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# Magnetic Vortex Core Observation in Circular Dots of Permalloy

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Spin structures of nanoscale magnetic dots are the subject of increasing scientific effort, as the confinement of spins imposed by the geometrical restrictions makes these structures comparable to some internal characteristic length scales of the magnet. For a vortex (a ferromagnetic dot with a curling magnetic structure), a spot of perpendicular magnetization has been theoretically predicted to exist at the center of the vortex. Experimental evidence for this magnetization spot is provided by magnetic force microscopy imaging of circular dots of permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) 0.3 to 1 micrometer in diameter and 50 nanometers thick.

*Keyword:* Magnetic vortex / MFM / Submicron magnetic dot / Turned-up magnetization core

Ferromagnetic materials generally form domain structures to reduce their magnetostatic energy. In very small ferromagnetic systems, however, the formation of domain walls is not energetically favored. Specifically, in a dot of ferromagnetic material of micrometer or submicrometer size, a curling spin configuration (that is, a magnetization vortex) has been proposed to occur in place of domains. When the dot thickness becomes much smaller than the dot diameter, usually all spins tend to align in-plane. In the curling configuration, the spin directions change gradually in-plane so as not to lose too much exchange energy, but to cancel the total dipole energy. In the vicinity of the dot center, the angle between adjacent spins then becomes increasingly larger when the spin directions remain confined in-plane. Therefore, at the core of the vortex structure, the magnetization within a small spot will turn out-of-plane and parallel to the plane normal. Although the concept of

such a magnetic vortex with a turned-up magnetization core has been introduced in many textbooks [1], direct experimental evidence for this phenomenon has been lacking. That is because, as suggested by theoretical calculations, the size of the perpendicular magnetization spot at the vortex core should be fairly small. So, it is impossible to distinguish a fraction of perpendicular magnetization from the surrounding vortex magnetic structure with conventional magnetization measurements.

We have reported magnetic force microscopy (MFM) measurements on circular dots of permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) and given clear evidence for the existence of a vortex spin structure with perpendicular magnetization core [2]. In MFM, a low-moment ferromagnetic tip of CoCr was used to minimize the effect of stray fields. Sample scans were taken in air at ambient temperature. An MFM image of an array of  $3 \times 3$  dots of permalloy  $1 \mu\text{m}$  in diam-

## SOLID STATE CHEMISTRY — Artificial Lattice Alloys —

### Scope of research

*By using vacuum deposition method, artificial multilayers have been prepared by combining various metallic elements. The recent major subject is an interplay of magnetism and electric transport phenomena such as the giant magnetoresistance effect. Fundamental magnetic properties of metallic multilayers have been studied by various techniques including Mössbauer spectroscopy using Fe-57, Sn-119, Eu-151 and Au-197 as microprobes, and neutron diffraction. Microstructured films such as wires and dots were successfully prepared by electron-beam lithography and novel magnetic and transport properties are investigated.*



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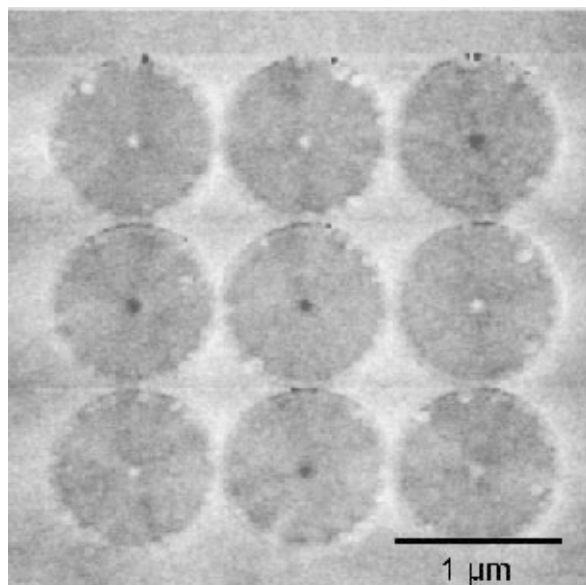
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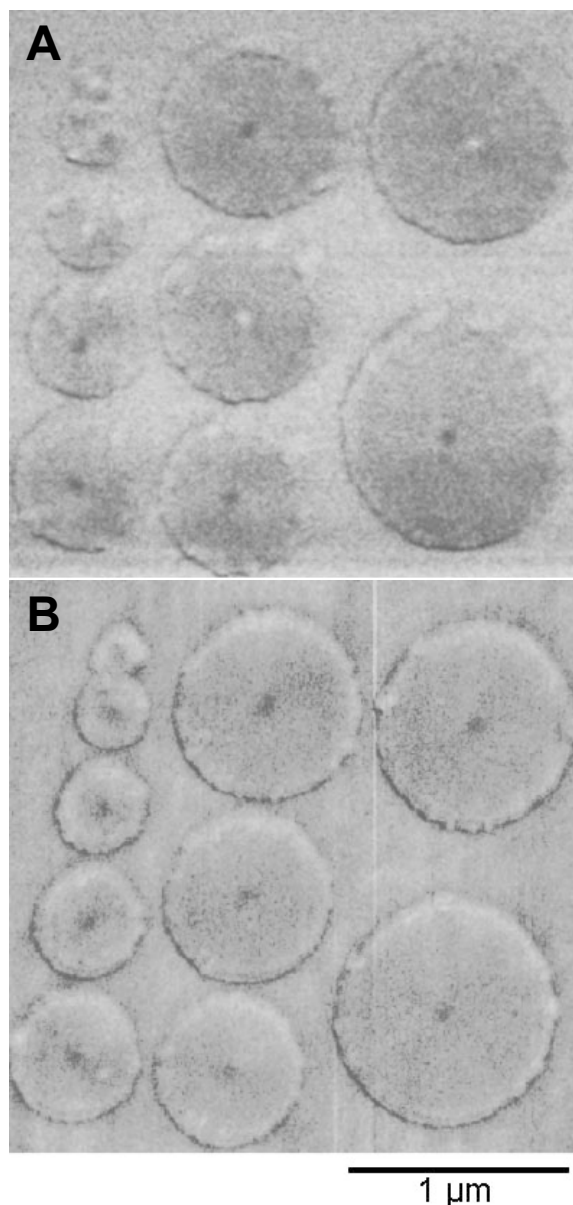


**Figure 1.** MFM image of an array of permalloy dots 1  $\mu\text{m}$  in diameter and 50nm thick.

eter and 50 nm thick is shown in Fig. 1. For a thin film of permalloy, the magnetic easy axis typically has an in-plane orientation. If a permalloy dot has a single domain structure or shows a domain pattern, in MFM a pair of magnetic poles reflected by a dark and white contrast should be observed in either case. In fact, the image shows a clearly contrasted spot at the center of each dot. It is suggested that each dot has a curling magnetic structure and the spots observed at the center of the dots correspond to the area where the magnetization is aligned parallel to the plane normal. However, the direction of the magnetization at the center seems to turn randomly, either up or down, as reflected by the different contrast of the center spots. This seems to be reasonable, as up- and down-magnetizations are energetically equivalent without an externally applied field. The image shows simultaneously that the dot structures are of high quality and that the anisotropy effective in each dot is negligibly small, which is a necessary condition to realize a curling magnetic structure. (The spots in Fig. 1 around the circumference of each dot are artifacts caused by the surface roughness, mainly resulting from unremoved fractions of the resist layer.)

MFM scans were also taken for an ensemble of permalloy 50nm thick dots with varying diameters, nominally from 0.1 to 1  $\mu\text{m}$  (Fig.2). These images were taken after applying an external field of 1.5 T along an in-plane direction (Fig.2A) and parallel to the plane normal (Fig.2B). Again, the two types of vortex core with up- and down-magnetization are observed for dots larger than 0.3  $\mu\text{m}$  in diameter (Fig.2A). In contrast, after applying an external field parallel to the plane normal, all center spots exhibit the same contrast (Fig. 2B), indicating that all the vortex core magnetizations have been oriented into the field direction.

From the above results, there is no doubt that the contrast spots observed at the center of each permalloy dot



**Figure 2.** MFM image of an ensemble of 50-nm-thick permalloy dots with diameters varying from 0.1 to 1  $\mu\text{m}$  after applying an external field of 1.5 T along an in-plane direction (A) and parallel to the normal(B).

correspond to the turned-up magnetization of a vortex core. To resolve a vortex core by MFM, it is necessary to pin the position of the core so that it is not affected by a stray field from the tip. In the experiments reported above, the vortex cores apparently have been so stable that a clear contrast appears in the MFM imaging process. Magnetic vortices are novel nanoscale magnetic systems, and it will be of great importance in the near future to study the dynamical behavior of turned-off magnetizations.

#### References

1. A. Hubert and R. Schafer, *Magnetic Domains* (Springer, Berlin, 1998)
2. T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, T. Ono, *Science* 289(2000)930