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PROGRESS TOWARD THE CROSSTIE MEMORY V.(U)
JAN 78 L J SCHWEE, W E ANDERSON, Y J LIU
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PROGRESS TOWARD THE CROSSTIE MEMORY V

BY L. J. SCHWEE W. E. ANDERSON
Y. J. LIU R. N. LEE

RESEARCH AND TECHNOLOGY DEPARTMENT

5 JANUARY 1978

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NAVAL SURFACE WEAPONS CENTER
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This is the fifth annual technical report of progress toward the crosstie memory and it emphasizes work done during the past year. There are four previous reports which can be obtained upon request of the authors of this report. The previous reports present a basis for this report.

In the crosstie memory, information is stored, propagated and detected in magnetic domain walls of Permalloy films about 370 Å thick. Serrated edges on narrow thin film permalloy strips are used to center a domain wall in each

→ next page

20,000,000

150,000 sq. cm.

strip and provide stable positions for crossties and Bloch lines. The magnetoresistance effect in the information bearing film is used for detection. The anticipated performance of the crosstie memory includes a shift rate of 20×10^6 bits/sec, a bit density greater than 1.5×10^5 bits/cm^2, and operating temperature range from -50°C to 100°C, nonvolatility, low cost and low power consumption. Also, the memory can be fabricated on Si or SiO_2 and integrated with semiconductor devices.

At this time all the necessary functions associated with the shift registers have been demonstrated and shown to be compatible. Present emphasis is being placed on widening the margins of operation so that a reliable and manufacturable device will result.

SUMMARY

The purpose of this report is twofold. First, it is intended to serve as an annual report to the Naval Air Systems Command. Second, it is intended to summarize in one place our present knowledge, techniques, and opinions concerning the Crosstie Memory. There are also available several papers referenced in this and previous reports which have been presented at the Intermag Conferences and Conferences on Magnetism and Magnetic Materials. These papers can be found in the IEEE Transactions on Magnetics and the AIP Conference Proceedings.

The work reported here was funded by NAVAIR Task No. WF54545602.

J R Dixon
J. R. DIXON
By direction

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Chapter 1

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.

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.

TABLE I (U)

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 5M 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

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[1] J. E. Juliussen, "Magnetic Bubble Systems Approach Practical Use," Computer Design 15 No. 10, 81-91 (1976).

Chapter II

PROPAGATION

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.[2] 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.

Field-Determined Propagation With Crosstie Motion

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 3. 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. Although the analogy limps in terms of magnetization directions about a crosstie, it is useful to consider the crosstie as a current carrying conductor with smaller current directed opposite to 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[2] 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 4 and the Bloch lines were 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 5. The equivalent magnetic field which is a function of the strip geometry can be written approximately 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 5 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

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[2] L. J. Schwee, H. R. Irons, W. E. Anderson, "The Crosstie Memory," IEEE Trans. Magn. MAG-12, 608-613 (1976).

Figure 5) 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 Figure 6, 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 Figure 6. The positions of the Bloch line and crosstie shown in Figure 6 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[3] to a thickness of about 3000 Å through a photomask and then the substrate was remasked and the permalloy was etched as shown in Figure 7. 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 and the spatially varying field the idealized fields shown in Figure 6 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

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

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

$$H_c = C. \tag{3}$$

The four phases used to propagate one shift register period (two serrations) are shown in Figure 8 for a strip having the dimensions shown in Figure 7. The plots show the fields, H_t, seen by the Bloch line and crosstie as a function of distance along the strip where

$$H_t = H_s + H_g + H_c \tag{4}$$

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 Figure 8 is the measured negative nucleation field using a uniform field. The applied fields $H_g + H_c$ 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 re-

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[3] L. T. Romankiw, S. Krongelb, E. E. Castellani, A. T. Pfeiffer, B. J. Stoeber, and J. J. Olsen, "Advantages and Special Considerations in Fabricating Bubble Circuits by Electroplating and Sputter Etching," IEEE Trans. Magn. MAG-10, 828-831 (1974).

quired 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. This experiment was tried but too much power was required to move the crossties and the 10 μm wide strips overheated. The method may be workable for wide serrated strips with shallow potential wells.

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 Figure 9. Here the hatched areas represent an oxidized or insulating region in the film below the permalloy. An alternative method is shown in Figure 9 (b). The thickness of the films are greatly exaggerated to show the concept in the drawing. Another method of obtaining the over and under current is shown in Figure 9 (c). Here 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 the permalloy most of the current will pass below or above the permalloy as desired. The techniques described in Figure 9 will allow the use of currents of about 5 mA instead of the 20 mA used in the narrow-wide conductor case, also the power in the coil or stripline will be less to achieve the same propagation fields as shown in Figure 9. The techniques shown in Figure 9 have not yet been tried.

Field-Determined Propagation of the Second Kind

In the experiment explained above the coercivity of the crosstie was less than the nucleation field for a new crosstie-Bloch line pair in between the original crosstie and Bloch line. Also, the fields were applied slowly so there was plenty of time for the crosstie to move. The question that must be addressed is whether memory speed will be limited by the mobility of the crosstie.

The answer to this is no, it will not be limited by crosstie mobility because if the fields are applied rapidly (with short risetimes), the crosstie will not have time to move and the duplication-annihilation process described in the time determined propagation section will come into play. The character of the applied fields can change in this case because the field at the trailing crosstie-Bloch line pair must be larger than H_a^+ and the field at the leading pair need only be less than H_a^+. Once the new Bloch line-crosstie pair is nucleated, there is no need to keep the leading Bloch line separated from the neighboring crosstie by a negative field. The rise time of the applied fields need be no faster than the crosstie acceleration time (7 nsec) for this alternate propagation scheme to occur.

In the course of the propagation experiments using crosstie motion we did on one occasion nucleate a new crosstie-Bloch line pair and the applied field at the trailing pair was not large enough for annihilation. By increasing the uniform field the trailing pair could be annihilated without annihilating the leading pair. It is expected that both modes of propagation can be made to work under similar conditions, and at intermediate frequencies a mixture of modes of propagation might occur. If the risetimes of the applied fields are fast enough, crosstie motion will not occur and the sinusoidally varying field can be reduced in amplitude.

In fact the narrow-wide conductor technique was designed with the duplication-annihilation scheme in mind. But when the film was placed above a stripline and 1 nsec risetime pulses were applied, enough current was induced in the narrow-wide conductor to nucleate unwanted "ones". There were long leads on the narrow wide conductors situated such that capacitive and inductive pickup could occur. When the change to a coil was made, the frequency had to become slow and the crosstie motion scheme was made to work. It is generally advisable to learn to walk first, and run later. That is the approach we ended up taking.

Of course there is no need to design things for both fast and slow risetime pulses. Fast risetime pulses can be used regardless of the clock rate of the register.

Generation

To generate a "one" in the crosstie memory a localized field must be applied which is larger than H_n^- shown in Figure 8. This is unlike the situation in bubble memories where it is difficult to generate a new bubble and easier to split one in two. In fact in several other shift register schemes using thin films the generation of spurious "ones" has historically been a problem because the nucleation field was too close in magnitude to the coercive force. This is not true in the crosstie memory because of the very low coercive force of the Bloch line. However the crosstie coercive force is dangerously close to the nucleation field as was explained in the section above. But this does not result in a problem for us. The details of generation are different depending on whether crosstie motion or nucleation-annihilation are used. In the case of crosstie motion a localized conductor creates a field greater than H_n^- if a "one" is desired, and the propagate fields move it out from under the conductor. The only problem involved is in physically locating the generate and propagate conductors in proximity so that the appropriate fields can be generated at the same location.

In the case of nucleation-annihilation, it is sufficient for the generate conductor to inhibit the Bloch line motion to the next cell if a "zero" is needed and to promote such motion if a "one" is needed. The propagate conductor can be arranged so it will not annihilate the original crosstie. However, if it does, it must be regenerated again when a "one" is desired.

Chapter III

DETECTION

Theory

The equation which describes the magnetoresistance effect in permalloy films is given[4] as

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

where $R_o = 1/2\ (R_{\parallel} + R_{\perp})$, $\Delta R = R_{\parallel} - R_{\perp}$ 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 ϕ = 45°. Therefore, a sensitive sensor would be configured with the current at 45° with respect to the nominal magnetization direction.

Experiment

Referring to Figure 10, 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 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[5] and the total signal is the number of segments times 0.1 mV. A bit stretching detector with 10 segments poorly defined because of a defective photomask gave a signal of 0.5 mV using a 5 mA current.

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.

The experiment was done using a Bitter solution to show the wall and the Bloch line could be seen as it traversed the detector area. The detector appeared as

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[4] J. P. Jan, Solid State Physics (Academic Press Inc.) New York, (1963) 5, 15.

[5] D. S. Lo, M. C. Paul, L. H. Johnson, G. F. Sauter, "Crosstie Memory" Government Microcircuit Applications Conference Digest of Papers, 6, 188-191 (1976).

shown in Figure 11 under test. The detector was displayed on closed circuit television with an oscilloscope placed next to the monitor. Each time the wall switched polarity when the Bloch line traversed the detector, a .5 mV signal change was observed on the oscilloscope. A current of 5 mA was used for the above test. Subsequently the current was doubled but the detector burned up.

Chapter IV

PERMALLOY ON SILICON

Virtually all of the expected applications of crosstie memories will entail interfacing with semiconductor devices. The most desirable way to accomplish this is to fabricate the permalloy film memory and the semiconductor devices on the same silicon wafer. This would greatly reduce the number of necessary pin connections and would substantially increase reliability. Moreover, the development of this kind of hybrid technology would open up a wide range of device possibilities not otherwise feasible. With this in mind, we have fabricated a crosstie memory register on a silicon substrate as a first step in demonstrating the feasibility of the hybrid technology.

Permalloy films were grown on as-received device grade wafers of silicon. No effort was made to remove the native oxide, and cleaning was limited to ultrasonic rinses in deionized water and methanol. All films to date have been deposited on the polished (100) surface of n-type (P doped) silicon.

The permalloy was evaporated from a beryllia crucible and a quartz oscillator thickness monitor was used to control the deposition. The permalloy source material was chemically cleaned in a nitric-hydrofluoric bath and then rinsed in deionized water and methanol just prior to installation in the vacuum system and pump-down. Pumping was accomplished with cryogenic fore-pumps and a 140 li/sec sputter-ion pump. The base pressure was of the order of 10^{-8} Torr and depositions took place in the 10^{-7} Torr range. (It is noteable that the usual formation of a slag on the surface of the melt was not a problem during these depositions. It was not determined whether this was due to the chemical cleaning of the source material or to the absence of pump oil vapor.)

It was expected that the optimum conditions for deposition on silicon would not differ significantly from those for a glass substrate. This did not prove to be the case. Although excellent films are obtained on glass with a substrate temperature of about 300C, the sticking coefficient on silicon is very low in this temperature range, and nucleation and growth is extremely slow and difficult to reproduce. Excellent permalloy film growth on silicon is obtained, however, for substrate temperatures in the range of 150C to 175C. These temperatures are sufficiently low to minimize reactions between the permalloy and the silicon to form silicides.

Our results suggest that the sticking coefficient of permalloy on silicon is fairly low even at the 150C substrate temperature. Nucleation and growth at relatively low fluxes was uncertain at best, and reproducible growth at rates below 10 Å per second could not be obtained. The deposition efficiency increased at higher fluxes, and excellent films were reproducibly grown at rates between 35 Å/sec and 50 Å/sec. At these growth rates, deviations from the targeted thickness were less than the uncertainty (± 25 Å) in the thickness measurements themselves.

The measured magnetic properties of a film grown on silicon are fairly good. A 325 Å film, for example, had an anisotropy field of 4 Oe and a coercivity of 1.8 Oe. Although no magnetic field was applied during growth (other than the stray fields), the dispersion was fairly low.

No unusual difficulties were encountered in the photolithographic fabrication of crosstie memory registers on these films. Adhesion was excellent and there was no apparent degradation of magnetic properties due to processing. Examination of the registers under a microscope with the use of a Bitter solution showed that wall placement was good and the crosstie formation and annihilation fields comparable to those obtained with glass substrates.

Chapter V

GEOMETRICALLY DEFINED TRACKS

Crossties on Tracks

The Neel wall shift register tracks in the crosstie memory are subject to drift due to external magnetic distrubances. This limits freedom in design and narrows margins of operation, and a more positive technique in precisely locating them is desirable. We therefore sputter-etched the substrates to form steps about 200 Å deep and deposited on the substrates nickel-rich (relative to zero-magnetostriction composition) Permalloy films about 400 Å thick with their easy directions along the step edges. The nickel-rich composition gives rise to negative magnetostriction in the film which is relieved along the step resulting in a local easy axis perpendicular to the step edge. It is then energetically favorable for Néel walls to situate along the edges as we show in Figure 12 with a 400 Å 0.14% nickel-rich Permalloy film. This phenomenon is consistent with the observation of Néel or crosstie walls formed along scratches in the easy direction of a Permalloy film.[6] Naturally in a shift register we pre-etch the substrate to form steps at the center of serrated strips. Isotropic Permalloy films are chosen so that shift register tracks can bend around corners in compliance with etched serrated strips whose edges produce the needed anisotropy for initial wall placement.

Spikes on Tracks

Local anisotropy along etched steps inside a single domain results in an unusual magnetization distribution. The magnetization vector on the edges turns away from the general direction at zero field. If the local easy direction along a step is orthogonal to that of the rest, the result is a Néel-wall-like region consisting of two back-to-back half-Néel-walls. We have observed such a region in the Permalloy film mentioned above. This region is bistable with the presence or absence of regions of reversed magnetization bounded by magnetic "spikes", and thus makes a digital memory possible. A "spike" can be viewed as a half-crosstie which is like a crosstie at one end and a Bloch line at the other. Such spikes have also been observed along the scratches of reference 6 with the magnetization distribution around them suggested there.

Just as a "one" is represented by a region of negative Néel wall bounded by a crosstie and a Bloch line in the crosstie memory, so is a "one" in the spike memory represented by a "down" region bounded by an "up" and a "down" spike. In Figure 13 we show some spikes observed at a step in the same film mentioned above.
The spikes can be propagated along tracks defined by the edges with properly designed field configuration using overlaid conductor patterns. In a shift register serrated strips are again powerful in positioning data bits and initializing magnetic moments except now one side of the strips will have reversely directed serrations. We are currently making further investigations on the characteristics of such a memory scheme.

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6. S. Methfessel, S. Middelkoek, and H. Thomas "Domain Walls in Thin Ni-Fe Films," IBM J. Res. Dev., 4, 96-106 (1960).

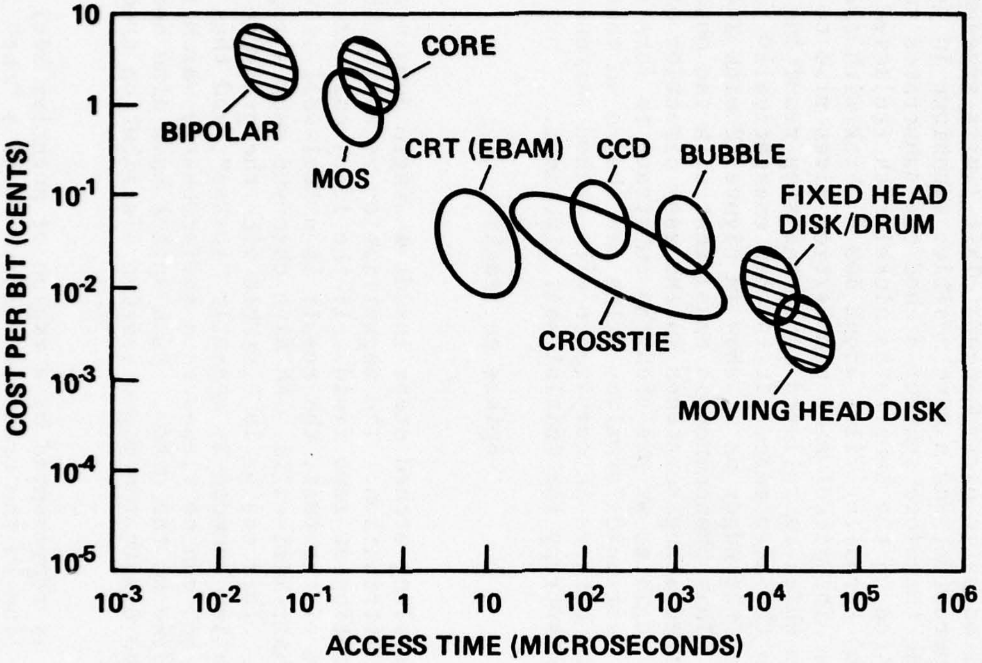

FIGURE 1. COST VS. ACCESS TIME.

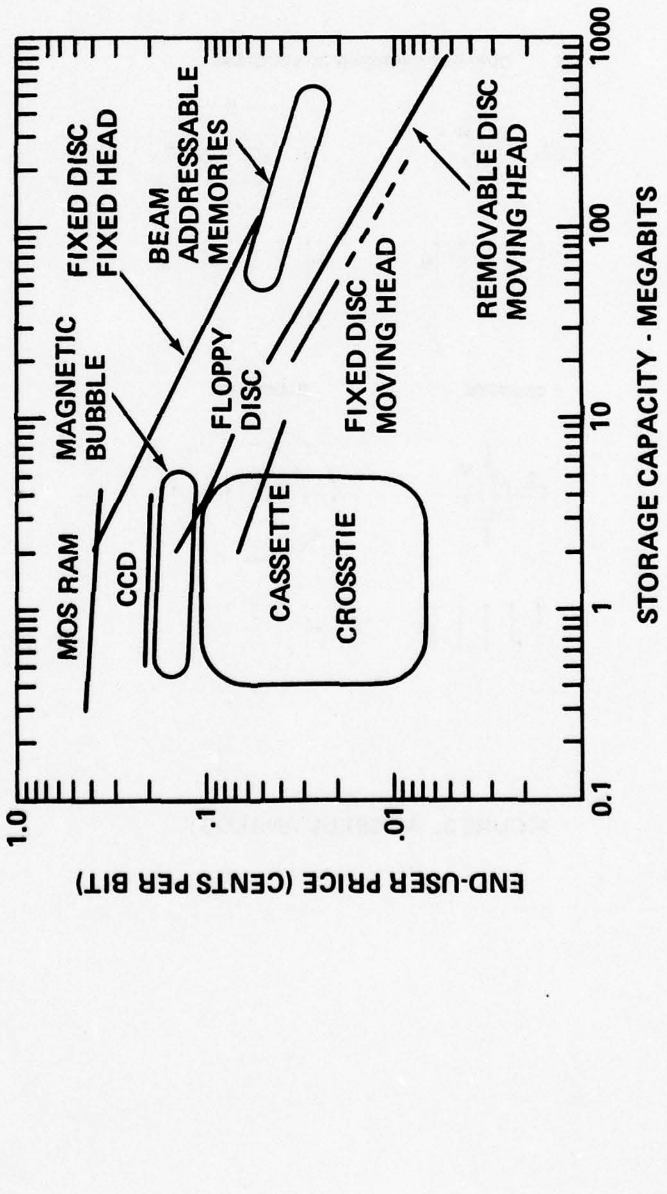

FIGURE 2. COST VS. STORAGE CAPACITY.

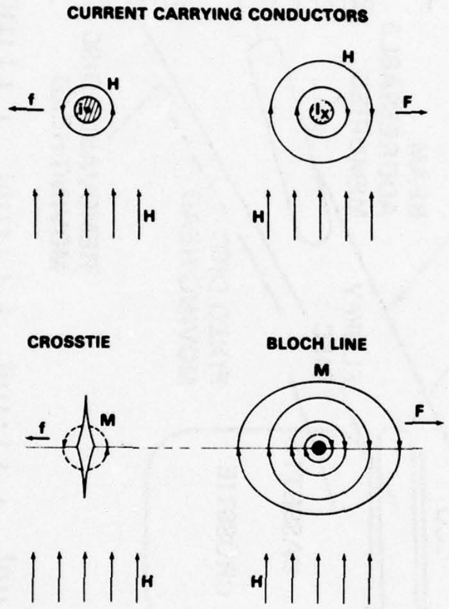

FIGURE 3. A USEFUL ANALOGY.

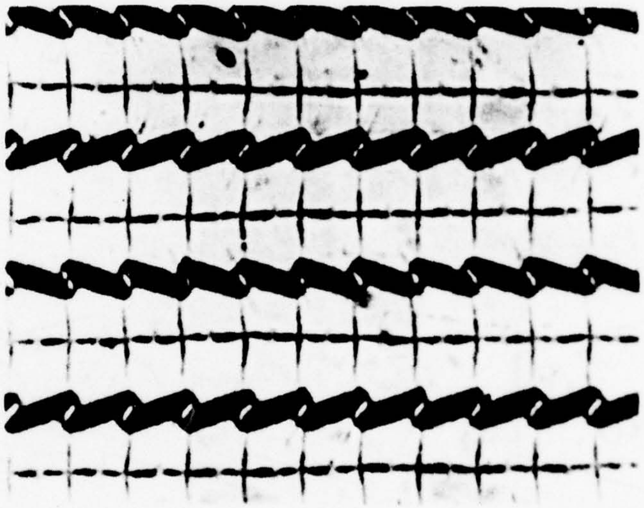

FIGURE 4. CROSSTIES AND BLOCH LINES IN STABLE POSITIONS.

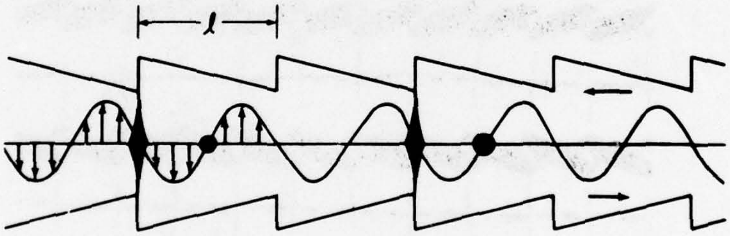

FIGURE 5. EQUIVALENT MAGNETIC FIELD OF THE SERRATED STRIP.

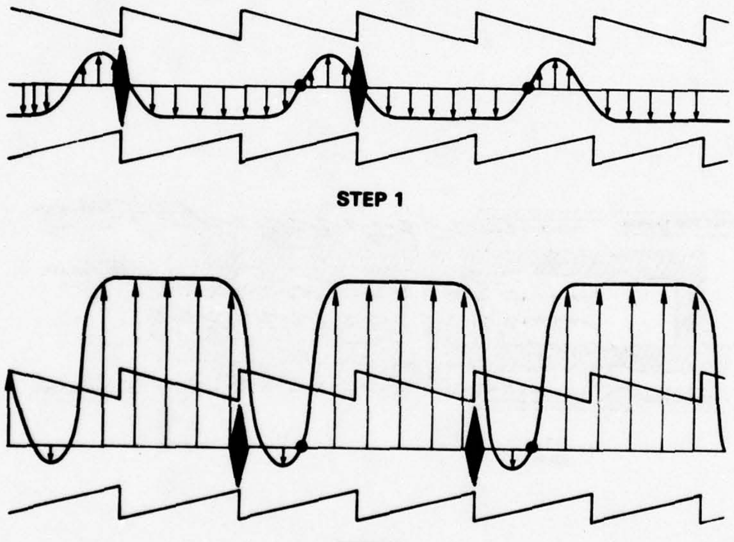

FIGURE 6. IDEAL STEPPING FIELDS FOR THE BLOCH LINE AND CROSSTIE.

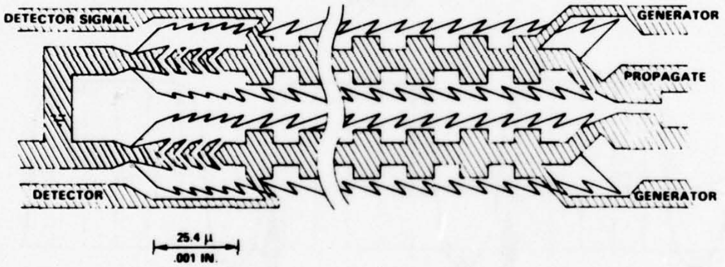

FIGURE 7. SERRATED STRIPS WITH NARROW–WIDE PLATED CONDUCTORS.

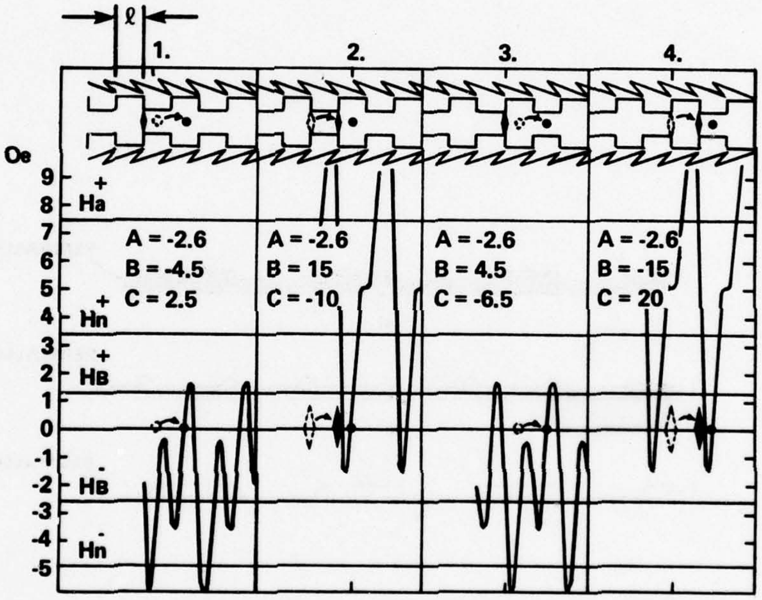

FIGURE 8. RESULTANT FIELDS DUE TO THE SERRATED STRIP AND APPLIED FIELDS.

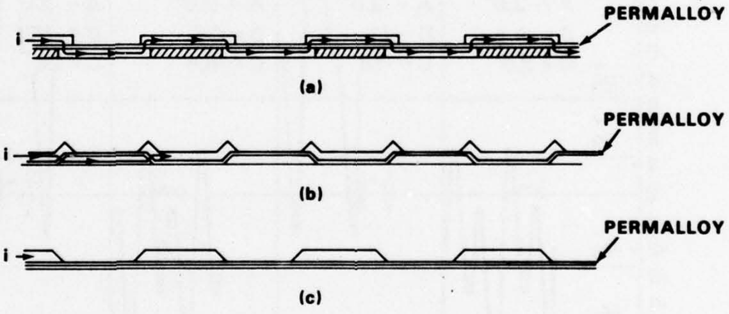

FIGURE 9. METHODS OF OBTAINING OVER AND UNDER CURRENT PATHS.

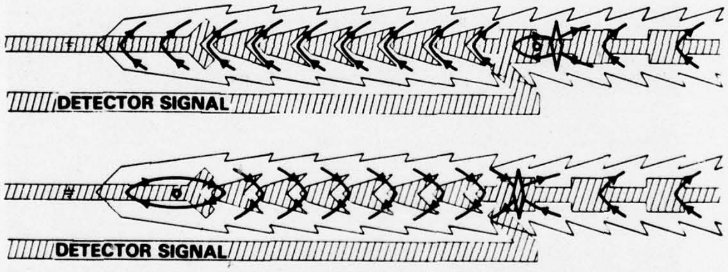

FIGURE 10. BIT STRETCHING DETECTOR.

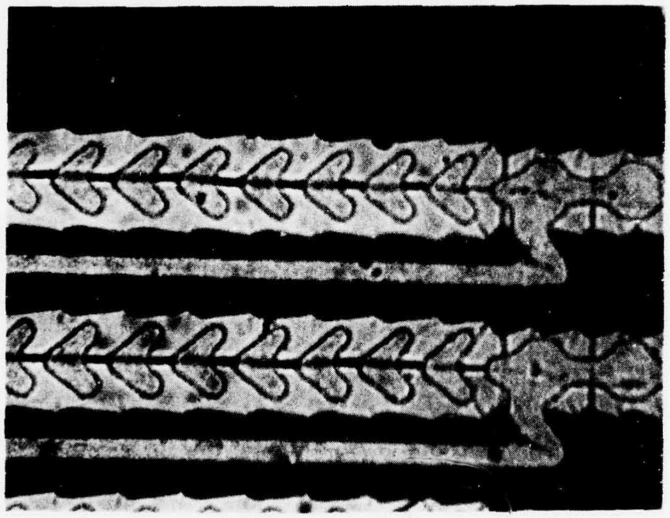

FIGURE 11. PHOTO OF DETECTOR UNDER TEST.

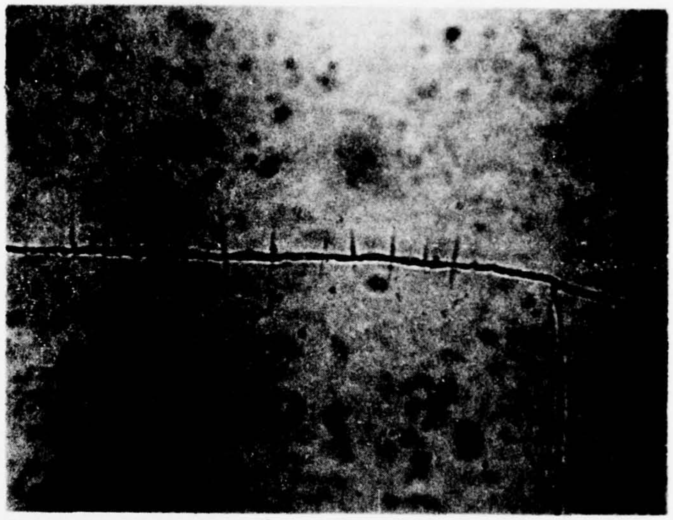

FIGURE 12. CROSSTIE WALL ON SPUTTER–ETCHED STEP.

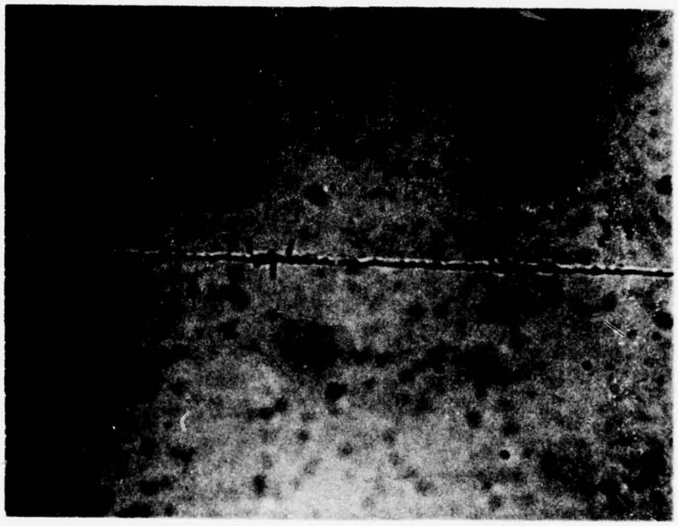

FIGURE 13. SPIKES ON A SPUTTER–ETCHED STEP.

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