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A High-Speed Read Only Store Using Thick Magnetic Films

Abstract: This paper describes a high-speed, magnetic film, read only store of about 300K bits. The device and its implementation into a system have many unique advantages, including loose magnetic tolerances, minimal delay in the cell, linear drive-sense coupling, and ease of information change.

The basic device consists of a thick, anisotropic magnetic film sandwiched between the conductors of a strip transmission line. The cell utilizes the coupling between parallel word and sense line sections obtainable through the hard axis characteristics of an anisotropic permalloy film to store a binary ONE state. For a ZERO the coupling is inhibited by saturating the film with a small permanent magnet. Switching of the film can be described qualitatively, and to a large extent quantitatively, by a quasistatic analysis. A dynamic analysis describes the behavior of the film more completely and aids in optimization of some film parameters.

The ROS system is designed in four planes of 256 words by 288 bits each. A single array plane was built and tested with a cross-section of drive and sense circuits. Because of the linear drive-sense relationship, the array can preferably be driven with a low current directly from a logic stage. The worst-case access time, including one level of decode, was measured to be 19 ns; the corresponding cycle time was 45 ns.

Introduction

A read only store (ROS) is a semipermanent memory that is read electronically, and in which the information is changed at a much slower rate, usually by some mechanical means. There are many possible applications for read only stores, including table look-up, program storage, supervisory programs, and encoding. Such a memory is attractive since it can operate at high speed and can still be inexpensive compared with conventional memories.

In recent years a number of technologies have been employed or suggested for achieving read only storage,[1,2] each with certain advantages and disadvantages. Two major drawbacks of these ROS systems are their relatively slow speed and the difficulty in changing the stored information. These systems are not fast enough to operate with the presently emerging high-speed circuits. Furthermore, the information change generally involves a major disturbance of the memory array. In the ROS system presented in this paper the stored information can be changed very easily and can also be read at very high speed.

The primary objective was to achieve a large size, high-speed memory within the capabilities of existing technologies. Since the basic cell uses a magnetic film, and since cost is a major concern in ROS design, the question of mass production of usable films was considered. The philosophy adopted throughout this work has been that of designing a memory around film parameters that are easily obtained, and of making the memory operation less susceptible to variations in film properties.

The memory was designed to fulfill a specific requirement of 1024 words by 288 bits per word, with a 50 ns access time and 100 ns or faster cycle time. First a discussion of the basic device, its properties, and requirements is presented. A description of the implementation and performance of the full memory system then follows.

Device operation

The thick film read only store (TFROS) cell[3] exploits the linear hard axis *B-H* loop of an anisotropic permalloy film. The cell is implemented as shown in Fig. 1. It consists of a strip transmission line with a film and a "Figure 8" type of sense loop sandwiched in between. A pulse applied on the transmission line creates a field along the hard axis HA, causing unbiased films to switch toward this direction. The resulting hard axis flux induces a ONE signal in the sense line section parallel to the word line. When the field

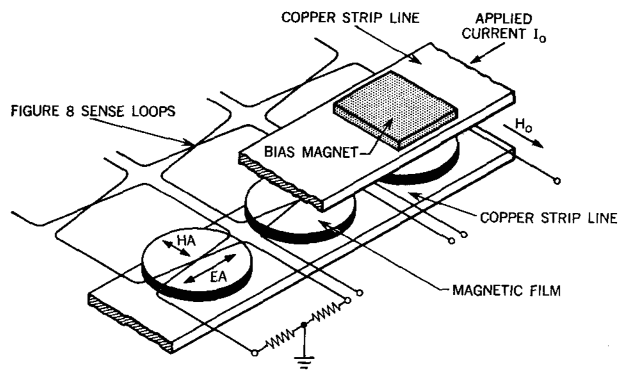
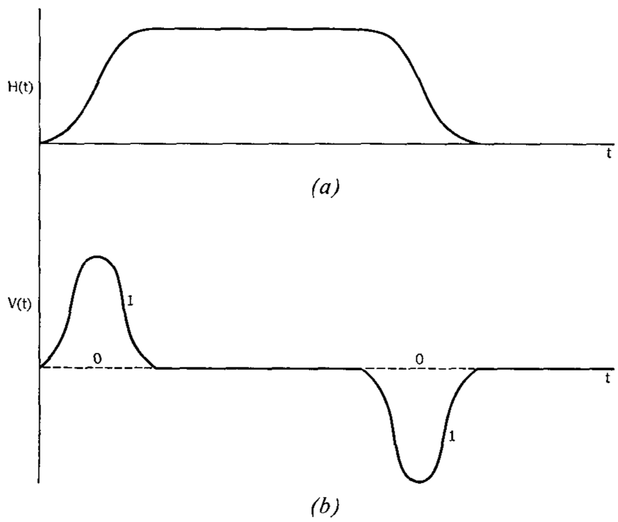


Figure 1 Exploded view of memory cell.

Figure 2 Idealized waveform. (a) Applied pulse field, (b) sense signal.



is removed, the film relaxes back into the easy axis and a signal of opposite polarity is induced. A ZERO is obtained by saturating the film in the hard direction with a small permanent magnet, thus inhibiting switching and preventing any signal from being induced in the sense loop. Idealized waveforms are shown in Fig. 2.

This memory cell has several favorable features: the switching is rotational, with no appreciable delay in the cell; the coupling between drive and sense lines is linear below a comparatively large saturation field and thus there is no threshold to overcome, permitting complete freedom in choice of a drive level; the operation of the cell is relatively insensitive to film parameters; and finally, the information content is readily changeable since the information is stored in a pattern of permanent magnets external to the array and requires no physical connection. The information content of the memory may be changed by removing a card containing the pattern of magnets and replacing it with another. The speed potential of this device can be utilized for both medium and high speed applications. Furthermore, electrical changeability can be included as an extension to this technique.[2a,2b]

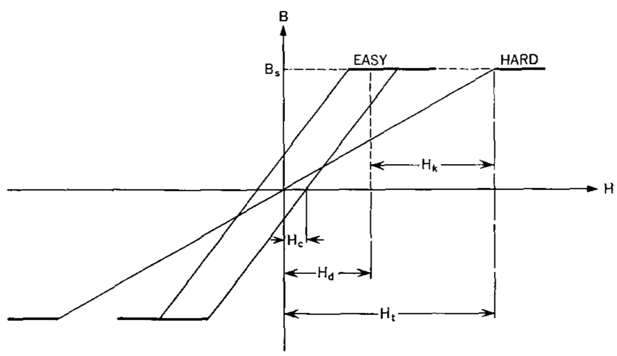
"Thick" films are used in this memory to give large sense signals, and to provide a large demagnetizing field to assist in the fast resetting of the film after reading. A thick film is defined as one for which the shape demagnetizing field, H_D, is not negligible compared to its coercive force, H_C, so that it tends to demagnetize itself. In a thin film, the magnitude of the demagnetizing field is less than the coercive force so the film can remain as a single domain. Idealized low-frequency hysteresis loops in the easy and hard directions are shown in Fig. 3, where H_K is the anisotropy field. Typical values are less than 0.5 Oe for the coercive force and 3 to 5 Oe for the anisotropy field.

Since H_D is much larger than H_C, the film is normally in a demagnetized state with a domain pattern similar to that shown in Fig. 4a. A photograph of an actual film taken by means of a Kerr apparatus is shown in Fig. 4b. Adjacent domains are magnetized in opposite directions to give a closed flux path configuration within the film and hence a minimum energy state. When these films are pulsed in the hard direction with fast risetime pulses, the magnetization vectors (M) rotate within each domain and the domain walls remain substantially fixed. Assuming typical values of parameters, the results of Ford[4] indicate that if the switching occurred by domain wall motion, the required time would be substantially more than an order of magnitude larger than the observed switching times.[3] Thus the switching does not take place by domain wall motion but presumably is a type of rotational process.

Sense signal dependence on film parameters

Since a voltage threshold detector is used, the peak sense signal voltage is of interest, although the conclusions

Figure 3 Idealized *B-H* loop along easy and hard axes for an anisotropic, thick film.



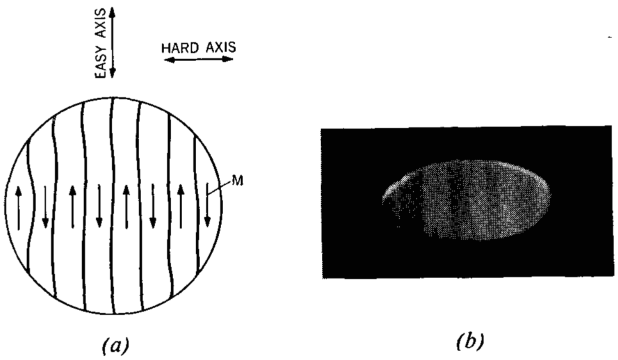


Figure 4 Multidomain structure of an anisotropic thick film. (a) Idealized magnetization orientation, (b) photograph of domain pattern obtained using the Kerr effect.

drawn here remain essentially unchanged if total flux is sensed. For all but high frequencies or fast risetime pulses, the switching of the film is determined by the 60 cps hysteresis loop since the switching of the film follows the applied field with no time lag. At very high frequencies or for very fast risetime pulses, the switching of the fill will lag somewhat behind the applied field due to damping and noncoherent rotation of the magnetization, although the 60 cps loop still gives a good qualitative description of the film behavior.

• *Quasistatic Analysis*

The dependence of hard axis flux on film thickness and anisotropy can be determined from the 60 cps *B-H* loop. Below saturation the slope μ of the hard axis *B-H* loop of Fig. 3 is given by

$$\mu = B_S/(H_K + H_D). \qquad (1)$$

The demagnetizing field at the center of a circular bit is approximately

$$H_D = (K/D)B_ST,$$

where

H_D = demagnetizing field in Oe
B_S = saturation flux density in gauss
T = thickness in cm
D = diameter in cm
K = constant of value 0.79 Oe/gauss.

The flux switched per unit drive field is

$$\phi/H_A = \frac{B_STD}{H_K + KB_ST/D} \qquad (2)$$

where ϕ is in lines when the applied field, H_A, is in Oe.

Figure 5 is a plot of Eq. (2) for cell dimensions used in the memory array. For thin films the demagnetizing field is negligible and the flux is linearly dependent on thickness. For large thicknesses the demagnetizing field is much greater than the anisotropy field, and the flux approaches a constant value.

In the region of saturation in Fig. 5, where the anisotropy field is negligible, Eq. (2) can be written $\phi_{sat} = (D^2/K)H_A$ and the flux will be independent of film thickness and saturation fiux density. This is quite advantageous from a fabrication standpoint and is consistent with the philosophy of designing the memory to be insensitive to variations in the film parameters.

Referring to Fig. 5, it is desirable to keep the anisotropy field small in order to get maximum signal for a given drive current. Anisotropy fields of 3.5 Oe are easily obtained with 80/20 Ni-Fe films, either evaporated or electroplated. It is difficult to obtain well-oriented films with lower values of H_K. From Fig. 5 it can be seen that reducing H_K from 3.5 to 2 Oe does not increase the flux substantially. Films with an anisotropy field of 3.5 Oe were used in the memory, since this value can be consistently obtained over large areas, and is again consistent with the design philosophy of simplifying the film fabrication problems.

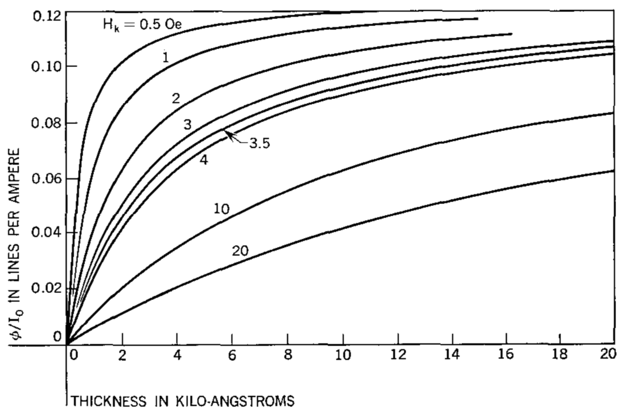
Dynamic analysis

Since the peak sense signal is not only a function of the total flux switched, but also of the rate at which it switches, a dynamic analysis is necessary for complete characterization of the switching behavior. It is possible to analyze a thick multidomain film in a manner similar to that of a thin film.[5] The analysis is based on the assumption of coherent rotation of the magnetization within the multidomain structure. The sense signal was calculated by a computer solution[6] of Gilbert's equation.[7]

$$\dot{\bar{M}} = -\gamma(\bar{M} \times \bar{H}) + \alpha\frac{\bar{M}}{M} \times \dot{\bar{M}}\,. \qquad (3)$$

The pulse drive field H was assumed to be $\sin^2 (\pi/2t_r)t$

Figure 5 Sense flux per unit drive field vs film thickness based on a quasistatic analysis.



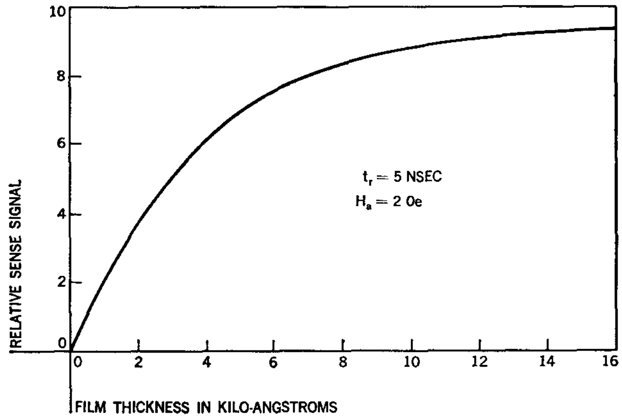


Figure 6 Calculated relative sense signal as a function of film thickness.

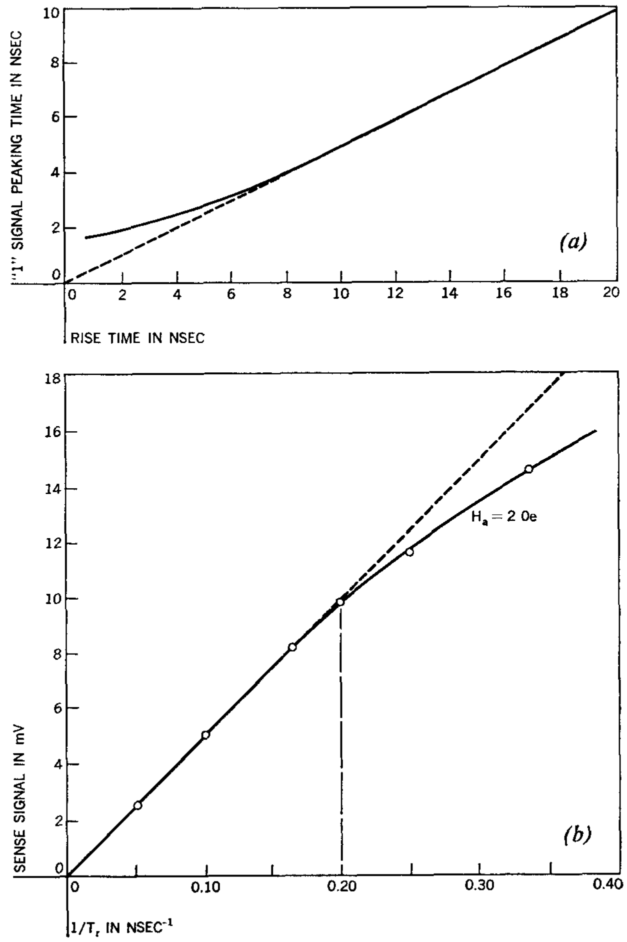


Figure 7 Measurements of (a) sense signal peaking time vs risetime for 1/8 and 1/16 inch diameter bits, (b) peak signal vs risetime for 1/32 inch diameter bits. The dotted line is the design center.

during the rise time t_r. The gyromagnetic ratio γ is a constant. The sum of eddy current and intrinsic damping of the film gives rise to the damping constant α.

- *Effect of film thickness on sense signal*

The quasistatic analysis given previously shows that the flux, and hence the sense signal, saturates with increasing film thickness. This effect is made more pronounced by the increase of eddy-current damping with thickness. The eddy-current damping constant has been expressed as a function of film thickness for permalloy as[9] $\alpha_e = 1.3 \times 10^{17} \delta^2 \text{ sec}^{-1}$, where δ is the film thickness in cm.*

Since the damping constant is a coefficient of the loss term in Eq. (3), the energy loss increases as film thickness increases. The energy loss results in a retardation of the rotation of the magnetization. Therefore an increase in damping will cause a decrease of the peak sense signal. Figure 6 shows the calculated peak sense signal as a function of film thickness for a drive field of 2 Oe. As expected, the sense signal exhibits a more pronounced saturation effect than that of Fig. 5. A 10 kÅ film was used in the memory, since this results in the sense signal being relatively insensitive to variations in thickness.

- *Effect of* READ *field risetime on sense signal*

The sense signal was calculated as a function of risetime for an applied READ field of 2.0 Oe. The calculation included the effect of the frequency dependence of the intrinsic damping constant, which has been given by Goodenough and Smith[8] as

$$\alpha_i = \frac{4\pi \times 5.79 \times 10^{-2}}{f^{0.65}},$$

where f is in Mc/sec.

* The equivalent intrinsic damping constant of permalloy films is 8.1×10^8 sec^{-1} for a 5 ns risetime pulse and is independent of film thickness.[8]

The results are shown in Fig. 7(b). The sense signal increases linearly with the reciprocal of the risetime up to about 5 ns and then increases more slowly thereafter. This behavior is due to the nature of intrinsic damping constant, which is inversely proportional to a power of frequency less than unity; for faster risetimes the intrinsic damping becomes proportionally greater, and at a risetime of about 5 to 6 ns the flux lagging effect begins to influence the sense signal. The peaking time of the sense signal is also affected by fast risetimes, as shown in Fig. 7(a). A risetime of about 5 ns was chosen for the design of the memory.

- *Effect of* READ *field amplitude on sense signal*

Since the hard axis *B-H* loop is linear below saturation (see Fig. 3) the sense signal will be a linear function of the READ field for fields less than H_T. Both measured and calculated sense signals are plotted as a function of READ field in Fig. 8 for a 10 kÅ thick anisotropic film and a

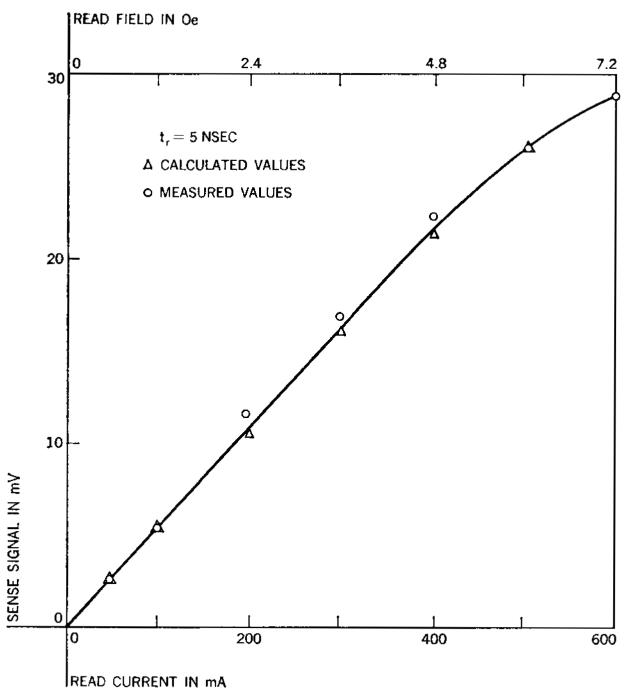
READ pulse with a 5 ns risetime. For READ fields below 4.8 Oe, the sense signal is linearly related to the READ field with a slope of about 50 mV/A. Above this point there is a slight decrease in the slope due to a nonlinear increase in the damping.

Device operation with isotropic films

Up to this point, memory operation with anisotropic films has been considered. However, virtually identical operation can be obtained using an isotropic molybdenum-permalloy tape having a very low coercive force.[10] The isotropic material has the distinct advantage of being commercially available in large quantities and of reducing the problems of film alignment within the array.

An isotropic film can be thought of as consisting of a number of anisotropic film layers with randomly oriented easy axes. (This, in fact, is one way of fabricating an isotropic film.)[11] Such a film will be isotropic in that its characteristics will be independent of orientation, but a similar rotational switching mechanism exists as with anisotropic films. Using a simplified model, it can be shown that a random superposition of very thin uniaxial anisotropic film layers must have a total thickness of $\pi/2$ times that of a single, well-oriented uniaxial anisotropic film to yield the same sense flux for a given applied field. Thus a thicker isotropic film should perform in the same way as the anisotropic film.

Figure 8 Sense signal vs READ current/field for a 10 kÅ anisotropic film of 1/32 inch diameter.



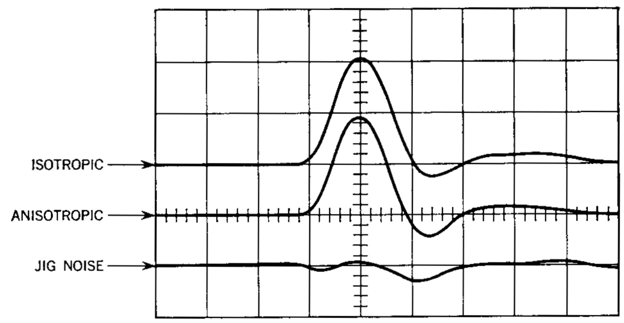


Figure 9 Comparison of sense signal obtained from anisotropic and isotropic films.

Measurements were made on rolled and annealed isotropic films 1/8 mil (32 kÅ) in thickness. A comparison of ONE and ZERO signals from both films is given in Fig. 9. The films can be and were used interchangeably with no appreciable difference in memory operation.

Memory system

A block diagram of the system is given in Fig. 10. The array is organized into four planes of 256 words × 288 bits. The output of corresponding sense lines on each of the four planes passes through a four-way OR circuit to a bank of 288 sense amplifier - tunnel diode latch circuits. One driver per word line is used, eliminating the problems of delay, recovery, and waveshape deterioration in a matrix. For the system designed, one driver per word line is economically feasible.

A cross-sectional model of one plane of 256 words × 288 bits was built and tested and the loading effects of the other planes were simulated. Therefore, the performance of the single plane is the same as for the fully implemented memory. The system was designed to be compatible with current switching logic of the ACP variety.[12] This circuitry has voltage levels of ±0.2 V and a rise time of about 5 ns.

Permanent magnets

The purpose of the permanent magnet is to store a ZERO at a given bit location by saturating the magnetic film. Thus, for the idealized *B-H* loop of Fig. 3, the minimum acceptable field from the permanent magnet must be at least equal to the sum of H_K and H_D.

The upper limit of permanent magnet field strength occurs when the stray fields from adjacent magnets in a worst-case pattern begin to reduce the ONE signal of a given bit position. This will occur when the sum of the READ and stray fields exceeds the saturation field (H_K+H_D) of the film. Since in general the READ field is considerably smaller than the saturation field, an appreciable stray field can be tolerated, allowing a considerable variation in magnet strength.

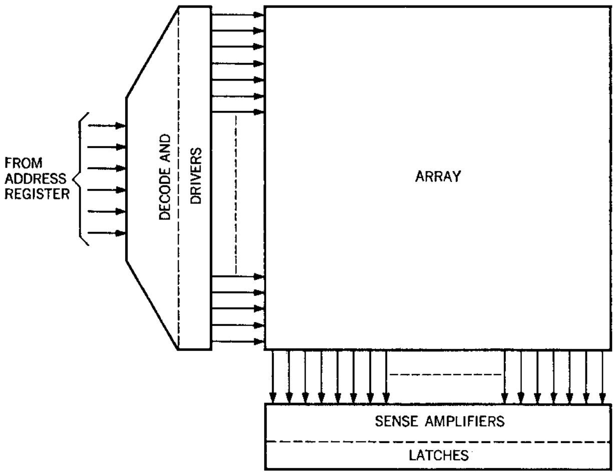


Figure 10 Block diagram of memory.

Calculated and measured values of the saturation field, H_T, are given in Table 1 for 35 × 40 mil rectangular film spots with magnetization in the long direction. Agreement is good, considering the approximate nature of the calculations, which are based on elliptical geometry.

The fabrication techniques and field strength measurements for the permanent magnets are given in Ref. 13. In the final implementation, barium ferrite particle magnets 28 × 28 × 5 mils were used, which provided a field of about 32 Oe. The vertical spacing of the magnet is not critical, since distances of up to about 7 mils between the film and the magnet can be tolerated with no change in performance. These magnets were satisfactory in all respects.

Array properties

Each plane of the array consists of 256 word lines and 288 orthogonal sense lines. The dimensions and spacings of the lines are given in Fig. 11(a). The word lines are a pair of parallel strip conductors, and the figure 8 type of sense lines are two complementary square wave patterns, as shown. No physical ground plane is present in the array; the drive and sense are balanced for noise suppression.

The array is fabricated from layers of printed circuit sheets, as shown in Fig. 11(b). All conductors are 1/2 oz. copper, with the top word lines etched from single-sided, copper clad 1-mil epoxy glass, the sense lines from double-sided, copper-clad, 1-mil epoxy glass. The 288 sense lines are made in six separate belts of 48 each. Epoxy glass is used as the printed circuit backing material because its dimensional stability eases registration problems. The spacer material is Mylar of the proper thickness. The film substrate is 1-mil Mylar. The layers are kept in intimate contact by vacuum pressure acting through holes in the electrically inactive portions of the array to pull down a flexible overlay sheet. The vacuum chamber is located underneath the array.

The vacuum system was used for convenience in the development phases of this memory system. In practice, the array would be laminated and the magnet cards held in place by a pressure plate. Since the spacing between magnet card and array is not critical, any convenient system for mounting the cards and applying light pressure would be suitable.

Physical and electrical characteristics of the word and sense transmission lines are given in Table 2. The values given are for lines loaded with unbiased films. If the films are biased off, the loading on the lines is slightly reduced, resulting in minor changes of a few percent in the values given.

Both word and sense lines are terminated in their respective characteristic impedances, except at the driver end of the word lines.

The cell of the TFROS is linear and bidirectional; in such an array sneak path noise may be a problem. The worst-case sneak path noise for the size of the TFROS array plane was calculated to be 4% of the nominal ONE signal, and in practice was too small to be measured.

Some residual coupling exists between the word and sense lines, even with the film biased off, which gives rise to a ZERO signal of nonzero amplitude. Balanced drive and sensing are used to reduce common mode noise. However, since the two halves of the sense lines are not coplanar, differential mode noise will be coupled to the sense line from the READ field.

Table 1 Saturation field for 35 × 40 mil spots with magnetization in long direction

	10 kÅ (35 × 40 *mil*) *anisotropic film*	30 kÅ (35 × 40 *mil*) *isotropic film*
Calculated H_T (Oe)	12	28
Measured H_T (Oe)	13	30

Table 2 Characteristics of word and sense transmission lines

	Length, in.	Z_0*, ohms*	*Delay, ns*	*Attenuation, percent*
Word line	16	78	3.2	negligible
Sense line	17	116	6.0	15

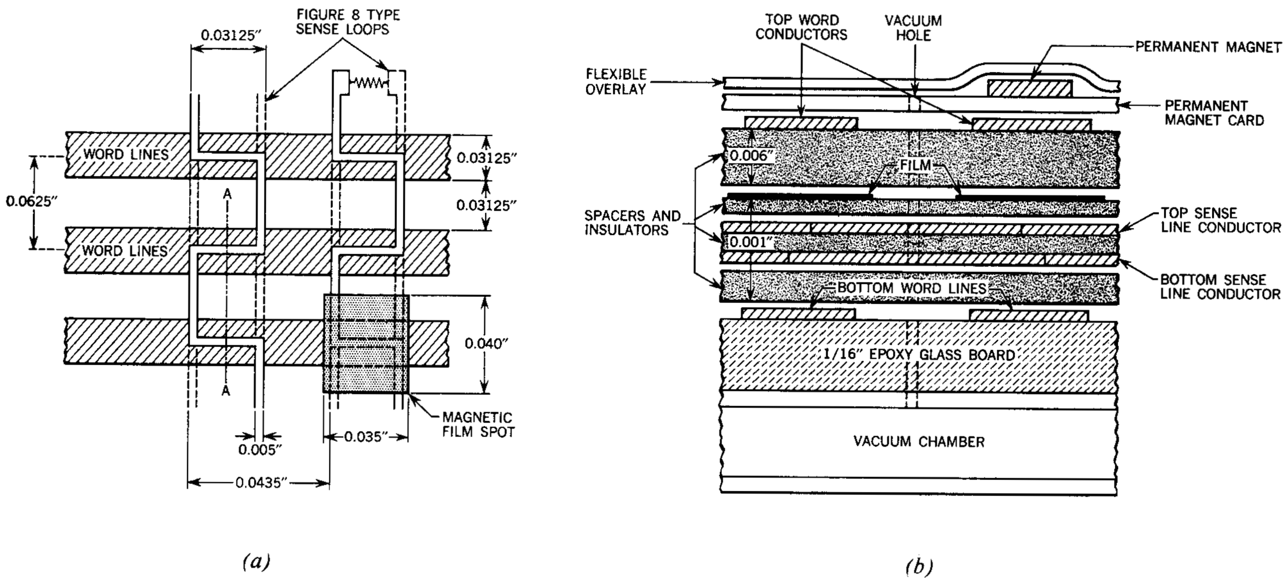


Figure 11 Section of array. (a) Layout, (b) cross section at A-A on layout.

One component, the capacitive noise, arises because the physical location is slightly different for the top and bottom halves of the sense line, and a different voltage willl be induced in each. The other component, the inductively coupled noise, arises because of the changing magnetic field enclosed by the loop formed by the top and bottom sense lines and their terminations.

Because of the directional properties of the coupling between word and sense lines,[14] the inductive and capacitive noise will be of opposite polarity at one end of the sense line and will be of the same polarity at the other end. The inductive and capacitive noise can be made to cancel by adjusting the spacing of the various layers in the array until the two noise components are of equal magnitude and then sensing at the end at which they have opposite polarity. This cancellation is shown in the photographs of Fig. 12. The cancellation is insensitive to small variations in the spacings.

The reversal of the sense line square-wave pattern will result in the two noise components cancelling at a given end of the line for, say, even numbered word lines, and adding for the odd-numbered lines. To avoid this, alternate word lines must be driven from alternate ends of the array, and sensing is performed at the sense line ends where the noise components subtract.

Another possible source of differential noise occurs if the drive waveforms on the top and bottom word line halves are not identical, especially during the risetime of the word field. In practice, the film apparently tries to act as a ground plane during the word pulse risetime which necessitates placing the film in the median plane between the top and bottom word lines, creating a symmetrical structure.

The signal/noise ratio over the 256 word × 288 bit array is about 7 : 1 and is entirely adequate.

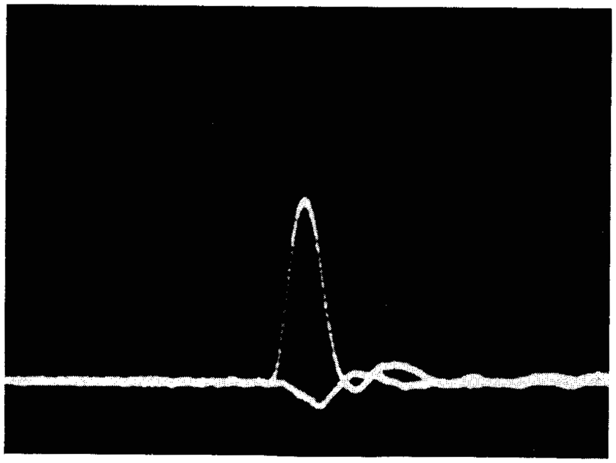
Circuits

The TFROS array is a linear attenuator for word currents up to 400 mA, thus requiring

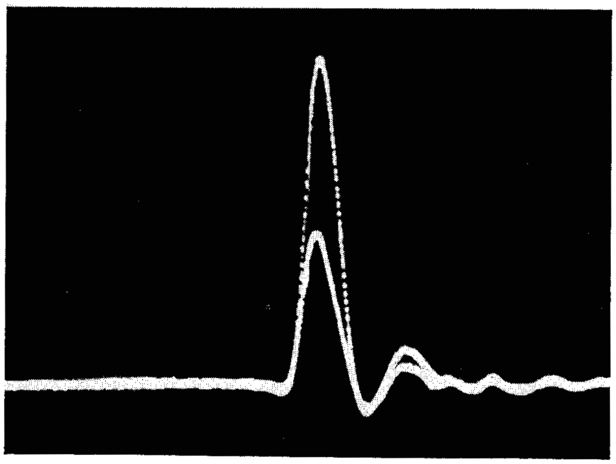
(gain of driver) × (gain of sense amplifier) × (array attenuation) = 1.

Linear amplification stages generally have lower delay per stage than switching stages. Therefore, to minimize the access time, as much as possible of the total over-all gain should be in the linear amplification states, i.e., the sense amplifier. The only restriction is that the driver must be sufficient to give an acceptable signal/noise ratio at the detector.

The decoded word line information is supplied by a logic stage. Ideally, this stage would drive the line directly. However, the logic stage was not designed for use as a memory driver, and additional requirements of a balanced drive and a d-c level shift are necessary. Both requirements were met by use of a transformer with a center-tapped secondary. The drive circuitry is given in Fig. 13 and consists of an ACP logic circuit driving a 2 : 1 stepdown transformer. The logic circuit is modified to operate at 25 mA of emitter current instead of the normal 15 mA by simply changing the emitter supply voltage. A word current of 25 mA with a 6 ns risetime is obtained, which gives one mV of sense signal.



(a)



(b)

Figure 12 Directional coupling effects of sense line noise obtained with a 200 ma, 5 ns rise time pulse: (a) Subtractive end. (b) Additive end.
Horizontal scale: 10 ns/div
Vertical scale: 5 mV/div

The major portions of the cost of high-speed control memories are due to the drive and sense circuitry. A considerable saving in circuit cost is achieved with this read-only memory since it can be driven from a simple logic stage, thus virtually eliminating word driver costs, while requiring only a nominal increase in sense circuit complexity.

The sense amplifier is shown in Fig. 14 and consists of two series-shunt feedback pairs in cascade to amplify the nominal signal to 600 mV. Tolerances of $\pm 5\%$ on bias current and tunnel diode peak current are sufficient to insure proper triggering and discrimination at the sense amplifier output.

The decoupling diode between the sense amplifier and the tunnel diode detector provides a voltage threshold of

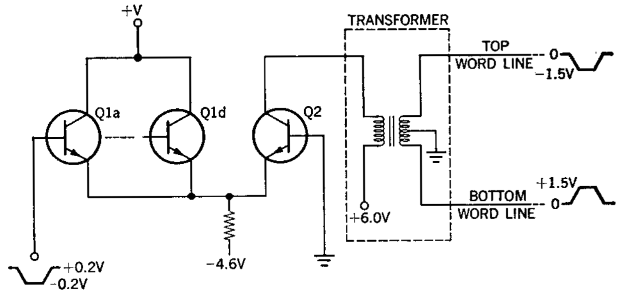


Figure 13 Schematic diagram of word driver.

300 mV, which serves to improve the signal/noise ratio at the tunnel diode. The minimum signal/noise ratio at the output of the sense amplifier that the tunnel diode can discriminate is calculated for worst-case conditions to be 2.6.

The OR connection of the sense signals of the four memory planes is accomplished by having separate Q1 transistors for each plane and paralleling their outputs at the input of Q2.

The purpose of the gate pulse is to perform the AND function with a ONE signal to trigger the tunnel diode register. Removing the gate pulse resets the register prior to the start of the next READ cycle. The gate pulse can also be used to perform logic at the array output. The output swing of the tunnel diode register can directly drive an ACP logic stage.

Performance

A photograph of the access time, including the one level of decoding of the logic stage, is given in Fig. 15. For maximum array delay, another 4 ns of delay must be added. This results in a maximum access time (including one level of logic) of 19 ns. The access time is broken down as in Table 3.

The cycle time was measured to be approximately 45 ns, agreeing with calculations. It is limited by the recovery of the transformer and is subject to the restriction that the same word cannot be accessed twice in succession.

Table 3 Breakdown of access time in nanoseconds

Array delay	9.2
Drive and sense balun/transformer delay	2
Delay for one logic level	3
Sense amplifier/T.D. delay	4.8
	19 ns

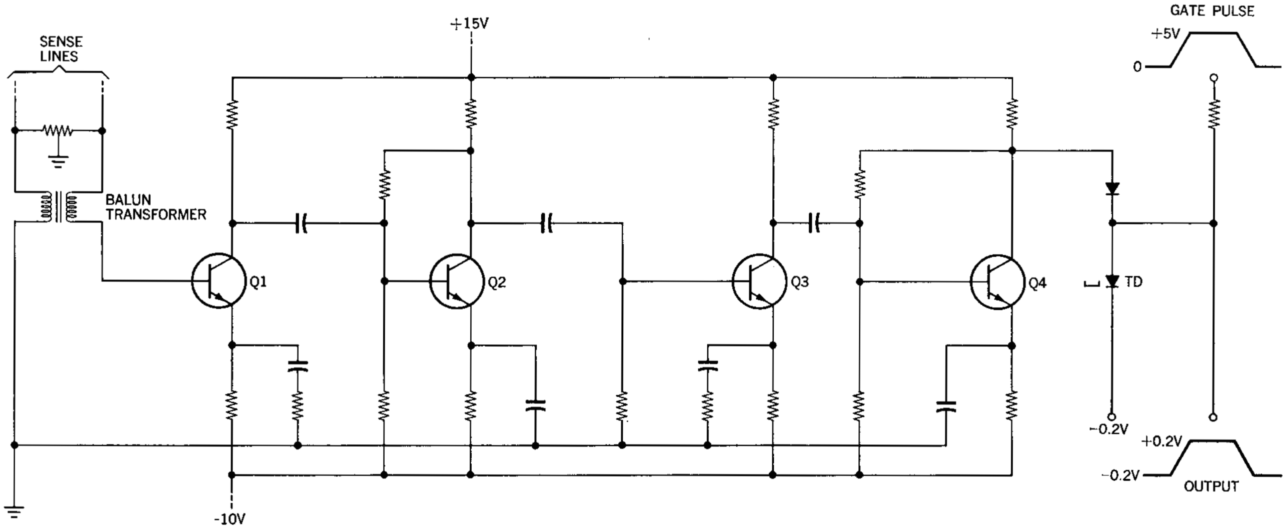
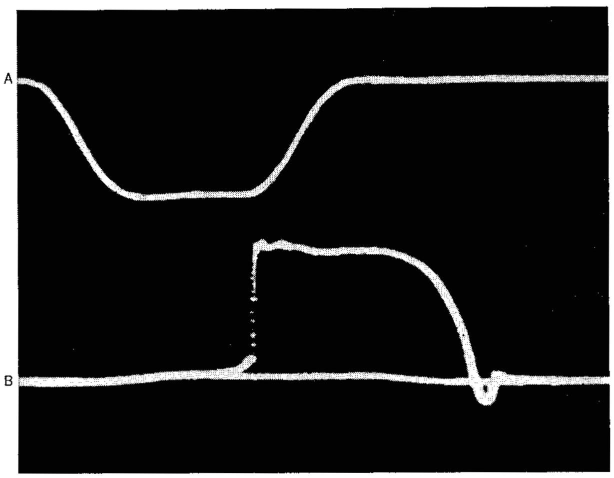


Figure 14 Schematic diagram of sense amplifier and detector-register.

Figure 15 Typical waveforms obtained from (a) word driver, (b) tunnel diode output.
Horizontal scale 5 ns/div
Vertical scale 200 mV/div



Conclusions

A new type of read-only memory has been built and tested sufficiently to demonstrate feasibility. The basic cell employs a thick magnetic film as the high-speed sensing element to sense the information which is stored as a pattern of magnets on a card. Since the magnet card is separate from the array, the latter can be permanently laminated or sealed and the information can be changed very simply and reliably. The advantages of this system stem from a combination of several important features, namely card changeability, high speed, wide mechanical and electrical tolerances, and a linear drive-sense relationship which results in a wide range of operating levels.

Circuit costs can be minimized by using low-level drivers, giving an additional increase in speed with only a minor increase in sense circuitry.

The feasibility model was driven from a modified logic circuit. For a memory containing four arrays of 256 words and 288 bits per word, an access and cycle time of 19 and 45 ns respectively was achieved, including one level of decode logic. Additional stages of decode and miscellaneous cable delays would lengthen the access time but not necessarily the cycle time in a fully implemented machine. The cycle time was limited primarily by the word transformer recovery time.

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