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A Coupling Phenomenon Between the Magnetization of Two Ferromagnetic Thin Films Separated by a Thin Metallic Film—Application to Magnetic Memories

J. C. BRUYÈRE, O. MASSENET, R. MONTMORY, AND L. NÉEL

Abstract—A new type of magnetic interaction between two ferromagnetic thin films separated by a third metallic nonmagnetic thin film is studied. This coupling tends to bring the magnetization of the ferromagnetic materials into parallel alignment. The coupling is shown to be dependent upon the intermediate material and its thickness, and on the nature of the ferromagnetic media present. These interactions are observed for intermediate metal thicknesses up to 300 Å in the case of Palladium. The measured surface energy of this coupling is of the order of 0.1 erg/cm². A study of the variation of the coupling with temperature is given.

INTRODUCTION

IT IS WELL KNOWN [1] that two parallel ferromagnetic films separated by a nonmagnetic film less than 500-Å thick show different types of interactions. The simplest coupling that exists between ferromagnetic thin films is caused by the demagnetizing field which tends to align the magnetization of the ferromagnetic materials in an antiparallel orientation. Fuller and Sullivan [2] and Spain [3], [4] have shown evidence for an interaction between the elementary domain walls. It is also well known that the thin films show an “orange-peel” surface topography. Néel [1] anticipated the existence of magneto-static interactions when a correlation exists between the interfacial topographies with regard to the ferromagnetic media. The anticipated coupling energy is of the order of 0.01 erg/cm² for an intermediate layer 100-Å thick and for wavelength irregularities of 400-Å and 40-Å amplitude. Since these three types of interactions are independent of the nature of the intermediate layer, there is no reason why it may not be an insulator.

The new type of coupling described below is observed only if the intermediate material is conducting and if it is less than about 500-Å thick for the films that have been studied.

EXPERIMENTAL CONDITIONS

The multiple thin films are prepared by vacuum evaporation using a conventional vacuum of $3 \cdot 10^{-6}$ mm of Mercury in the presence of a magnetic field, onto a heated glass substrate. The first layer deposited is a Permalloy type alloy (81 per cent Ni, 19 per cent Fe), between 1000-Å and 2000-Å thick, with an uniaxial anisotropy. The top layer is a cobalt—nickel—iron alloy having zero magnetostric-

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tion, 1800-Å thick with an induced uniaxial anisotropy. These alloys are chosen so that the two materials have different true coercive fields.

Their thicknesses are measured using an oscillating piezoelectric quartz crystal placed in the vacuum chamber [5].

The magnetic characteristics of the multiple films are studied at low frequencies using a special Kerr effect apparatus allowing the hysteresis loops of the two magnetic components of the sandwich to be seen separately on the oscilloscope screen. These measurements are made outside the vacuum chamber.

To study the phenomenon as a function of temperature, the films are placed on a support which can be heated or cooled in another vacuum system. The hysteresis loops are also observed using the Kerr effect at 50 c/s.

METHOD OF MEASUREMENT

The existence of a coupling between two ferromagnetic films is represented by a coupling energy term E_c . At the same time, the observation of hysteresis loops lead to the introduction of a fictitious coupling field h related to the energy by

$$E_c = J \cdot h \cdot e$$

where J is the spontaneous magnetization of the observed ferromagnetic film and e is the thickness of this film. The two ferromagnetic media have true coercive fields H_c and H_c' such that $H_c \ll H_c'$.

If the hysteresis loop in the common easy magnetization direction is observed using an alternating field H with an excursion such that $H > H_c'$, it can be shown that the apparent coercive fields observed will be

$$H_c + h; H_c' - h'$$

h is the fictitious coupling field acting on the medium having a coercive field H_c ; h' is the fictitious coupling field acting on the medium having a coercive field H_c' . If H_c and H_c' is known or measured, h and h' can be easily determined (see Fig. 1).

RESULTS

Experiments at Room Temperature

Figure 2 gives the results obtained for intermediate Palladium layers. For thicknesses greater than 300 Å, the coupling is no longer measurable. For thicknesses less than 50 Å, the value of the coupling field h is such that the

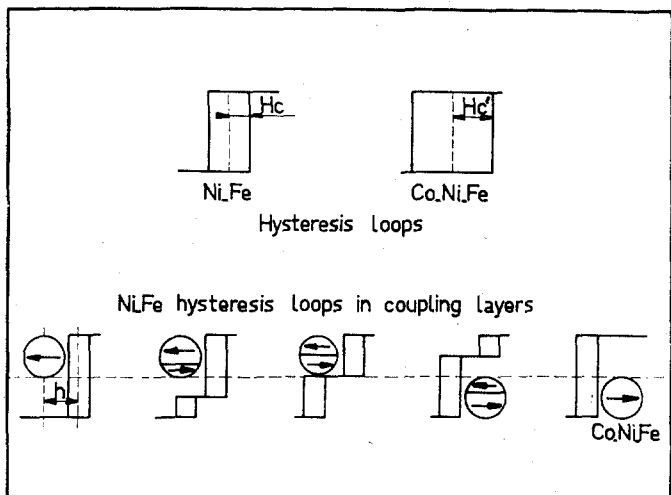


Fig. 1. Different shapes of hysteresis loops for multiple layer coupling.

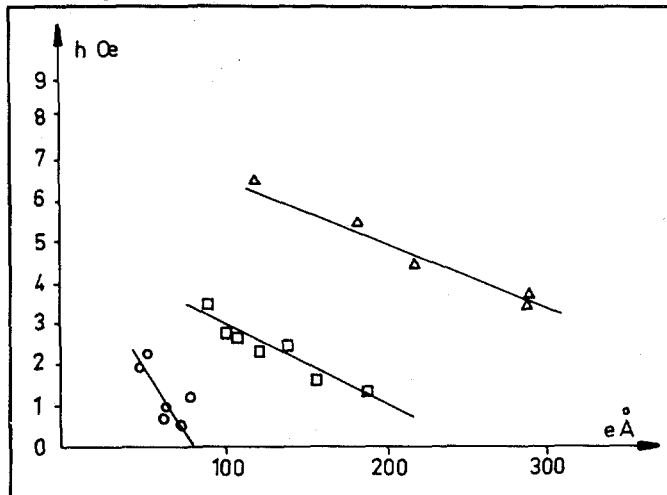


Fig. 3. Coupling field h vs. intermediate layer thickness. \square Chromium; Δ Silver; \circ Gold. 45 per cent, 45 per cent, 10 per cent Co-Ni-Fe alloy. Ni-Fe layer of 1800 Å.

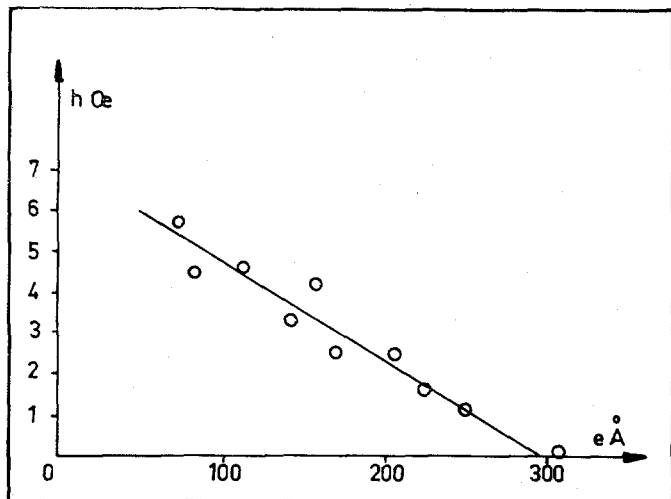


Fig. 2. Coupling field h vs. Palladium layer thickness. Ni-Fe layer of 1800 Å. 35 per cent, 52 per cent, 13 per cent Co-Ni-Fe alloy.

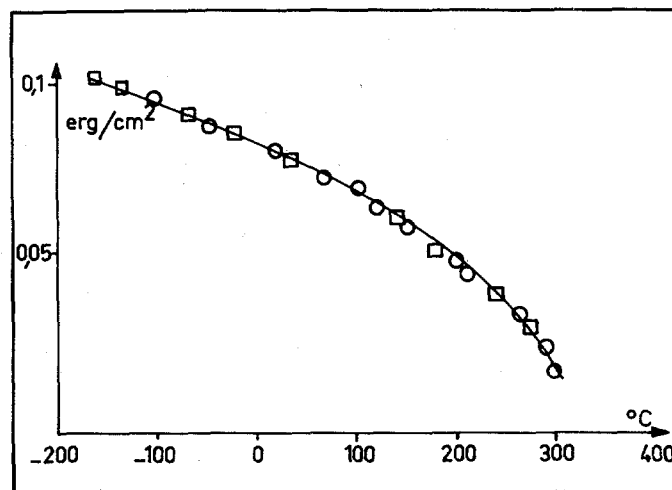


Fig. 4. Coupling energy vs. temperature for a 75-Å intermediate layer of Palladium. \circ heating; \square cooling.

difference between H_c and H_c' is less than $h + h'$. In this case, the hysteresis loops for the two magnetic layers in the easy direction are the same. Two distinct loops appear in the hard direction, however, but it is not experimentally possible to obtain a value of the coupling field. Moreover, if the thickness is less than 50 Å, there is a possibility of the intermediate layer becoming porous and hence, of quite different phenomena appearing.

Let J be the magnetization of the Ni-Fe layer ($J = 900$ emu), e its thickness (1800 Å) for $h = 6$ Oe, and let the coupling energy E_c be 0.1 erg/cm², i.e., ten times the maximum energy anticipated by L. Néel [1] for magneto-static coupling.

The results for intermediate layers of chromium, silver, and gold are summarized in Fig. 3. Several series of experiments have been carried out, especially one using an alloy composed of 45 per cent Ni, 45 per cent Co, 10 per cent Fe, and another using 52 per cent Ni, 35 per cent Co,

13 per cent Fe [6]. The bulk spontaneous magnetizations of the two alloys are almost the same (± 10 per cent). It is to be noted that for a chromium thickness of 75 Å, the coupling strength is three times as great when the composition of the Co - Ni - Fe layer goes from 35 per cent, 52 per cent, 13 per cent to 45 per cent, 45 per cent, 10 per cent. Using gold or silver and an alloy consisting of 35 per cent, 52 per cent, 13 per cent Co - Ni - Fe, the coupling fields are weak and hence the results are scattered; the use of an alloy of 45 per cent, 45 per cent, 10 per cent always increases the coupling strength, and the results are more accurate. A linear decrease of the coupling strength with intermediate metal thickness is observed for the following metals: Au, Pd, Cr, Ag, In.

Experiments at Varying Temperatures

The variation of the coupling energy with temperature for a specimen having an intermediate layer of Palladium

75-Å thick is shown in Fig. 4 with the temperature varying continuously from -180°C to 300°C . A significant decrease of coupling energy with rise in temperature is observed. Similar experiments carried out using samples with intermediate layers of Cr, Ag, Au show a much slower variation with temperature.

It has also been observed that, for a sample showing no coupling phenomena at room temperature (the Palladium layer was thick: $> 300 \text{ \AA}$), an appreciable coupling field appeared on cooling. At -180° the measured coupling field was 1 Oe. There is no thermal hysteresis.

The observation of the rapid variation of coupling energy with temperature for Pd suggests that this phenomenon cannot be of a magnetostatic origin. In fact if it had been, it could only be explained by a decrease of the spontaneous magnetization or by a reversible modification of the layer structure.

APPLICATION TO MAGNETIC MEMORIES

A memory element consisting of a "reading" layer with a weak anisotropy field separated from a "memory" layer with a higher anisotropy field by an appropriate metallic layer can be made. After recording the information, a magnetic field pulse applied in the hard direction turns the "reading" layer magnetization perpendicular to the

easy direction, while the "memory" layer magnetization is turned through less than 90° . At the end of the pulse, the memory layer magnetization returns spontaneously to its original position, bringing with it the "reading" layer magnetization, because the two magnetizations are coupled.

The interest of this type of memory element lies in its novel construction and use. In fact, the coupling energy can easily be adjusted to the desired value by changing the nature and thickness of the intermediate layer material. Finally, the fact that there is a "positive" coupling (that is, one which tends to bring the magnetizations of the two films parallel) allows the strip lines to be placed outside the memory element.

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