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77-1404

ADVANCED MASS MEMORIES [+]

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Abstract

An overview of advanced mass memory technologies such as magnetic bubbles, charge coupled devices, and the crosstie memory is presented comparing density, speed, power, and costs. The newest concept is the crosstie memory and the latest developments are explained. In the crosstie memory information is stored in magnetic domain walls rather than in domains and the walls are used as shift register tracks. The crosstie memory can be fabricated on a silicon chip or wafer with integrated semiconductor drivers, decoders, detection amplifiers and possibly a microprocessor.

I. Introduction

Memories in use in computers today are based on technologies which have been developed, refined and used for about 25 years. Because of such refinement it has been very difficult for new memory technologies to replace the old technologies even though for years there has been a well recognized access gap and capacity gap. However this is no longer the case because charge coupled devices are sure to partially fill the access and capacity gaps. Magnetic bubbles will also be used especially where nonvolatility is important. A third but less developed technology called the crosstie memory shows promise to compete with both charge coupled devices and bubbles. In Figure 1 a cost vs. access time plot is shown. The well established technologies are hatched. The four new technologies are shown within the access gap. Much of the data in Figure 1 is taken from J. E. Juliussen.[1] The capacity gap is demonstrated in Figure 2 where again some of the data is taken from Juliussen. With the proliferation of micro- and minicomputers the technologies in the capacity gap become more and more important. Also as the demand for larger advanced mass memory increases, nonvolatility will become increasingly important. This puts bubble memories and the crosstie memory right in line for price competitiveness in microcomputer-based systems.

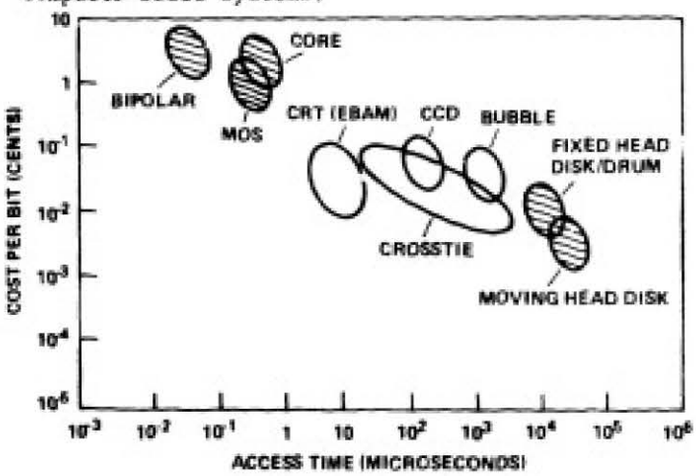


Fig. 1 Cost vs access time.

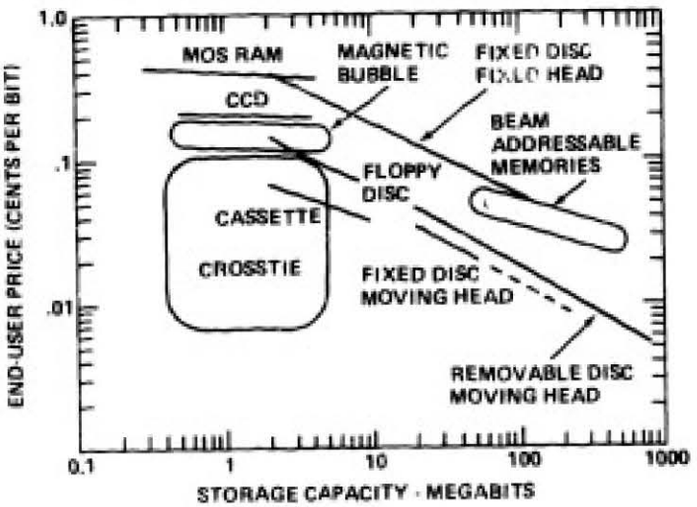


Fig. 2 Cost vs storage capacity.

The general characteristics of large capacity memory chips are compared in Table 1. The bubble memory uses a major-minor loop organization and requires additional chips for power and interfacing. The characteristics shown for the crosstie memory represent a guess as to what such a chip might look like when available. The other memories are presently available.

II. Demands on Advanced Mass Memory

A new technology which would fill the access gap has many demands placed on it. It must be a compromise between the slow, high density, low-cost bulk store and the fast, random access store. If the best of both types can be combined, both types of memory could be in large part replaced.

The demands on the technology can be broken down to specify its desired embodiment. For greater speed there can be no mechanical parts. For high density it should be a serial memory. For fast access it must have random access to a block which can be read serially at high speed. For low cost the memory should be constructed using photolithographic processes. It should be nonvolatile to prevent memory loss in case of power failure, to minimize power consumption, and to minimize errors due to operation of the system. Battery requirements for 24 hour storage of a million bits of information are rather forbidding even for charge coupled devices.

Charge coupled devices have sufficient speed and are easy to address but they are volatile. Bubble memories are slow but nonvolatile. The crosstie memory represents an attempt to provide fast access with nonvolatility.

III. The Crosstie Memory

The domain walls found in anisotropic permalloy films about 370 Å thick have bistable states which

[+] This research was supported by the Naval Air Systems Command.

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TABLE I

General Characteristics	MOS RAM	CCD	Bubbles	Crosstie
Access Time	300 nsec	50 μs	4 ms	10 to 100 μs
Transfer Rate	2 M bits/sec	1 to 5 M bits/sec	100 K bits/sec	5-20 M bits/sec
Storage Capacity/Chip	64 K bits	64 K bits	92 K bits	128 K bits
Nonvolatile	no	no	yes	yes
Power/Megabit (W)	10	10	10	5
Weight/Megabit (lb)	4	2	3	2
Decoding on Chip	yes	yes	no	yes

make a memory possible. Also the wall itself can serve as a shift register track. The wall is known as a crosstie wall although it may or may not have crossties depending on the magnitude and sense of the last field applied. A qualitative description of a crosstie wall is shown in Figure 3. The crosstie wall[2] can be considered to be made up of Néel[3] wall sections of opposite polarity. Just as a domain wall is considered to be a boundary between domains, the crosstie and Bloch line can be considered to be boundaries between Néel walls of opposite polarity. In other words, the Bloch line and the crosstie are boundaries within a boundary. It is very helpful to think of crossties and Bloch lines in this way because the behavior is analogous to the behavior of walls with respect to domains. Notice that the crosstie length equals the Néel wall width. The maximum number of crossties which normally occur in permalloy with H_k (induced anisotropy field) equal to 4 Oe is about 8,000 per inch or 3,000 per cm. This number is doubled[4] for an anisotropy of 16 Oe and the Néel wall becomes narrower.

The crosstie and Bloch line are different in that the Bloch line has a coercive force of about 0.1 Oe and the crosstie has a coercive force of about 3 Oe. The Bloch line has a mobility[5] of ~48,000 cm/Oe-sec. This is the highest mobility measured to date in magnetism.

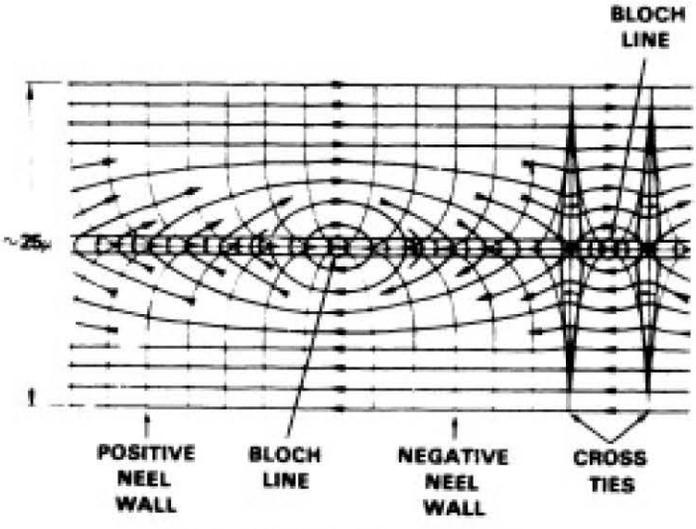


Fig. 3 The crosstie wall.

IV. Static Stability Conditions For Néel Walls And Crosstie Walls

Ranges of stability[6] are shown in Figure 4 for a 400 Å thick film. The boxes represent field

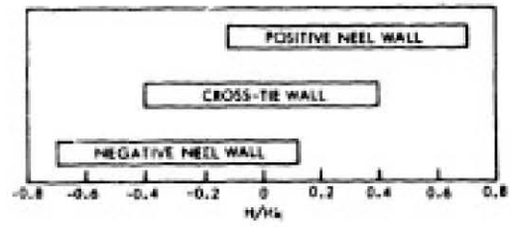


Fig. 4 Static stability conditions for a 400 Å thick film.

ranges over which the walls are stable as a function of field applied along the hard direction of the film. Suppose first that we have a field of $-0.6H_k$ applied to the film. Then the wall must be a negative Néel wall and it will remain a negative Néel wall as long as fields between $-0.7\ H_k$ and $0.12\ H_k$ are applied. Once a field larger than $0.12\ H_k$ is applied, crossties will be nucleated and the crosstie wall is stable as shown. To obtain a positive Néel wall, a field larger than $0.4\ H_k$ must be applied. At this thickness with no applied field the wall can be crosstie, positive Néel, or negative Néel, depending on the magnitude of the last field applied and the state previous to the application of that field.

V. Wall Stability and Film Thickness

To study the wall stability as a function of thickness a film was chosen which varied in thickness from 200 Å to 640 Å along its 3-inch length.

The film anistropy varied from 4 Oe at 200 Å to 4.8 Oe at 640 Å. This was taken into account in the normalization used in Figure 5 where the field applied along the hard direction is normalized to H_k. Stability conditions for Néel and crosstie walls as functions of thickness are plotted.

To understand Figure 5 it is helpful to compare Figure 4 with the values shown in Figure 5 at 400 Å. Note that the stability range for a crosstie wall is independent of thickness. Between 300 Å and 640 Å little variation was seen in the field required to move and destroy the walls. The only parameter that varies with thickness is the crosstie nucleation field. Above 480 Å crossties are always present at zero applied field.

Below 440 Å it is possible for a negative Néel wall to invert by the motion of a Bloch line which can be generated at the film edge or at a defect. Below 400 Å it becomes difficult to find the nucleation of crossties because of Bloch line motion. For example, if we have a negative Néel wall and the field is slowly changed from negative values to pos-

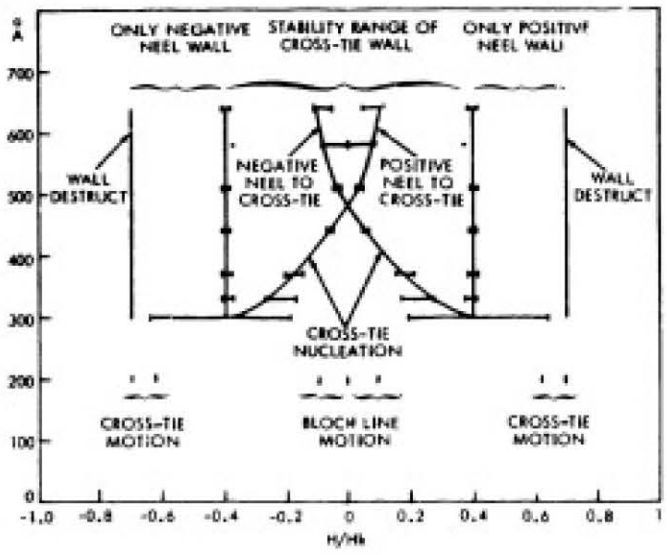


Fig. 5 Static stability conditions as a function of film thickness.

itive, at about 0.05 H_k several walls will reverse polarity by Bloch line motion. Only on those walls where such reversal did not occur can crossties eventually be nucleated. This results from the fact that crosstie nucleation implies Bloch line generation and at these fields reversal by Bloch line motion is favored. In other words, as soon as a crosstie and Bloch line are generated, the Bloch line will move close to the neighboring crosstie. Here Bloch line motion can be observed between crossties.

It is easy, however, to generate periodic crossties about 4 μm apart if 1 to 5 nsec pulses are used with films as thin as 300 Å. The field required to generate crossties [7] is higher for short pulses as shown in Figure 6. There is a danger in making the above measurements if a thick Bitter solution (a suspension of fine magnetic particles) is used. The Bloch line always moves very rapidly in the absence of a Bitter solution as can be seen using a magneto-optic technique [8], whereas if a Bitter solution is used, it will move slowly moving Bitter solution with it at low field values. The Bitter solution often has enough field associated with it and responds sufficiently slowly to move the Bloch line back where it came from after fast pulses have been used to move it.

If a positive pulse (1-5 nsec) is applied to a + Néel wall, nothing happens. If a similar pulse is applied to a -Néel wall, periodic crossties appear. This is illustrated in Figure 7.

Annihilation of a crosstie-Bloch line pair can occur if a pulse is of sufficient amplitude and time duration for the neighboring Bloch line to move to a crosstie. By using a 7 nsec pulse 5 Oe in amplitude all periodic crossties 4-5 μm apart are annihilated, since Bloch line mobility is ~48,000 cm/Oe-sec.

The Bloch line is naturally repelled by a crosstie and in zero applied field it will move about 15 μm to 25 μm from a crosstie. If a 1 nsec pulse creates a new crosstie-Bloch line pair within the old crosstie-Bloch line pair, the old Bloch line will be repelled by the new crosstie and move along

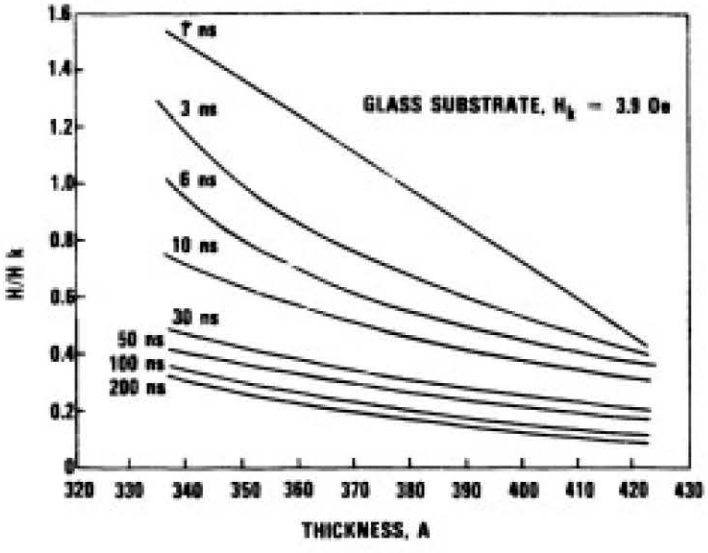


Fig. 6 Amplitude of the pulsed magnetic field required to generate crosstie as a function of film thickness.

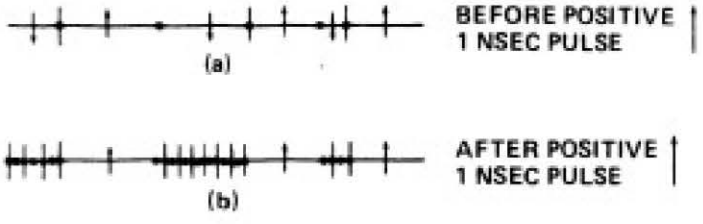


Fig. 7 Wall before and after the application of a 1 nsec pulse.

the wall till it is about 15 μm away.

All of the above behavior is analogous to what one would expect in nucleating, enlarging, and annihilating domains. The Néel walls represent a sizable area compared to the Bloch line and crosstie just as domains normally do compared to domain walls.

VI. The Serrated Strip

Since domain walls are to be used as shift register tracks, it is necessary to locate them in predetermined positions. This can be done by using thermal annealing procedures [5,9] or by etching the permalloy into serrated strips [10]. The serrated strip method simplifies procedures so that conventional mask aligners can be used and a higher density of information is possible.

An example of serrated strips is shown in Figure 8. The strips are aligned along the easy axis of the film if anisotropic films are used. Isotropic films can be used also and then there is no prefered direction for the serrated strips and they can bend around corners. Since the magnetization of permalloy films lies parallel to surfaces and edges in its lowest energy state and a high energy state results when poles are formed at surfaces and edges, the magnetization rotates back to form two domains after a field is applied perpendicular to the strip.

A fast magnetic pulse (1-10 nsec) along the opposite direction forms crossties provided the film thickness is between about 300 and 450 Å. The

crosstries form at the necks of the strip as shown in Figure 8. The width of the strip neck is 10 μm in the figur.. The Bloch lines are in potential wells in between the crosstie locations. The wall terminates at the beginning and end of the strip as desired. The width of the strip has a large influence on th roperties of the crossties because of demagnetizing fields. The static properties are compared with the properties observed in a large unetched film in Table II. All these films were 350 Å thick.

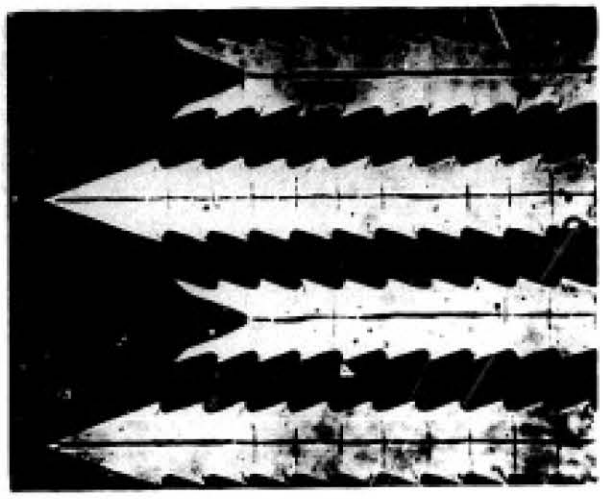


Fig. 8 Serrated strips 10 μm wide at the neck.

TABLE II

Static Magnetic Property Comparison

Type of Film	Wall Placement Field	Crosstie Nucleate Field	Bloch Line Movement Field	Crosstie Annihilate Field
Unetched film	4 Oe	0.8 Oe	0.1 Oe	1.6 Oe
Serrated, 25μm Width	80 Oe	2.5 Oe	1.0 Oe	6.5 Oe
Serrated, 10μm Width	~500 Oe	7.5 Oe	6.2 Oe	19.0 Oe

In the unetched film, which can be considered an infinite plane sheet, the Bloch line has a coercive force of about 0.1 Oe. In the serrated strips the coercive force remains the same but the potential wells and the demagnetizing effects of the strip increase the field required to force a Bloch line into a neighboring well or along the wall. The magnitude of the field required to move the Bloch line in different directions differs slightly as does the magnitude required to nucleate and annihilate crosstie-Bloch line pairs when positive or negative fields are used. But these differences are small and average values are shown in Table II. If pulses are applied perpendicular to the strip (up or down in Fig. 8), the field along the strip should be nearly zero or the wall will move up or down in the strip. In the absence of fields applied perpendicular to the strip a 2 Oe field can be applied along the strip before the wall will move. This corresponds to the normal coercive force of the wall. The width of the strips, the angle of the teeth, and the size of the serrations modify the behavior of crossties and Bloch lines. The edge effects of the strips can in some cases overwhelm the film properties.

VII. Time Determined Propagation

In the crosstie memory the combination of a Bloch line, negative Néel wall and a crosstie are considered to be a "one", the absence of this Bloch line-crosstie pair is considered to be a zero. With a single conductor placed above and parallel to the serrated strips it is possible to effect propagation in strips about 25 μm wide. This has been previously described.[11] A small amplitude (3 Oe) negative pulse about 20 nsec long was used to move the Bloch line to the next potential well. Then a 10 nsec pulse (15 Oe) positive pulse was applied to relocate the crosstie. During the application of the large positive pulse a new crosstie-Bloch line pair formed within the original Bloch line-crosstie pair and the trailing Bloch line-crosstie pair was annihilated. Thus the original Bloch line and a new crosstie ended up one serration farther along the strip. This technique only worked for pulses with amplitude and time duration within a few percent, and attempts to increase the margins of operation have been unsuccessful. Consequently a field determined propagation technique has been adopted.

VIII. Field Determined Propagation

To explain the field determined propagation scheme it is helpful to make an analogy. The Bloch line and crosstie behave in a magnetic field much as current carrying conductors as shown in Figure 9.

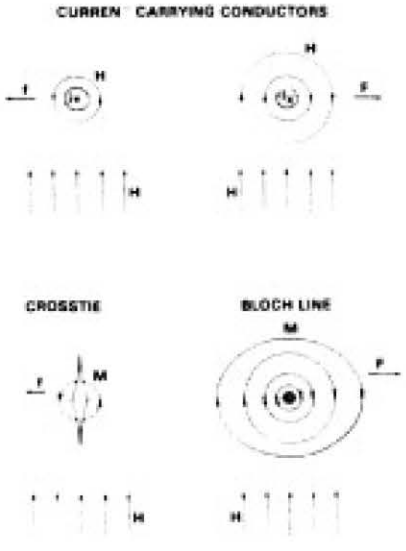


Fig. 9 A useful analogy.

Just as a current in a wire produces a circular magnetic field about it which interacts with a uniform field to give rise to the Lorentz force, so also the circulation of the magnetization about a Bloch line gives rise to a force in a uniform field. The Bloch line and a current carrying conductor can then be considered as circulations in a uniform potential flow with resulting forces. The crosstie can also be considered analogous to a current carrying conductor except that the current is smaller and in the opposite direction from that of the Bloch line. Also the crosstie has much more friction

than the Bloch line, a 3 Oe coercive force compared to 0.1 Oe for the Bloch line.

Previously we described the serrated strip as having potential wells for the crossties and potential wells for the Bloch lines so that the crossties were in stable positions as shown in Figure 8, and the Bloch lines are in stable positions in between the crosstie positions. We can just as well describe the stable positions in terms of a force field or magnetic field as shown in Figure 10. The equivalent magnetic field which is a function of the strip geometry can be written as

$$H_s = A \sin \frac{2\pi x}{\ell} \text{ Oe.} \qquad (1)$$

Notice that if the Bloch line was moved forward a bit it would be pushed back by the magnetic field so that the positions shown in Figure 10 are stable positions. If the Bloch line and crosstie positions were interchanged, they would be in unstable positions. The value of A can be easily measured by applying a uniform field (down in Figure 10) until the Bloch line jumps to its next stable position. The value of A is then equal to the applied field.

In order to move the bit to the next serration two steps are required. First the Bloch line is moved and then the crosstie. The ideal field configuration for stepping the Bloch line is shown in Fig. 11, Step 1. Next fields must be applied to move the crosstie. The fields used for crosstie movement must be larger because of the greater coercive force of the crosstie. The ideal fields for this operation are shown in Step 2 of Fig. 11. The positions of the Bloch line and crosstie shown in Fig. 11 are stable positions to which they have moved as a result of the applied fields. To experimentally confirm the validity of such an approach gold was plated [12] to a thickness of about 3000 Å through a photomask and then the substrate was remasked and the permalloy was etched as shown in Fig. 12.

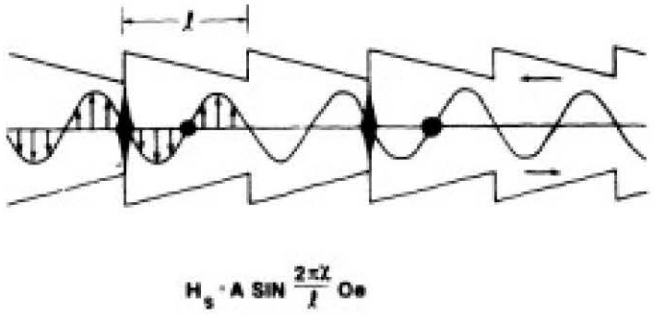


Fig. 10 Equivalent magnetic field of the serrated strip.

The distance between serrations was 8 μm and the width of the strip at the necks was 15 μm. The narrow part of the plated gold conductor was 6 μm wide and the wide part of the conductor was 12 μm wide. A 1 mA current through the narrow-wide conductor corresponds to about 1 Oe applied field in the narrow section and 0.5 Oe in the wide section. The gold is thin enough so that the crosstie and Bloch line can be seen through the gold using a Bitter solution. In addition to the currents through the narrow-wide conductor a coil was used so that by superimposing the uniform coil field

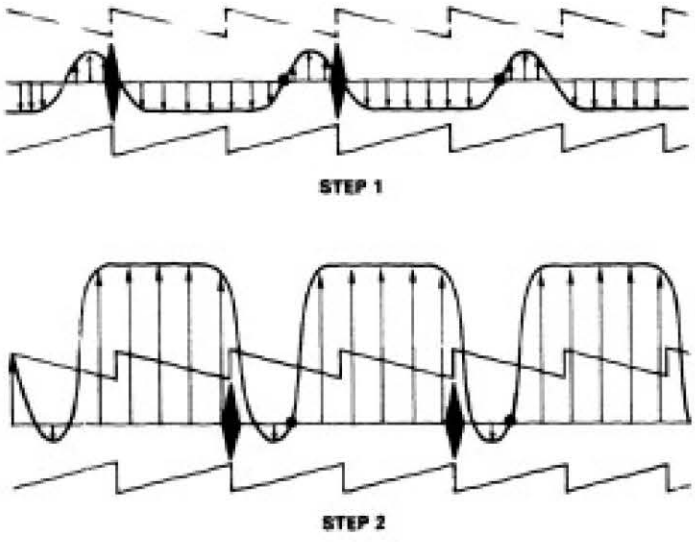


Fig. 11 Ideal stepping fields for the Bloch line and crosstie.

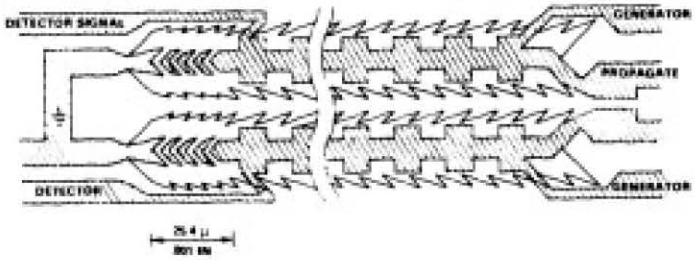


Fig. 12 Serrated strips with narrow-wide plated conductors.

and the spatially varying field the idealized fields shown in Fig. 11 could be simulated. Propagation resulted as expected. A 20 mA current was needed in the narrow-wide conductor to provide sufficient field for crosstie movement. The field difference resulting from the 20 mA current was about 10 Oe at adjacent serrations. The narrow-wide field can be approximated by a sinusoidal field given by the equation

$$H_g = B + B/3 \sin \pi x/\ell \quad \text{where} \qquad (2)$$

in the experiment described B was equal to ±15 Oe for crosstie movement and ±4.5 Oe for Bloch line movement. The field due to the coil was constant with respect to distance along the serrated strip and can be described by the equation

$$H_c = C. \qquad (3)$$

The four phases used to propagate one shift register period (two serrations) are shown in Fig. 13 for a strip having the dimensions shown in Fig. 12. The plots show the fields, H_t, seen by the Bloch line and crosstie as a function of distance along the strip where

$$H_t = H_s + H_g + H_c \qquad (4)$$

In each of the four phases the values of B and C change but the value of A remains the same and it is taken to equal the field H_B^- which is the negative uniform field required to move the Bloch line along the serrated strip. It is thus a measure of the depth of the potential well in which the Bloch line

is stable. The value of H_n^- in Fig. 13 is the measured negative nucleation field using a uniform field. The applied fields $H_o + H_c$ should not exceed H_n^- or crossties and Bloch lines can be generated where "zeros" are supposed to be. H_B^+ is the positive uniform field required to move a Bloch line from its potential well and H_n^+ is the field needed to generate a new crosstie-Bloch line pair. H_a^+ is the uniform field required to annihilate Bloch lines and crossties in the serrated strip.

The fields of phases 1 and 3 are identical except that they are displaced by one serration length. The same is true of phases 2 and 4. In phase 1 the Bloch line moves to its stable position as shown and cannot move beyond that point. In phase 2 the Bloch line is trapped again and cannot move back toward the crosstie because of the local negative field between them. Thus the crosstie is forced to move.

The narrow-wide gold strip used in the above experiment demonstrated the validity of the field propagation technique. However it is not the only method that can be used. For example, the wide part of the narrow-wide conductor can be eliminated completely so that the current must go through the permalloy. Less current is then needed through the strip but the resistance of the strip increases considerably and for strips about 256 bits long the voltages are high enough to dissociate the water in the Bitter solution and corrode the permalloy. However a hydrocarbon based Bitter solution can be used in this case.

The most efficient method of applying the required fields would result if the current could be forced to go above the strip on one serration, under the strip on the next and so on as shown in (a) of Fig. 14. Here the hatched areas represent an oxidized or insulating region in the film below the permalloy. An alternative method is shown in Fig. 14 (b). The thickness of the films are

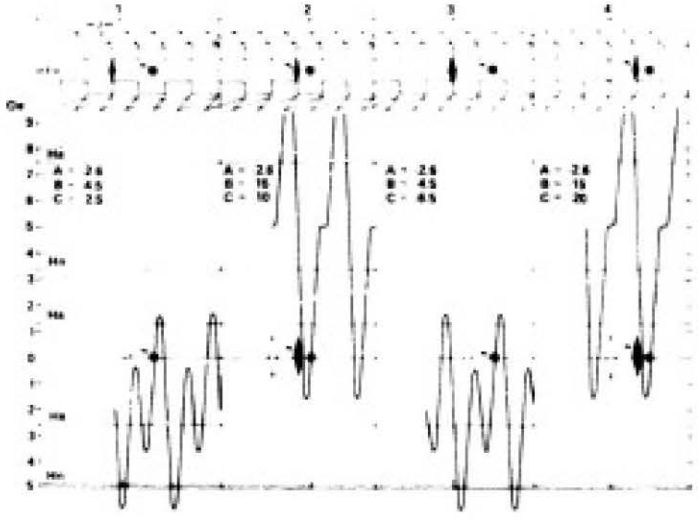


Fig. 13 Resultant fields due to the serrated strip and applied fields.

greatly exaggerated to show the concept in the drawing. Another method of obtaining the over and under current is shown in Fig. 14 (c). Here a metal film about 400 Å thick underlies the permalloy with another metal film about 4000 Å thick above the permalloy on every other serration. If the metal films are about 10 times more conductive than

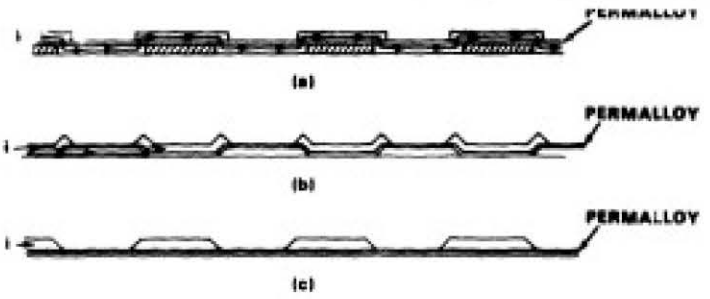


Fig. 14 Methods of obtaining over and under current paths.

the permalloy most of the current will pass below or above the permalloy as desired. The techniques described in Fig. 14 will allow the use of currents of about 5 mA instead of the 20 mA used in the narrow-wide conductor case. The currents in the coil or stripline will also be smaller to achieve the same propagation fields as shown in Fig. 13.

IX. Generation

Referring to Figure 12, it can be seen that the serrated strip terminates on one end in an arrowhead and on the other end in a tail. Propagation can be effected in either direction, but the better technique is to propagate from tail to head because the large pulse required for annihilation is then in the same direction as the field used to set the wall in the serrated strip initially. Therefore, the information should be entered at the tail of the strip. A crosstie forms where the wall terminates on the tail and a Bloch line occurs next to it. A local conductor is needed at this location to push the Bloch line into the next potential well in case a "one" is desired or to prevent such Bloch line motion in case a "zero" is desired. Once the Bloch line enters the next potential well, the propagation conductor takes over and steps a "one" along.

X. Detection

The equation which describes the magnetoresistance effect in permalloy films is given [13] as

$$R = R_o + 1/2\ \Delta R \cos 2\phi \qquad (5)$$

where $R_o = 1/2\ (R_\perp + R_\parallel)$, $\Delta R = R_\parallel - R_\perp$ and ϕ is the smaller angle between the current direction and the magnetization. When the current is parallel to the magnetization, M, $R_\parallel$ is measured. When the current is perpendicular to M, $R_\perp$ is measured. In permalloy films about 350 Å thick $R_\parallel$ is 2% to 3% larger than $R_\perp$. It can be shown that the rate of change of R with respect to ϕ is a maximum when $\phi = 45°$. Therefore, a sensitive sensor would be configured with the current at 45° with respect to the nominal magnetization direction.

Referring to Figure 15, the method of detection is illustrated. The currents used for propagation are also used for detection. The current at the end of the narrow-wide conductor enters the permalloy and spreads out at about 45° into the next plated gold segment where it becomes confined again so that it can spread out again through the permalloy. The arrows indicate the direction of the magnetization when a positive or negative wall is present at the detector. The positive Néel wall corresponds to a "zero" and in this case the current

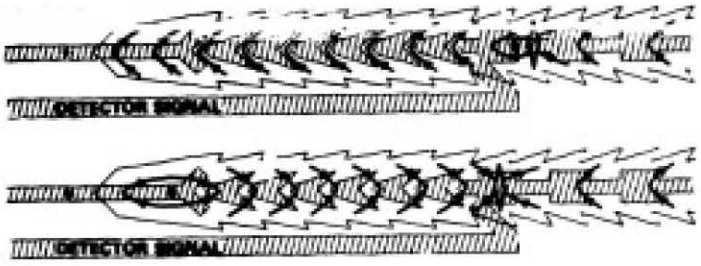


Fig. 15 Bit stretching detector.

through the permalloy is nearly perpendicular to the magnetization so the resistance of the permalloy is low. The negative Néel wall corresponds to a "one" and in this case the current through the permalloy is nearly parallel to the magnetization so the resistance of the permalloy is high. The change in resistance for each segment is about 0.1 mV for a 5 mA current and the total signal is the number of segments times 0.1 mV.

As the figure makes clear the bit is stretched in the detector area. This is accomplished by providing smaller potential wells for the Bloch line in the detector area. Also the current while in the gold segments provides a magnetic field which drives the Bloch line along the wall. The bit stretching does take time however, because the current moving the Bloch line must persist until the Bloch line traverses the detector. Some compromise can be made between shift rate and detector output if a signal larger than 0.1 mV is needed or desirable.

XI. Permalloy on Silicon

Experiments indicate that Permalloy can be satisfactorily deposited on semiconductor grade silicon. To produce films with zero magnetostriction the iron content of the Ni-Fe source must be increased by 0.6% compared with the 82.8% Ni-17.2% Fe source normally used for glass substrates. By fabricating the crosstie memory on silicon chips or wafers the amplifiers for the detectors can be fabricated on the spot so that most likely only a fraction of a millivolt will be required at the detector output. Also, the drive electronics and decoding can be integrated so that the memory will appear to the user as a convenient semiconductor memory except that it will also be nonvolatile. The integration of the memory with a microprocessor is also an attractive possibility.

To be economically attractive, it appears necessary to provide circuitry on the silicon chip so that several shift registers can share a common sense amplifier and a common driver.

XII. Features of The Crosstie Memory

The crosstie memory has the following features: It has the high speed of $\sim$20 M bits/sec, high bit density $\sim 10^6$-10^7 bits/in^2 (1.5-15x10^5 bits/cm^2), it is nonvolatile, it requires little power, no external bias fields or coils are needed, it has silicon wafer compatability, no single crystal magnetic material is required, it has a temperature range from -50 to 100°C, and it uses present thin film technology.

XIII. Conclusion

The advanced mass memories now emerging and being developed which were originally conceived as "gap filler" technologies will probably find their greatest market in microcomputer-based systems. Such systems are particularly important in avionics. The EBAM memories on the other hand are expected to find their place in land-based, large storage situations. As microcomputer-based systems become more powerful, nonvolatility will become increasingly important. A fast high density, nonvolatile memory which is integrable with silicon technology appears very desirable for future systems.

ACKNOWLEDGEMENTS

The authors wish to thank R. S. Sery of this laboratory for his measurements of the dynamic properties of crossties and many magnetoresistance measurements. They also thank O. J. VanSant, Jr., of this laboratory for programming the mask generator. Also they thank D. I. Gordon of this laboratory for his continued interest in the progress and support of the project.

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