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Device and Array Design for a 120-Nanosecond Magnetic Film Main Memory

Abstract: Device and array design considerations are described for a manufacturable 120-nsec cycle magnetic film memory containing 600,000 bits in the basic operating module. Worst-case testing is done in such a way as to provide quantitative values for such effects as adjacent bit-line stray field, ground-plane current spreading, flux trapping in metallic ground planes and strip lines, and magnetic-keeper efficiency. Worst-case output signals exceeding 3.8 mV are achieved with a 8-nsec rise-time word pulse of 510 mA. Bit current is 100 mA.

Introduction

When work began in earnest on the 120-nanosecond, 600,000 bit memory, about nine years after the use of magnetic thin film storage elements was first suggested by the pioneering work of Blois¹ and Conger,² a number of gross engineering decisions could be made based on previous results obtained by the authors and others. Coupled film approaches such as those discussed by Daughton and Chang³ were not attempted, in spite of very attractive flux closure properties, because commercial fabrication appeared not to be practical within the planned time schedule. Similarly, anticipated fabrication difficulties caused one to pass by the exciting possibilities for ultra high-speed, noncoincident-current memories using biaxial films as proposed by Pugh.^{4,5}

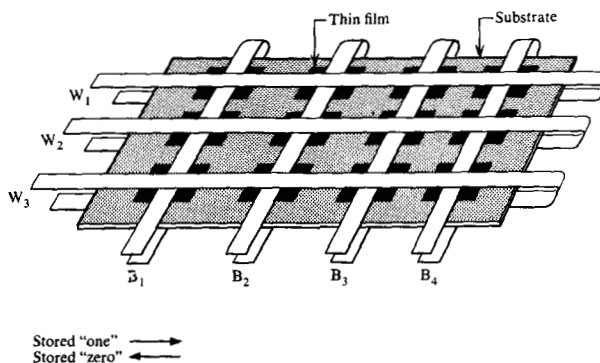
A word-organized, orthogonal drive scheme was selected because of the resultant high-speed, nearly-coherent device switching,^{6,7} as opposed to the much slower wall motion switching associated with parallel drive schemes. In addition, this mode offered relaxed tolerances on drive currents and film properties,^{8,9} and had previously been used in the Lincoln Laboratory TX-2¹⁰ and FX-1 computers, in the IBM Research feasibility model,¹¹ as well as in the Univac 128-word by 36 bit-per-word, 600-nsec scratch pad memory.

It was clear that drive and sense circuitry would be expensive, and that the maximum number of bits should therefore be served by one drive or sense line. To achieve

this, bits must be spaced close together to reduce line delay and attenuation. Also, drive currents should be minimized and output signal maximized to permit the most economical implementation of drive and sense circuitry.

A major question, requiring early decisions, was whether to use magnetic films deposited on metallic ground planes as proposed by Bradley⁹ and Proebster¹¹ or to use films deposited on glass or mica as was done in the Lincoln Laboratory TX-2 and FX-1 memories and in the Univac scratch pad memory. Figure 1 illustrates how the bit and word lines wrap around an insulating substrate with magnetic films. If the substrate were a conductor, the return lines could be eliminated by terminating (or shorting) the bit and word lines to the substrate. Return paths for

Figure 1 A 3×4 bit memory array schematic with word lines W_1 , W_2 , and W_3 and bit lines B_1 , B_2 , B_3 and B_4 .



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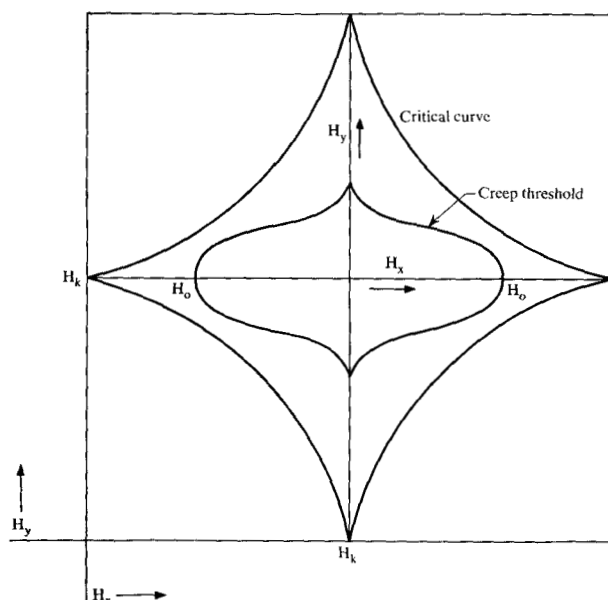


Figure 2 Idealized critical curve with creep threshold indicated.

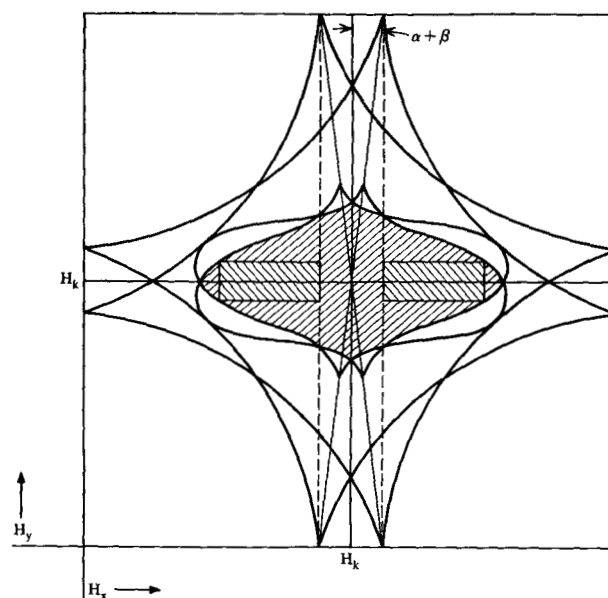


Figure 3 Critical curves and creep threshold curves illustrating effect of skew and dispersion on drive field tolerances.

current flow are then provided by the substrate or ground plane. In addition to reducing the number of strip lines in the memory, this scheme also reduces line impedance and stray fields since the thickness of the substrate does not intervene between the drive line and its electrical return path. A significant advantage of a conducting substrate, frequently overlooked, is the greater uniformity of bit properties which can be achieved on a good thermal conductor due to uniformity of substrate temperature during film deposition.

Major disadvantages of metal substrates include current spreading in the ground plane, which effectively reduces drive margins, and the trapping of the magnetic flux of the bit, which increases the bit field required to switch the film.¹² The first of these problems can be overcome electronically with some increase in memory cycle, power, and circuit cost. A magnetic keeper^{12,13} can greatly lessen both problems with some increase in fabrication complexity and array noise as will be described later.

With the above considerations in mind, the major thrust of the program was aimed at the orthogonal drive mode, with single layer films deposited on metallic ground planes, and the use of a keeper to solve the ground plane eddy-current problems.

A description¹⁴ of the resultant memory including operating characteristics and some general design considerations was first given by Q. W. Simkins at the 1965 Fall Joint Computer Conference.

Basic device considerations

The basic requirements for a magnetic film memory device can be understood by referring to the idealized critical curve¹⁵ for single-domain rotational switching, and to the internal creep threshold¹⁶ curve shown in Fig. 2. Rotational switching is possible when the sum of the applied fields, $H_x + H_y$, exceeds the critical curve. In practical films, single domain behavior does not occur for all of the field configurations implied in Fig. 2. The various reversal processes are adequately discussed in the literature.^{16,17} In the write operation used in this design, a field H_y (word field) is applied along the magnetic hard axis by a current pulse in the word line. When H_y exceeds H_k (the anisotropy field), the magnetization will be aligned parallel to the hard axis. A very small field H_x (bit field), resulting from a current pulse in the bit line, will cause the magnetization to rotate slightly toward the positive or negative X axis depending on the polarity of the pulse. If H_y is reduced to zero when H_x is "on," the magnetization will rotate in the direction of H_x until it lies along the easy axis. H_x may then be turned "off" and the film will remain in this stable storage state.

To avoid loss of stored information the film must be stable against all fields which may be applied between the time information is stored and the time it is finally read. It is evident from Fig. 1 that as information is written into bit W_2B_3 , for example, bits W_1B_3 and W_3B_3 along the same bit line see the same bit field H_x . Such a disturb

field could occur as many as 8 million times per second in the proposed memory. H_0 represents the easy direction threshold field, characteristic of the film, below which domain walls will not be caused to propagate through the film no matter how often a bit-disturb pulse is applied. In addition to the disturb field along the easy axis, there can occur simultaneously a hard-direction disturb field due to word leakage currents or stray fields from the adjacent word lines. This disturb effect, called domain wall creep, was studied in detail by Middelhoek.¹⁶ So long as the combined disturb fields from the bit line and word lines are within the creep threshold illustrated in Fig. 2, the information will be retained in the film.

This simplified picture is complicated by many things, among which are dispersion (α) and skew (β), illustrated in Fig. 3. If the easy axis of a film is rotated β degrees from the word line, we say it has a skew of β . The easy axes of all films fabricated on the same substrate will not be exactly parallel, so skew is an unavoidable problem. The maximum positive and negative skew in an array might be represented by the rotations of the two critical curves in Fig. 3.

Dispersion relates to microscopic angular deviation in the easy axis direction within a film due to variations in internal stresses, grain boundaries, and atomic pair alignment. The measured dispersion angle, α , is the angle from the hard axis at which a large magnetic field must be applied in order to assume that, as the applied field is reduced, 90% of the film's magnetization will rotate in the same direction. To denote this specific measure of dispersion a subscript 90, for 90%, is frequently added as follows: α_{90} . For angles less than α_{90} , more than 10% of the film will rotate in the opposite direction, resulting in a multi-domain state. (A more detailed discussion of anisotropy in films, critical curves, and switching phenomena can be found in a review article by Pugh.¹⁸)

The two rotated critical curves in Fig. 3 schematically represent the extreme values for $\alpha + \beta$ in the array. To guarantee full switching, the bit field must exceed the dotted vertical lines

$$H_b \geq H_k \sin(\alpha + \beta) + kH_{de}. \quad (\text{Static})$$

The word field must exceed the anisotropy field plus demagnetizing field of the bit when driven into the hard direction

$$H_w > H_k + H_{dh}, \quad (\text{Static})$$

where $H_{dh} \cong 4\pi MD/L$ and M is the saturation magnetization, D is film thickness, L is the width of the device in the hard direction, and H_{de} is the easy direction demagnetizing field computed similarly. The constant k assumes a value between 0 and 1 that depends on the angle of M at the time of writing. Finally, to avoid creep, the vector sum of H_b plus the stray word fields must be confined within the

shaded region enveloped by the two creep threshold curves in Fig. 3. The two oppositely shaded rectangles indicate the acceptable operating range for disturb fields as bounded by minimum and maximum H_b and an assumed maximum hard direction disturb field.

The range of permitted values of H_b are the device operating margins which must accommodate variations from the nominal bit drive plus a variety of other effects. As will be discussed, these other effects can demand most of the device margins, leaving little (if any) margin for the associated electronics.

Stray fields from neighboring drive lines will occur for bit lines as well as word lines. Adjacent bit-line fields are necessarily smaller than fields from the line directly over the bit, but are large enough that they cannot be neglected.

The static magnetic field of the neighboring bits at the location of the bit under consideration increases with the packing density and depends upon the stored information. These fields increase the required bit drive and reduce the allowable disturb field. In the worst case for storage, all bits within an angle of roughly $\pm 55^\circ$ to the easy axis are magnetized opposite to the bit under consideration and all other bits are magnetized parallel to it. In practice, 80% of the total field is contributed by the four nearest neighbors, and only the field component parallel to the easy axis has to be considered.

Since the bit field required to select a bit is usually less than one oersted, the device will be sensitive to extraneous fields such as the earth's field. Adequate shielding for the array must be provided.

The conducting ground plane

By depositing the magnetic film elements on a metallic ground plane, the return drive lines of Fig. 1 can be eliminated. The ground plane will provide the return path, and the field applied to the bit will be the sum of the field from the current in the drive line and the field due to the current in the ground plane. Three advantages result: (1) Stray fields from adjacent lines will be reduced since these fields are nearly proportional to the separation of the outgoing and returning drive currents, (2) line impedances and drive power requirements will be reduced for the same reason, and (3) only half as many drive lines will have to be fabricated and packaged in the array. With these advantages come two very significant disadvantages, as pointed out by Pohm et. al.¹²: (1) Flux from the bit may be trapped in, or repelled by, the ground plane and (2) the low frequency components of the drive currents will spread throughout the ground plane, reducing the image field.

The first of these effects is illustrated in Fig. 4. In Fig. 4a the lines of return flux $\mathbf{B}$ from the film are shown for a static case (film along easy axis), being equally distributed in the ground plane and air, since the permeabilities of the

two are about equal. If the magnetization of the film is quickly reversed by 180° , the flux shown in Fig. 4a in the ground plane will decay with a fundamental time constant of about 700 nsec, as reported by Shahan and Townsend.¹⁹ Since the ground plane flux persists in the same direction while the air flux reverses instantaneously, the new flux closure pattern will have three times the lines above the ground plane as in the static case. This is illustrated in Fig. 4b.

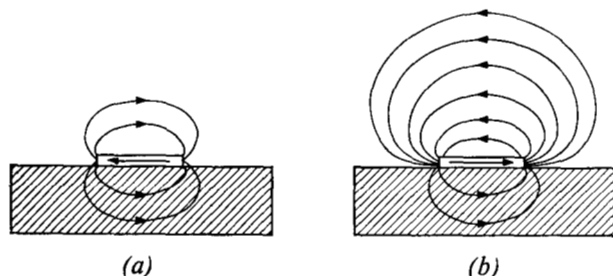
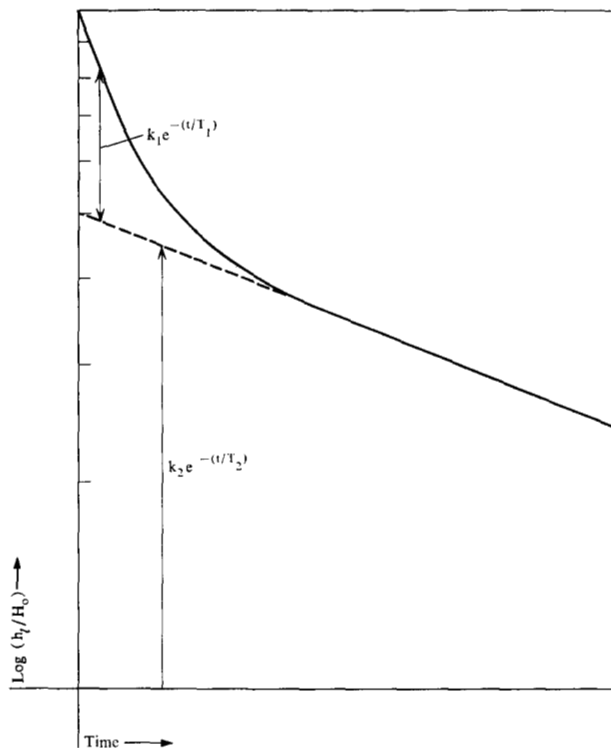


Figure 4 Static magnetic flux is equally distributed in air and through the metallic ground plane in (a). Immediately after magnetization of bit is reversed (b), old flux lines remain trapped in ground plane while newly formed reverse-direction lines have not yet penetrated it.

Figure 5 Trapped flux in ground plane and strip lines decays with two different time constants.



The disturb sensitivity of the bit is dramatically increased with three times the normal demagnetizing field acting on it. However, only six disturb pulses can occur within the trapped flux time constant, and their effect is negligible compared to the 10^7 pulses per second which may occur in the memory.

These dynamic demagnetizing fields increase the bit and word fields required for writing as indicated below:

$$H_b \geq H_k \sin(\alpha + \beta) + H_{ds} (1 + 2k), \quad (\text{dynamic})$$

$$H_w > H_k + 2H_{dh}. \quad (\text{dynamic})$$

Here H_{ds} and H_{dh} are static demagnetizing fields in the easy and hard magnetic directions, respectively, and the equations are valid where the pulse widths are short compared to the time constants involved. The increase in bit drive due to the metal ground plane is particularly dramatic. For example, for a bit that is 1000 Å thick and 27 mils wide, the static demagnetizing field would be about 1.5 Oe. If this film had an H_k of 5 Oe, it would require at least 0.15 Oe of easy axis field to tip the magnetization by 5.7° in the absence of a conducting ground plane. With the conduction ground plane and short pulses, at least 1.8 Oe would be required.

Flux trapping and enhancement of demagnetizing fields are caused by the strip lines as well as the ground plane. Fig. 5 indicates how the total eddy-current field decays with time for a particular device-strip line geometry.^{19,20} These data indicate comparable contributions from strip lines and ground plane, but with a 70-nsec time constant associated with the line and a 700-nsec time constant for the thick ground plane. The relative magnitudes of the two effects, and the time constants, are dependent on the line and device geometries.

Ground plane current spreading is illustrated in Fig. 6 for a single drive line over a conducting ground plane. If a short current pulse is sent down the drive line, the return current in the ground plane will be confined directly under the drive line. For longer duration pulses or repeated pulses, the return current will tend to spread out in the plane as illustrated in Fig. 6a, approaching more and more the dc case in which current would flow throughout the entire ground plane. When the pulse is terminated, the inductance of the spread-out current causes it to continue to flow. This is possible only by completing the current loop in the ground plane by a reverse current component directly under the line as shown in Fig. 6b.

The field seen by a magnetic film directly under the drive line is illustrated in Fig. 7 for rectangular current pulses of 50% duty factor. As the first pulse starts, a full field of amplitude H_b acts on the bit with $0.5H_b$ caused by the current in the drive line and $0.5H_b$ caused by the returning ground plane current. With a 50% duty factor this latter contribution will ultimately drop to $0.25H_b$, so that after

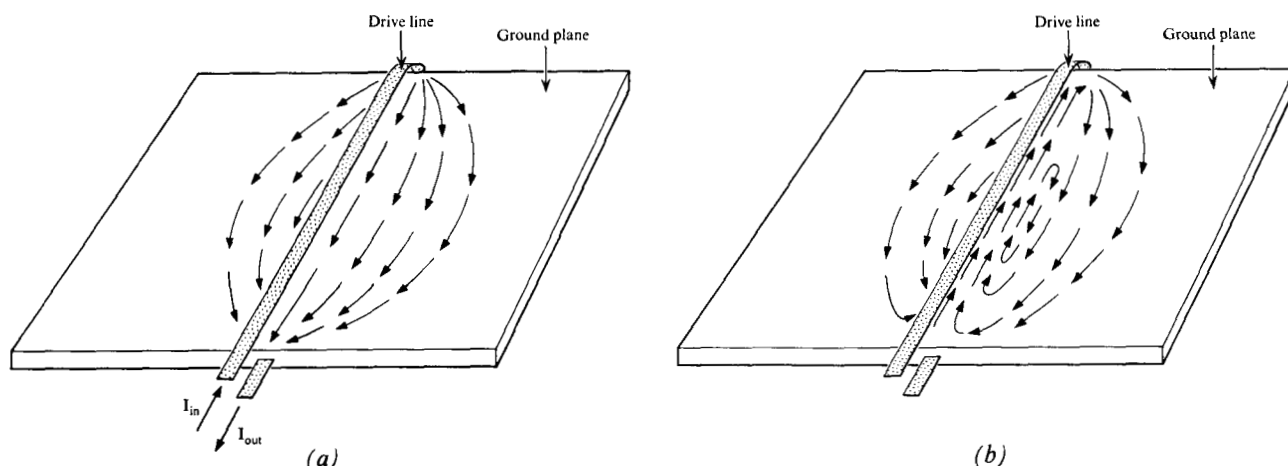


Figure 6 Ground plane current spreading for single drive line over ground plane (a) for pulse on, and (b) for pulse just terminated.

many pulses, the total field seen by the bit will be $0.75H_b$. A portion of this decay occurs during the first pulse as the current starts to spread out. Measurements of this phenomena have been described by Shahan and Townsend.¹⁹ Calculations, in reasonable agreement with experiment, have also been made.²¹

These effects must be considered carefully since the time constants are long compared to the memory cycle. For a duty factor of 16%, as actually occurs on the bit-line of the present design, the maximum field reduction is 8% and the nominal bit drive must be increased by this amount. A bit field increased by 8% can also occur by preceding the bit pulse of interest by a series of opposite-polarity pulses. If the increased bit pulse is accompanied by an adjacent word line pulse while the preceding pulses are not, an enhanced disturb effect may result. This and many other possible combinations are considered in constructing a worst-case test pattern.

Worst-case test pattern

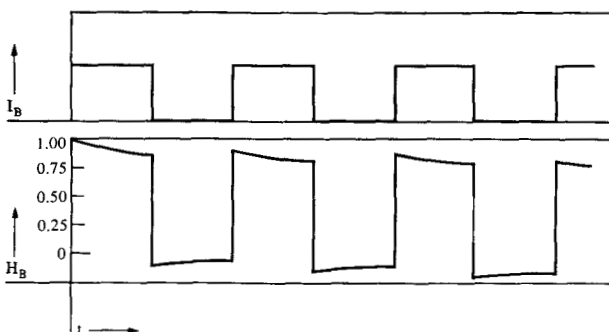
A good rule of thumb in designing a test pattern for memory elements is that anything that *can* happen, ultimately *will* happen. Therefore, a worst case test pattern must include all effects known to be deleterious to device performance. These include (a) the magnetic state of neighboring storage locations which contribute maximum stray field to oppose the writing operation and later increase the disturb effects, (b) exercise of the film to be tested to provide maximum adverse eddy current-fields in opposition to the writing bit field, (c) a writing operation using the most seriously degraded word and bit pulses anticipated, (d) the most severe disturb condition the film can realistically experience, (e) the most severe use of adjacent lines from the standpoint of stray fields, and (f) readout

using the most seriously degraded word pulse anticipated. The pulse test program is illustrated in Fig. 8, and consists of five parts: PRECYCLE, PUMP AND SET, WRITE, DISTURB, and READ.

During PRECYCLE, the bit to be selected (W_i, B_i) is saturated by 10^3 write operations, of coincident word and bit pulses, in a direction opposite to the desired information state. This is done to ensure maximum bit spreading and that each microscopic region of the bit will be oriented opposite to the subsequent write pulse.

The PUMP AND SET sequence consists of a series of 10^3 bit pulses and coincident adjacent word line pulses. The bit pulses are of the same polarity as the subsequent write pulse and, therefore, pump up a ground current whose field at the bit will oppose that of the subsequent write pulse. The bit pulses plus the coincident adjacent word line pulses write information into the adjacent bits on the same bit line of such polarity that their resultant stray fields will oppose the write field to be applied to the selected bit. The

Figure 7 Bit field H_b vs. time for rectangular current pulses I_b of 50% duty factor.



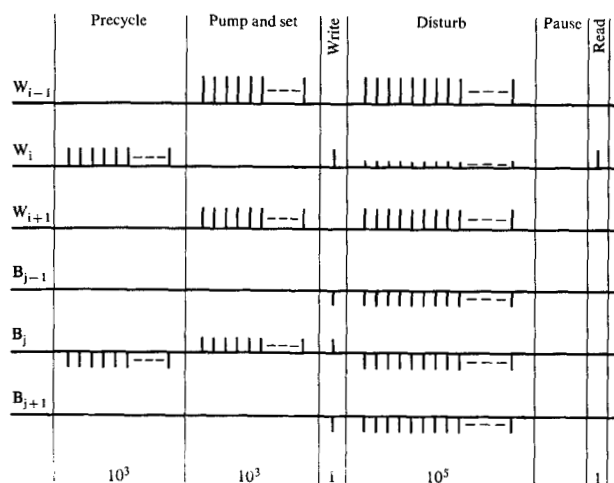


Figure 8 Worst-case pulse pattern for bit under word line W_i and bit line B_j .

length of time for the PUMP AND SET sequence must be sufficient to permit the to-be-selected bit to acquire an equilibrium flux closure pattern as illustrated in Fig. 4a so that writing will result in the maximum demagnetizing field illustrated in Fig. 4b.

The WRITE pulse follows the last PUMP AND SET pulse by a time no greater than would occur in the memory cycle to realize the effects of the pumped-up ground plane current. A bit pulse is simultaneously sent down the adjacent bit lines of such polarity that their stray field will oppose the writing bit field. The net bit field acting on the bit at write time will be the field from the bit pulse minus the field from the pumped-up ground plane current, the stray field from the adjacent bit lines, the static field from the adjacent bits, and the demagnetizing field from its own lines of flux which remain trapped in the ground plane during switching.

The DISTURB portion of the cycle is designed to destroy the written information by domain wall creep. Bit pulses of polarity to reverse the written information are applied over the bit with a duty cycle low enough that negligible current will be pumped up in the ground plane. Adjacent word pulses are alternately applied to lines W_{i+1} and W_{i-1} coincident with the bit pulses. This is more severe than using only one adjacent word line, since walls may creep in from both edges of the bit. Disturb sequences up to 10^{10} cycles were studied and it was determined that little additional loss of information occurred after 10^5 disturbs. Theoretically a more severe disturb pattern might consist of bit pulses with polarity of the write pulse to pump up ground currents to enhance the subsequent bit disturb pulses applied with coincident word disturb pulses. Experiment revealed this was not as severe as the pattern actually applied, due to the restoring

influence of the bit pump pulses which are applied in bursts of 10 to 100 between each burst of disturb bit and word pulses.

In addition to the adjacent word line pulses, small pulses (10 mA) were applied directly to the word line over the bit to simulate leakage and sneak currents coupled into the word line.

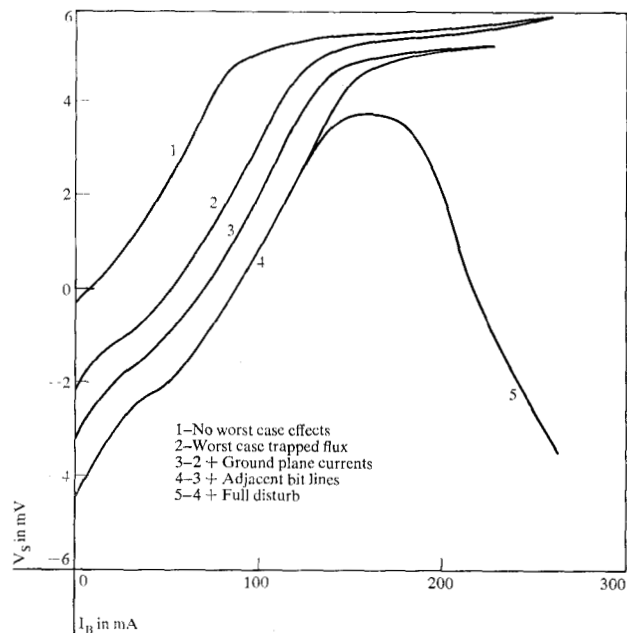
The READ pulse is preceded by a pause long enough for the various transient effects to subside so that circuit noise will be minimized. After the pause, a single READ pulse is applied to word line W_i . The pulse is designed to simulate the most seriously degraded word pulse in the array. Sensing (in the tester) is accomplished on a short loop terminated for minimum reflection at its output end. The detected signals must be sufficiently larger than specification to account for all uncertainties of calibration, tester noise, etc.

It was considered desirable to include in this pulse program the effects of worst-case circuit performance as well as worst-case device conditions by including tolerances of $\pm 10\%$ on the drive levels. Word current and bit current used during writing are below nominal while currents used for pre-cycle and disturb are set at the appropriate percentage above nominal.

The nature of the above effects is illustrated by the 1-0 plots of Fig. 9, in which the peak output signal produced

Figure 9 Output voltage from bit versus bit drive current for fixed word current. The five curves show the effect of increasingly severe pulse patterns:

- (1) no worst case effects, (2) trapped flux, (3) ground plane currents plus (2), (4) adjacent bit line currents plus (3), (5) full post-write disturb series plus (4).



by the READ operation is plotted as a function of bit write current for various pulse patterns. The individual curves represent the effects of various deleterious pulse patterns applied prior to and during the write operation, and with subsequent disturb pulses. These curves show how a signal in excess of 5 mV for bit currents from 100 mA to more than 300 mA is reduced to less than 4 mV over a very narrow range of bit currents by increasingly severe pulse patterns. Small additional effects (such as an increased number of disturbs) could further reduce the operating margins to make the device completely inoperative.

The horizontal displacement of the curves near $V_s = 0$ is a measure of the effective loss of bit current (ΔI_0) resulting from each effect. It is necessary to know the numerical magnitude of each effect if one is to optimize the device and array design. It also provides a method for simulating any worst-case conditions which may be impractical to test directly on a memory-plane tester. Curves such as those in Fig. 11 obtained for a number of devices over a range of experimental conditions also facilitate the simulation of, or allowance for, numerous other deleterious effects associated with insertion of devices into a mechanical memory structure. These include misregistration or skew of devices with strip lines, magnetostrictive skew induced in the devices by the pressure system, and stray fields not fully shielded from the array.

The magnetic keeper

Magnetic keepers were considered early in the design because of the possibility of reducing many of the deleterious effects on the device produced by the ground plane and array design. Trapped flux and stray field effects are reduced in a straightforward manner by providing a low reluctance return path for flux lines through the keeper. Less obvious is its relation to effects associated with current spreading in the ground plane. Without a keeper,

current-induced lines of **H** and **B** are nearly zero above the strip line when the ground plane current is well confined under it. This is due to the opposite and nearly equal flux generated by the strip line current and its image current. As the image current spreads out, lines of **H** and **B** increase above the strip line and decrease between it and the ground plane. A keeper placed close above the line allows **B** to increase but holds **H** very small due to the high permeability. This is accomplished by formation of magnetic poles on the surface of the keeper. The magnetic poles generate an **H** field between the strip line and ground plane of proper polarity to compensate for the loss of field associated with current spreading. Further details on these mechanisms have been discussed by Ravi and Koerber.¹³

The efficiency of a keeper in reducing each of these deleterious effects can be obtained from 1-0 plots of the type shown in Fig. 9 taken with and without the keeper.

Efficiency of a keeper, E_k , is defined by

$$E_k = \frac{\Delta I_0 - \Delta I_k}{\Delta I_0},$$

where ΔI_0 is the equivalent bit current associated with a given effect without a keeper and ΔI_k is the same current, with a keeper.¹³ Some typical data are shown in Table 1 for Permalloy and ferrite keepers.

The high permeability of Permalloy and its availability in sheet form made it seem attractive for array fabrication. However, its efficiency was not as high as that of non-conductors, probably because its conductivity prevented adequate penetration of lines of **B** at high frequencies, which is a requisite of good keeper action. This is indicated by its lower general efficiency compared to ferrite (Table 1) and especially by the fact that its best relative performance is in reducing stray adjacent-bit field effects which are the lowest-frequency effects listed.

An inexpensive method has been developed for fabricating flexible ferrite sheets of adequate permeability and minimal remanence. The process consists of mixing fine, screened ferrite powder with a suitable binder such as silicone rubber. The resulting slurry is spread on a substrate such as Mylar until dry. The dry sheet is easily stripped from the Mylar and has a good surface finish. It is made in long strips which are later cut into 3×3 in. squares and placed atop the strip lines opposite the metallic ground plane and deposited devices.

The gap between keeper and magnetic devices (determined by the thickness of the word and bit/sense strip lines) is one of the fundamental determinants of keeper efficiency. In Fig. 10, an experimental curve shows how keeper efficiency varies with the size of the film keeper gap. For this reason, it was desirable to keep the distance occupied by the word and bit/sense strip lines as small as mechanically possible. The lines ultimately designed have a total package thickness of less than 4 mils.

Table 1 Worst-case effects and keeper efficiency

Worst case effects	Efficiency as a percentage reduction in worst case effects	
	Metallic keeper	Non-metallic keeper
Trapped flux	40	64
Ground plane current spreading	55	73
Stray field from adjacent bit lines	67	75
Stray field from adjacent bits	80	99+
Overall efficiency	56	73

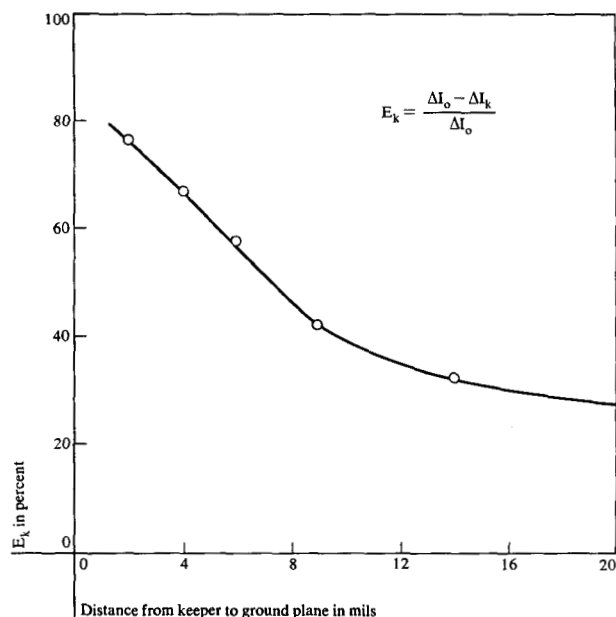


Figure 10 Keeper efficiency vs. distance of keeper to magnetic film in mils.

With the same experimental test program, the films used as in Fig. 9 were tested again with a keeper of efficiency $E_k = 67\%$. The results are shown in Fig. 11. The improvement is obvious. This keeper and film are typical of those used in the present design.

Strip line considerations

The gross features of the strip line and array configuration result from four basic decisions: (1) use of slotted lines to reduce eddy currents, (2) use of separate but coplanar bit and sense lines and directional coupling to reduce write noise, (3) inclusion of a dummy sense line for cancellation of word noise, and (4) placement of the word line nearest to ground to reduce word drive power.

Even though strip word line eddy-current decay is much more rapid than ground plane current decay, as illustrated in Fig. 5, the effect is still quite significant for the narrow word pulses required to meet the performance objectives. Furthermore, since the keeper significantly reduces the flux penetration of the ground plane, the relative importance of flux in the strip lines is increased, thus making slotting of drive lines more important with a keeper than without. For this design, the desired, 0.015-in. word line is slotted into two 0.005-in. strands with a 0.005-in. gap as illustrated in Fig. 12. This not only reduces the magnitude of flux trapping, but also the decay time constant. Further benefit might have been obtained by using a larger number of finer strands, but this would have imposed unduly severe requirements on the line fabrication technology.

Minimizing write noise was an important requirement.

Use of separate bit and sense lines avoids the large $I_b Z_b$

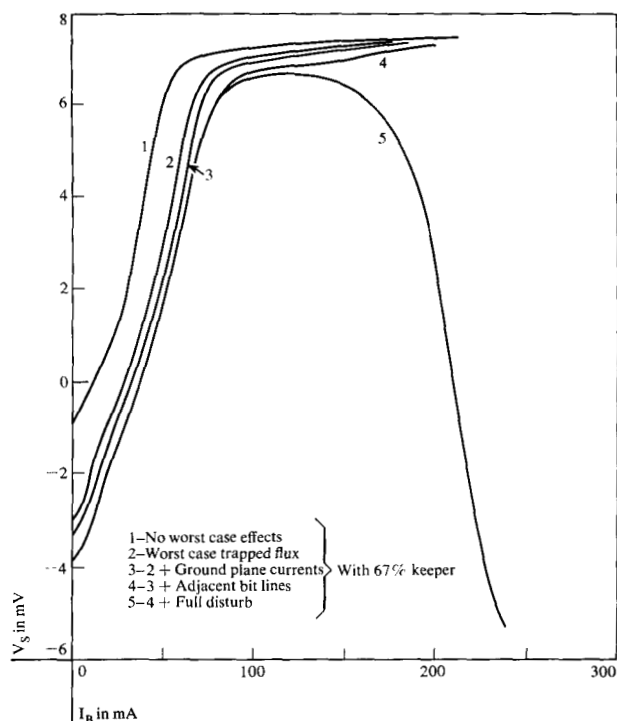
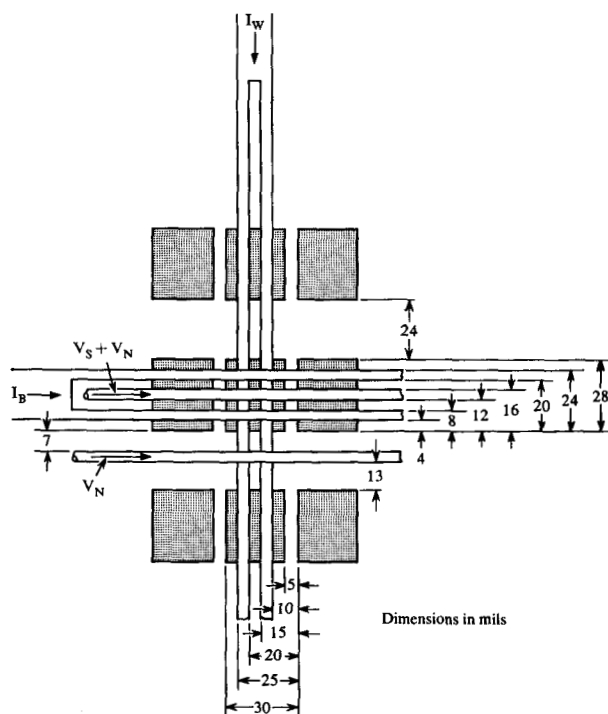


Figure 11 Output voltage from bit vs. bit drive current for fixed word current. Conditions and bit identical to that of Fig. 9 except for the addition of a keeper with 67% efficiency.

Figure 12 Device layout showing detail of striplines and their relation to the etched bits.



noise "seen" by a sense amplifier on a common bit/sense line. In the memory $I_b Z_b$ exceeds 3 volts. By slotting the bit line a sensing strand can be inserted between the two segments of the bit line. With such an arrangement it is possible to maintain separate, but coplanar, bit and sense lines for which the large inductively and capacitively coupled noise components can be effectively minimized by exploiting the concept of directional coupling.²² This requires the lines to be accurately terminated and the bit driver and sense amplifier to be located at opposite ends of the array. This arrangement would provide excellent write noise cancellation except for two things: (1) Stray fields from adjacent bit lines couple the sense line, giving a noise signal whose polarity is dependent on the information being written into the adjacent bits, and (2) the magnetic characteristics of the keeper and the finite conductivity of the ground plane prevent the full benefit of the directional coupling from being realized. In practice, sufficient write noise is still present on the sense line that it is desirable to provide another level of cancellation by sensing between two separate planes driven in parallel by the same bit driver.

When a given word line is selected, the resulting voltage transient causes a displacement current to flow in the sense line. This produces a voltage at the sense amplifier which has the shape of di/dt and is referred to as read noise. It is comparable in amplitude to the signal and peaks 1 to 3 nsec ahead of the signal. A number of schemes might be utilized to cancel this noise, but for the fast signals in this memory, the preferred way is to provide a dummy sense line for each active sense line. The difference mode signal between the sense and dummy sense lines, represented by $(V_s + V_n) - V_n$ in Fig. 12, should correspond to the device signal alone. The degree of cancellation of read noise is limited primarily by variations in word-sense coupling capacitance and variations in line impedance. Since the dummy sense line is 11 mils from its own nearest bit strand and 17 mils from that of the neighboring device, it cannot be used for substantial write noise cancellation.

To prevent signal pickup in the dummy sense line, it is necessary to remove the magnetic material in the region under that line. Magnetic material is also removed between words to reduce magnetic coupling between word lines and thus reduce undesirable domain wall creep problems. The use of discrete bits requires accurate registration between strip lines and substrates. As shown in Fig. 12, the bit size is 25×30 mils and bit centers are 30×54 mils corresponding to about 620 bits/in². The substantial overlap of the bit beyond the boundaries of the word and bit lines provides for line misregistration while making efficient use of the stripline geometry. For the same reason the dummy line is kept at 7 mils from the edge of the bit with which it is paired to minimize flux pickup even when

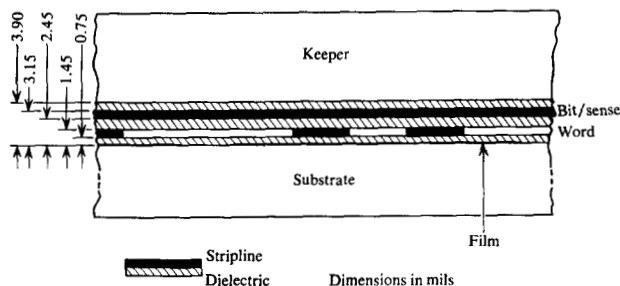


Figure 13 Device cross-section.

misregistered. Even with these allowances, it has been found that word line misregistration of ± 3 mils and bit-sense line misregistration of ± 5 mils will cause up to 12% signal loss.

A cross-sectional view of the strip line package is shown in Fig. 13. Effective flux closure through the keeper depends on minimizing the separation between keeper and film. This requirement must be traded with the thickness of available laminate, the thickness tolerances, and the line attenuation problems associated with making the conductor very thin. The package shown in the figure has a total gap of 3.90 mils. The conductor thickness of 0.7 mils maintains reasonable attenuation, and the word-to-sense separation of 1.0 mils keeps read noise levels sufficiently low so that excessively high cancellation ratios (between sense and dummy sense) are not required.

Location of the word line nearest to the film substrate provides low word line impedance (approximately 20Ω), easing voltage and power requirements in the word drive circuits. It also minimizes stray fields from adjacent word lines. These advantages are obtained at the expense of increased write noise which results from the greater spacing of the bit and sense lines from the ground plane as well as from their proximity to the ferromagnetic keeper.

Device requirements

Many device measurements had been made while the strip line and array design were taking final form, and the results of such experiments as misregistration and keeper performance were influential in arriving at the array features described in Figs. 12 and 13. With the array defined in detail, however, serious work could be done to optimize film and specify the operating characteristics of the device. There should, of course, be a relationship between the static film properties and the operating characteristics of the device. Word drive is controlled to first order by the anisotropy and demagnetizing fields (H_k and H_d), bit drive by the angular dispersion (α_{90}) and H_k , and device signal by the film thickness. The straightforward optimization that this implies is destroyed by the actual complexities of the situation: by dynamic demagnetizing fields that introduce complicated thickness dependencies into drive currents, by the nonuniform nature of the

applied fields from slotted lines, and especially by the fact that the various film properties cannot be controlled independently.

Strain sensitivity can be kept small by control of film composition, since the magnetostriction constants are composition dependent and have a zero-value composition for all ranges of Co additions to Permalloy of interest. Measurements of strain sensitivity are routinely made on all films by observing the easy axis rotation when the substrate is subjected to a fixed anisotropic strain. Analysis of the memory's mechanical pressure system combined with device performance requirements indicated that, in such a test, one could accept up to 2° easy axis rotation when the 3 × 3 × 0.08 in. copper substrate was loaded with ten pounds of force along a diagonal. It has been possible to routinely attain this level of control, corresponding to a compositional variation of ±0.2%, about the zero magnetostriction point.

Previous experience indicated that we could not expect worst case signal levels greater than about 50% of the theoretically available saturation flux. Thus films would have to be at least 800 Å thick. To determine optimum film properties, a series of films were prepared for pulse measurement that spanned a thickness range of 700 to 1000 Å and with considerable variation in dispersion and wall motion threshold as a result of processing parameters and Co content. H_k was reasonably constant and equal to about 5 Oe. With these films it was possible to measure the film dependence of the various worst case effects discussed earlier. Results for a 900-Å film with $H_0 = 4$ oersteds and $(\alpha_{90} + \beta) < 2$ degrees are indicated in Table 2.

The total of these effects is 27 mA, a surprisingly large percentage of the ultimately determined nominal drive current of 100 mA. (Without a keeper, this total would be nearly 80 mA.) Additionally, it is necessary to allow about 15 mA to cover the expected 2-3° of skew variation over the substrate.

In the worst case, then, we may require as much as 42 mA of bit current merely to overcome the adverse fields opposing the desired writing direction. The remaining 48 mA (up to the nominal less 10%) are required to tip the magnetization from the word field direction through

Table 2 Worst-case effects on experimental film.

Parameter	Worst-case effect in mA of bit current (ΔI_k)*
Bit line ground plane current spreading	5
Adjacent bit line stray field	4
Ground plane and strip line trapped flux eddy fields	18

* Film thickness 900 Å, $H_0 = 4$ Oe, $(\alpha_{90} + \beta) < 2^\circ$.

an angle great enough to ensure a coherent return of the magnetization to a high-remnance easy axis state.

Further single-bit studies combined with full-plate testing indicated that a best yield could be obtained in 1050 Å permalloy films with 3 per cent cobalt processed to obtain the following device specifications:

Bit drive $I_b = 100 \text{ mA} \pm 10\%$

Word drive $I_w = 510 \text{ mA} \pm 10\%$

Device signal $V_s > 3.8 \text{ mV}$ (with 8-nsec rise pulse)

Strain sensitivity less than 2° rotation for 10 lb. load.

V_s is the absolute minimum signal of any bit on the bit plate. The actual test levels are set higher to account for any uncertainties in the bit plate tester and to account for the potential 12% loss which can occur if word and bit/sense lines are misregistered by ±3 and ±5 mils respectively.

Acknowledgments

The authors gratefully acknowledge the important contributions of numerous co-workers, especially Q. W. Simkins, W. Dietrich, C. G. Ravi and C. J. Townsend.

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Received July 22, 1966