Anisotropy characteristics in a Permalloy film induced by a nonuniform magnetic field

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Inhomogeneities were observed for the first time in the magnetic structure of a thin Permalloy film, induced by a strongly nonuniform magnetic field applied in the plane of the substrate during fabrication of the samples. The films were obtained by vacuum deposition using a molecular-beam epitaxy system. A nonuniform field was created on the substrate using four samarium–cobalt magnets. The anisotropy of local sections of the samples was measured using a scanning-ferromagnetic-resonance spectrometer. A strong correlation was observed between the distribution of the magnitude and direction of the local magnetic anisotropy of the film and the magnetic-field distribution in the plane of the substrate. [S1063-7834(98)02407-1]

It is a well-established fact that polycrystalline Permalloy films deposited in an external magnetic field exhibit uniaxial magnetic anisotropy. In this case, the uniformity of the applied field in many respects determines not only the dispersion of the angular direction of the axis but also the magnitude of the anisotropy. It is also known that uniaxial anisotropy also occurs in films in the absence of a magnetic field when an atomic flux is obliquely incident on the substrate.[1] In this case, the axis of anisotropy is oriented in the plane of the film perpendicular to the direction of the atomic flux and the magnitude of the anisotropy is mainly determined by the angle of incidence of the atoms and the substrate temperature during deposition.

The Permalloy films studied here were deposited in a highly nonuniform magnetic field with a comparatively small average angle of deflection of the atomic flux from the normal to the substrate, $\varphi \approx 20°$. The aim of the study was to examine the correlation between the distribution of the magnetic anisotropy in the plane of the samples and the inhomogeneities of the applied magnetic field against the background of the uniaxial anisotropy of the oblique deposition process.

We investigated films of thickness $d=6.5$ nm, obtained by vacuum deposition using an Angara molecular beam epitaxy system, specially modified to deposit magnetic materials.[2] Permalloy having the composition $Fe_{20}Ni_{80}$ was evaporated from a crucible and deposited on a $50\times20\times0.5$ mm glass substrate heated to 473 K. The crucible was placed $\sim$200 mm from the center of the substrate. In this case, the atomic flux was incident at the angle $\psi \sim 65°$ to the long side of the substrate. The rate of deposition of the film was $\sim$0.03 nm/s.

The substrate was situated in a highly nonuniform magnetic field created by two pairs of rectangular samarium–cobalt magnets measuring $20\times5\times5$ mm and $10\times5\times5$ mm. The magnets were attached to a holder in pairs along the long sides of the substrate and were positioned with the pairs facing each other (Fig. 1). The pair of larger magnets was oriented with unlike poles facing while the pair of smaller magnets had like poles facing. As a result, the planar component of the magnetic field on the substrate varied not only in magnitude between 0 and 2.0 kOe but also in direction. Figure 1 shows the distribution of the field lines on the substrate obtained by a powder method.

The distribution of the magnetic inhomogeneities in the plane of the samples was measured using a scanning-ferromagnetic-resonance spectrometer developed and built at the L. V. Kirensky Institute of Physics.[3] A noteworthy feature of this spectrometer is that ferromagnetic-resonance signals can be recorded over a wide frequency range 0.1–5.0 GHz by means of a set of interchangeable microwave heads. The area of the local region being measured is determined by the diameter of the aperture in the screen of a microstripe cavity in the head. In this experiment we used a head with a 1 mm diameter aperture and a pump frequency $f=2.2$ GHz. At this frequency all the samples have an average ferromagnetic-resonance line width $\Delta H \approx 8$ Oe which varies within $\pm10\%$ from one point to another over the area of the film.

Figure 2 gives the distribution of the resonant field $\mathbf{H}_r$, which is directed along the long side of the substrate in the experiments, over the plane of the film. The orientation of the substrate corresponds to that shown in Fig. 1, i.e., during deposition the section of the film with negative x coordinates was situated in the field of the repelling magnets. In order to eliminate edge effects, the measurements were only made in the central part of the sample measuring 14×40 mm. It can be seen that the resonant field is nonuniform and varies by almost 20 Oe over the area of the film.

Note that, for a control sample deposited without any magnets, the resonant field decreases monotonically with increasing x and y coordinates, varying only by 5 Oe. As a result, the set of measured $\mathbf{H}_r(x,y)$ values forms a surface resembling an inclined plane. The slight nonuniformity of the resonant fields observed in the plane of the control sample is a consequence of the relationship between the di-

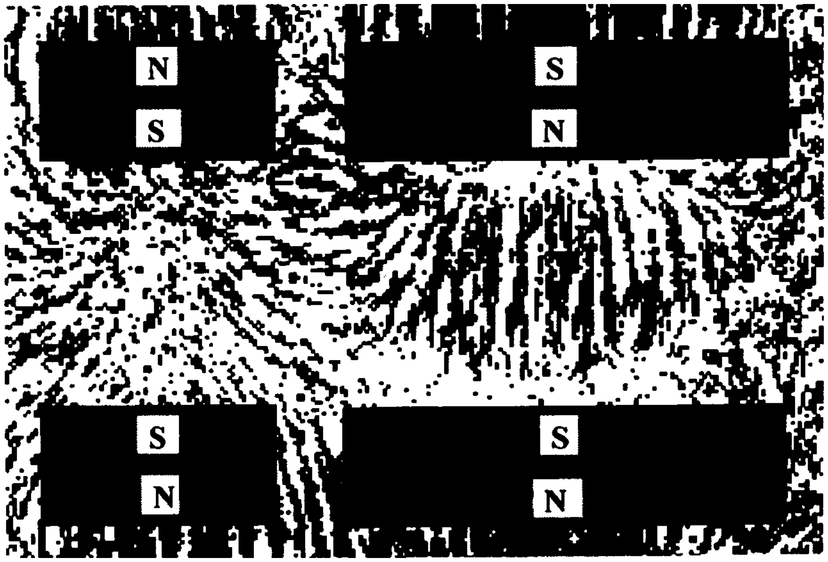

FIG. 1. Pattern of magnetic field lines from four samarium–cobalt magnets positioned along the long sides of the substrate.

mensions of the substrate and the distance between the substrate and the crucible during deposition of the films. In this geometry, the angles of incidence of the atomic flux on the plane of the substrate clearly vary appreciably at various points, which produces a corresponding deviation in the direction of the axis of anisotropy and its magnitude.

The magnitude of the anisotropy field $\mathbf{H}_k$ for local sections of the samples and the orientation of the axes of easy magnetization α_k were determined from the dependences of $\mathbf{H}_r$ on the angular direction α of the magnetic field, measured relative to the long side of the substrate. Figure 3 gives angular dependences of the resonant field for five sections of the sample distributed along the line $y=-7$ mm (see Fig. 2). The numbers of the curves correspond to the x coordinate of the particular local section.

It can be seen that all the curves have two minima and two maxima, typical of uniaxial magnetic anisotropy. The difference in the position of the minima on the $\mathbf{H}_r(\alpha)$ curves indicates that the direction of the axis of easy magnetization varies from one section of the film to another. The variation in the difference between the maximum and minimum values of the resonant fields on the curves indicates that the anisotropy is nonuniform. It was established that the orientation of the axis of anisotropy varies within 60° over the area of the sample while the anisotropy field varies almost eightfold. Table I gives the angular directions and the magnitude of the field of uniaxial magnetic anisotropy measured for several local sections along the edges of the sample and at its center.

For the control sample at the center of the film, we find $\mathbf{H}_k \approx 15$ Oe, and the axis of easy magnetization is inclined at an angle $\alpha_k \approx 45°$ to the long side of the substrate, which is consistent with the angle of incidence of the atomic flux on this section during deposition. A small deviation of the angle of incidence of the atoms on other sections of the substrate caused by the deposition conditions leads to a monotonic variation in the orientation of the axis of anisotropy within $\pm 10°$. In this case, the anisotropy field also varies monotonically over the area of the film, only by a factor of two.

An analysis of experimental results using samples deposited in a nonuniform magnetic field and control samples

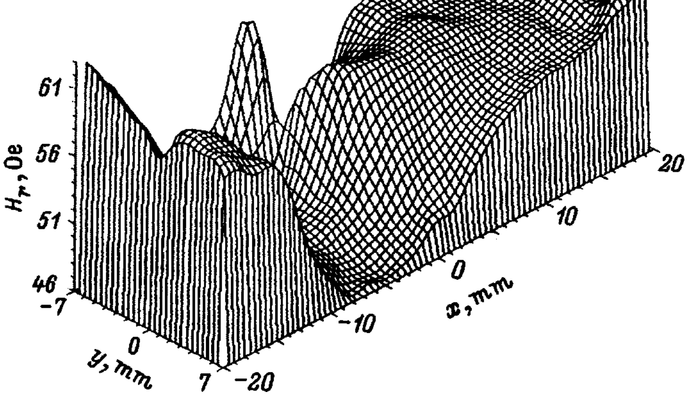

FIG. 2. Distribution of ferromagnetic resonance field over the area of the film.

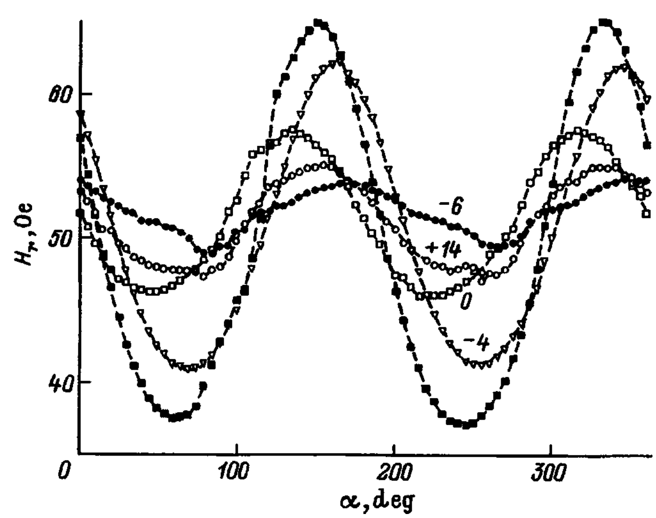

FIG. 3. Angular dependences of the resonant field obtained at five points along the line $y=-7$ mm. The numbers on the curves correspond to the x coordinate.

reveals a clear correlation between the distribution of the magnitude and direction of the uniaxial anisotropy over the plane of the film and the distribution of the magnitude and direction of the applied magnetic field. In particular, in the region of the film $x \geqslant 10$ mm (Fig. 2) which was deposited in the strongest, comparatively uniform magnetic field, the direction of the axis of anisotropy and its magnitude show only slight variations along the x and y coordinates and are mainly monotonic, almost as in the control sample. However, compared with the control sample, the axes of anisotropy in local sections were turned through almost 20° in the direction of the orienting magnetic field and the magnitude of the anisotropy was reduced substantially (see $x=14$ mm column in Table I).

In the rest of the film, which was deposited in the nonuniform field produced by the repelling magnets (Fig. 1), the orientation of the axis of easy magnetization and the magnitude of the anisotropy exhibited stronger nonmonotonic variations. In this part of the sample the angle of deflection of the anisotropy axis increases toward the edges of the substrate, having a well-defined minimum in the central part of the film on the line $y=0$ (see Table I).

TABLE I. Angles α_k and fields of uniaxial magnetic anisotropy in the sample.

y, mm	x, mm							
	−16		−6		0		14	
	H_k, Oe	α_k, °	H_k, Oe	α_k, °	H_k, Oe	α_k, °	H_k, Oe	α_k, °
−7	13.8	62.1	2.36	82.8	8.5	28.7	3.8	76.4
0	11.5	38.9	8.34	37.8	7.64	37.8	6.57	61.6
7	17.5	55.4	13.7	37.9	11.3	28.0	5.35	46.4

As was to be expected, the parameters of the uniaxial magnetic anisotropy of this film $\mathbf{H}_k$ and α_k differ only slightly from the parameters of the control sample in the sections deposited in weak magnetic fields. This indicates that the formation of uniaxial anisotropy in each section of the film in this experiment takes place under conditions of strict competition between two mechanisms: a mechanism associated with the inclined incidence of the atomic flux on the substrate and an orientational mechanism caused by the external static magnetic field. The measurements have shown that the magnetic field can not only deflect the direction of the anisotropy axis formed by the inclined incidence during the film growth process but can also substantially reduces its magnitude. This effect was observed most clearly in the section of the film with the coordinates (–6; –7) (see Fig. 2 and Table I). This section was deposited in a strong field generated by the unlike poles of two magnets positioned on either side of the substrate (Fig. 1).

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