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Controllability of rotation of magnetization vortex in Fe particles

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The controllability of rotational sense of the magnetization vortex was studied by Fresnel mode of Lorentz transmission electron microscopy. In iron particles of around 100 nm in diameter, magnetization vortex was found to be stable, and two different rotational senses, clockwise and counter-clockwise, of magnetization vortex were observed. In order to control the rotational sense of the vortex, gradient magnetic field was applied to the specimen by making use of the objective lens field of a TEM. The results have shown that for the examined 120 particles, one rotational sense increased 20% than the other after application of gradient field, although some particles behaved oppositely or remained unchanged.
Key words: Lorentz electron microscopy, magnetization vortex, rotational sense, gradient field

1. INTRODUCTION

The dot-bit magnetic recording, in which one bit-cell consists of an isolated magnetic particle, has been considered as promising next-generation high density recording method. In an isolated circular-shaped magnetic particle the competition among magneto-static energy, quantum exchange interaction and crystalline anisotropy determines the magnetization distribution. A number of studies have dealt with the dependence of the magnetization feature on particle size [1-3]. One unique characteristic of such magnetic particles is the formation of magnetization vortex, i.e. the magnetic flux is closed inside the particle to avoid free magnetic poles. For the evaluation of a characteristic of submicron magnetic particles, Lorentz transmission electron microscopy(LTEM) is a powerful means[4]. We have experimentally confirmed that magnetically isolated disc-like iron particles of certain sizes have magnetization vortices using several modes of LTEM, such as Fresnel, Foucault, and differential phase contrast modes. Two rotational senses of vortices (clockwise or counter-clockwise) were found equally in number. In this study we focus on the controllability of the rotational sense of the magnetic vortices and investigate the possibility of its application in developing a new recording method. We propose to control the rotational sense by applying a strong lateral field and then removing it in a direction vertical to the field as shown in Fig.1.

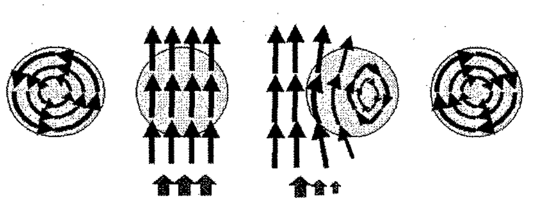

Fig.1 Schematic illustration of rotational control operation

2. EXPERIMENTAL

Iron particles were prepared by ion beam sputtering. Amorphous carbon films were used as support and protective top layer. Both materials were deposited in the same vacuum chamber without exposure to air. The (100) cleaved surface of NaCl single crystal was used as the substrate, which was removed by floating and skimming the film on water after deposition. The film was annealed at about 600°C to promote the grain growth up to a proper size.

The lateral gradient field was applied by making use of the objective lens field of a TEM(JEM2010). It is known that the objective lens produces strong magnetic field vertical to the observation plane. In our experiment, the specimen was tilted by an angle of 70°, namely the angle between the specimen and the magnetic field was 20°. We consider that the magnetic field was strong enough to make the specimen magnetically saturated in this direction. Then gradient field was exerted to the specimen by pulling out the specimen gradually from the field while keeping the specimen tilted. Tilting the specimen to opposite direction (ex. from 70° to -70°) and pulling it out in the same direction reverse the field direction in Fig.1, that is, the rotational sense of the magnetization vortex would be controlled by changing the tilt direction. With the specimen tilt of 70°, 94% of the field was effectively applied to the specimen in the lateral direction. In this manner, the rotational sense and its controllability of 120 particles of 100-200nm in diameter were investigated by Fresnel mode of LTEM.

We also conducted a simulative computation of magnetization distribution with the aid of MATLAB (copyright Mathworks Inc.).

3. RESULTS AND DISCUSSION

The shapes of the particles were characterized by scanning transmission electron microscope as ellipsoid, or spheroid, and there was a relatively wide particle size distribution.

Under-focused Fresnel images of the Fe particles after applying the two different gradient fields are shown in Fig.2. The bright spot at the center of the particle corresponds to the center of the magnetic vortex, which is equivalent to the domain wall in a magnetic domain structure. The clockwise vortex exhibits a bright spot

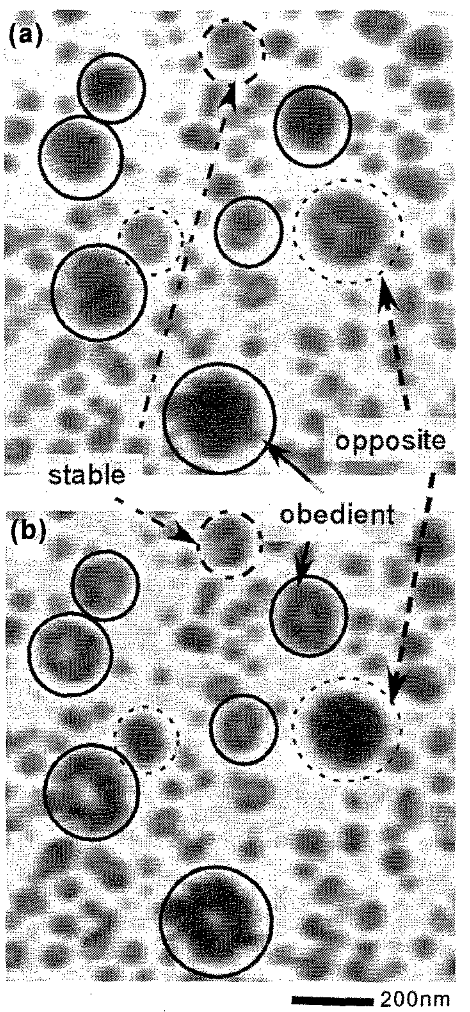

Fig.2 The Fresnel images of iron particles after application of gradient field for counter-clockwise(a), and that for clockwise(b).

in under-focused images, on the other hand the counter-clockwise vortex exhibits a dark spot. We have confirmed that the particles with sizes of 100-200 nm tended to have stable magnetic vortex structure and the rotational sense of such a vortex was readily recognizable.

As shown in Fig.2 the rotational sense of some particles changed following the controlling operation (comparing the particles indicated by solid circles between Fig.2(a) and (b)), while others behaved oppositely or remained unchanged (indicated by dotted and chained circle respectively). The statistic examination results of 120 particles (100-200 nm) subjected to repeated reversal procedure have shown that the clockwise vortex increased by 20% after "clockwise operation". We also found that the reversal of the rotational sense was well reproducible. This is also true for the particles which opposed to the operation. That is some particles always behave in accordance with the applied gradient field (as shown in Fig.1), and some particles always behave oppositely.

A possible reason for the opposite behavior is the intrinsic magnetic anisotropy. Because of the deviation from the perfect circular shape of the particle, shape anisotropy could be induced. Besides, crystalline anisotropy may not be negligible although pure iron has a low anisotropy constant. The anisotropy could cause preferential magnetization orientation in certain part of a particle which would determine the whole magnetization distribution, or the rotational sense of the vortex. In our method of applying the gradient field, the direction of the field vector was changed by tilting the specimen to opposite direction while the direction of field removal was fixed. In the case that after saturation the magnetization at one side of the particle persisted, where the field is weaker than the other side (Fig.1-3), the vortex would evolve from the other side where the field is stronger. Thus the rotational sense could follow the direction of external field rather than that of field gradient.

We have studied another possibility by computing the magnetization distribution during the rotational control operation, and have conducted a simulation for an isotropic circular particle exerted in a gradient field. A vortex particle, which has a stable magnetic vortex at zero field, was prepared and was confirmed to exhibit a typical magnetization curve as shown in previous work[1-3]. The particle was assumed to have no crystalline anisotropy and consist of two-dimensionally distributed magnetic clusters. The computation showed that the magnetization rotation would be opposite to the

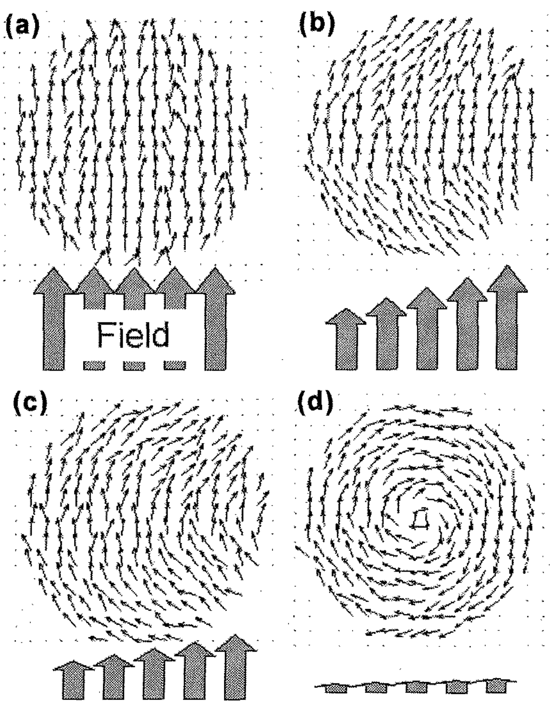

Fig.3 Simulated rotational operation on a circular particle. The thin arrows represent the magnetization inside the particle and the thick ones external field. After saturation(a), the field was removed with small gradient(b,c). The resulting rotation is opposite to the counter-clockwise intention(d).

intended sense when the field gradient is too small (Fig.3). After saturation, a gradient of the field was generated, and then the intensity of the field was decreased. The magnetization in the part of the particle where the field was stronger kept in the same direction with the external field while that of the other part curved in order to avoid formation of magnetic poles. Eventually, as shown in Fig.3, the magnetization tends to rotate clockwise although the applied lateral gradient field was intended to be the counter-clockwise operation. Note that the direction of the field gradient is opposite to that of Fig.1 while the resulting vortex exhibits the same rotational direction as Fig.1. In our experiment, the field gradient might not be large enough to realize the ideal operation (Fig.1) on all the particles.

It is known that the magnetization vortex state becomes less stable as the diameter of the particle becomes smaller and there is critical size where the magneto-static energy of the single domain state is equivalent to the spin exchange energy of the vortex. In case of a spherical iron particle, this critical diameter has been estimated to be around 32nm[5], although a particle of this size is difficult to be experimentally examined. With the magneto-crystalline anisotropy, a single domain state would be more stable for a single crystalline particle. In case of flat disc-shaped particles, it has been shown that the larger the thickness/diameter ratio becomes, the smaller the size limit becomes [1]. However, by applying homogeneous external field, such as in magnetization curve measurement, only the single domain state may appear [2] even when the vortex state is energetically the most stable magnetic structure. In order to experimentally investigate the stability of magnetic vortices, a strong gradient field should be applied to the specimen instead of using a uniform field.

Since one particle can have two different magnetic states, clockwise magnetic vortex or counter-clockwise, and the possibility to control the rotational sense has been proved, a vortex can be used as a recording bit. In this recording method arrays of very closely-packed dots would be allowed because there is no stray field from the neighboring particles. In addition the size of the particle with stable vortex structure can be reduced by use of isotropic material. The lateral field gradient could be easily produced by the small recording head with strong field. Thus we consider that the magnetic vortex has potential possibility to be applied in high density magnetic recording.

4. CONCLUSION

Magnetization vortices were confirmed on iron particles, and were basically able to be controlled by external lateral gradient field. Although the sense of the magnetic particles were likely to behave oppositely under improper conditions such as large magnetic anisotropy or small field gradient, the possibility of new recording method using the rotational sense of the magnetic vortex has been indicated.

5. ACKNOWLEDGEMENT

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