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Basic Deposited Integrated Magnetic Circuit Element for Fast Computer Circuitry

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***Abstract*—A deposited configuration, consisting of a magnetic thin film and coupling loop, was studied with a view to the future development of integrated magnetic circuitry. A line charge model, predicting flux linkages of coupling loops to an accuracy of about one percent was established. The almost complete linkage of the film flux with a deposited loop, due to the very close coupling, was verified. A decrease of about 20 percent in film flux at both ends of the easy axis was noted for the experimental assemblies used. Circulating loop currents were shown to be the chief parasitic factor which modified the switching of the magnetic film. The change in switching time due to eddy currents was small when the loop conductor size was of the same order as the magnetic film. For resistive loop loading, the average field during switching is a good measure of the slowing due to the loading. The film-loop assembly has good potentialities as a circuit element, with good transmission of both read-out and control signals occurring in the loop. The field calibration for these control signals was shown to be the same for both bias and drive field applications.**

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THE GENERAL TREND in computer design towards machines having large memory and logic arrays and having short operating times is further characterized by the use of miniaturized circuitry with low power dissipation. The potentialities of magnetic thin films, having short switching times for moderate drive fields, will be greatly enhanced by the development of integrated circuitry [1], [2], that is, circuitry of magnetic films and associated electrical connections made on the same substrate. A fundamental element, consisting of a magnetic thin film closely coupled by, but insulated from, a deposited loop, is the basis of almost all of the more complicated circuitry. It is important, therefore, to study this fundamental element in detail in order to understand the more complicated circuits.

The close coupling of deposited loops around magnetic films results in almost complete linkage with the magnetic film flux but, owing to variation of the flux within the film, the flux linkage varies with the relative position of the loop and magnetic film. The interaction between a switching magnetic film and a deposited coupling loop is primarily due to the effect of circulating loop currents. The effect of eddy currents is quite small, unless the loop conductor area is large relative to the film area. Good transmission of both read-out and control signals occurs in the loop. The loop bias and drive fields can be accurately predicted from the loop dimensions.

Film Assembly and Test Equipment

The magnetic film and coupling loop assemblies were made four at a time by vacuum deposition. With the glass substrate heated to 300°C, the assembly was formed from layers of Permalloy (83 percent nickel, 17 percent iron), aluminum (conductor material), and silicon monoxide (insulator material). Deposition of the five layers was effected without opening the vacuum in the system. Static measurements were made on each film before it was accepted for high-speed switching experiments. It was required that the static B-H loops along both the hard and easy axes be similar to those for the other films of the set. Deposited loop resistance was recorded with acceptable values in the range of 1 to 10 ohms. The insulation resistance between the Permalloy and loop was determined; in many cases, where the resistance between the two conductors was less than 1 kΩ, presumably caused by pinholes in the silicon monoxide layers, the resistance could be increased to an acceptable value of about 10 kΩ by applying a potential difference of 20 volts across the insulation. A projective view of a complete film assembly is shown in Fig. 1(a). The standard film size (0.45 inches × 0.36 inches × 1500 amperes) is shown, together with a loop conductor 0.03 inches wide, which, because of equipment limitations, was the minimum width loop attainable. The test equipment utilized a high voltage dc supply, discharge cable, and mercury relay system to generate a fast-rise high current pulse. The magnetic field was generated in a strip-line section having a center conductor 1.2 inches wide and 0.05 inches thick, situated symmetrically between two ground planes 1 inch apart. Using a maximum charging voltage of 5 kV, a drive field of 6.5 Oe was obtained in the test region centered directly beneath the center conductor. The duration of this field pulse was 500 ns. It had a rise time of about 1 ns and a repetition rate of 60 pps. The two loops, deposited and external, were arranged as shown in Fig. 1(b). The spring-mounted deposited loop probe, consisting of a ceramic-covered copper wire, pressed against the end tab of the deposited loop conductor, while the ground plane of the loop was held in contact with the strip-line ground plane by clamping the substrate into position. In all tests, the magnetic drive field was applied perpendicular to the loop axes so that an air-flux compensation loop was not required for the external loop.

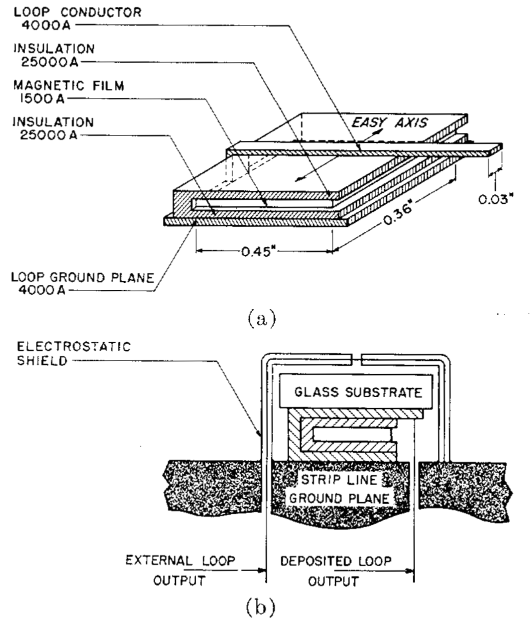

Fig. 1. Film assembly and coupling loop configuration.

The output of either loop, displayed on a sampling oscilloscope, could also be integrated with respect to time, by means of an integrator unit which compensated for drift in the analog output of the sampling oscilloscope. The frequency response of the measuring system was limited by the 0.8-ns risetime of the sampling oscilloscope circuitry, since the analog signal was slow compared to the response time of the operational amplifiers in the integrator unit.

In all experiments, the magnetic drive field was applied along the hard axis of the film, with a reset field applied between pulses to set the magnetization in one direction along the easy axis. When the drive field exceeded the anisotropy field H_k, the final position of the film magnetization, with the drive field still present, was assumed to be along the hard axis. When complete rotation to the hard axis was desired, as in the measurement of flux change magnitudes, a drive field of about $2H_k$ was used to ensure this condition.

Magnetic Film Flux Distribution

The flux distribution of a rectangular magnetic film was investigated by observing the flux changes within various external and deposited coupling loops. All experimental flux change measurements were expressed as flux ratios, rather than relating them to theoretical flux values, derived from film magnetization, thickness, and width. This method avoided errors due to inaccuracies in the forementioned quantities and also obviated the need for accurate calibration of the oscilloscope-integrator unit. (In a few cases not treated explicitly in this paper, correlation between experimental and theoretical flux values was obtained to about 20 percent). Comparison of the flux change within an external loop, whose loose coupling results in an appreciable amount of flux closure within the loop, to the flux change within a deposited loop, which is assumed to have negligible closure flux, was used to study the external flux distribution. Comparison of flux changes within various deposited loops associated with the same magnetic film was used to study the internal flux distribution.

A model, previously used by Oguey [3], for the external flux distribution of a single domain rectangular magnetic film having its magnetization directed parallel to one edge of the film, can be obtained by representing the film magnetization by two uniform magnetic line charges of opposite polarity. These line charges lie along the two opposite edges of the film, at either end of the single domain and extend the length of the film, perpendicular to the direction of magnetization. The flux linkage of a coupling loop having its axis parallel to the film magnetization equals the internal film flux φ_m, less the closure flux φ_c, within the loop. When the film magnetization is switched through 90°, the change in flux linkage, taking account of the eddy currents [4] induced in the thick ground plane [Fig. 1(b)], is given by $(\varphi_m - 2\varphi_c)$. Using the film flux model just presented and the dimensions shown in Fig. 2, the ratio R of flux change to film flux for a loop situated on the film centerline can be shown [4] to be given by:

$$R = 1 - 2\varphi_c/\varphi_m$$
$$= 1 - \frac{l}{\pi a}\{xI_A(x) - I_B(x)\}\Bigg|\begin{array}{l} x = (b+a)/2 \\ x = (b-a)/2 \end{array} \qquad (1)$$

where

$$I_A(x) = \frac{2}{l}\tan^{-1}\frac{2hx}{l[(l/2)^2 + h^2 + x^2]^{1/2}}$$

$$I_B(x) = \frac{1}{2}\ln\frac{\{[(l/2)^2 + h^2]/h - [(l/2)^2 + h^2 + x^2]^{1/2}\}^2 + (lx/2h)^2}{(l/2)^2 + x^2}.$$

By assuming a two-dimensional external flux pattern, an approximate value for R is obtained, which is within a few percent of the exact value over a wide range of film and loop dimensions. This value is given by

$$R_A = 1 - \frac{2}{\pi}\tan^{-1}\frac{2h}{l}. \qquad (2)$$

As can be seen from the foregoing equation, the flux closure within a deposited loop (where $h << l$) is negligible compared to the film flux, and so the value of R also gives the ratio of flux change in an external loop to that occurring in a deposited loop, when both loops are situated on the film centerline.

The change in flux linkage of a loop can be measured by integrating the loop output voltage with respect to time. Although the output and induced voltage waveforms may differ, because of the effect of the transfer voltage ratio of loop circuitry, it has been shown theoretically [5] that the

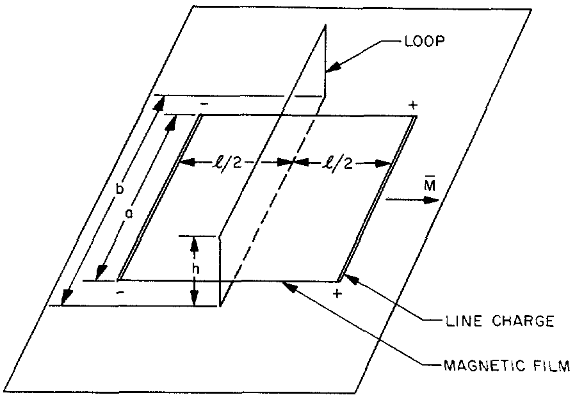

Fig. 2. Rectangular magnetic film and coupling loop.

ratio of the integrated output voltage to the integrated induced voltage depends only on the steady-state attenuation of the loop and its termination impedance, provided the loop is linear. When the loop has zero shunt conductance, this ratio is expressed by $r_0/(r_0 + r_l)$, where r_0 is the steady-state resistance of the loop termination and r_l is the total series loop resistance. The predicted value of the ratio of the output fluxes of an external and deposited loop F_r is given by

$$F_r = R\frac{r_0 + r_d}{r_0 + r_e} \qquad (3)$$

where

r_0 = termination resistance (53.5 ohms)

r_d = deposited loop resistance

r_e = external loop resistance (0.118 ohms).

The experimental values of F_r were determined for a number of film assemblies, having a narrow loop on the film centerline. These values, expressed as a function of the deposited loop resistance, with the film dimension l parallel to the loop axis as a parameter, are shown in Fig. 3. The theoretical values of F_r, corresponding to both the exact flux ratio and its two-dimensional approximation, are also shown. The dashed straight lines, representative of the experimental data, have almost identical slopes to the corresponding theoretical curves, thus verifying the dependance of F_r on the deposited loop resistance. It also seems as if the two-dimensional approximation generally gives the better correlation with the experimental curve. As will be shown later, this better fit arises from a cancellation of the error due to the two-dimensional approximation by the error due to the simple line charge model.

The variation of flux through the magnetic film and the average flux linkages of wide deposited loops were measured by flux switching experiments performed on a number of film assembly sets. The various width loops and their locations relative to the magnetic film are indicated in Fig. 4.

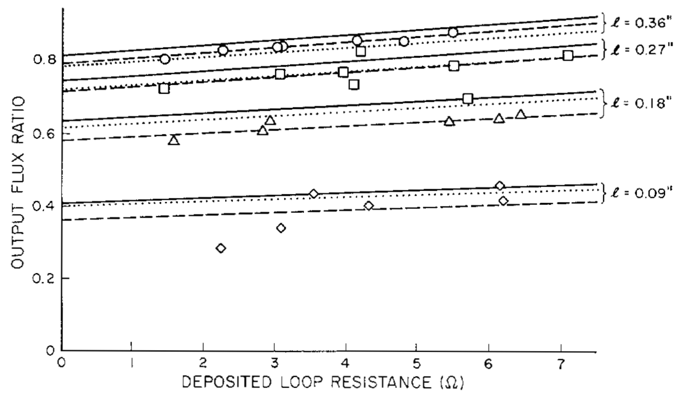

Fig. 3. Output flux ratio F_r as a function of deposited loop resistance with the film dimension l parallel to the loop axis as a parameter. The solid and dotted curves are based on the exact flux ratio and its two-dimensional approximation, respectively. The dashed curves are representative of the experimental data.

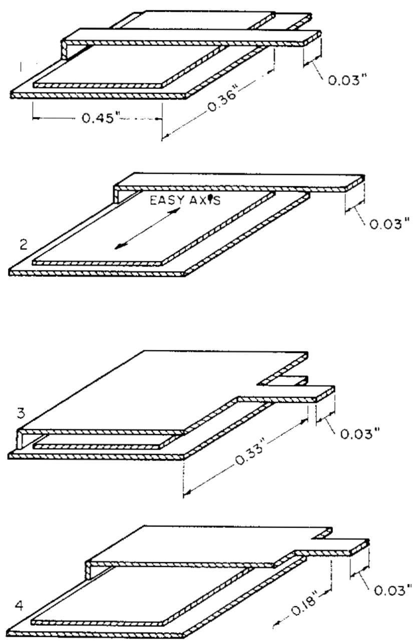

Fig. 4. Film assemblies for measurement of flux variation in magnetic film and flux linkages of wide loops.

TABLE I

Assembly	R_D	R_E
1	1.000	0.780
2	0.818	0.521
3	0.973	0.782
4	0.437	0.396

Since the films of each set were deposited at the same time, they are presumably identical so that flux measurements on the four films of each set can be directly compared to each other. The mean of the results obtained from a number of film sets are shown in Table I (all flux measurements have been corrected for the effect of loop resistance). The quantity R_D is the ratio of deposited loop flux change for each assembly to the deposited loop flux change for assembly 1. The quantity R_E is the ratio of the external loop flux change for each assembly to the deposited loop flux change for assembly 1.

The values of R_D indicate that the flux through the magnetic film varies along the easy axis direction, being about 20 percent less near the ends of the film relative to the value on the film centerline. The values of R_E for assemblies 1 and 3 indicate that the presence of the deposited loops has no effect on the flux change of the magnetic film, and the decrease in R_E as the external loop moves from the centerline to the edge of the film is consistent with the line charge model predictions.

Assuming linear, quadratic, and cubic flux variations along the easy axis direction [i.e., flux at distance x from film centerline $= \phi_0 (1 - Kx^n)$, where ϕ_0 = flux on film centerline, $n = 1, 2, 3$ for linear, quadratic, and cubic variations, respectively], the average flux linkage of a loop of any width can be determined. By calculating the R_D value for assembly 2 for each type of flux variation and using the experimental value of R_D for assembly 2 to determine the appropriate values of K, the corresponding values of R_D for assemblies 3 and 4 were calculated. In addition, by using systems of line charges which correspond to the foregoing flux variations, the value of R_E for assembly 1 was determined. The results of the foregoing calculations together with the corresponding R_D and R_E values for a constant easy axis flux distribution are compared with the experimental values in Table II.

TABLE II
FLUX VARIATION

	Constant	Linear	Quadratic	Cubic	Experimental
R_D (assembly 3)	1.000	0.916	0.940	0.955	0.973
R_D (assembly 4)	0.500	0.427	0.437	0.445	0.437
R_E (assembly 1)	0.818	0.767	0.785	0.791	0.780

It can be seen that, of the four cases considered, the quadratic variation predicts the flux ratios with the best accuracy, being slightly better than the cubic variation in this regard. In the quadratic case, the flux varies by 21.8 percent along the easy axis direction, and the line charge model consists of two uniform line charges at both ends of the easy axis, of the strength ± 0.782 relative to the total film flux, and a uniform line charge distribution of strength $\pm 1.744\ x/l^2$ at a distance x from the film centerline.

Interaction of Magnetic Film and Deposited Coupling Loop

Film-loop interactions arise from eddy currents and circulating loop currents. The importance of these fields in modifying film switching was investigated experimentally. Switching experiments were first performed on the set of film assemblies depicted in Fig. 5 which have similar magnetic films but various loop configurations. The results are shown in Fig. 6. At any given drive field, the switching time becomes progressively longer as additional loop circuitry is added. The change in switching time as the loop

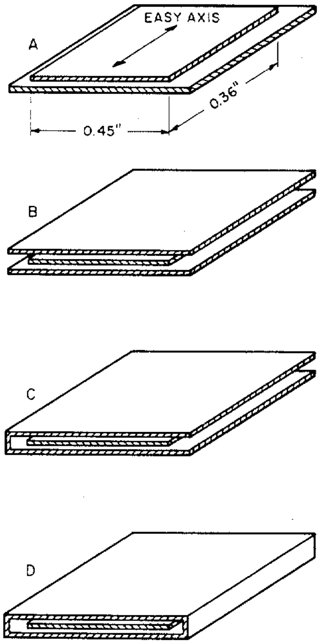

Fig. 5. Film assemblies for study of effect of loop loading on film switching. All loops are the full width of the film. Film A has no loop conductor; film B has a loop conductor which is not connected to the ground plane conductor; film C has a loop conductor connected to the ground plane conductor at one end; and film D has a loop conductor connected to the ground plane conductor at both ends.

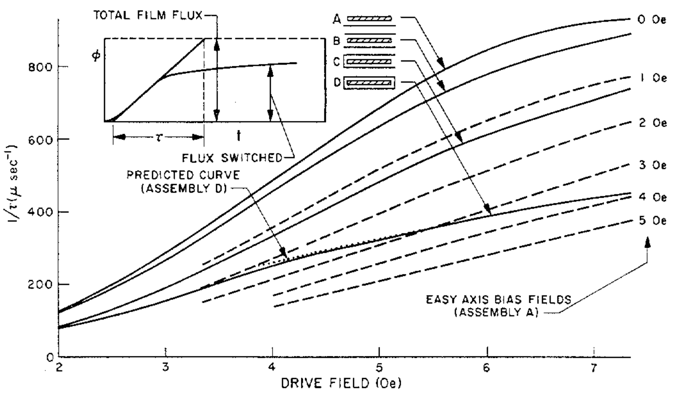

Fig. 6. Variation of film inverse-switching time as a function of drive field with the loop loading as a parameter. The definition of switching time is given in the inset, the total film flux being measured by switching the film at maximum drive field and the decreased flux switched being obtained for fields of the order of H_k($\approx$4.5 Oe) due to incomplete rotation of the film magnetization to the hard axis.

circuitry is modified can be explained in the following manner.

It is first assumed that eddy currents have little effect on film switching since the loop conductors are not large compared to the film size and so flux-closure paths exist through nonconducting material. The change in switching time due to the deposited loop can then be attributed to the effect of circulating loop currents.

The electrical lengths of the loops are short compared to the widths of the switching pulses, and so the loop loading is considered to consist of a lumped impedance terminating a short loop, which has a voltage induced along its length. For assembly D, this loading is considered to be purely resistive, since the loop capacitance is ineffective in a shorted loop and the L/R time constant is small ($<$ 0.05 ns). The resistive field always opposes the change in film magnetization so that the average field is a measure of the total slowing of the switching due to loop loading during the entire switching time. It can be shown [4] that this average field $H(O - T)$ is given by

$$H(O - T) = \varphi_T/TRw \tag{4}$$

where φ_T = total flux change in the direction of the loop axis, T = total switching time, R = loop resistance, and w = loop width. This field acts along the loop axis and thus the conditions of assembly D can be simulated by switching assembly A with various steady fields applied in this direction. The results of such an experiment are shown by the dashed lines of Fig. 6, where it is seen that the simulated average field H_{av} decreases with increased switching time.

According to (4), the value of $H_{av}\tau$ should remain constant as the drive field is changed. Values of $H_{av}\tau$, corresponding to various $1/\tau$ values for assembly D, were obtained by interpolation between the bias curves for assembly A. These field values, together with the corresponding values of $H_{av}\tau$, are shown in Table III.

TABLE III

H_D (Oe)	$1/\tau$ (μs^{-1})	H_{av} (Oe)	H_{av} τ(Oe-ns)
$3^1/_3$	188	2.10	11.20
4	251	2.32	9.25
$4^2/_3$	300	2.70	9.00
$5^1/_3$	345	2.96	8.58
6	389	3.27	8.40
$6^2/_3$	425	3.61	8.50
$7^1/_3$	450	3.89	8.65

It can be seen that the variation of $H_{av}\tau$ is quite small, especially at the higher field values where the loop loading simulation is most accurate.

The switching curve for assembly D was predicted by assuming that $H_{av}\tau$ remained constant at all switching times and that, in the middle of the range (H_{av} = 3 Oe), the predicted switching time was identical with the measured value. The predicted curve for assembly D is shown in Fig. 6 (dotted curve) and is seen to be close to the experimental curve over the entire range of drive field values. Using the measured value of $1/\tau$ corresponding to H_{av} = 3 Oe, in (4), a loop resistance of 0.28 ohms was obtained in comparison to a theoretical dc value of 0.21 ohms. The discrepancy between these two resistance values is chiefly attributable to the presence of oxide layers, frequently encountered in the film assemblies, between the loop conductor and loop ground plane, thus increasing the effective loop resistance. (The increase of resistance due to high frequency effects is negligible since, at 1 K Mc/s, the skin depth of aluminum is 27 000 amperes, which is much greater than the 3500 amperes thickness of the loop conductor.) The comparison between the two resistance values is considered to be reasonable especially when the effects of possible additional factors such as increase of aluminum resistivity due to impurities, errors in the values of film magnetization, film and loop conductor thicknesses, are noted.

According to Fig. 6, the loading of assemblies B and C can be simulated at all drive fields by application of constant fields of $^1/_4$ Oe and $1^1/_3$ Oe to assembly A. Capacitive loading is predominant in these two cases. The constant field simulations cannot be readily explained in a manner similar to the case of assembly D since it can be shown [4] that the average field in this case is equal to zero over the entire switching period and that the average field is proportional to $1/T^2$ during each of the periods in which the rate of voltage change is of one sign.

In the preceding discussion, it was assumed that eddy current fields are small, since the loop conductors are about the same size as the magnetic film. The validity of this assumption was examined by the following experiment. The film assembly consisted of a magnetic film (0.36 inches $\times$ 0.36 inches) with a deposited aluminum ground plane (0.625 inches $\times$ 0.625 inches), and an aluminum foil loop conductor (0.001 inch thick) of variable size. The two conductors were not in electrical contact, being separated by silicon monoxide layers each about 10 microns thick. This arrangement was chosen to keep capacitive currents small and so only the eddy current field was considered to be effective in slowing the film switching. Figure 7 shows the effect of various loop conductors on the switching time of the assembly. It can be seen that the eddy current field increased rapidly when the loop conductor size exceeded the film dimensions. However, it is clear that the eddy current field, due to a conductor size of the same order as the magnetic film, was much less than the field due to a conductor of infinite extent. It can be concluded that a loop conductor which covers only a small fraction of the film perimeter has only a small eddy current field.

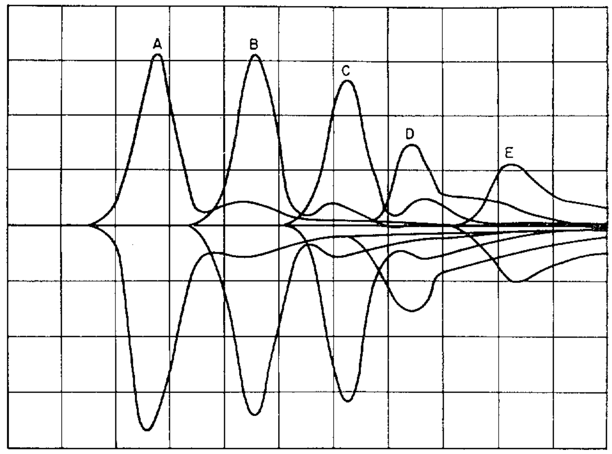

Fig. 7. Effect of eddy current field on film switching. Assembly A has no loop conductor and assemblies B, C, D, and E have loop conductor sizes of 0.35, 0.37, 0.45, and 0.56 inches square, respectively. In all cases the magnetic film is 0.36 inches square. The horizontal scale is 1 ns/div. and the vertical scale is 400 mV/div.

Film-Loop Assembly as a Circuit Element

Utilization of the film-loop assembly in high-speed circuitry depends on being able to use the loop both as a high-speed read-out conductor and as a magnetic field source to control high-speed film switching. The high-speed read characteristics of deposited loops were studied by switching film assemblies and comparing the waveforms obtained on external and deposited loops. In general, it was found that deposited loop switching times were less than the corresponding external loop switching times. Thus, although the presence of the deposited loop may have an appreciable effect on the film switching speed, the effect of the deposited loop transfer function on the observed waveform is quite small. As verified by a detailed circuit analysis of the loop circuitry [4], the small size of this effect is due to the short electrical length of the loop relative to the width of the switching pulses and to the relatively low transmission line damping ($<$ 6 dB) of the loop. In a few cases, the deposited loop switching times were longer than the external loop switching times and this result was attributed to large loop resistance, giving rise to excessive loop attenuation.

The biasing field of a deposited loop was investigated by switching a magnetic film in the presence of an easy axis bias field due to a deposited loop covering the entire film area and comparing the switching waveform to that obtained when an easy axis external bias field was used. The result of such an experiment is illustrated in Fig. 8, which shows the zero-bias switching waveform and the two reduced-amplitude waveforms, obtained by separate application of the two bias fields. It can be seen that when these two waveforms were adjusted, by variation of the bias fields, to have the same amplitude, the waveforms became practically identical. This similarity indicated that the deposited loop field acted uniformly over most of the film surface. (Small differences in these waveforms were attributed to nonuniformity of the deposited loop field near the current injection point.) By comparing, over a wide field range, the external and deposited loop fields which yielded similar amplitude switching signals, it was verified (to better than one percent accuracy) that the deposited loop field (in ampere-turns per meter) is given by the current per meter width of conductor.

The drive field characteristics of deposited loops were investigated by use of a film assembly, having two orthogonal deposited loops, placed parallel to the film magnetic axes. To effect switching of the entire film by the hard axis loop, this conductor was of the same extent as the magnetic film but was connected to the loop ground plane by a relatively narrow strip, thus resulting in moderate eddy current fields. The film switching was sensed by a narrow easy axis loop, situated on the film centerline and contributing little to the total eddy current field. The upper and lower waveforms of Fig. 9 were obtained by switching the film from both directions of the easy axis. The middle waveform represents the pick-up in the loop and was obtained by applying the drive field while film switching was blocked by a large field ($>$ 100 Oe). It can be seen that the lack of symmetry in the switching signals is due to this large pick-up signal, which was attributed to capacitive coupling between the deposited loops. The film flux output

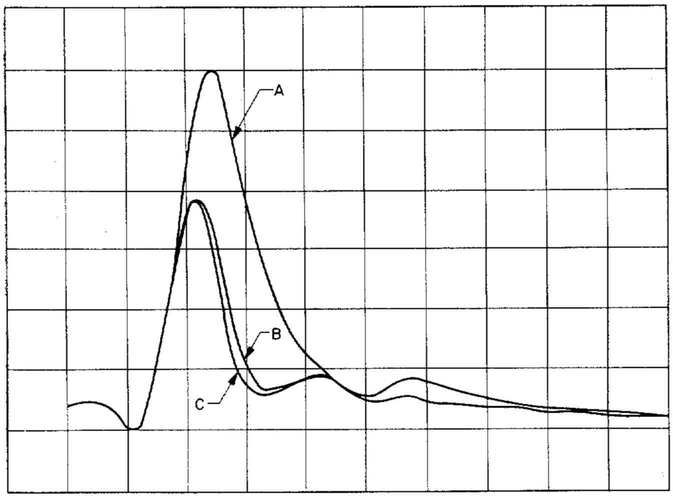

Fig. 8. External loop waveforms for $6^2/_3$ Oe drive field, with deposited loop and external bias fields. Trace A is with a zero bias field. Trace B is with a 2.7 Oe deposited loop bias field. Trace C is with a 2.7 Oe external bias field. The horizontal scale is 1 ns/div., and the vertical scale is 200 mV/div.

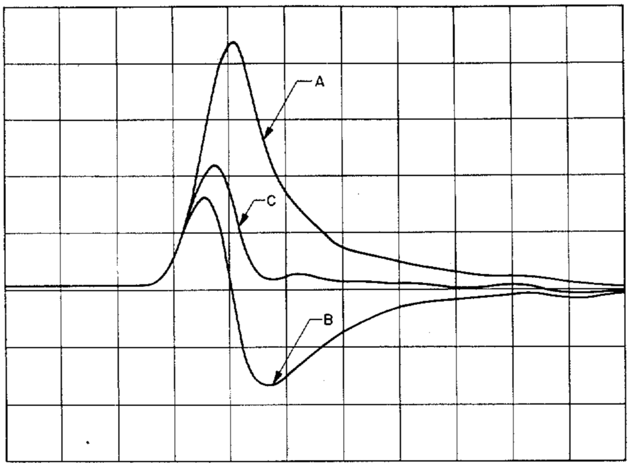

Fig. 9. Deposited loop output due to 6 Oe deposited loop drive field. Trace A is with a positive reset field. Trace B is with a negative reset field. Trace C is with a 100 Oe blocking field. The horizontal scale is 1 ns/div. and the vertical scale is 200 mV/div.

was obtained by taking the mean of the two flux outputs, when the film was switched from both directions of the easy axis. By comparing flux outputs due to the deposited loop drive and an external drive, the field calibration already obtained for the deposited loop bias field was verified with an accuracy of 5 percent. (Fields of the order of H_k were used, so that the flux output was a sensitive measure of field strength.) It was noted that, at corresponding drive fields, the film switching time with a deposited loop drive was about 50 percent longer than with an external drive. This result was attributed to risetime differences in the two drive field pulses and to further slowing of the deposited loop pulse in the input circuitry.

Conclusions

The internal flux of magnetic films varies along the easy axis direction in a quadratic manner, a 20 percent decrease at both ends of the axis being observed for the assemblies investigated. (Very close to the ends, departures may occur from this value because of the effect of local fields of reversed domains.) The system of line charges corresponding to this flux variation predicts the external flux pattern of the magnetic film and so can be used to calculate the flux linkage of loops coupling the film. The effect of loop circuitry on the flux output of a switching magnetic film is due solely to the steady-state attenuation of the loop and its termination impedance, thus indicating that the loop circuit behaves in a linear manner.

Extremely close coupling exists between a magnetic film and a deposited coupling loop. Thus, significant miniaturization of integrated deposited circuitry is feasible without incurring appreciable flux loss by closure within the coupling loop (e.g., a film one mm^2 having loop insulation layers 2.5 microns thick has about $^1/_4$ percent flux closure within the loop). The variation of film flux along the easy axis direction indicates the need for accurate deposition of the loops relative to the magnetic films if similar flux outputs are to be obtained from similar films. This flux variation must also be considered in the design of multiturn loops, which extend over an appreciable amount of the film surface. The magnitude of this flux variation, which may increase as the film size decreases, may become a limiting factor in a miniaturization of integrated deposited circuitry.

Good transmission of both read-out and control signals occurs in a deposited loop, and so the feasibility of using integrated deposited circuitry for high-speed switching applications basically depends on keeping loop eddy current and circulating loop current fields small. The slowing due to eddy current fields, caused by loop conductors about the same size as the coupled film, is quite small, especially when an appreciable amount of the film perimeter is not covered by the loop conductor. The circulating loop current, due to loop capacitance, can be kept small by using thick insulation layers. This latter field decreases rapidly with film size and so is not a significant factor in miniaturized circuitry. The slowing of film switching, due to a resistive loop field such as occurs in a loop coupling two magnetic films, can be accurately predicted, provided that the loop resistance is known, from the switching characteristics of the isolated film by calculation of the average loop field during the switching process. This result has been found useful in the investigation of the basic design of integrated deposited circuitry.

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