PHYSICAL REVIEW B VOLUME 19, NUMBER 2 15 JANUARY 1979

Magnetoconductivity modulation of thin ferromagnetic films by substrate electrostriction

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(Received 1 June 1978)

Signals accompanying the metallic field effect in Permalloy films that are quadratic in the applied charge density and sensitive to the direction θ and magnitude H of an applied magnetic field are caused by electrostrictive strains in the substrate transmitted to the films. This magnetoconductivity modulation results from changes in magnetization direction induced by strain-dependent contributions to the uniaxial anisotropy energy K. It shows an overall 4θ dependence for an in-plane field, with a phase determined by the direction of the easy axis relative to the current, and an amplitude at given θ varying as $1/H$. Quantitative agreement between observed and predicted signals is good, and permits their use as a sensitive method for probing the strain dependence of K. Simultaneous data on very similar signals linear in the charge, also shown, bear directly on the metallic-field-effect in ferromagnetic metals.

I. INTRODUCTION

A thin metallic film bonded to a dielectric substrate, such as the electrode plate of a capacitor, is strained when the dielectric itself deforms under electric fields applied to the capacitor. If the metallic film is also ferromagnetic, this strain generally affects its magnetization distribution. Hence all of the film's magnetization-dependent properties, and in particular its electrical conductivity, will respond to the electric fields in the dielectric substrate.

We have observed such a response in the course of studying the metallic field effect (MFE) in thin ferromagnetic films,[1] and present here a quantitative verification of the predicted interaction. Once the effect has been properly identified, the observable changes in film conductivity with magnetic variables, such as magnetization $\vec{M}$, applied field $\vec{H}$, and uniaxial anisotropy energy K, are easily established and involve little new physics. Nevertheless, they are presented here in their own right, first to call attention to identifiable competing signals existing at the MFE level, and second, because the unusual features of the response reveal new details about the nature of K in Permalloy films. Finally, they also have a close bearing on the origin of the simultaneously observable MFE signals, taken up in more detail in a companion paper.[2]

The MFE is the change of surface conductance Σ_s of a metal with electrostatic charging. It is usually measured on a thin metal film forming one plate of a capacitor. With a surface charge density of amplitude q and varying like $q\sin\omega t$, the observed change of film conductance at ω and 2ω (Ref. 3) is described by

$$\delta\Sigma = -\delta\Sigma(\omega)q\sin\omega t + \delta\Sigma(2\omega)q^2\cos 2\omega t\,. \qquad (1)$$

The first harmonic $\delta\Sigma(\omega)$ is a true surface effect caused by changes in surface scattering of current carriers under the influence of q.[4] Hence it really describes a change in surface conductance $\delta\Sigma_s(\omega)$, and can be identified as a metallic field effect. Largely because of the characteristic phase relation of Eq. (1), the second harmonic was originally assumed to arise from the same mechanism, and all of Eq. (1) was interpreted in terms of a specific model of the MFE.[3] However, more recent data, both on nonmagnetic films[5] as well as those presented here, show that $\delta\Sigma(2\omega)$ is roughly proportional to the film thickness. This identifies it as a volume effect not specifically associated with surface interactions, and therefore it should not be designated as a metallic field effect proper.

Nevertheless, it is important to understand the origin of $\delta\Sigma(2\omega)$, if only as a signal adding to and perhaps interfering with the true MFE. This is one purpose of this paper. In addition, however, we shall use the understanding of $\delta\Sigma(2\omega)$ to draw rather specific conclusions about the origin of $\delta\Sigma(\omega)$. This follows from the fact that despite their differing regions of interactions, in the surface and in the bulk, respectively, both $\delta\Sigma(\omega)$ and $\delta\Sigma(2\omega)$ exhibit a surprisingly similar and characteristic response to applied magnetic fields, which suggests that the same type of mechanism is responsible for both signals. In anticipation of this connection, most of our experimental data will display both $\delta\Sigma(\omega)$ and $\delta\Sigma(2\omega)$. In this paper, however, the emphasis in analysis and interpretation is on $\delta\Sigma(2\omega)$, and specifically on its dependence on the magnetic state of the metal, as this state is altered by strain.

If we are dealing with a volume effect, the specific conductance Σ $(=\sigma t)$ is altered by strain both

through geometrical changes of dimensions, such as the thickness t, and through changes in the conductivity σ. In a polycrystalline electrically isotropic film, the magnetization-dependent conductivity is given by

$$\sigma = \sigma_0 - \Delta\sigma \cos 2\theta_M , \tag{2}$$

where $\Delta\sigma$ measures the magnetoconductive anisotropy, and θ_M is the angle between $\vec{M}$ and the direction of the current. All three parameters in Eq. (2) may be strain dependent. Changes in σ_0 and $\Delta\sigma$ reflect altered scattering cross sections, while a change in θ_M is the result of magnetorestrictive effects on the equilibrium direction of the magnetization.

This last mechanism can be expected to be strongly H dependent, because the direction of $\vec{M}$ is determined by both the anisotropy energy K and the magnetostatic energy $\vec{H}\cdot\vec{M}$. Thus at very large $\vec{H}$, θ_M will vary only little with strain, while in small fields the change of θ_M can become quite large. Since the variations in θ_M will depend on the strain-sensitive component of K, the observed variations can, in fact, be used to probe K for any such a contribution.

In this paper we report on observed changes in σ caused by the strain dependence of σ_0 and θ_M. However, no effects attributable to $\Delta\sigma$ have been seen.

Section II develops a quantitative description of these effects based on a simple model of a magnetic thin film. In the subsequent sections the experimental results are given and interpreted in terms of this description. Additional measurements are presented to corroborate the quantitative agreement and to explore further consequences of this proposed basic mechanism for the magnetoconductivity modulation in ferromagnetic film electrodes.

II. THEORETICAL MODEL OF MAGNETOCONDUCTIVITY MODULATION

Let us consider a single domain of a ferromagnetic film having a uniaxial anisotropy energy K, and subject to an in-plane applied magnetic field. Its energy density is given by the familiar expression

$$E = -HM\cos(\theta - \theta_M) + K\sin^2(\theta_M - \theta_e) , \tag{3}$$

where the angles of $\vec{H}$, $\vec{M}$, and the easy axis with respect to the x axis are θ, θ_M, and θ_e, respectively. The equilibrium direction θ_M is determined by

$$HM\sin(\theta - \theta_M) = K\sin 2(\theta_M - \theta_e) . \tag{4}$$

The simplest influence of an applied strain on the equilibrium direction is through a change in K. If K goes to $K+\delta K$, then according to Eq. (4),

$$\delta\theta_M = -\frac{\sin 2(\theta_M - \theta_e)}{2h\cos(\theta - \theta_M) + 2\cos 2(\theta_M - \theta_e)}\frac{\delta K}{K} , \tag{5}$$

where h is the usual reduced field $h = H/H_K = HM/2K$. More complicated effects of strain may also involve a change of the easy axis direction $\delta\theta_e$. Essentially, this would only add a phase change in the angular argument of the numerator of Eq. (5). More interestingly, the observed uniaxial anisotropy K of Eq. (4) may actually be composed of several uniaxial contributions, differing in strength and easy axis direction,[6] with not all contributions equally susceptible to strain. For example, if K is composed of a field-induced anisotropy K_m at θ_m, and a strain-induced anisotropy K_t at θ_t, Eq. (5) becomes

$$\delta\theta_M = -\{\sin 2(\theta_M - \theta_t)/[2h\cos(\theta - \theta_M) + 2\cos 2(\theta_M - \theta_t) + 2\kappa\cos 2(\theta_M - \theta_m)]\}\,\delta K_t/K_t \tag{6}$$

where now $h = HM/2K_t$, and $\kappa = K_m/K_t$. This equation contains all the same major features as Eq. (5), and little generality is lost by basing the further development in this section on Eq. (5).

The strain dependence of K of Eq. (5) is known for small strains to be linear.[7] Thus we can write

$$\frac{\delta K}{K} = \sum_{i=1}^{6} \eta_i e_i , \tag{7}$$

where, for our purposes, the natural coordinate system for defining the strains e_i and the tensor η_i puts the film normal along the z axis. The strains entering in Eq. (7) are determined by the planar strains e_1, e_2, and e_6 transmitted to the ferromagnetic film by the dielectric substrate. If the dielectric is isotropic, or of sufficiently high symmetry, it develops an isotropic planar strain under an electric field normal to the metal plane. In mica, for example, this isotropic strain in the cleavage plane, due to the Maxwell stress tensor, is given by[8]

$$e_1 = e_2 = \tfrac{1}{2}(s_{11} + s_{12} - s_{13})\frac{(q\sin\omega t)^2}{\epsilon_{33}} = sq^2\sin^2\omega t , \tag{8}$$

where the s_{ij} are the elastic constants of mica and ϵ_{33} is the principal dielectric constant normal to the cleavage plane. In addition, $e_6 = 0$, and, because of symmetry, e_1 and e_2 are independent of the choice of the x and y axes.

If the ferromagnetic film is firmly bonded to the substrate, e_1 and e_2 are fully transmitted to the film, and are constant throughout the film thickness as long as it is sufficiently thin. In the film itself there is an additional strain component e_3 because the normal stress in the film vanishes. If permalloy is elastically isotropic, and described by a Poisson's ratio α, e_3 is given by

$$e_3 = -[2\alpha/(1-\alpha)]e_1 . \tag{9}$$

In terms of these strains, Eq. (7) simplifies to

$$\delta K/K = \{\eta_1 + \eta_2 - [2\alpha/(1-\alpha)]\eta_3\} e_1 = \eta e_1 . \tag{10}$$

The coefficients η_1, η_2, and η_3 are expected to be distinct because magnetically the thin film is uniaxial.

By combining Eqs. (2), (5), (8), and (10), we obtain the relative change in film conductivity caused by strain modulation of the film's anisotropy energy when the mica is charged

$$\delta\sigma/\sigma_0 = -2(\Delta\sigma/\sigma_0) s\eta F(h,\theta;\theta_e)(q\sin\omega t)^2 , \tag{11}$$

where s and η are the effective coupling coefficients defined in Eqs. (8) and (10), and the electrical current is along x.

Equation (11) contains all the characteristic features of the proposed model. It provides a quadradic dependence on q of the form contained in Eq. (1). The magnitude of the signal follows from the known, or independently measurable values of $\Delta\sigma/\sigma_0$, s, and η. Finally, its dependence on the magnetic state of the film is described by the function

$$F(h,\theta;\theta_e) = \frac{\sin 2(\theta_M - \theta_e)\sin 2\theta_M}{2h\cos(\theta - \theta_M) + 2\cos 2(\theta_M - \theta_e)} , \tag{12}$$

in which θ_M is known through Eq. (4). This dependence has a number of unexpected features. First, at fixed θ, F shows an inverse dependence on h, vanishing at large fields and becoming very pronounced when h is of order unity. Second, at fixed h the dependence of F on the field angle θ is roughly like 4θ, with θ_e fixing the phase. At low h, where the differences between θ and θ_M become noticeable, F follows the orientation of $\vec{M}$, and distortions of the 4θ dependence will become evident.

Except for s, all the parameters of Eq. (11) depend on the composition and properties of the particular permalloy film under investigation. s follows from the properties of mica, and has the value[9]

$$s = 5.4\times 10^{-2}\ (\mathrm{C/m^2})^{-2} . \tag{13}$$

It is interesting to note that near electric breakdown, where mica supports a maximum surface charge density $q \sim 10^{-3}$ C/m^2, the strains of Eq. (8) are of the order 10^{-8}. The fact that such small strains give easily observable effects suggests that this coupling offers a very sensitive probe into magnetic properties.

Any measured changes in conductance will include, in addition to the effect of Eq. (11), the strain dependence of σ_0 and of the sample shape. The overall change of specific conductance leads to the following explicit form of the second harmonic amplitude of Eq. (1):

$$\delta\Sigma(2\omega) = \tfrac{1}{2}\Sigma s[2\alpha/(1-\alpha) + \gamma + (2\Delta\sigma/\sigma_0)\eta F(h,\theta;\theta_e)] , \tag{14}$$

where the first term is the net geometrical contribution and γ is the effective coefficient of strain dependence of the nonmagnetic conductivity σ_0.

III. EXPERIMENTAL RESULTS

The Permalloy film samples of different compositions and thicknesses are prepared by evaporation of rf-heated melts deposited unto scratch-free muscovite mica at 300 °C, and then annealed at 460 °C, all while in a transverse magnetic field of 10–20 Oe. Contact electrodes and the capacitor counterelectrodes are of 1000-Å silver. A typical sample has a film resistance of 50 Ω and a specific capacitance of 10^{-5} F/m^2. Magnetically, it is uniaxial, although the easy axis direction is not necessarily along the annealing field. All electrical measurements are carried out in air.

Field-effect measurements use the phase-sensitive techniques already described,[4] modified, as shown in Fig. 1, to allow simultaneous recording of the first and second harmonics. Data are usually taken in a constant in-plane magnetic field as a function of θ, starting from the film's easy axis direction.

Typical results at two different nominal compositions are shown in Figs. 2 and 3. The top curves give the variation of the resistivity ρ with θ. In the range of fields covered here they are independent of the strength of H, and show the 2θ variation expected from Eq. (2). The bottom curves, smoothed-out connections of the experimental points, give the rms values of the unit square conductance $\delta\Sigma(2\omega)$ at four fields. At low fields they show a strong angle-dependent signal described by a distorted 4θ variation. At higher fields this signal decreases and approaches a pure 4θ variation. At the highest fields $\delta\Sigma_\infty(2\omega)$ is independent of θ. The signals at both compositions are of similar magnitude when H is

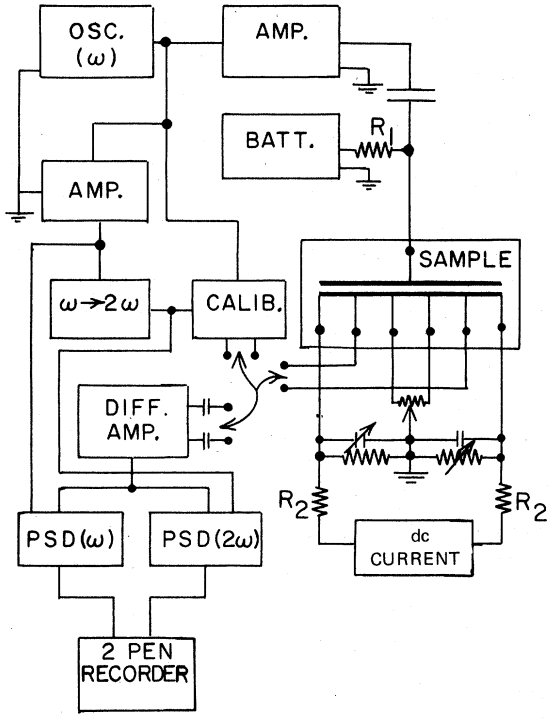

FIG. 1. Block diagram of the field-effect measurement system, with two phase-sensitive detectors (PSD).

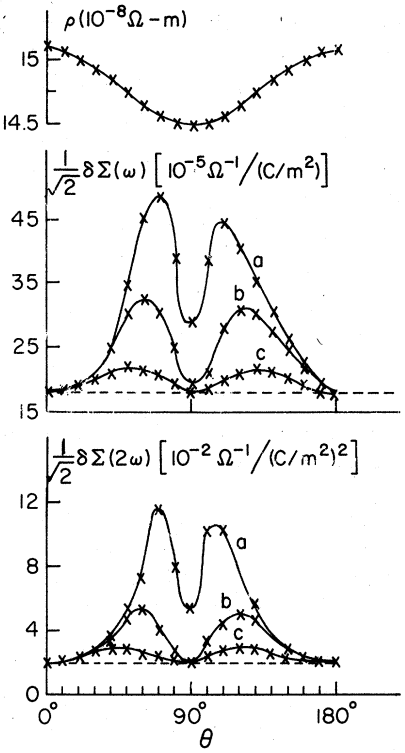

FIG. 3. ρ, $\delta\Sigma(\omega)$, and $\delta\Sigma(2\omega)$ vs θ for a 90-10 Permalloy film of 280 Å. *a*, *b*, and *c* denote 45, 120, and 530 Oe and the dashed lines describe the high-field behavior.

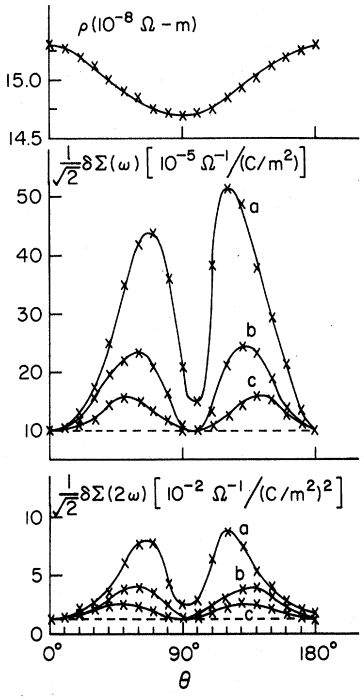

FIG. 2. ρ, $\delta\Sigma(\omega)$, and $\delta\Sigma(2\omega)$ vs θ for a 80-20 Permalloy film of 300 Å. *a*, *b*, and *c* denote 20, 54, and 110 Oe and the high-field curves are given by the dashed lines.

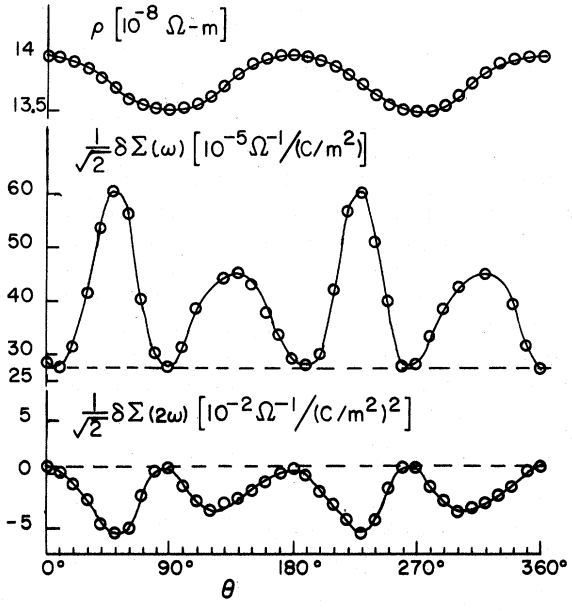

FIG. 4. ρ, $\delta\Sigma(\omega)$, and $\delta\Sigma(2\omega)$ vs θ for an 80-20 Permalloy film of 350 Å at 20 Oe.

scaled by a factor of about 4. In both figures, the θ-dependent signal appears to ride above $\delta\Sigma_\infty(2\omega)$, but inverted behavior also occurs, as shown, for example, in Fig. 4, for another nominal 80-20 composition.

Samples of one composition prepared at the same time in different thicknesses t, and with similar magnetic properties, exhibit signals of both $\delta\Sigma_\infty(2\omega)$ and the amplitude of the θ-dependent part (at a given field) proportional to t. In contrast, the first harmonic response is independent of t, within the reproducibility of all other properties, forcing the conclusion that $\delta\Sigma(2\omega)$ is a bulk effect, while $\delta\Sigma(\omega)$ is characteristic of the metal-insulator interface. Nevertheless, the strong and nearly identical θ dependence of the first harmonic suggests that both signals arise from very similar interactions.

The scales of $\delta\Sigma(2\omega)$ and $\delta\Sigma(\omega)$ in Figs. 2–4 show that in typical films both signals contribute in similar magnitude to Eq. (1) at the experimental maximum value of $q \sim 10^{-3}$ C/m^2. Thus most MFE experiments, especially those using dc charging, require a careful analysis to separate these two contributions.

IV. INTERPRETATION

The experimental curves of Figs. 2–4 show all the major features predicted by Eq. (14).

The high-field contribution is identified with the first two terms of this equation. The overall magnitude is characteristic of all metals and can be predicted from independent measurements of γ.[10] The field and θ-dependent variation must be governed by $F(h, \theta; \theta_e)$ and an amplitude A composed of the product

$$A = \Sigma s \eta \Delta\sigma/\sigma_0 . \tag{15}$$

As a matter of fact, inspection of some of the qualitative features of Figs. 2–4, such as the unequal size of the peaks below and above $\theta = 90°$, indicates that a proper analysis of the experimental curves requires use of the generalization of F based on Eq. (6), and given by

$$F(h, \theta; \theta_t, \theta_m, \kappa) = \frac{\sin 2(\theta_M - \theta_t)\sin 2\theta_M}{2h\cos(\theta - \theta_M) + 2\cos 2(\theta_M - \theta_t) + 2\kappa\cos 2(\theta_M - \theta_m)} . \tag{16}$$

A match of the experimental points of Figs. 2 and 3 to Eq. (16) is shown in Figs. 5 and 6, using the parameters indicated in the captions. The value of $\theta_m = 90°$ was assumed from the direction of the annealing field, and the values of H_K, θ_t, and κ used in the match also describe correctly

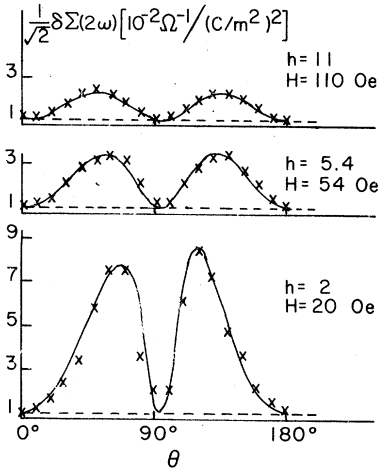

FIG. 5. Match of experimental points of Fig. 2 of three fields to Eq. (16), using the parameters $H_K = 10$ Oe, $\theta_t = 5°$, $\theta_m = 90^0$, $\kappa = 0.1$, with the common amplitude $A = 0.37\ \Omega^{-1}\ (C/m^2)^{-2}$.

the observed effective uniaxial properties of each film. It is evident that Eq. (16) successfully describes the observed behavior at all fields, reproducing the proper variation of the amplitudes as well as the pure 4θ variation at high fields and the distortions at low fields, especially near the hard axis. Such an overall match defines the various parameters quite uniquely, and thus yields a wealth of information about the magnetic characteristics of the sample.

The amplitude A is related through Eq. (15) to

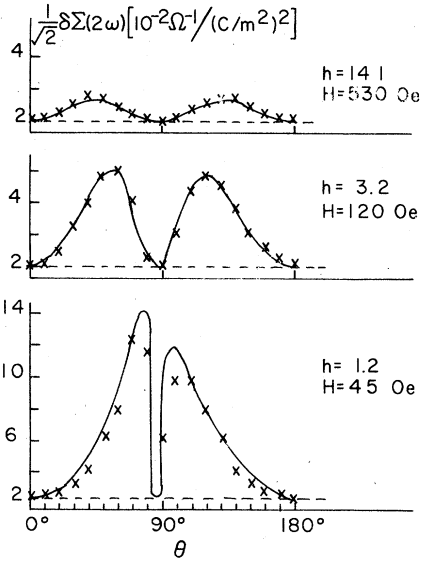

FIG. 6. Match of experimental points of Fig. 3 to Eq. (16) at three fields, using the parameters $H_K = 38$ Oe, $\theta_t = -5^0$, $\theta_m = 90^0$, $\kappa = 0.03$, and the common amplitude $A = 0.25\ \Omega^{-1}\ (C/m^2)^{-2}$.

other known or independently measurable quantities. Thus Σ and $\Delta\sigma/\sigma_0$ follow from the upper curve of Figs. 2 and 3, and s is given by Eq. (13). The additional unknown is the strain dependence of the anisotropy energy η defined by Eq. (10). Although variations of $\delta K/K$ under longitudinal and transverse applied strains have often been measured,[7] the particular combination of η_i required in Eq. (10) is rarely known. In an independent study[11] we have carried out the necessary measurements of η on the same film samples used for field effect measurements. Table I lists these η's, and all other quantities entering into A for a typical group of films at the two nominal compositions, and gives the comparison of measured and predicted amplitudes.

This table emphasizes, first of all, that there is a noticeable variation in electrical and magnetic properties between samples of the same composition, which are probably caused by small changes in the actual compositions and in other deposition-dependent parameters. By and large, the gross difference in properties in the two groups agrees with the trends known in the literature.[12] They also confirm that near the 80-20 composition the magnetostriction goes through zero, leading to η's of both signs. The amplitude A predicted from Eq. (15) and the measured value of A are listed in the last two columns. The agreement of both numbers is very satisfactory, both with respect to magnitude and sign, and, in fact, shows a stronger correlation than the variation of individual properties from sample to sample. All discrepancies are easily within the cumulative limits of error of the more than four independent measurements that go into the predicted A. Any systematic error is most likely caused by uncertainty in the value of s from Eq. (13). Our thin mica substrates may, in fact, have slightly different elastic constants, or there is a small electrostrictive contribution to s,[8] which was not included in Eq. (13) because it is not known. A final possibility is, of course, that our model does not account for all of the observed signal $\delta\Sigma(2\omega)$. By and large, however, Eqs. (15) and (16) give a full quantitative description of the observed second-harmonic effects, and apply equally well to samples exemplified by Figs. 2 and 3, or Fig. 4.

As a further confirmation of the role of transmitted strains on $\delta\Sigma(2\omega)$, we compared the measurements of $\delta\Sigma(\omega)$ and $\delta\Sigma(2\omega)$ before and after the sample was epoxied rigidly between two glass slides that effectively inhibited any lateral strain of the mica. As seen in Fig. 7, this clamping suppresses most of both $\delta\Sigma_\infty(2\omega)$ and the θ-dependent signal. The residual signal depends on

TABLE I. Electrical and magnetic parameters of thin Permalloy films at two compositions, and the predicted and measured values of the amplitude A of Eq. (15).

	Thickness t (Å)	Conductance Σ ($\Omega^{-1}/\square$)	Anisotropy field H_K (Oe)	Magnetoresistive anisotropy $\Delta\sigma/\sigma_0$	Strain coeff. of K η	A Predicted [Ω^{-1} (C/m^2)$^{-2}$]	A Measured [Ω^{-1} (C/m^2)$^{-2}$]
90-10	260	0.24	36	2.0×10^{-2}	1.4×10^3	0.36	0.35
	280	0.22	38	2.0	1.2	0.29	0.25
	540	0.42	26	2.3	3.5	1.8	1.4
80-20	280	0.2	6	1.9	~0	~0	~0.002
	300	0.18	10	1.8	3.1	0.54	0.37
	300	0.22	5	1.9	−2.0	−0.45	−0.41
	400	0.32	4	1.8	~0	~0	−0.05

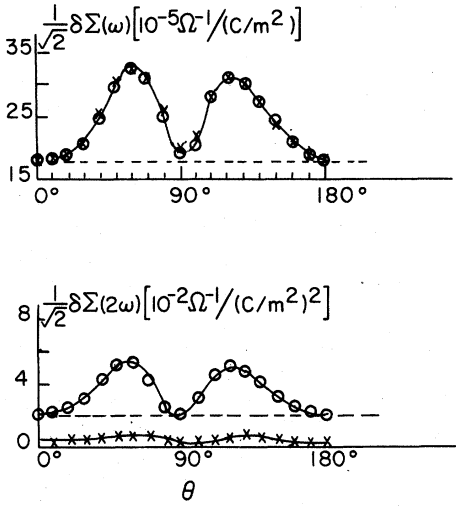

FIG. 7. Effect of clamping on the $\delta\Sigma(2\omega)$ and $\delta\Sigma(\omega)$ vs θ curves for the film of Fig. 3 at 120 Oe. O and × denote experimental points before and after the sample is glued between glass slides.

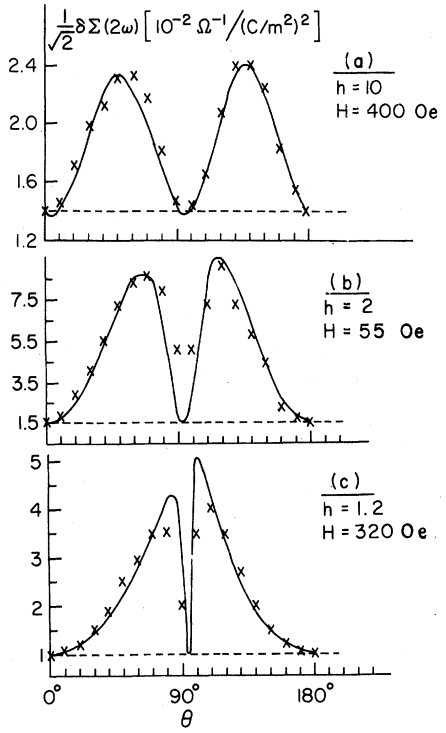

FIG. 8. $\delta\Sigma(2\omega)$ of a 260-Å 90-10 film under static strains e. (a) $e=0$: $H_K=40$ Oe, $\theta_t=5^0$, $\kappa=0.2$, $A=0.35$ Ω^{-1} $(C/m^2)^{-2}$; (b) $e_{\|}=2\times10^{-4}$: $H_K=27.5$ Oe, $\theta_t=5^0$, $\kappa=0.1$, $A=0.38$ Ω^{-1} $(C/m^2)^{-2}$; (c) $e_{\perp}=10^{-3}$: $H_K=270$ Oe, $\theta_t=5^0$, $\kappa=0.01$, $A=0.06$ Ω^{-1} $(C/m^2)^{-2}$.

how thin the epoxy bond between sample and glass slides can be made, and, in fact, measures the effectiveness of the clamping. (A similar clamping by a thin oxide on the exposed film surface would offer an additional alternative for the systematic difference between $A_{\text{pred.}}$ and $A_{\text{meas.}}$ of Table I.) In contrast, it is startling to observe from Fig. 7 that the first-harmonic signal $\delta\Sigma(\omega)$ is not at all affected by this clamping.

V. STRAIN-DEPENDENT ANISOTROPY ENERGY CONTRIBUTION

The interpretation of the $\delta\Sigma(2\omega)$ curves exemplified by Figs. 5 and 6 requires the use of Eq. (6) rather than Eq. (5) because of the asymmetry in the peak heights in the first and second quadrants, and also because on a given sample the easy axis direction θ_t sometimes differs from the effective easy axis direction θ_e determined by Eq. (4). Thus for the film of Fig. 4, θ_t is close to 0°, while θ_e is near 60°, indicating that $\kappa\sim1$, which also accounts for the large asymmetry.

Hence these measurements establish unambiguously that our samples show at least two contributions to the uniaxial anisotropy energy, of different strengths and easy axis directions. The contribution independent of strain lies along the direction of the magnetic field during annealing, and the strain-sensitive term K_t lies close to the long direction of our samples. At the 80-20 composition both contributions are of similar magnitude, while at 90-10 K_t predominates. While our own measurements of the K of Eq. (4), based on magnetoresistance behavior, were only accurate enough for showing a rough internal consistency between the predicted and measured values of K and θ_e, it is clear that the study of $\delta\Sigma(2\omega)$ offers a sensitive tool for analyzing the contributions to the anisotropy energy.

This is brought out further by studying the effect of a static strain in the film sample on the behavior of $\delta\Sigma(2\omega)$. Figure 8 compares the results of an unstrained 90-10 film with those under a relatively small static strain along the easy axis, and then a rather large static strain along the hard direction. In the first case K_t decreases somewhat, while in the second it increases markedly. Both changes are of the expected magnitude and direction,[13] and in order-of magnitude agreement with the η values of Table I, though these apply to a somewhat different strain configuration. One piece of new information is that the direction θ_t remains invariant under such static strains. Another is that while up to strains of order 10^{-4} the amplitude A of Eq. (15) remains unchanged, at a strain of 10^{-3} A decreases markedly. However, the quantity $K_t\eta$ is nearly constant at all strains, so that the value of δK_t is roughly linear in strain, independently of K_{0t}.

VI. CONCLUSIONS

The second harmonic accompanying the MFE in ferromagnetics shows a marked magnetic field dependence. This signal is a bulk effect arising from the modulation of the film conductivity induced by changes in the uniaxial anisotropy energy when the film substrate deforms in applied electric fields. We have demonstrated that this model gives a full quantitative account of the observed signals, and that further consequences of the model are verified.

Applied to magnetic films, the second harmonic of the MFE provides a delicate probe for the properties of the strain sensitive contributions to the anisotropy energy. With respect to the MFE proper, the strikingly parallel behavior shown by the magnetic field dependence of the second and first harmonics indicates that the mechanisms responsible for both signals must have similar origins.

ACKNOWLEDGMENTS

We acknowledge with thanks the guidance and support of Mary Eschwei in the preparation of these samples, and the contributions of David Lischner towards the instrumentation, and in many discussions. This work was supported in part by NSF Grant DMR 73-07501 and the Joint Services Electronics Program. It is based on work submitted by P. Mazumdar in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the Polytechnic Institute of New York.

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