. The ac magnetic susceptibility depends on the current I, the external field H, and their past history. The out-of-phase component of the ac susceptibility is mainly due to eddy currents particularly sensitive to the wall movement. The information about the domain pattern has to be interpreted from the induced signal.

The domain configuration of the {100} whisker with external fields and a large current has been deduced from the ac susceptibility measurement recently[2]. The deduced domain structure is shown in Fig. 1. This configuration is also designed

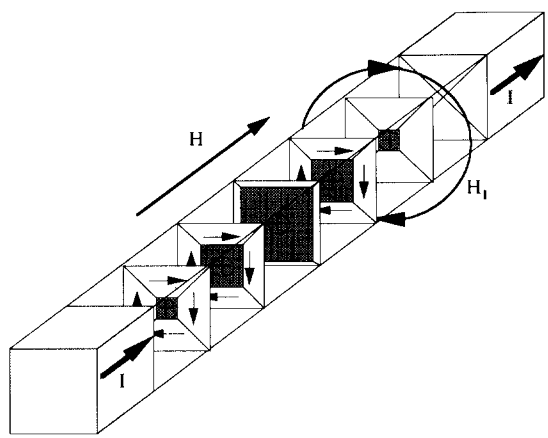

Fig. 1. Domain structure in a {100} iron whisker with external magnetic field and current. The applied current transforms the Landau structure to the rotated structure. Without the external field, the whisker has a very small central domain in the mid-plane of the whisker. The size of the domain grows with the applied field. The domain configuration is designed to reduce the demagnetizing field at edges of the whisker.

to minimize the demagnetizing energy. The domain pattern at the mid-plane of the whisker consists of five domains, four of which surround "one" domain at the center. Walls around the central core are too small to induce any ac signal at zero field. A simple model based on this configuration has been suggested and the in-phase (real) and out-of-phase (imaginary) components of the ac signal as a function of external fields are well explained[3]. But the effect of the current variation on the ac response is not well-understood, yet. In this paper, experimental data of the ac magnetic susceptibility measurement as a function of currents will be presented with and without external field. These data will be explained quantitatively with the previous model.

Ⅱ. Experiments

The {100} whisker used for the measurement has the dimensions 200 μm × 200 μm × 1.5 cm. Fine copper lead wires for current are connected to the edges of the whisker with GaIn solder to reduce the stress. A two-turn pickup coil is placed in the mid-plane of the whisker.

Detailed ac magnetic susceptibility measurements have been described in Ref. 3. The magnetic response of the {100} whisker which has the simple Landau domain structure shows a characteristic behavior as described in Ref. 3. If the induced ac signal shows the characteristic response, the sample is treated as exhibiting the Landau structure. Only samples with Landau structures are used for our measurement.

The ac driving field is 700 Hz in the range 10 to 100 mOe. The ac magnetic field is too small to change the domain structure of the whisker but large enough to vibrate walls lying in {100} planes. Currents applied along the principal axis vary in the range of 200 mA. As mentioned before, the ac response depends on the history of applied fields and currents. Initially the dc external magnetic field, which is strong enough to saturate the center of the whisker with 200 mA, is applied along the principal axis of the {100} iron whisker and then the field decreases to 0.5 ~ 1 Oe that is strong enough to make the central core enlarged. The small external field has to be applied along the magnetization of the central domain in the mid-plane. If the external field is opposite to the magnetization of the core, nothing happens until a larger external field nucleates a new central domain. The out-of-phase components of the ac signals are measured as a function of applied currents with and without the external field.

Ⅲ. Result

The out-of-phase components of the ac responses with the variation of currents are shown in Fig. 2. The measurement for Fig. 2(a) is done

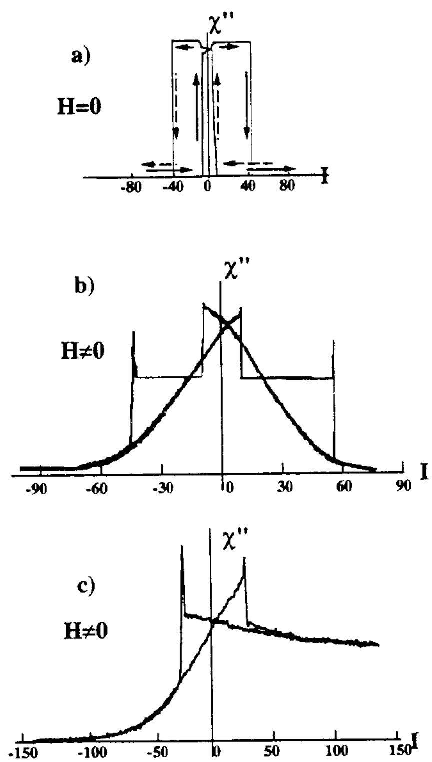

Fig. 2. Measured out-of-phase components of the ac susceptibility for a {100} whisker as a function of applied currents without external field (a) and with two different fields (b) and (c).

without any external magnetic field. No out-of-phase component of the ac signal is induced when the {100} whisker has the magnetization pattern rotated. Only 90° walls lying in the {110} planes do not easily vibrate with the small driving field. The magnitude of the high susceptibility in Fig. 2(a) is equal to that measured without applied current and zero field. The discontinuous changes in the ac signal correspond to the transformation from one stable domain structure to another. The ac susceptibility for Fig. 2(a) can be understood with the change in deduced domain configurations shown in Fig. 3 : As the current increases from the negative to positive value, the domain structure of the {100} whisker is changed from the rotated, to the Landau, and to the rotated structure.

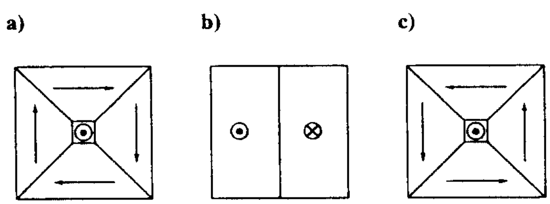

Fig. 3. Domain structures in the mid-plane of a {100} whisker while current is applied into the cross section (a). As the applied current decreases toward zero current, the rotated structure (a) is transformed into the Landau structure (b). As the current increases further, the magnetization near surfaces are changed again. The corresponding domain configuration is shown in (c). The difference between (a) and (c) is the magnetization of the domain near a surface. The magnetic moment per unit length, *m*, multiplies 100 for the y-axis scale.

The difference between Fig. 2(a) and (b) is the area of the central domain in the mid-plane of the whisker. When the applied current is large enough to rotate the magnetization pattern, no ac susceptibility is observed without external magnetic field as shown in Fig. 2(a). As the dc external field is applied along the magnetization of the central domain in the mid-plane, the length of the domain walls around the inner domain becomes large enough to induce the ac signal easily. The change in the magnetic flux from the four walls can be detected with the pickup coil. Figs. 2(b) and (c) show the intensities of the ac responses depend on the external magnetic field, the magnitude and the direction of the applied currents. The current-dependent ac signal, before transforming one stable structure to another, can be explained with the varying size of the central domain; the current makes the central domain shrink and then the vibration of the shrunk walls becomes weaker. The large increase and decrease of ac signals at critical currents indicate sudden changes in the domain configuration. The magnetic response at the critical currents in Fig. 2(b) can be interpreted as the domain structure is changed from the rotated, to the Landau, and to the rotated state. The ac susceptibility in Fig. 2(c) is explained with the domain pattern varying from Fig. 3(a) to (c). This magnetic behavior is identified by the surface observation with a magnetic garnet film.

Ⅳ. Discussion

We can not explain measured signals for all currents ; especially the ac magnetic signals at the transformation from the rotated structure to the Landau structure and at the opposite transformation can not be explained analytically. But slopes of the ac signals in Figs. 2(b) and (c) try to be calculated with the previous model. For calculating the ac response, we have to find the relation between the applied current and the magnetization and then the ac magnetic susceptibility can be obtained as a function of the applied current. These calculations are possible with the micromagnetic treatment based on the previously suggested model[2].

The {100} whisker with a small external field H and current I has the domain structure as explained before[4]. The total energy of the deduced domain configuration consists of the energies from the external field and the applied current, the demagnetizing energy, the wall energy, and themagneto-elastic energy. The total energy density in the system can be expressed in terms of the magnetic moment per unit length, m, as

$$E_T = -\mathrm{H} \cdot m + \frac{1}{2} 4\pi D m^2 - \frac{0.9\sigma_{100}\sqrt{2m}}{\sqrt{M_s}} - \frac{6B_{me}}{25}\left(m\log m - m + \frac{31m^2}{4}\right) + \frac{2m^{\frac{3}{2}} I}{15d\sqrt{\pi M_s}} \qquad (1)$$

where $2d$ is the width of the whisker, σ_{100} is the energy density of a 90° wall lying in the {100} plane, M_s is the saturation magnetization of the iron whisker, and B_{me} is the constant for the magnetostriction. The demagnetizing factor $4\pi D$ depends on the dimensions of the whisker. These energies compete with each other to find the stable structure for the given magnetic field and current. The energy from the current, the demagnetizing energy, and the magneto-elastic energy keep the central domain small. But the energy from the external field and the wall energy try to expand the central domain.

The effective field defined as $H_{eff} = -\partial E_T / \partial m$ vanishes at equilibrium[2]. From the above definition, the relation between the field from the current and the other fields can be obtained. As the applied current varies, the field from the current is balanced by the magneto-elastic field, the wall field, the external field, and the demagnetizing field. The effective current as a function of the magnetization is given by

$$I = 5d\sqrt{\pi M_s}\left[\frac{H}{\sqrt{m}} - 4\pi D\sqrt{m} + \frac{0.9\sigma_{100}}{\sqrt{2M_s m}} + \frac{6B_{me}}{25\sqrt{m}}\left(\log m + \frac{31m}{2}\right)\right] \qquad (2)$$

The current is plotted against the magnetization with a few small external fields in Fig. 4. When the field from the current is applied opposite to the

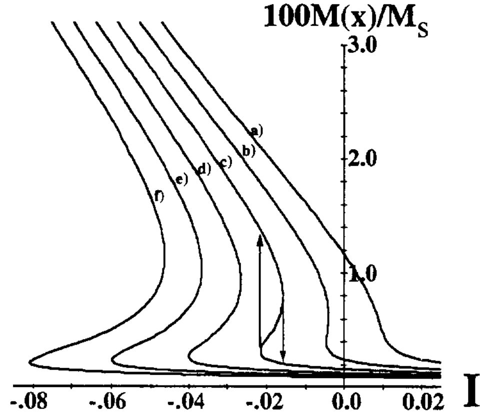

Fig. 4. Calculated relation between the magnetization and the applied current with different external fields, a) H = 0.053 Oe, b) H = 0.052 Oe, c) H = 0.051 Oe, d) H = 0.05 Oe, e) H = 0.049 Oe, and f) H = 0.048 Oe. If the applied field is smaller than 0.052 Oe, the whisker can have more than one domain configuration in the region of the negative currents and the size of the central domain can increase or decrease suddenly at specific currents.

magnetization of the surface domain, the central domain grows continuously with the external field larger than 0.052 Oe. With the field smaller than 0.052 Oe, the whisker can have more than one domain configuration for small negative currents. The size of the central domain can increase or decrease suddenly as the applied currents vary in the negative value. The change in the size of the central domain might be detected with the ac susceptibility measurement. At certain fields the energy is a double-well function of the size of the central domain, which determines the magnetization. It is expected that the effect of the quantum tunneling of magnetization might be observed when currents and external fields at low temperatures are applied properly. This magnetic process is not observed with our ac susceptibility measurement, yet. The magnetic processes at transitions will be discussed further in the future.

The dc susceptibility for varying currents, defined as $1/\chi_o = \alpha(0) = \partial H / \partial m$, is given by

$$\frac{1}{x_o} = \alpha(0) = \frac{H}{2m} + 2D\pi + \frac{0.9\sigma_{100}}{m^{3/2}\sqrt{2M_s}} + \frac{3B_{me}\,(\log m - \frac{31m}{2} - 2)}{25m} \quad (3)$$

The effective current is plotted against the magnetization and the calculated dc susceptibility with a small field as shown in Fig. 5(a). The figure shows the dc susceptibility increases smoothly as the current decreases toward the negative value and is expected to become infinite at critical currents. The slope of the dc susceptibility is similar to that of our observed data but the behavior near the critical currents is not observed yet. Our experimental data can be explained that the domain structure near the critical current may be changed from the rotated to Landau structure rather than the central domain becomes larger. Or the magnetization of the surface domain is flipped by the applied current.

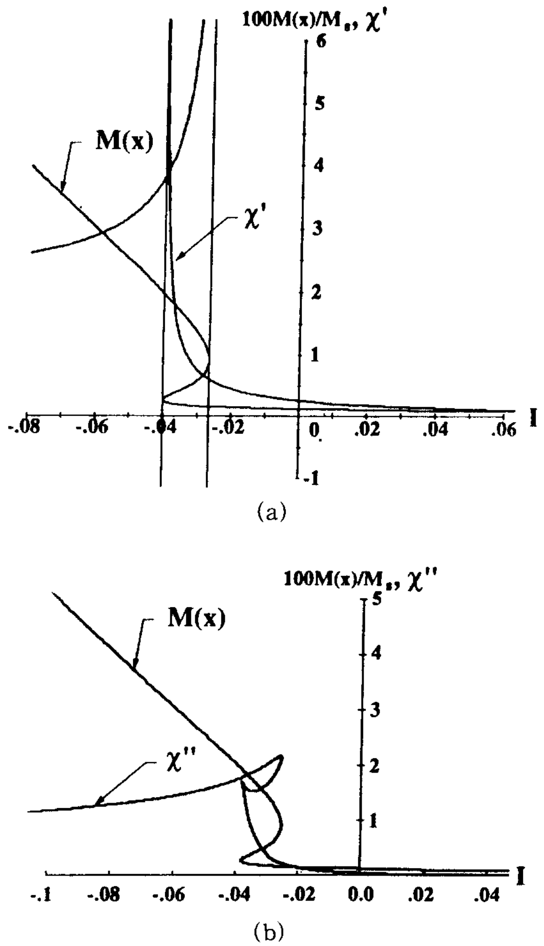

Fig. 5. Calculated dc susceptibility (a) and ac susceptibility (b) while currents varying with the external field H = 0.051 Oe. The frequency used for the calculation is 300 Hz.

The ac susceptibility x'' can be written in terms of a magnetic stiffness $\alpha(0)$ and a magnetic viscosity $\beta(0)$, which is related to the wall movement inside a whisker. The eddy current has been obtained for our domain configuration[2]. The expected ac susceptibility is approximately given by

$$\frac{1}{x_{ex}} = \frac{1}{x' - i x''} = \alpha(0) + i\omega\beta(0) = \frac{1}{x_o} + i\frac{\omega}{\omega_1}\log(\frac{m}{d}), \quad (4)$$

where ω is the frequency of the driving field and ω_1 is the constant related with the eddy current. The ac signal depends on the external field, the current, and the frequency of the driving field. The relation between the calculated susceptibility and the effective current with a small magnetic field is plotted in Fig. 5(b). As the current decreases from the positive to negative value, the calculated ac susceptibility behaves similar to those in Figs. 2(b) and (c). But the measured ac responses near critical currents do not increase as much as the calculated susceptibility does. This behavior has to be clear with further experiments.

V. Conclusion

The size of the central domain decreases with the field from the current along the surface magnetization but grows with the field opposite to the magnetization in the surface domain. Depending on the current, the growth of the central domain can be a continuous or discontinuous process. The measurement of the out-of-phase component of the ac magnetic susceptibility can identify the role of the applied current in the {100} whisker while a small dc external field is applied along the magnetization of the central domain.

The micromagnetic calculation based on our model is possible to explain the current dependence of the ac susceptibility. The existence of the double well as a function of the external field and applied current can be predicted with the calculation. But predicted magnetic processes are not observed and the magnetic behavior at critical currents remains unsolved.

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전류에 의한 철단결정의 교류 자기감수율 : 전류 변화에 의한 효과

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{100} 철단결정에 자기장을 가해주거나 혹은 자기장 없이 전류만을 변화 시킬 때의 교류 자기감수율에 관하여 연구하였다. 작은 자기장과 전류를 철단결정에 걸어줄때, 단결정의 단면적 중앙근처에는 정사각형 자구가 형성된다. 실험을 통하여 이 자구의 자기화 방향으로 자장을 걸어주면 걸어주는 전류크기와 전류방향의 영향을 받음을 보인다. 이 실험 결과는 전류에의해 중앙에 형성된 자구가 전류의 증감함에따라 변화하는 자구크기로 설명할 수 있다. 실험으로 측정된 자기감수율을 설명하기 위하여 미세 자기이론을 사용하였으며, energy 값을 구하기 위하여 간단한 model을 설정하였다. 이 model로부터 교류 자기감수율을 구할 수 있었으며, 이때 계산한 교류 자기감수율은 한 안정된 구조에서 다른 안정된 구조로 변화하는 전류를 제외한 거의 대부분 전류에 대하여 정량적으로 설명할 수 있었다.