Magnetic Anisotropy of Epitaxial Iron, Nickel, and Cobalt Films

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Measurements were made of the first constant of crystal anisotropy K_1 and $K_\perp = K_N - 2\pi J_S^2 - K_1$ of the films, Fe, Ni, and Co, epitaxially grown on NaCl, LiF, and MgO crystals. Here K_N is the constant of anisotropy perpendicular to the plane of a film, and J_S is the saturation magnetization.
The conclusion is drawn that the fact that $K_\perp \neq 0$ in films cannot be explained only by stress. Stress accounts only for the difference between K_1 of single-crystal films and K_1 of in massive single crystals.

veral authors[1–6] have measured the first magneto-
alline anisotropy constant K_1, and the constant
of magnetic anisotropy normal to the film plane.
$K_\perp = K_N - 2\pi J_S^2 - K_1$, where K_N is the directly
sured constant, and J_S is the saturation magneti-
on. We have carried out a systematic investigation
he effect of the substrate (NaCl, LiF, and MgO
tals) on K_1 and $K_\perp$ of Fe, Ni, and Co single-crystal
s.

he films were prepared by thermal evaporation in a
uum of 10^{-4} Torr. The rate of the deposition was
ut 100 Å/sec, and the range of thickness 200–1500 Å.
substrate temperature during the evaporation of
and nickel films was 120–140°C, of cobalt films
30°C.

able I shows the values of $K_\perp$ and K_1 of film as de-
ited on NaCl substrates, and removed from these
strates. It also shows $K_\perp$ and K_1 for films deposited
LiF and MgO. As is seen from this table, the value
$K_\perp$ of single-crystal Ni films approaches zero upon
noval from the NaCl substrate. This fact indicates
presence of stress in the films on NaCl crystals and
dominating role in the establishment of $K_\perp$.

Freedman[3] showed that stresses in single-crystal Ni
ms on NaCl crystals are compressive and arise from
difference of thermal expansion coefficients of NaCl
d Ni. By analogy, compressive strains must also
se in Fe and Co films on the NaCl crystals and in
, Ni, and Co films on the LiF crystals.

Fe films on MgO crystals cannot be in a compressive
ate because the thermal expansion coefficient of MgO
very small. Electron diffraction investigations showed
at crystal lattices of Ni and Co films on MgO are
a tensile state. The reason for the tensile stress of
ch films is the misfit of the lattices of the film and
bstrate.[7] On surfaces of Ni/MgO films thicker than
400 Å cracks were observed; these cracks lower the
rage stress in the film. On the Co/MgO films such
cracks were not seen. Another origin of tensile stress in Co/MgO films may be the formation of a surface layer containing impurities, i.e., O_2 or other gases, when the temperature of the film was high. Upon cooling the film, this layer prevents the rest of the film from contracting. The presence of this surface layer in Co/MgO films was demonstrated by electron diffraction.

TABLE I. Mean values $K_\perp$ and maximum values K_1 of films.

	$K_\perp \times 10^{-6}$ erg cm^{-3}			$K_1 \times 10^{-5}$ erg cm^{-3}		
	Fe	Ni	Co	Fe	Ni	Co
NaCl	−2.0	+0.8	−2.0	+3.0	−0.8	···
Glass	−1.0	0	−1.0	+3.4	−0.5	···
LiF	−3.0	+0.5	−2.0	+4.0	−0.9	−6.5
MgO	−2.0	−2.0	+2.0	+4.2	−1.0	−14.0

Since the average magnetostriction of Fe and cubic Co is positive, films of these metals in compression on the NaCl and LiF crystals must have negative values of $K_\perp$. This was actually observed (Table I). However, unlike Ni films, when Fe and Co films are removed from the NaCl crystals, $K_\perp$ does not assume a value close to zero, but remains negative and large in absolute value. Consequently, besides the strains mentioned above, there are other reasons for the existence of an easy axis perpendicular to the plane of the film, or alternatively a decrease in the saturation magnetization of the film. Evidently only such reasons can account for $K_\perp < 0$ of Fe films on MgO crystals. $K_\perp > 0$ of the Co/MgO films may be partially accounted for by tensile stresses.

By inserting P_2O_5 powder into the vacuum system, we obtained $K_\perp > 0$ for Fe and Co films on all substrates. The value of $K_\perp$ of these films decreased with time and often became negative in several weeks.

It has been suggested[6] that the reasons why the anisotropy normal to the film plane is less than for pure shape anisotropy ($2\pi J_S^2$), may be (1) shape of crystallites, pores, or other defects, or (2) surface anisotropy. Our observations indicate that at least one of the origins of the anomalous part of $K_\perp$ is the effect of gas atoms in the film. The investigation of this effect is not finished.

On the other hand, the effect of strains can account

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for the difference between K_1 in films and K_1 in bulk crystals. The removal of Fe films from NaCl crystals increases K_1 because the absolute value of the magnetostriction constant in easy [100] directions is larger than in hard [110] directions. In Ni films the absolute value of the magnetostriction constant in easy directions [110] is lower than in hard directions [100], and upon removal of these films from their substrate (NaCl), K_1 decreases.

We measured K_1 of Co/MgO and Co/LiF films at a temperature of $-190°C$. K_1 of Co/MgO film doubled its room temperature value, while K_1 of Co/LiF films showed very little change. This proves that the origin of the large value of K_1 is strain.

It follows from Table I that compressive stress in Ni films on LiF crystals and tensile stress in Ni films on MgO crystals cause nearly equal increases of K_1. At the same time, $K_\perp$ of these films greatly differ in their absolute value. The explanation is that tensile stress in Ni/MgO films is not uniform. The strains are large in the layer close to the substrate and become smaller moving away from it. Because of this nonuniformity of the strain, $K_\perp$ in such films apparently cannot be precisely calculated from the energy expression

$$E = K_\perp \sin^2\varphi,$$

and Chikazumi's method does not give accurate results.

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