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Some Magnetic Properties of Vacuum-deposited Coupled Films

Abstract: The magnetic properties of vacuum-deposited multilayer films constructed in a closed-flux configuration in an integrated structure have been studied as a function of: a) film thickness; b) substrate temperature, and c) the character of the conductor metals. It is found the static magnetic properties of the magnetic layers depend on the material in the previous layers as well as the thickness and deposition temperature of those layers. Techniques of optimizing and controlling the magnetic properties are discussed.

Introduction

Since the discovery by Blois of a uniaxial anisotropy in thin magnetic films, a number of schemes have been proposed to utilize films as a digital storage medium. An earlier version of a magnetic-film memory plane, the so-called flat-film memory, consists of a substrate and a single layer (500 to 1,000Å) of Permalloy film. In a laminated structure, the strip lines (bit and word lines) are formed separately on an insulating carrier (for example, Mylar) and are placed onto the memory plane. In an integrated structure, these lines are deposited onto the memory plane with adequate insulation layers between the storage film and the conductors.

Some advantages of magnetostatically coupled films over the flat-film approach were recently shown by Suits and Pugh[1] and Chang et al.[2] These advantages include opportunities for (1) smaller memory cells as a result of reduced demagnetizing field, (2) larger signals, and (3) a larger capacity. In such a coupled-film memory, an additional layer of magnetic material is placed between the two conductors of the flat-film configuration. A study was recently undertaken to investigate the feasibility of fabricating an *integrated* coupled-film memory by vacuum deposition techniques. The material problems encountered in fabricating an integrated coupled film memory and proposed technological solutions for fabricating the structure are presented in this paper.

Figure 1 presents a cross-sectional view of a typical multilayer structure where the flux is magnetostatically coupled in the easy axis of the film (CEA). The easy axis of the magnetic films is horizontal and the two films are magnetostatically coupled around the bit-sense line. When the easy axis of the films is along the lines (into the paper in Fig. 1), then the structure is termed CHA (closed hard axis). In this structure, the word line separates the two magnetic elements and the bit-sense line lies on top.

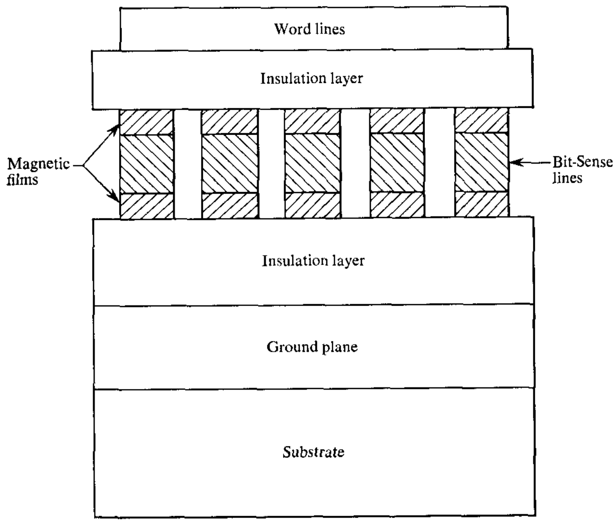


Figure 1 Cross-sectional view of a typical closed easy-axis memory plate.

In the CEA structure, the flux is no longer closed during the read operation, since both films have their magnetization driven in the same (hard) direction. A magnetic keeper material may be used to accomplish flux closure in this condition. If utilized, the keeper would be placed over the word

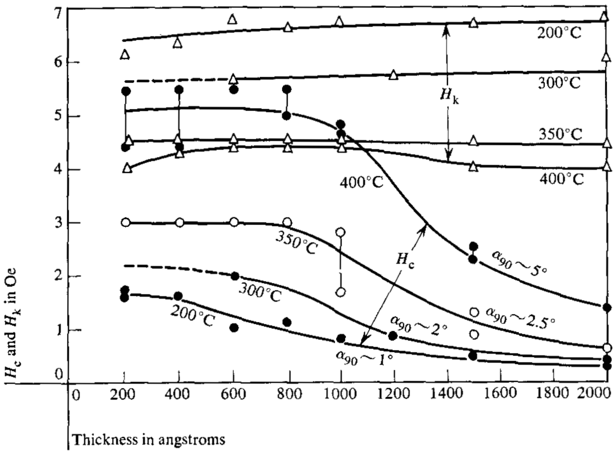


Figure 2 Variation of H_c and H_k of 3% Cobalt-Permalloy films with film thickness and substrate temperature.

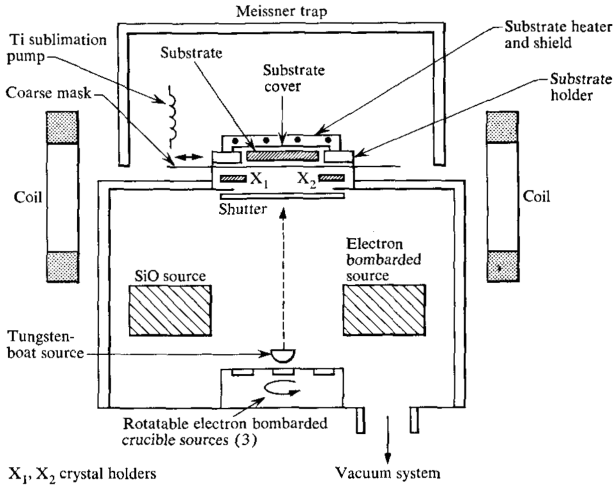


Figure 3 Arrangement of components within the vacuum evaporator. X_1 and X_2 denote quartz crystal holders for monitoring thickness and evaporation rate.

line (Fig. 1) for the CEA structure. The role of the ground plane is to provide the return paths for the currents sent through the bit-sense lines and the word lines. Thus, two insulation layers are required. The typical range of the thickness of the layers are 6 to 12μ for an evaporated ground plane; 6 to 12μ for insulation; 500 to 3000Å for Permalloy films; and 1 to 6μ for strip lines.

Since both structures (CEA and CHA) are physically alike, there is essentially no difference in the fabrication processes. The difference in the direction of easy axis is simply achieved by changing the direction of a d-c magnetic field applied during the evaporation of the magnetic films.

In contrast to the laminated flat-film memory, in which only a single magnetic film is deposited onto a ground plane, the completely integrated coupled-film structure presents several yield problems with respect to the fabrication metallurgy. These have to do with (a) reliable electrical insulation between the ground plane and the first conducting layer; (b) reliable electrical insulation between the drive lines; and (c) fabrication of two magnetic films having controllable, reproducible, and required properties.

These problems are complicated by effects originating in metal physics: (a) the nucleation and growth of each evaporated layer will be influenced by the preceding layer; (b) the possibility that interfacial diffusion and alloying between magnetic films and metal conductors can bring about a consequent change in magnetic properties; (c) the possibility that surface roughness and a large grain size of the conductor may introduce a shape anisotropy into the magnetic layer; (d) the build-up of a large mechanical stress in the multilayering resulting in adhesion problems, and (e) the possibility of textured growth of the conductor and the upper Permalloy film (Fig. 1) and consequent crystal anisotropy effects.

Consideration of such possibilities suggests a rigid control of deposition parameters and, in particular, of deposition temperatures. The lower temperature limit is governed by the maximum tolerable skew of the easy axis, from angle of incidence effects, while the upper limit is mainly restricted by the roughness of the conductor layer (resulting from the grain growth) and interfacial diffusion. The desired range of magnetic properties determines the choice of the alloy composition for magnetic films as well as the deposition temperature, and the film thickness. The substrate temperature is especially critical when a ternary alloy (such as Cobalt-Permalloy) is used because of the large temperature dependence of the magnetic properties (Fig. 2). The material and the thickness of the conductor layer are determined by the systems design, being chosen to give minimum attenuation of the drive currents and sense signals. Since the magnetostatic coupling of the two magnetic films requires a small separation, high conductivity metals are desirable. Four metals of high electrical conductivity, Au, Ag, Cu, and Al, satisfy the design requirements and were selected to be examined in this study.

Experimental techniques

Vacuum evaporator and accessories

The vacuum evaporator used for the fabrication of films consisted of a Veeco VE-401 system with an 18-inch glass bell jar containing the components identified in Fig. 3 and listed in the footnote below.*

* Components of the evaporation system: (1) Vapor Sources—three electron-bombarded crucible sources (these sources are rotated into the center line of the substrate for deposition); an electron-bombarded SiO source; a tungsten boat; an electron-beam gun. (2) Substrate holder with a heater and a cooling coil. (3) Coarse mask. (4) Shutter. (5) Titanium sublimation pump. (6) Liquid nitrogen trap. (7) Two quartz crystal holders for monitoring of thickness and evaporation rate. (8) Additionally, a pair of rectangular coils outside the bell jar produced a steady magnetic field of 60 Oe in the plane of the substrate.

The input power to the electron-bombarded source is electronically regulated, and thus the rate of evaporation is held nearly constant throughout the evaporation period. Typical evaporation rates for Permalloy range from 3 to to 5 Å/sec for an input power of ∽ 500 watts. The evaporation rates for the conducting metals and the SiO are much higher with typical rates varying from 10 to 50 Å/sec.

The substrate holder can accommodate a 4 in. × 4 in. substrate of any thickness up to 50 mils. It is made of OFHC copper and is located about 12 in. above the crucible sources.

The substrate temperature is monitored by a pair of iron-constantan thermocouples inserted into a $\frac{1}{4}$ in. OFHC copper plate. The substrate is placed on this copper plate. Another copper plate $\frac{1}{8}$ in. thick is placed 10 to 50 mils above the substrate as a heat sink, and is heated by radiation from tungsten filaments.

The coarse mask is so designed that many films of different geometry and thickness can be produced under identical fabrication conditions. This is particularly important in studying the dependence of magnetic properties as a function of the substrate history.

The combination of the titanium sublimation pump and the liquid nitrogen trap improves the vacuum during evaporation by almost an order of magnitude. Magnetic films (especially the lower layer) are usually evaporated in the high 10^{-6} to low 10^{-5} mm Hg range while the conductor and the silicon monoxide films are evaporated at a lower pressure. The lowering of the pressure during the evaporation of the conductor and SiO is mostly due to the gettering action of SiO and reduced outgassing of these sources.

The evaporation rate and the thickness of the films are monitored and determined by two crystal oscillators symmaterially located as shown in Fig. 3. At least one monitor remains operating throughout an evaporation period which lasts frequently more than 100 min. The accuracy of thickness measurement was ±5 percent.

• *Film fabrication procedures*

The selection of the glass substrate was based on smoothness, and the following types and thicknesses of glasses (as supplied by Corning Glass Works) were used: Type 7059, 25 to 32 mils in thickness; Type 0211, 6 to 12 mils in thickness. Substrates were cleaned ultrasonically in an Alconox solution followed by a vapor degreasing and then stored in the degreaser until ready for use. The metal substrates were cleaned ultrasonically and spin-coated with an insulation layer outside the vacuum system.

The melt source consisted of commercially supplied Permalloy of 83% Ni- 17% Fe (by weight) and 3% Cobalt-Permalloy (prepared by addition of high-purity cobalt wire to regular Permalloy in a crucible). The resulting alloy slug ($\frac{9}{16}$ in. diam. × $\frac{1}{2}$ in. height) is placed in an alumina crucible (capacity ∼2.5 cm³) which in turn is placed in a molybdenum susceptor. During the deposition the molybdenum shell is held at a positive high potential (+2000 volts) and is bombarded by electrons emitted from a single-turn tungsten filament. The crucible is therefore heated by radiation from this susceptor.

Table 1 Resistivity and melting point of conductor metals.

Element	*Resistivity ohm-cm*	*Melting point (degrees C)*
Al	2.82×10^{-6}	659
Au	2.44×10^{-6}	1063
Cu	1.72×10^{-6}	1083
Ag	1.59×10^{-6}	960

• *Measurements of static magnetic properties*

The static magnetic properties of the films are measured with a 60 Hz drive field on a Kerr magneto-optic hysteresigraph or an inductive-pickup loop tracer. The latter is especially useful in examining the switching behaviors of composite films. The wall-motion coercive force is measured when the easy axis loop opens slightly. The angular dispersion, α_{90}, is measured by Crowther's first method.[3] The anisotropy field is measured from a hard-axis loop by extrapolating the slope when the loop is closed. In films with large angular dispersion ($\alpha_{90} > 15°$) the measurement of H_k is often not possible due to open loops in the hard direction; thus, the equivalent coercive force in the hard-axis loop, $H_{c'}$ is measured.

Experimental results

Melting points and resistivities at room temperature of the four elements chosen for conductors are listed together in Table 1. Magnetic films were deposited on all four elements so as to determine the effects of the different metallurgies on the magnetic properties of overlaid magnetic films. The static magnetic properties and techniques for controlling these properties were examined for a coupled film structure using each conductor. These material experiments are now presented.

• *Gold conductor*

When Permalloy films are deposited on a gold layer (deposited on glass substrates), the magnetic properties are affected by the thickness of the gold underlayer*; in particular, the coercive force and the angular dispersion increase as a function of gold thickness, while the anisotropy field decreases. In Fig. 4 typical variations of H_c, α_{90}, and H_k with the thickness of a gold underlayer are shown. Substrate temperature during deposition was 250°C. The increase in H_c is always accompanied by an increasing α_{90}. The rates of

* Reference 6 discusses the magnetic properties of Permalloy films deposited on thin underlayers (100 to 1000Å) of Al, Ag, Au and Cu.

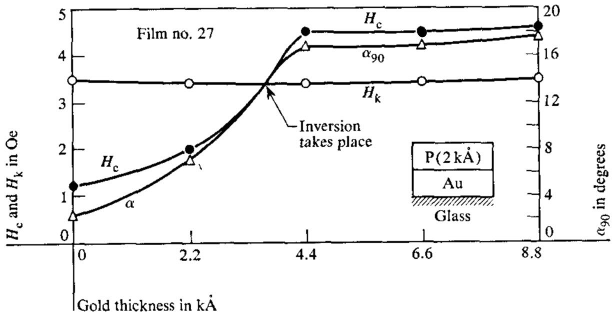
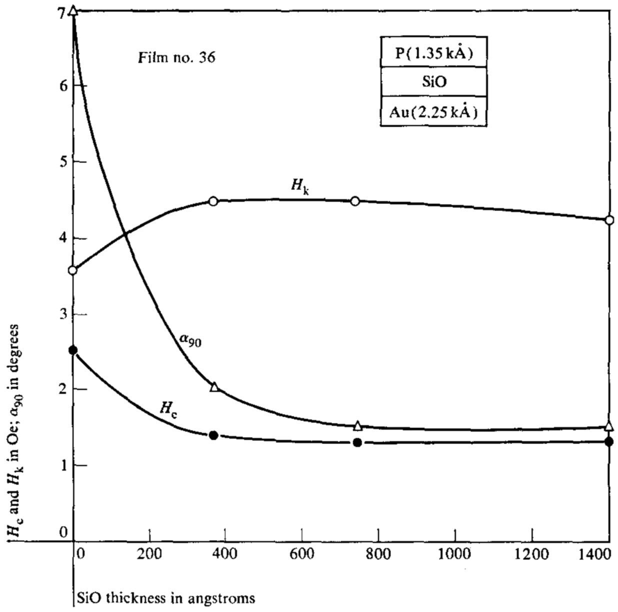


Figure 4 Variation of magnetic properties with gold thickness. (T_{sub} = 250°C).

Figure 5 Variation of magnetic properties of upper Permalloy as a function of SiO thickness. (T_{sub} = 150°C).



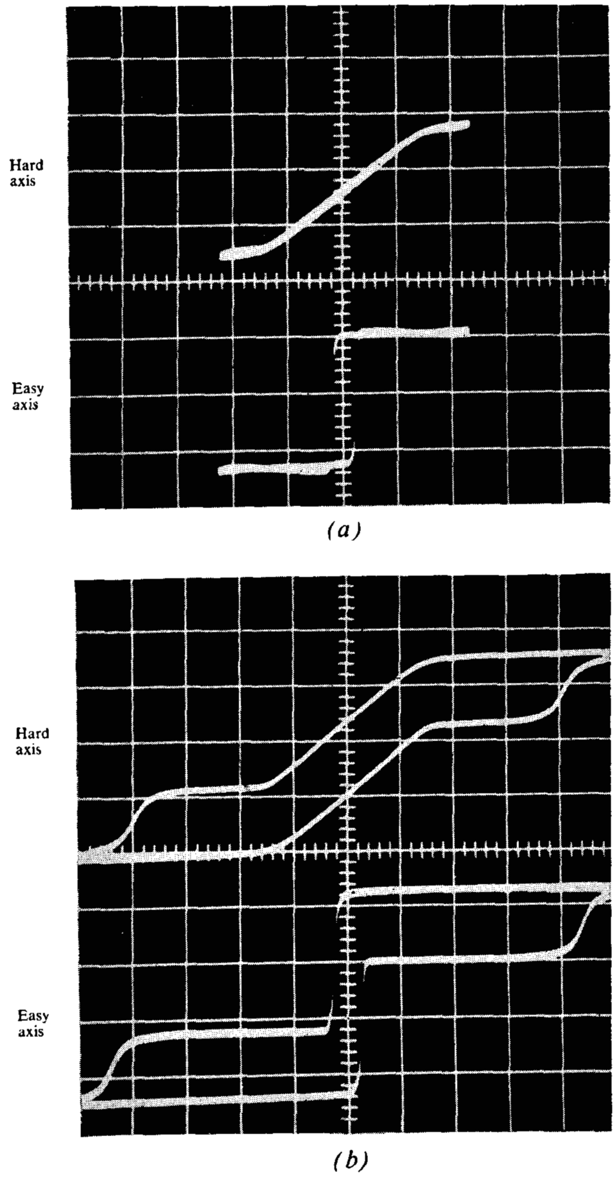


Figure 6 Hysteresis loop of (a) lower film alone and (b) combined loop. Horizontal calibration: 2 Oe/div. Vertical calibration: Arbitrary.

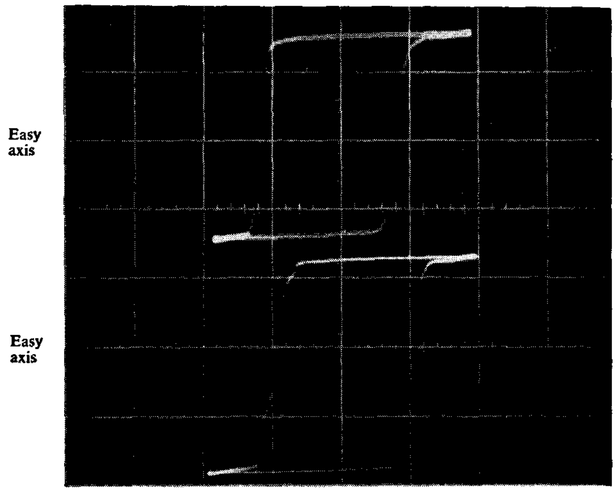
increase of H_c and α_{90}, are, in general, the same for all thicknesses up to the point where an inversion occurs.

The critical gold thickness at which an inversion occurs ($H_c \geq H_k$) decreases as a function of the substrate temperature (i.e., 8000 Å at T_s = 150°C; 6500 Å at T_s = 200°C; 3500 Å at T_s = 250°C). These films were fabricated under identically controlled conditions of substrate heating and cooling, heating and degassing of sources, and rates of evaporation so as to allow the magnetic properties to be compared with a high level of confidence. The reproducibility of the inversion point degenerates slightly at higher substrate temperatures.

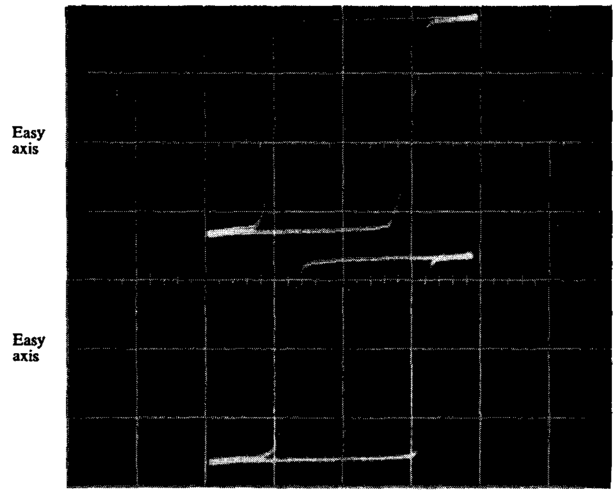
The large angular dispersion associated with thick Au underlayers is not desirable from a device point of view. A thin layer of SiO was introduced between the gold-Permalloy interface to improve the magnetic properties of the magnetic film (i.e., to reduce angular dispersion). The reduction in α_{90} and H_c achieved by a thin SiO layer is shown in Fig. 5. The minimum thickness of the SiO film required to lower H_c and α_{90} to normal values (i.e. $H_c < 1$ Oe and $\alpha_{90} < 2°$) depends upon the thickness of the underlying conductor and the substrate temperature.

When the above films (Permalloy on gold) are evaporated onto a lower layer of Permalloy (P_I), an even greater increase in H_c, H_c', and α_{90} (usually too large to measure) of the upper magnetic film is observed.* The magnetic properties of the lower layer remain intact. Typical *M-H* loops

* Here and subsequently, P_I will denote the lower Permalloy layer, P_{II} the upper Permalloy layer.



(a)



(b)

Figure 7 Hysteresis loops of lower film alone. The easy-axis loop is shifted by 0.10 Oe toward left (the upper trace in (a)) and right (the lower trace in (b)) as compared with unshifted loops (the lower trace in (a) and the upper trace in (b)) due to demagnetizing field from the upper film. Horizontal calibration: 0.5 Oe/div.

(from a 60-Hz inductive looper) on these films are shown in Figs. 6a and 6b. Shifted hysteresis loops of the lower film, a result of the coupling field from the saturated upper film, are also shown with an expanded H-axis in Figs. 7a and 7b.

As before, a thin layer of SiO was deposited between P_{II} and Au to control the magnetic properties. Figure 8 shows a typical variation of magnetic properties with SiO thickness. It appears that an SiO layer of 5000 Å can effectively reduce these values to the point where they are similar to films deposited directly on glass. The minimum amount of SiO needed in these films is more than that needed for the Permalloy deposited only on Au (Fig. 5). A thicker SiO layer is

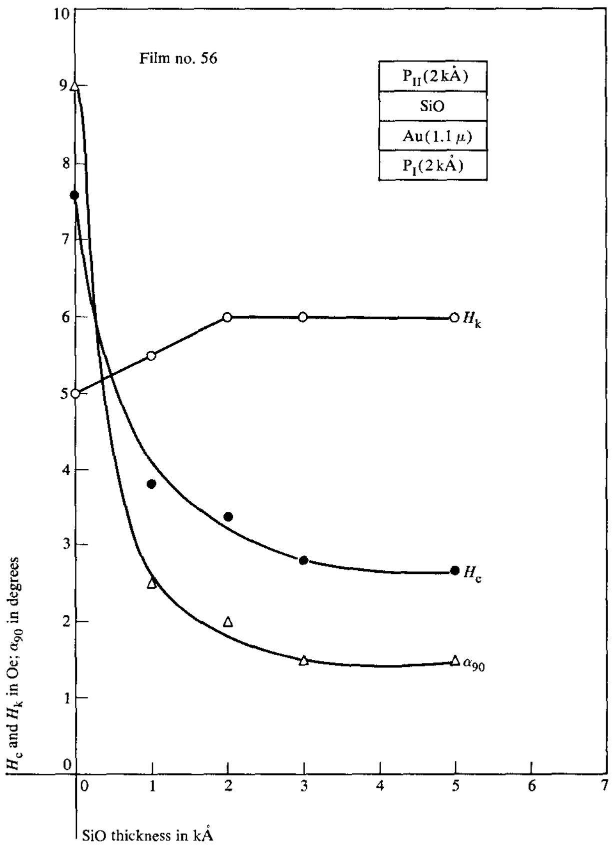


Figure 8 Variation of magnetic properties of upper permalloy as a function of SiO thickness. (T_{sub} = 200°C).

required to eliminate the effects of the rougher surface and larger grains resulting from (1) thicker Au layers and (2) the additional layer of the lower Permalloy.

- *Copper conductor*

The behavior of magnetic properties of the upper magnetic film (P_{II}) in coupled films using copper conductors are, in many respects, very similar to that reported above for gold. Typical results at 200°C substrate temperature for the full sandwich structure are shown in Fig. 9. The wall coercive force increases rapidly to more than 10 Oe for films with a conducting layer of 2000 Å when the substrate temperature exceeds 200°C. A slight increase in H_c of the lower Permalloy is observed as shown in the lower part of Fig. 9. This is attributed to the diffusion of Cu into the magnetic film (as evidenced by the loss of magnetic moment, M, of about 10 percent as measured by a vibrating-sample magnetometer). Similar changes in H_c and M resulting from the diffusion of Cu into Permalloy were also observed by Crowther.[7]

A thin layer of SiO on the copper conductor also reduces the values of H_c, H_c', and α_{90} of the upper Permalloy to

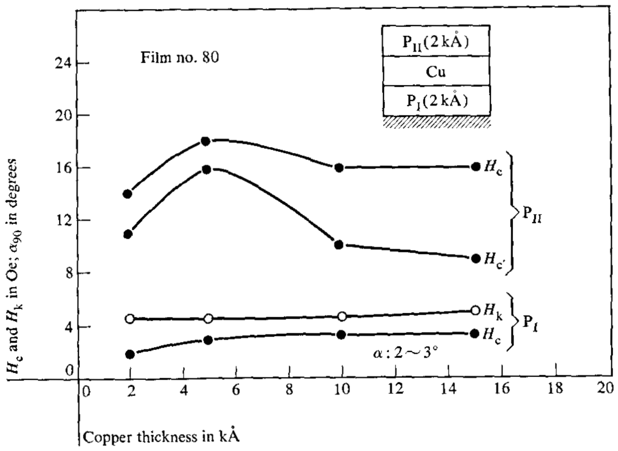


Figure 9 Variation of magnetic properties of Permalloy layers as a function of Cu thickness. (T_{sub} = 200°C).

nearly normal values. The minimum thickness of SiO needed to reduce α_{90} to ∽ 2° again depends mainly upon the thickness of the copper and the deposition temperature. For example, at 200°C substrate temperature and SiO 3000 Å thick, the following reductions are possible: α_{90} from greater than 20° to 2°, H_c from ∽ 15 to 2 Oe, and H_c' from 12 to 1 Oe. In general, as in the cases with other conductors, the thicker the conductor and the higher the deposition temperature, the thicker the SiO layer required to improve the upper magnetic layers.

Aluminum conductor

Because of the relatively high electrical resistivity of aluminum (2.8×10^{-6} ohm cm vs. 1.7×10^{-6} ohm cm for Cu), its use as a conductor is less desirable, especially for long strip lines, since the thickness required might be detrimental to magnetostatic coupling. Some attempt was made, however, to investigate the magnetic properties of the coupled structure with aluminum. The coercive force degraded very rapidly with thickness of the Al underlayer, approaching 10 Oe with only 1000 Å of Al for depositions at only 150°C. Higher substrate temperatures resulted in an even greater degradation of magnetic properties for a given Al thickness.

In contrast to the case with Cu conductors, no change in static magnetic properties of the lower Permalloy is found with substrate temperatures as high as 250°C, even though a small loss of M(<10%) was detected, as measured on a vibrating-sample magnetometer, in the upper Permalloy films deposited on Al conductors.

As with other conductors, a thin layer of SiO does reduce the values of H_c and H_c' drastically. For example, a 5000 Å-thick layer of SiO deposited on an Al conductor of 1000 Å reduced the wall coercive force to 1.5 Oe, although angular dispersion was still 5°.

Silver conductor

The magnetic properties of Permalloy films deposited on a silver layer are, as in the case with other conductors, similarly dependent upon the substrate temperature and the film thickness. A typical pattern of increasing H_c, H_c', and α_{90} of an upper Permalloy film is shown in Fig. 10. In no case did we detect a change in properties of the lower Permalloy film.

The effectiveness of the SiO layer in reducing the values of H_c, H_c', and α_{90} was very similar to the rate found for conductors of Au, Cu, and Al. Matched magnetic properties of both lower and upper layers can be obtained with 5000 Å-thick SiO on 4μ-thick Ag deposited at 150°C. As the deposition temperature increases, a thicker SiO layer is needed to reduce angular dispersion. For example, at a given Ag thickness of 4μ, the *minimum* α_{90} that can be obtained with an SiO layer of 5000 Å is ∽2° at 150°C, ∽6° at 200°C, and ∽12° at 250°C.

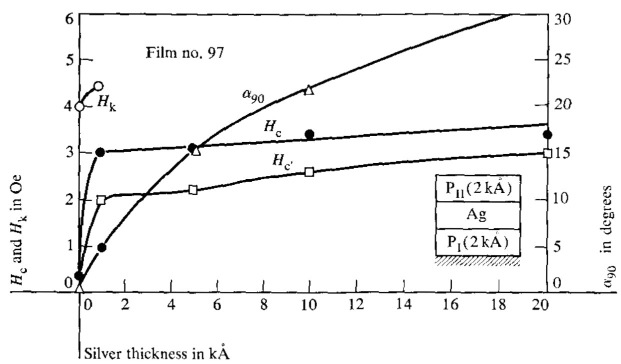
Comparison of conductors

Of the four metals examined so far, silver affords the highest electrical conductivity and the least change in magnetic film properties. It has, however, some disadvantages such as the low sticking coefficient of silver atoms during evaporation (resulting in "scattering" of the atoms and thus poor definition of the lines when films are deposited through a mask) and, as well, the incompatibility of etch rates with Permalloy. The final selection of the conductor must be a compromise between many interdependent factors, such as: (1) etchability, (2) effect on magnetic properties, (3) adhesion and mechanical failure (at interconnection junctions), and (4) cost. Gold may be less preferable because of a difficult etchability and a high cost. Silver and copper appear to be the better choices for strip line materials.

Discussion

The main differences in magnetic properties between films deposited on glass substrates and metallic underlayers are

Figure 10 Variation of magnetic properties of upper Permalloy as a function of silver thickness. (T_{sub} = 200°C).



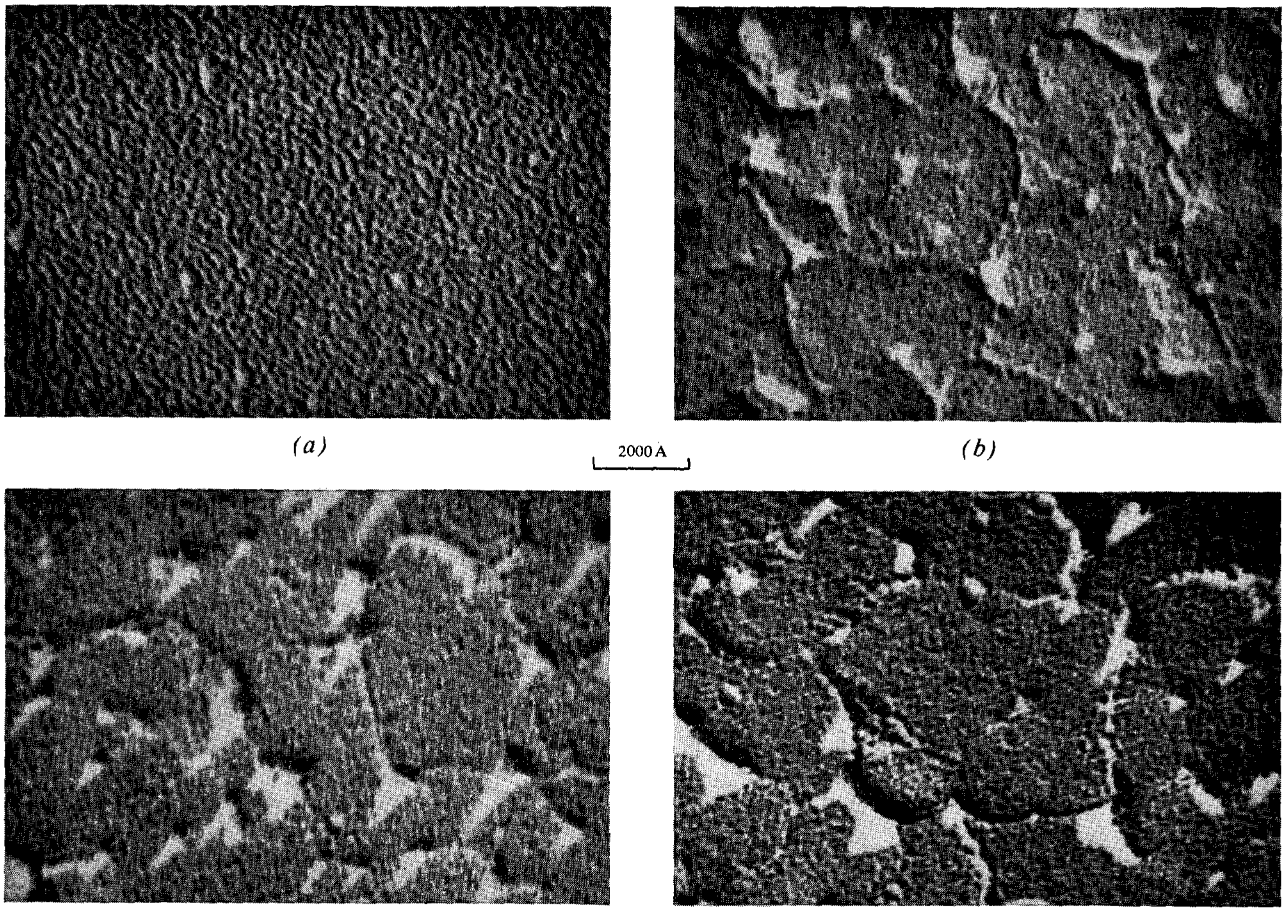


Figure 11 Surface conditions as examined by electron microscope (replication): (a) Permalloy film (2000 Å); (b) Permalloy (2000 Å) on Au (2200 Å); (c) Permalloy (2000 Å) on Au (4400 Å); (d) Permalloy (2000 Å) on Au (6600 Å). Magnification: 60000 ×.

that the latter have large angular dispersion, high wall-motion coercive force, and a large opening of the hard-axis hysteresis loop. Many factors, as pointed out earlier, affect the magnetic film properties. In subsequent paragraphs we will discuss possible origins of the anomalous magnetic behavior observed.

• *Effects of substrate surface condition on magnetic properties*
It is well known that magnetic properties (especially α_{90} and H_c) depend strongly upon the substrate surface condition.[4,5] For a given thickness (for example, 1000 Å), when Permalloy films are deposited at a temperature between 200 to 300°C on glass or SiO-coated metallic substrates, the values of H_c vary between 1 and 1.5 Oe and of α_{90} between 1 and 2.5°. Typical values for roughness of substrates of Type 0211 and Type 7049 glass are ∽250 Å and ∽60 Å, respectively.[8] However, the difference in H_c and α_{90} found on these substrates is very slight. In contrast, when the magnetic films are evaporated on evaporated metals (Au, Ag, Cu and Al), as shown in the preceding sections, the values of α_{90} and H_c increase rapidly as a function of the underlayer thickness. We shall now examine the reasons for the dependence of magnetic properties on underlayer structure.

• *Effects of evaporated metal underlayers*
We first analyze the detailed dependence of the static properties as a function of thickness of the metal underlayer at a fixed deposition temperature. The results shown earlier indicate a continuous deterioration in static properties of Permalloy as the conducting metal layer increases in thickness. The thickness range of <1000 Å has been investigated in detail and published earlier.[6] In that earlier work, large peaks of H_c, H_c', and α_{90} were observed in the 100 to 300 Å range with only a slight thickness dependence observed up to 1000 Å. The unusually large values of H_c and α_{90} observed are related to the island-structure growth of these films. This investigation also showed that, for the range of deposition temperatures used in this study, the conducting

layers are continuous for thickness greater than 1000 Å. Similar results have also been observed by Middelhoek[9] on a variety of metal underlayers.

Although the metal underlayer is continuous, the grain size manifests itself as a surface roughness. Fig. 11 shows the typical roughness of the Permalloy and the composite films (Permalloy or Au) as examined by an electron microscope (using surface replication). The Permalloy, although deposited at normal incidence reproduces the underlayer surface. The roughness is proportional to the grain size of the Au, and is most likely caused by anisotropic growth rates in different crystallographic directions. The roughness of these films is crudely indicated by their optical reflectivity; that is, when the films are exposed to an oblique-incident light beam, the surface does not appear mirror-shiny, but grayish. The surface roughness increases further when the upper Permalloy film and the conductor are deposited on the lower Permalloy film, as is evidenced by electron micrographs and an increased grayish reflectance of the multiple layers.

Although the predominant factor influencing the degraded magnetic properties appears to be the surface roughness, the effect of interfacial diffusion as mentioned earlier with copper and aluminum conductors cannot be neglected. A comparison of the static magnetic properties of conductors for a deposition temperature of 200°C suggests that diffusion has very slight effects in this temperature range; the difference may be masked by the predominant roughness effect and, also, may become more important in dynamic measurements, since the static properties give only an indication of device behavior.

- *Effects of SiO layer on surface roughness*

When a thin layer of SiO is introduced between the conductor and the upper Permalloy, the values of H_c and α_{90} are reduced drastically. The minimum thickness of the SiO layer needed to reduce these parameters depends upon many factors including the number of underlying layers, the boiling point and/or recrystallization temperature of underlayer metals, and the deposition temperature. In general, it is observed that the thickness of SiO required to obtain the desired properties is directly proportional to (a) the number of underlayers; (b) the thickness of the underlayer; (c) the inverse of the melting point of the underlayer; (d) the substrate temperature during deposition. The improvement of magnetic properties through the evaporation of SiO has been observed previously.[4]

The effect of surface tension for a material such as SiO is to minimize the total surface energy requirement by keeping the surface area as small as possible. This results in a general smoothing effect. When the deposition temperature is high, the arriving atoms have a high mobility; this mobility allows sufficient migration of atoms to smooth out the peaks and fill in the valleys. The typical trend in reducing the surface roughness is demonstrated in the electron micrographs in Fig. 12, as examined on the following structure: P_{II} (2000 Å) — SiO — Au (1.1μ) — P_I (2000 Å) all deposited at 150°C. As the thickness of the SiO layer increases [in (*a*) from 0, in (*b*) to 1000 Å, in (*c*) to 2000 Å, in (*d*) to 5000 Å] the surface becomes smoother on a larger scale. For the layer of 5000 Å SiO, the surface roughness has almost vanished. The resulting changes in magnetic properties are reductions of H_c from 7.5 Oe to 2.6 Oe and α_{90} from 9° to 1.5° (Fig. 8).

- *Effects of deposition temperature cycling on magnetic properties*

Since the magnetic properties of the upper Permalloy depend strongly upon the grain structure of the underlayer structure, one would like to control the structure of the underlayer, eliminating the need for the SiO layer. Ideally one wants a technique which would allow simultaneous etching of the coupled film structure and simplify the fabrication technology. As indicated previously, the effective grain size and roughness is a function of the boiling point of the material and the deposition temperature. If we normalize parameters by defining a reduced temperature $T_R = T_D/T_{BP}$ where T_D = substrate temperature during deposition, and T_{BP} = boiling point of evaporant, the effective roughness would be minimized by keeping T_R as small as possible. This means depositing the conductor at low substrate temperatures. Since the substrate temperature must be raised again for the magnetic layer deposition to eliminate angle-of-incidence effects, recrystallization may occur. However, based on kinetic studies by Nowick and Mader[10] in amorphous alloys, we propose that the effective roughness of a film deposited at T_1 will be greater than that for a film deposited at $T_2 < T_1$ and annealed up to T_1. This is a direct result of the greater atom mobility in surface diffusion during deposition.

Samples were prepared by depositing 2000 Å of Permalloy at 200°C, 1μ of Ag at −196°C, and cycling back up to 200°C for the P_{II} deposition. The coercivity of P_{II} for the temperature-cycled evaporation was 5 Oe as compared to 6 Oe for a non-cycled deposition. The similarity of the values of α_{90} and H_c between the films fabricated with different cycling temperatures indicates a poor effectiveness of the temperature-cycled substrate. This could be due to the recrystallization of Ag which occurs at room temperature under extreme conditions.[11] Because of the high stresses present in evaporated films,[12] it is apparent that recrystallization of the Ag does occur during heating (of the substrate) and evaporation of subsequent magnetic film (the time during evaporation often exceeds 30 min) at the temperature required for satisfactory magnetic properties. Although recrystallization has occurred, the temperature-cycled film has, as expected, slightly smaller grain sizes as examined in an electron microscope. Unfortunately, the effect is not as great as one would desire.

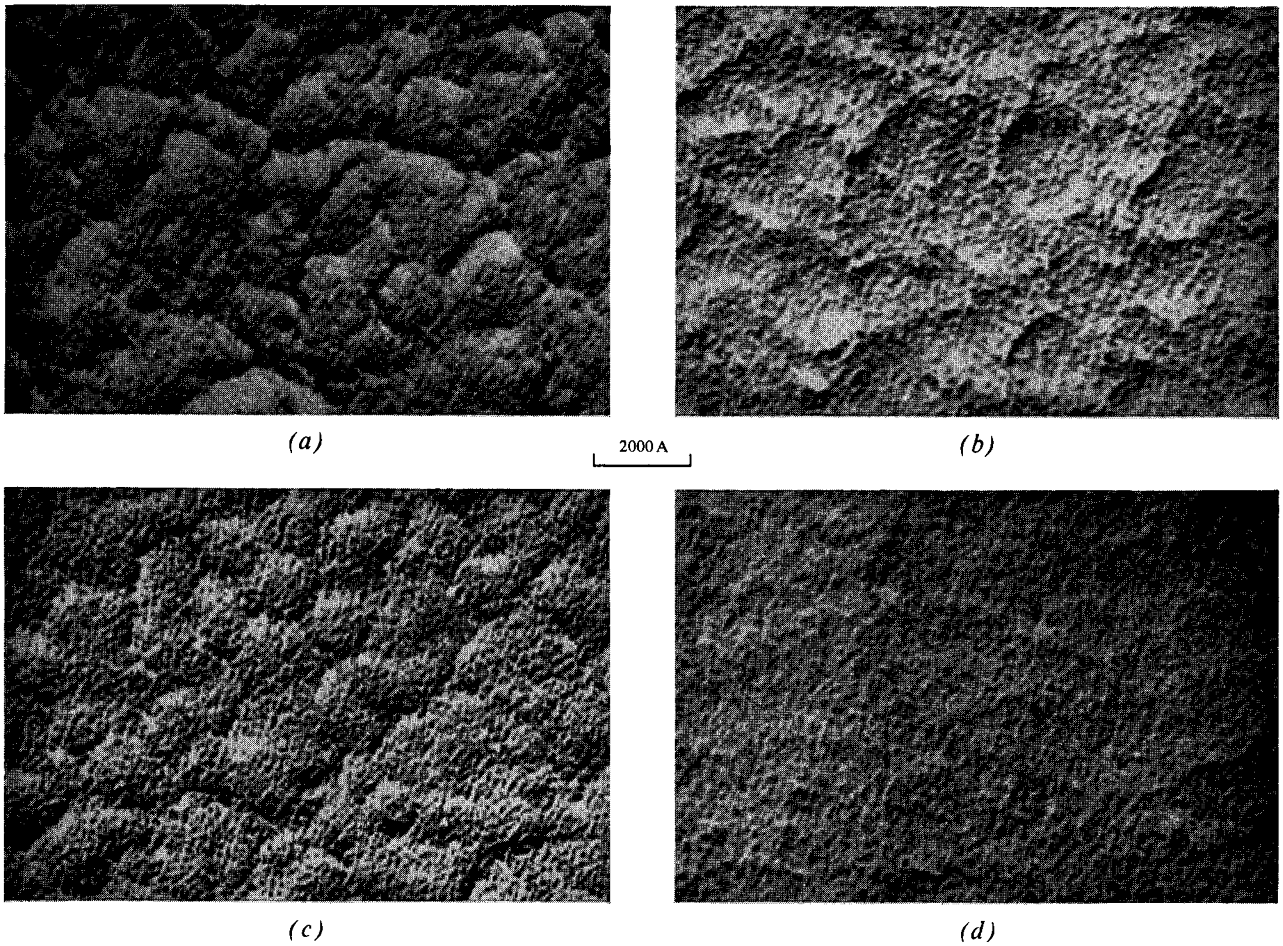


Figure 12 Replicated surface condition of [P_{II} (2000 Å)—SiO—Au (1.1μ)—P_I (2000 Å)] structure with varying SiO thickness. SiO thicknesses (*a*) 0 Å; (*b*) 1000 Å; (*c*) 2000 Å; (*d*) 5000 Å. Magnification: 60000 ×.

• *Effects of refractory metal film on magnetic properties*

The grain growth problem was partly solved by using a thin film of a refractory metal for smoothing of the conductor layer. One example is shown in Fig. 13 in which varying thicknesses of Ti were deposited at a lower substrate temperature. Although this fabrication technique is somewhat complicated, the resulting magnetic properties are very promising. When the Ti layer (and Ag) is deposited at the same temperature as for the Permalloy films, there results a decrease in α_{90} (from $>20°$ to 5°) and H_c (from 5.6 Oe to 3.2 Oe). The extent of such a decrease can be made larger if temperature cycling is combined with the use of the refractory metal.

Molybdenum films can also reduce the values of α_{90} and H_c. For example, in a multilayer film with a copper conductor of 1μ thickness, the values of H_c and α_{90} are, respectively, 7 to 10 Oe and $> 20°$. A thin layer of Mo (1600 A thickness deposited at 200°C as other layers) reduces these values, respectively, to 3.0 Oe and 4.5.°

Conclusions

The material problems associated with the fabrication of an integrated multilayer magnetic-film memory have been studied. It is observed that the static magnetic properties of the upper magnetic layer depend strongly on the material in previous layers as well as on the thickness and deposition temperature of those layers. The degradation of magnetic properties appears to be a result of demagnetizing fields caused by the surface roughness generated by those previous layers. The characteristics of the lower magnetic layer are, in general, not dependent upon the post-evaporated layers, except when it is exposed to a temperature high enough to cause recrystallization or diffusion between layers. Reproducible magnetic properties can be obtained by keeping $T_R = T_{\text{Deposition}}/T_{\text{Boiling Point}}$ as low as possible for all layers (consistent with control of angle-of-incidence effects), and using amorphous SiO for additional smoothing when required. The use of refractory metals for smoothing is also possible. The best combination of these effects will be de-

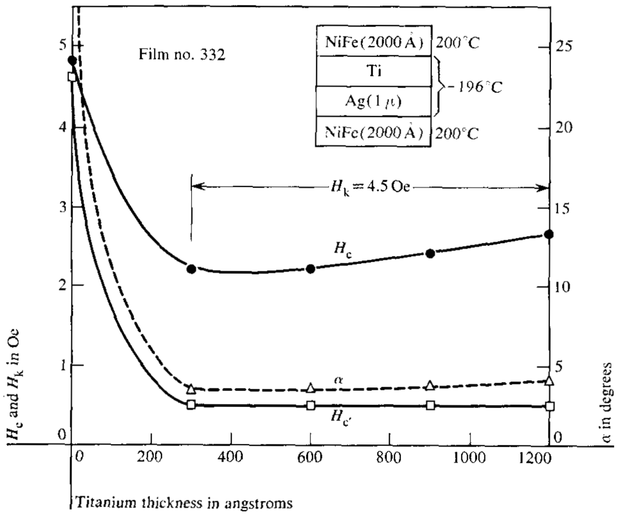


Figure 13 Variation of magnetic properties (of P_{II}) with Ti thickness.

termined by the specific device being generated. The materials and thickness of the layers in the device are, in turn, determined by the system design in order to achieve maximum signal and device stability with minimum attenuation.

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