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Brillouin Scattering and Diffracted MOKE from Arrays of Dots and Anti-Dots

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Abstract

The magnetic properties of nano-arrays have been investigated using Brillouin scattering, MOKE and Diffracted-MOKE techniques. The anisotropies in negative arrays are found to be due to the shape of the holes and not due to the array itself. The D-MOKE results allow us to extract the domain pattern at remanence.

In principle, it is possible to write down the magnetic energy of an array of particles or of a film with holes. This energy will contain contributions from the Zeeman term, crystalline anisotropy, shape anisotropies, exchange and dipolar coupling. The most challenging difficulty of this approach is that some of the terms, notably the dipolar fields due to shape anisotropies, are non-uniform and must be described locally. Micromagnetic calculations follow exactly this approach searching for the lowest-energy state of the system. However, these calculations require a knowledge of the strength of the various terms in the energy expression. Determining the importance of the various contributions is therefore of paramount importance in understanding the behavior of novel nano-array systems.

MOKE, diffracted-MOKE (D-MOKE), and Brillouin scattering are experimental techniques that have proved to be valuable in characterizing nano-arrays. MOKE and D-MOKE yield information on the magnetization hysteresis loops and are convenient substitutes for SQUID and other magnetometry techniques that are not always easy to apply to nano-arrays. Brillouin scattering provides information on the dynamic response similar to that obtained from FMR experiments but again having some advantages in dealing with small samples. Here we will describe the characterization of magnetic nano-arrays using these techniques.

One of the important questions in dot arrays is the role of inter-dot coupling. Point dipole calculations show that ground state is usually antiferromagnetic but details of the AF ground state depend on the orientation of the dipoles and the symmetry of the lattice. The estimated strength of the coupling for typical Fe or Co elements is, however, only a few Oe. In spite of the small coupling strength interdot coupling effects have been reported to date in a few instances.[1-3] In some cases the coupling is observed when the elements are in multiple domain states,[1-2] In Ref [3] coupling was found for a line of magnetic particles. However, our Brillouin and MOKE experiments[4] on mono-domain Fe dots showed that the magnon frequencies are quantitatively explained by conventional FMR theory with no interdot coupling and that shape anisotropy is likely to mask the effects of interdot coupling. Resolution of this issue requires further investigation and cannot be adequately addressed here.

There have only been a few investigations of negative arrays reported to date.[5-12] The majority of these have relied on magnetic force microscopy and micromagnetic calculations. Here we present the results of MOKE and Brillouin investigations of arrays with circular, elliptical and square holes on a square lattice. Because no theory of magnetization and magnons in negative arrays is yet available, the interpretation of our results is restricted to either qualitative considerations related to symmetry arguments, or to the formulation of simple approximations that attempt to describe the observed behavior. In this latter respect we will show that treating the arrays as anisotropic, continuous films provides a reasonable description of the results.

In Fig. 1 we show SEM images of the three samples to be discussed here. The thicknesses of the Fe films are 40, 60 and 60 nm, respectively. Details of the sample fabrication are given in [11 and 12]. In each of the samples, an unpatterned area surrounding the array was used as a reference. Brillouin spectra from the unpatterned and patterned areas of the array of circular holes (Fig. 1a) are shown in Figs. 2 a and b respectively. The spectra were recorded with a 5 pass interferometer so the two peaks in each spectrum are Stokes and anti-Stokes peaks. The similarity of the two spectra is indicative that the excitations are not dramatically affected by the holes in the array. For the unpatterned film, magnon peaks are expected from both the surface and a standing-wave (bulk) modes. For a film with uniaxial anisotropy, and the applied field along the easy or hard axis, the frequency of these modes can be approximated by[12]

$$(\omega/\gamma)^2 = [(H + D(\pi/L)^2 + 4\pi M)\ (H + D(\pi/L)^2 \pm 2H_a)]^{1/2} \qquad (1)$$

and

$$(\omega/\gamma)^2 = [(H + 4\pi M)\ (H \pm 2\ H_a)] + (2\pi M)^2\ [1 - \exp(-2qL)] \qquad (2)$$

where H is the applied field, γ is the gyromagnetic ratio, M the magnetization, L the film thickness, D the spinwave stiffness constant, q the wavevector probed in the experiment, and H_a the anisotropy field. In our array of circular holes the film thickness is such that the two modes have similar frequencies and are unresolved in the spectra. This overlap precludes any detailed interpretation of the Brillouin spectra. However, the hysteresis loops from this sample presented in [11] indicated that the unpatterned film had a small, in-plane, uniaxial anisotropy and that there was little change in the loop shapes when measuring on the array. Again indicating that the hole array does not greatly affect the magnetic properties of the film.

In Fig. 3 we show Brillouin spectra from the array with elliptical holes. These spectra were recorded with a tandem interferometer In this case the bulk and surface peaks are well resolved and can be fit to Eqs 1 and 2. The results of the fitting are shown in Fig. 4; the full and dashed lines correspond to the field applied along or perpendicular to the long axis of the ellipses. The unpatterned film has a small anisotropy with the easy axis perpendicular to the ellipse axis, in the patterned area the anisotropy is larger and is now along the ellipse axis. The fits to the data yield H_a = +40 and – 60 G for the unpatterned and patterned areas respectively. Magnetization data, shown in [12], yields H_a = <+50 and – 250 G. The internal consistency of the results for the unpatterned area is anticipated since Eqs 1 and 2 are expected to be valid. The discrepancy of the anisotropy extracted from magnetization and Brillouin data for the patterned area could be due to experimental uncertainties in analyzing the magnetization data or to the approximations of using Eqs. 1 and 2.

In Fig. 5 we show the frequency of the two modes observed in our array of square holes (Fig. 1 c), measured at a field of 0.5 kOe, as a function of rotation of the sample around its surface normal. The unpatterned area shows the expected behavior for a film with uniaxial anisotropy; the patterned area shows the same uniaxial anisotropy but superimposed with a four-fold anisotropy. Our magnetization results (Fig 6) do exhibit the uniaxial anisotropy but show no clear evidence for the four-fold perturbation.

Since all three samples have a square lattice, the measured anisotropies (viz. no anisotropy for circular holes, a uniaxial anisotropy for elliptical holes and a four-fold anisotropy for the square holes) provide a very strong indication that anisotropies are induced by the shape of the holes and not by the symmetry of the lattice.

In [11] it was shown, using D-MOKE, that the domain formation which occurs during magnetization reversal in the sample with elliptical holes, is very different when the field is along the long and short axes of the ellipses. It was shown there that the shape of the D-MOKE loops depends on the magnetic form factors that in turn depend on the size and shape of the domains.

In the square hole array D-MOKE loops also show that domain formation is different for different directions of the applied field. Figures 6 and 7 show the loops recorded on the 0^{th} and 1^{st} order diffracted beam. These loops, combined with the loops from 2^{nd} order, allow us to extract the shape of the domains that form during reversal. Figures 8 a and b are schematics of the domains that are present at remanence for the ϕ = 90° and 45° orientations of the sample. The ϕ = 135° orientation produces equivalent domains to those in Fig. 8b but domain formation for the ϕ = 0° (easy axis) is very different from those shown in Fig. 8a. The change in domain patterns for different field directions is consistent with the superposition of a uniaxial and a four-fold anisotropy in the array.

In summary, we have found that Brillouin scattering, MOKE, and D-MOKE techniques provide powerful and convenient tools with which to characterize magnetic nano-arrays. In arrays of Fe dots we have shown that the shape anisotropy of the individual elements plays a dominant role in determining the magnetic response of the array. In negative arrays we show that the anisotropy induced by the array is due to the shape of the individual elements and not by the symmetry of the lattice itself.

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Figures

1 SEM images of negative arrays. a) circular holes, b) elliptical holes, c) square holes

2 Brillouin spectra, recorded on a five pass interferometer, from our array of circular holes (Fig. 1a). a) unpatterned area, b) patterned area.

3 Brillouin spectra, recorded with a tandem interferometer, from our sample with elliptical holes (Fig. 1b). a) unpatterned area, b) patterned area.

4 Frequency vs field for the a) unpatterned and b) patterned areas of our ellipse array. Full and dashed lines are the fits according to Eqs. 1 and 2 for the field along the direction of the long and short axes of the ellipses.

5 Frequency vs. in-plane angle for our array of square holes. a) unpatterned area, b) patterned area.

6 0^{th} order MOKE loops recorded for various in-plane angles of our array of square holes.

7 1^{st} order D-MOKE loops recorded for various in-plane angles of our array of square holes.

8 Schematic of the domains at remanence in our array of squares for in-plane angles a) $\phi = 90°$ and b) $\phi = 45°$.

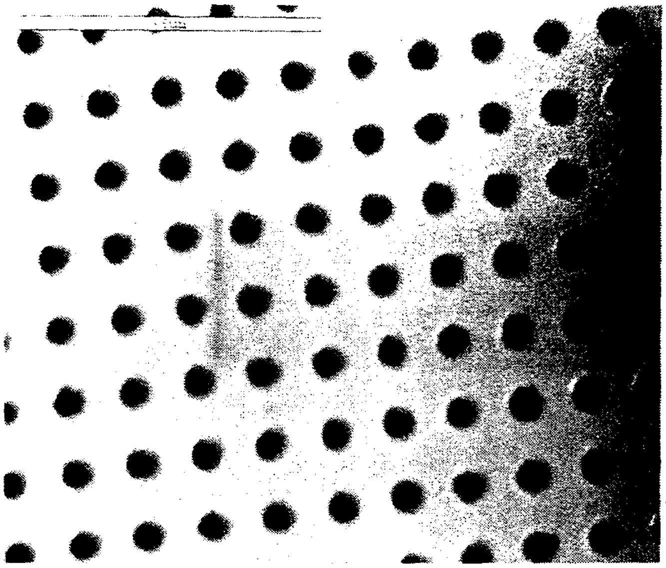


Fig1a

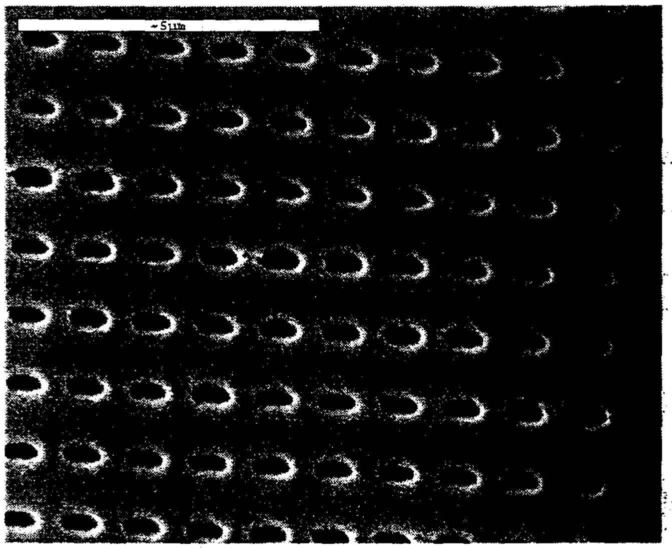


Fig1b

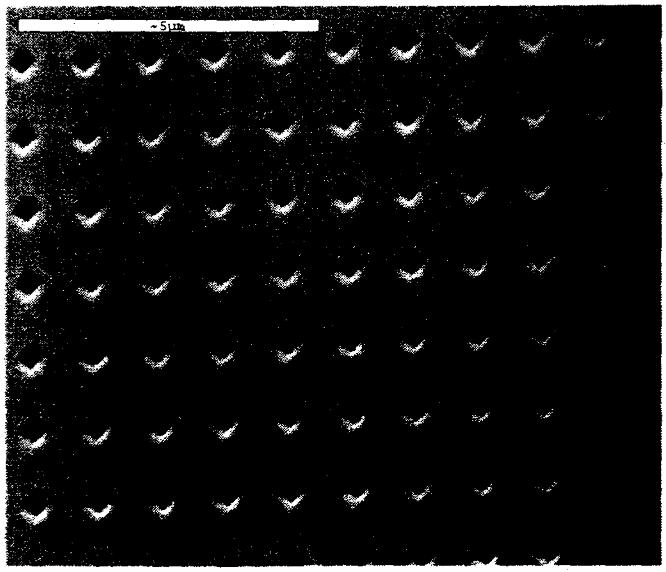


Fig1c

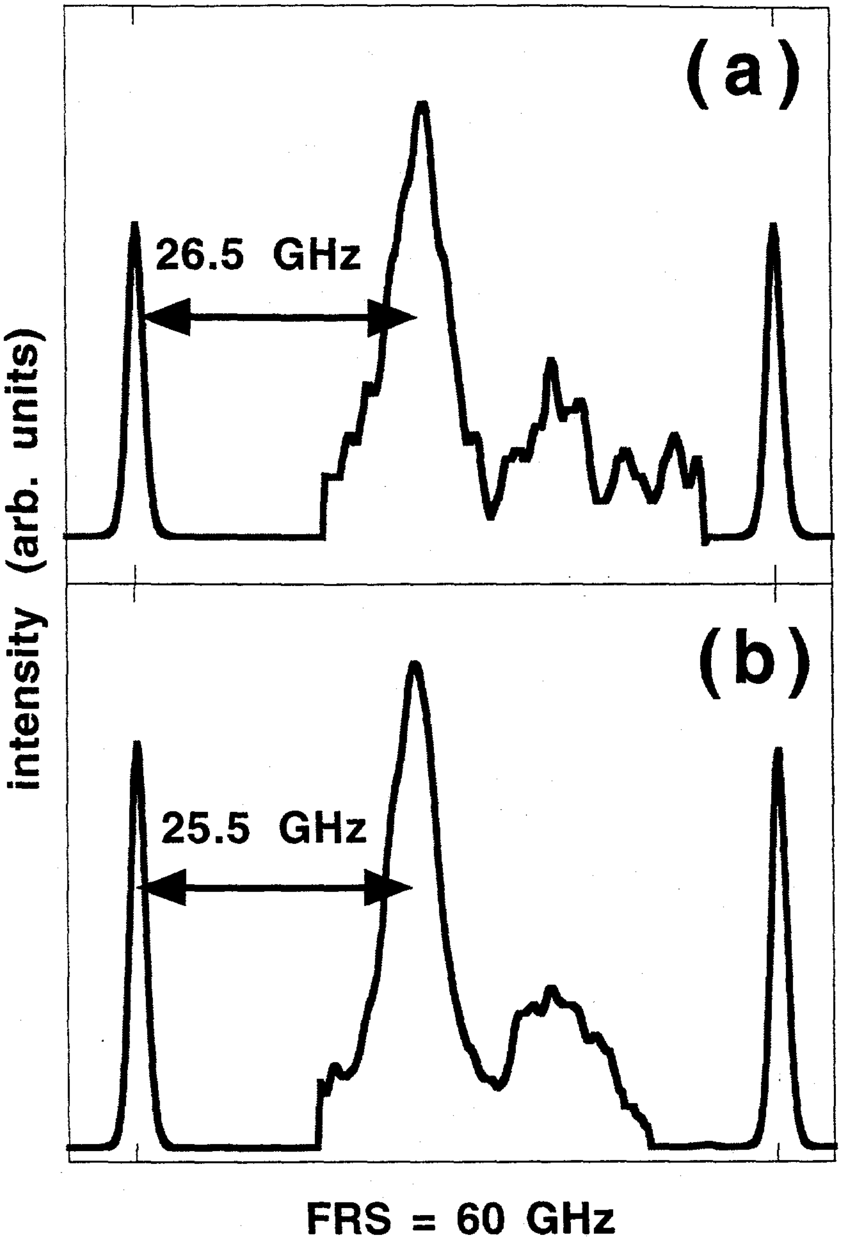


Fig 2

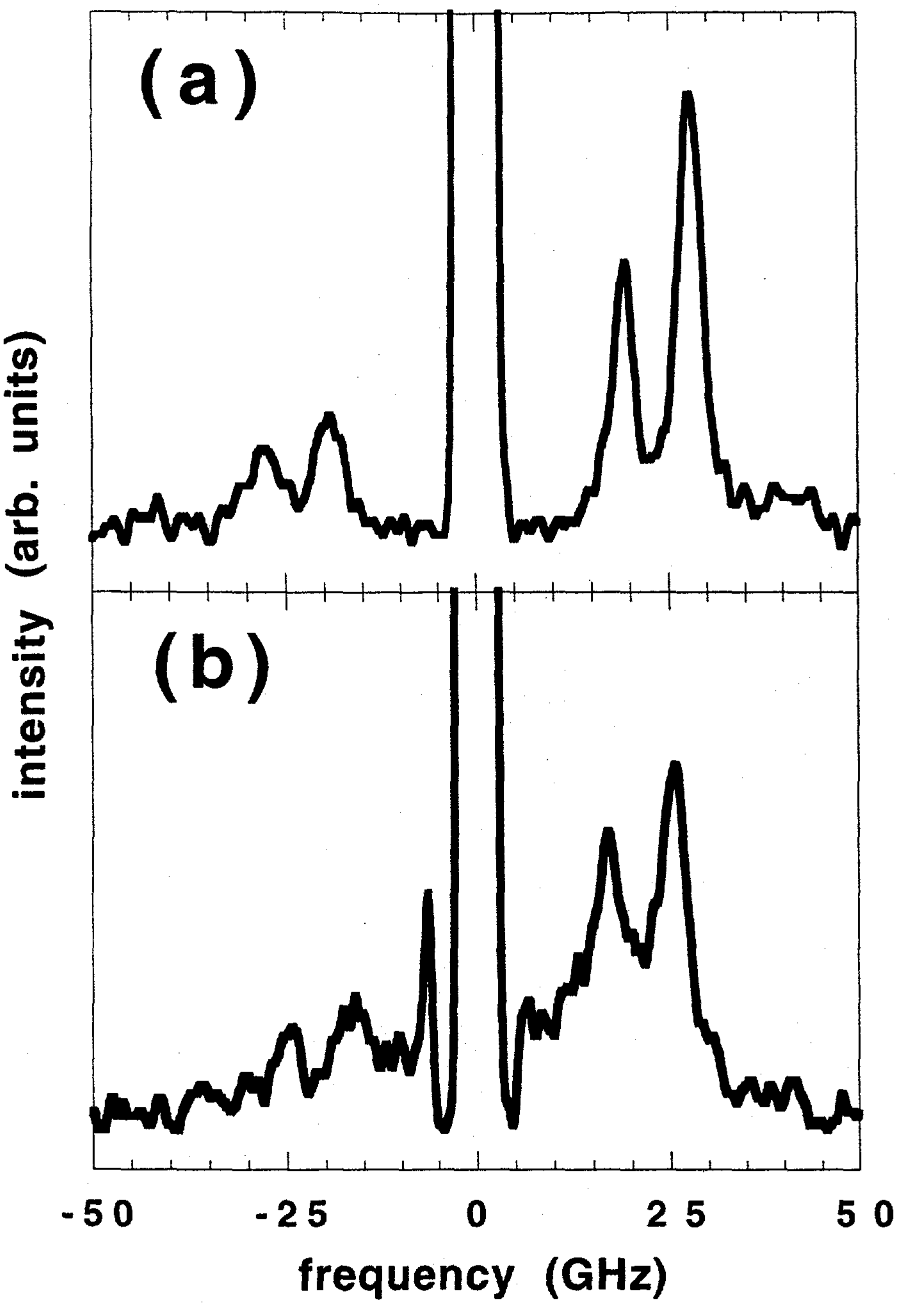


fig.3

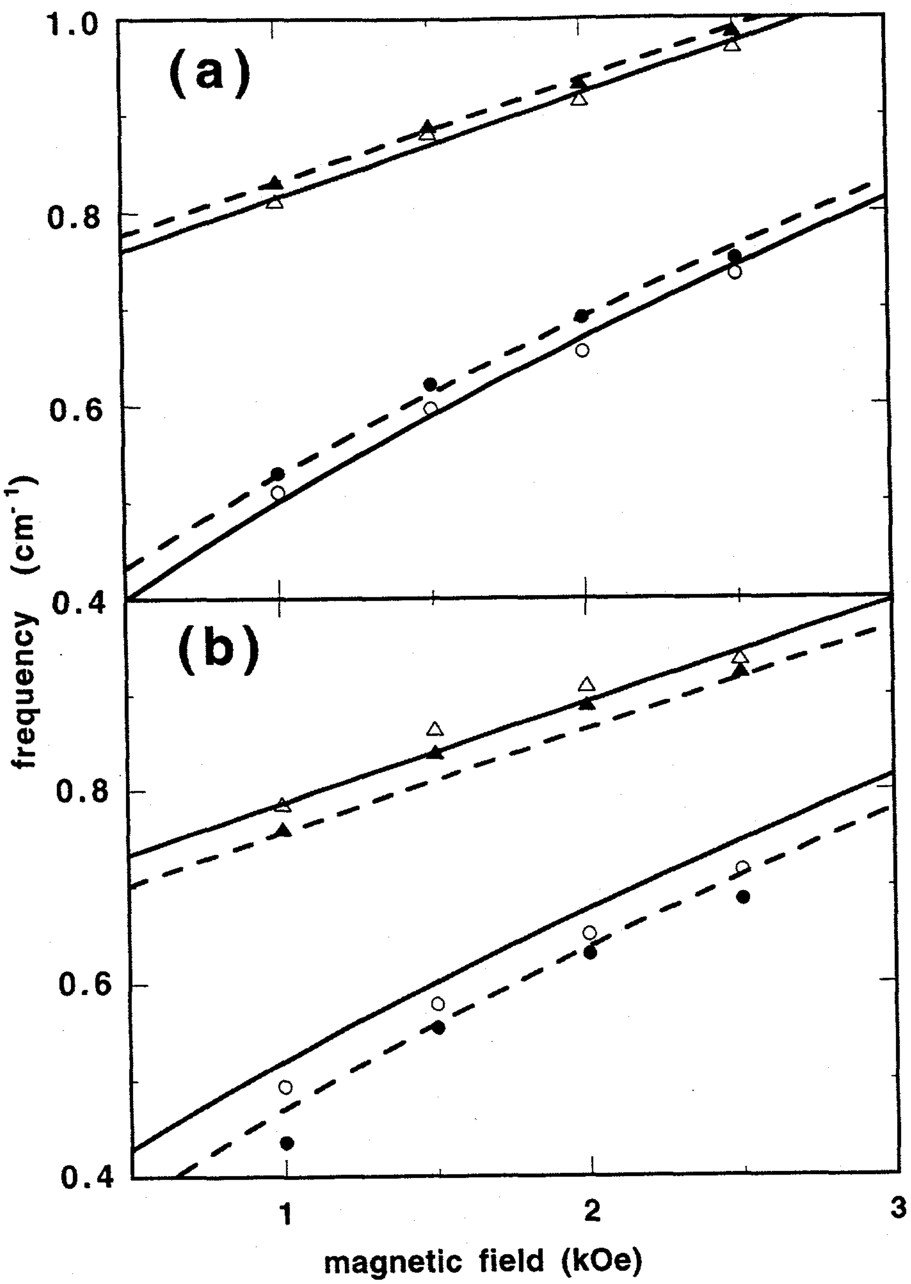
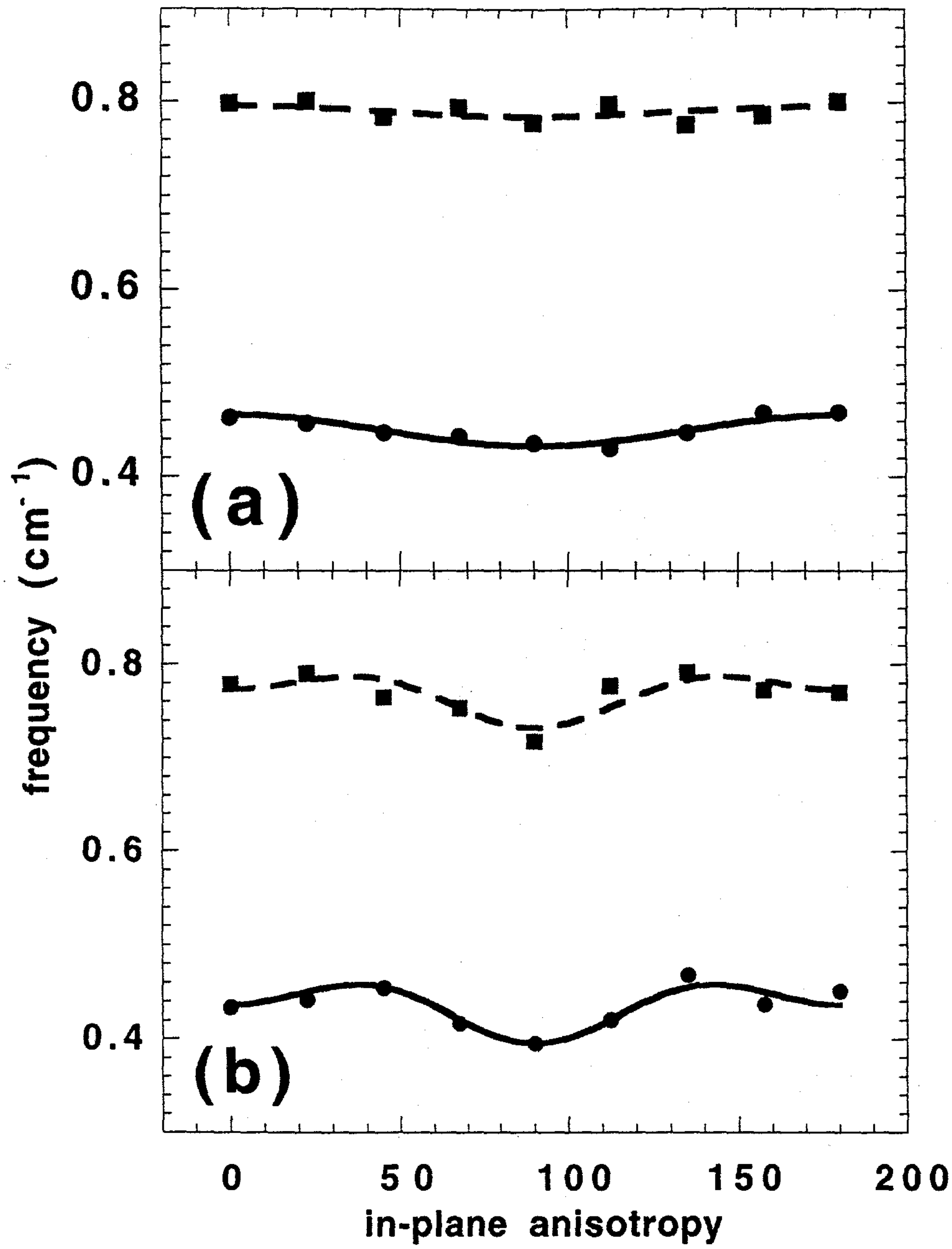


Fig 4


0.8
0.6
0.4
(a)
0.8
0.6
0.4
(b)
frequency (cm^{-1})
0
50
100
150
200
in-plane anisotropy

Fig

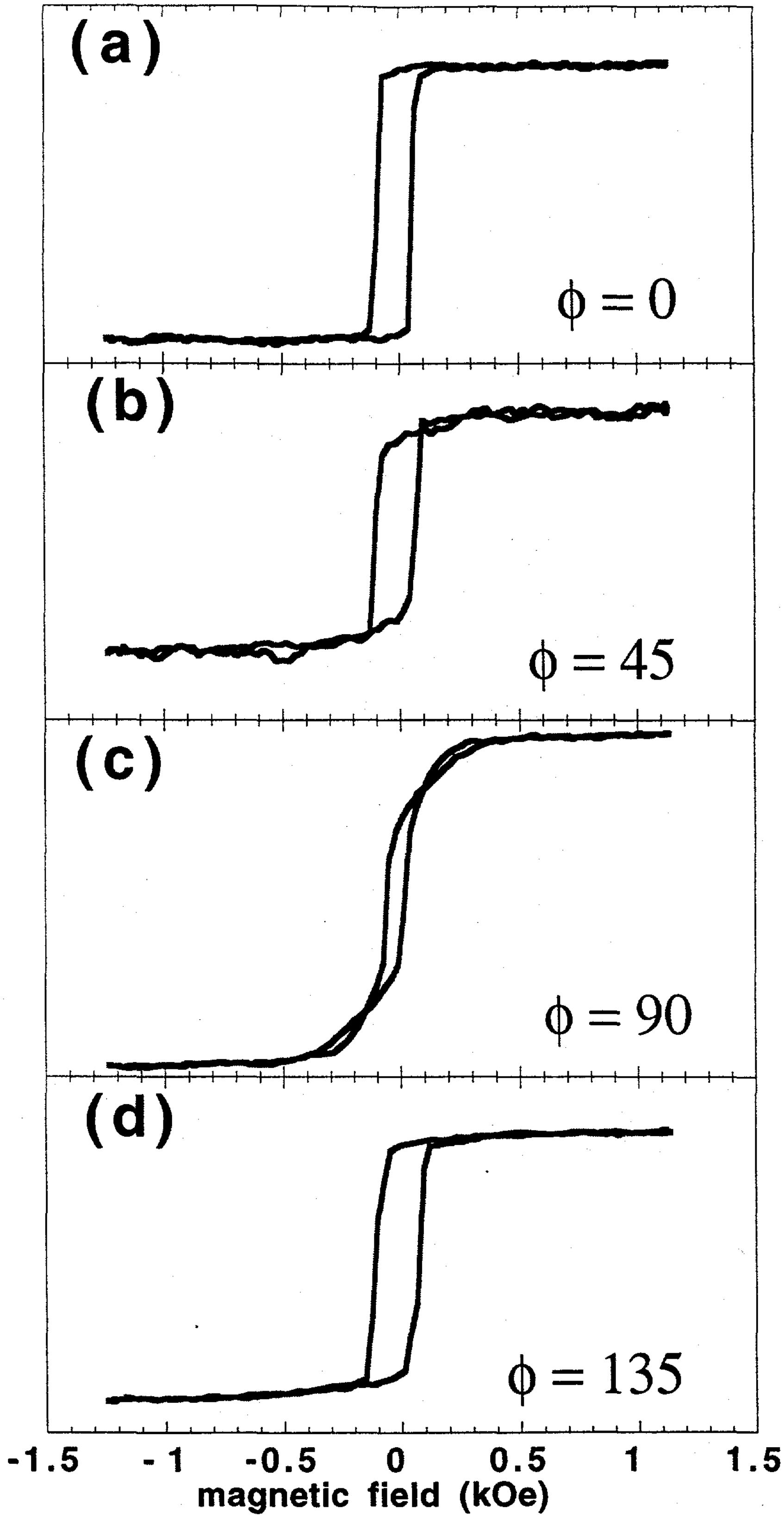


Fig 6

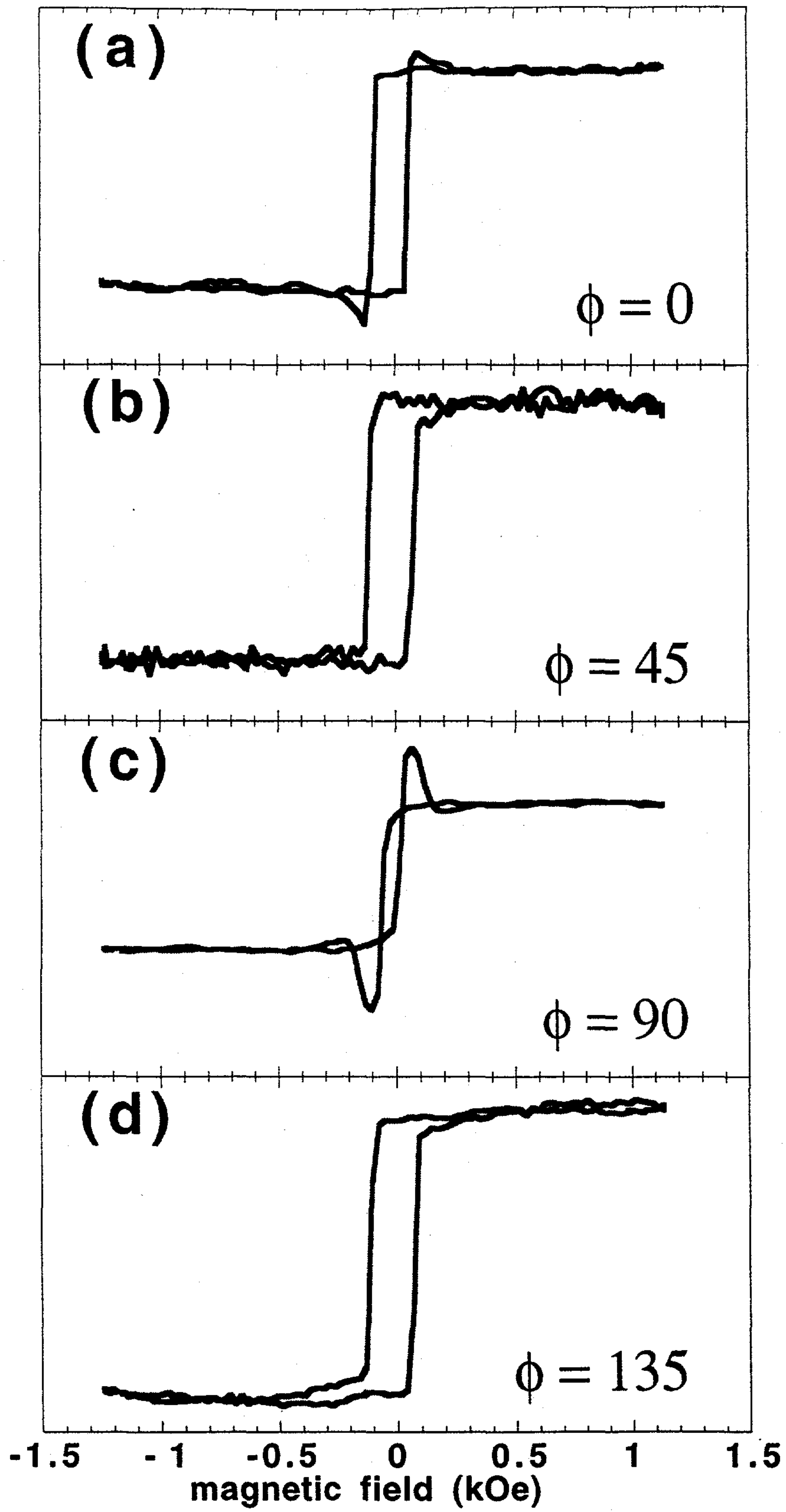
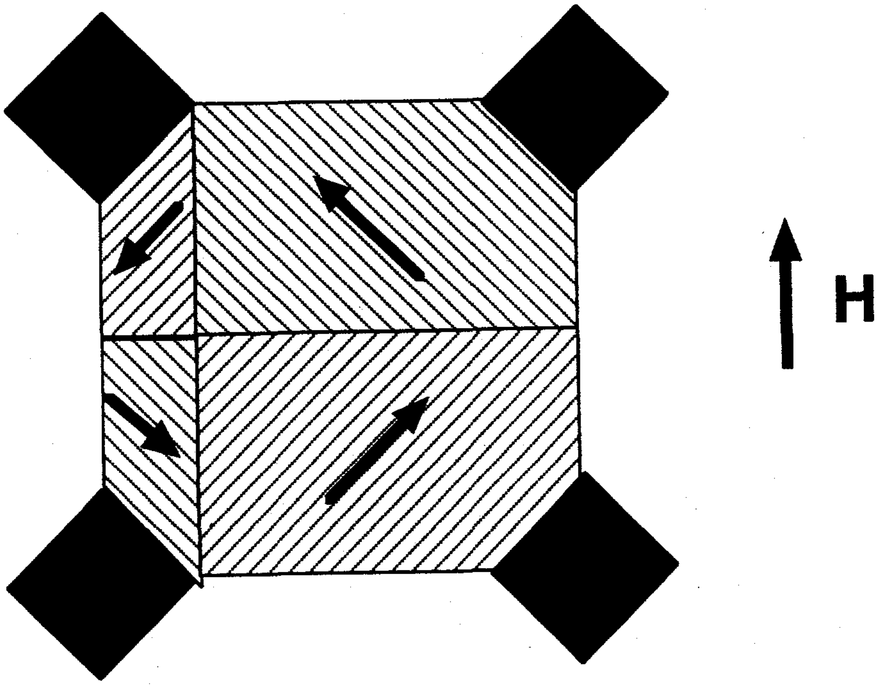
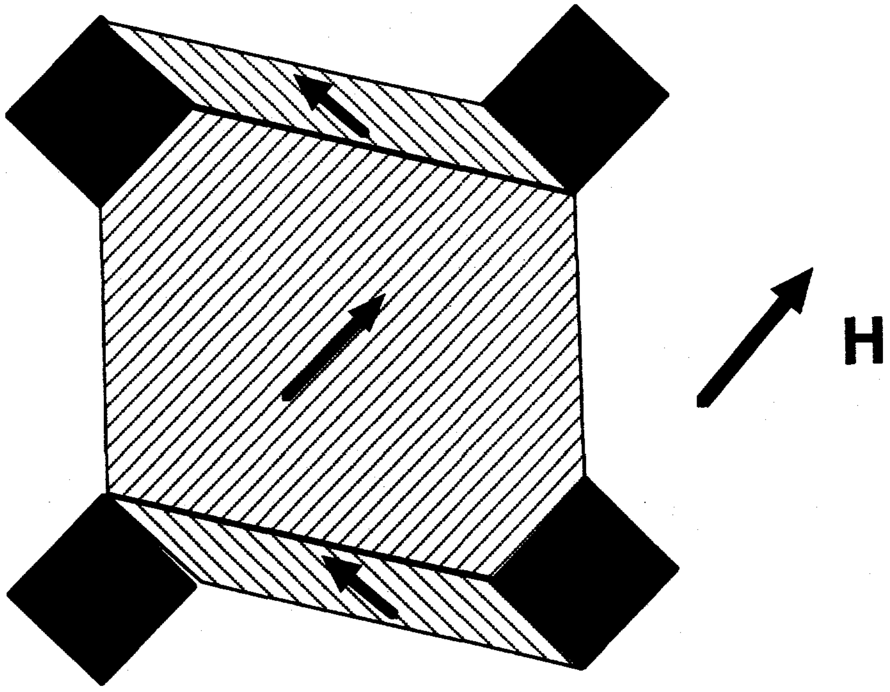


Fig 7





Fig