RECENT DEVELOPMENTS IN COMPUTER MEMORIES:
THE BUBBLE MEMORY

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التطورات الحديثة في ذاكرة الحسـابات
الذاكرة الفقاعيــة

بقلـــم
الدكتور كرت باتـــل
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خلاصة المقالـــة :

هناك حاجة ماسة لزيادة الامكانية الخزنية للحسابات في المستقبل القريـــب ، فمن ضمن الوسائل التكنولوجية الممكنة ، فقد اقترح استعمال الذاكرة الفقاعية بالحالـــة الصلبة كبديل لاستعمال الاسطوانة الكهروميكانيكية •

ان البحث يقدم الاسس واسلوب تشغيل وتنظيم الذاكرة الفقاعية المغناطيســـية كذلك يقدم ويشرح الخزن والتوليد والتشخيص والتحويل للمجالات للتوصل الى الذاكـــرة الفقاعية •

ABSTRACT

Large increases in the storage capacities of computers will be needed in the near future. Amongst other technologies, the bubble memory has been suggested as a solid state replacement for the electro-mechanical disc.

This paper outlines the fundamental basis of operation and the organization of a magnetic bubble memory. The physical implementation of the functions of storage, generation, detection and transfer of the domain are described in order to realize the bubble memory.

1. INTRODUCTION

The storage of information in present day computer systems is shared between high speed buffers, medium speed medium cost memories and low speed low cost mechanical devices. Over the next few years it is expected that a substantial increase in the capacity of medium speed memories will be required as users desire more and more storage. This fact plus the need to lower cost and increase reliability has led to the development of new technologies aimed at providing reliable low cost storage of high capacity [1]

Amongst various technologies currently being investigated is a promising alternative based on a stable magnetic domain configuration set up under certain conditions in thin films of some magnetic materials. Although the actual shape of this domain can be more strictly described as a right circular cylinder with its axis normal to the film, it is often called a 'bubble' due to its circular appearance when viewed under a microscope using polarized light and the Faraday effect. These domains were first observed in Barium Ferrite by Kooy and Enz of the Philips Laboratories[2] as early as 1960. However it was not until 1967 that Bobeck[3] searching for materials that would propagate isolated domains conceived the idea of using a magnetic bubble as a means of storage. Bobeck found that, under certain conditions, it was possible to move a domain from one location to another in a pre-determined manner using a superimposed rotating magnetic field. The presence or absence of the domain at a particular position is then the exact analog of say the state of a ferrite core and as such can be used as a means of storage. Successful methods developed at the Bell Laboratories to propagate domains at fast data rates led to the widespread belief that it was commercially feasible for bubbles to act as a basis for storage of large quantities of information(4).

2. THE MAGNETIC BUBBLE

Certain magnetic materials whose easy axis lie in the direction normal to the plane of the film due to uniaxial anisotropy, exhibit serpentine domains upon examination by polarized light. In the remanent state, the material effectively appears to be de-magnetized as equal areas of the film can be visualised to be magnetized in each of the two opposite directions (Fig. 1a). Upon the application of a uniform external magnetic field normal to the film, the width of stripe domains magnetized in the opposite sense to the applied field decrease (Fig. 1b) until a critical field H_s is reached when the cylindrical domain or 'bubble' is formed (Fig. 1c). Upon further increase of the applied field, the bubble decreases until a critical field H_{co} is reached at which point the bubble collapses leaving the film

Domain structure in an garnet with no applied field

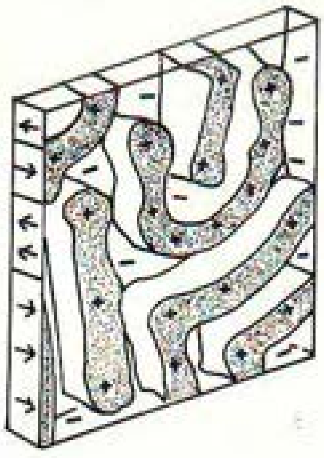


FIG: 1a

Domains magnetized antiparallel to applied field shrink as field increases

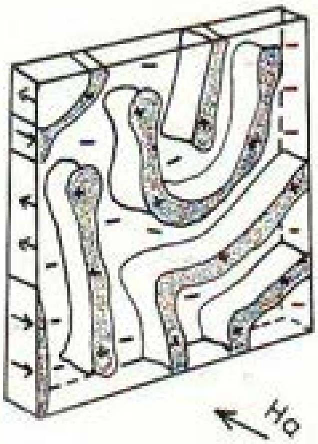


FIG: 1b

At higher values of applied field some domains shrink to cylindrical domdins before final collapse

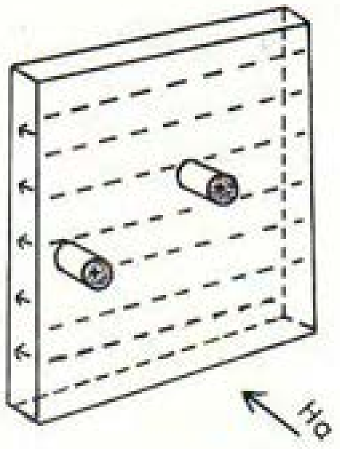


FIG: 1c

Between certain values both cylindrical and elliptical bubbles can exist together

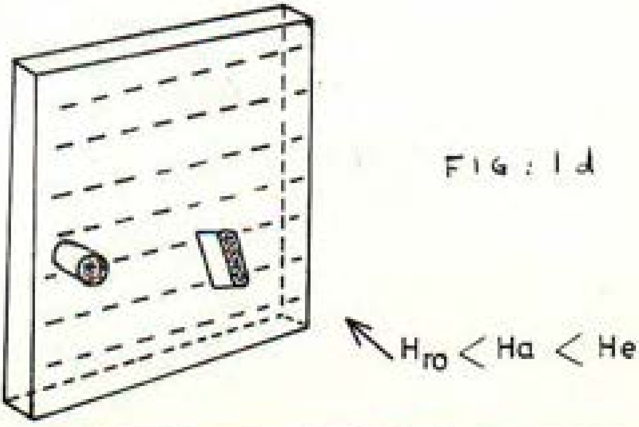


FIG: 1d

saturated in the direction of applied field. Further increase in the magnetic field only drives the film harder into saturation. Consider the case when the applied field is increased until the bubbles are formed and then decreased. It is found that at the elliptical instability field H_e the bubble reverses back to a serpentine domain. Due to hysterisis in the transition from stripe to circular domain, this elliptical instability field H_e is lower than the critical field H_s at which the bubble is formed.

Hence it is found that in the region between the two critical transition fields H_e and H_s both stripe and circular domains can co-exist (Fig. 1d). This region is usually about 20 per cent of the total range between H_e and H_{co} in which bubbles can exist. As a finite region of stability exists, all bias fields H_a must lie within this total region to ensure satisfactory operation of bubble devices.

For magnetic films to comply with the requirements of a bubble device, they must also possess the following qualities[5, 6, 7, 8, 9].

a. High anisotropy field H_K and High Nucleation field H_N.

This is to ensure that the magnetization vector is constrained normal to the plane of the film and that no self-nucleation takes place at low bias fields.

b. High mobility and low wall motion coercivity. For domains to be propagated at fast data rates with small force, it is essential that the mobility of the domain is high and wall motion coercivity low.

c. Small size. The packing density of bubbles is totally dependent on the size of the bubble. It is hence desirable that the bubble is made as small as possible. The limiting consideration on the size of the bubble is usually overlay yield. It will be shown in a later section that certain detecting generating and propagating elements called overlays need to be fabricated for the satisfactory operation of a bubble memory.

d. High temperature stability. Since material parameters such as the saturation magnetization of the film M_B determine the exact size of the bubble and the operating range of bias field, these parameters must have a low temperature co-efficient.

The first materials [10] used for bubble devices which satisfied these criteria were the ortho-ferrites of composition $RFeO_3$ where R is one or more of the rare-earth elements. However with the need for smaller bubble size and higher film yield, only the rare-earth garnets of composition $R_3Fe_5O_{12}$ are extensively used today. R is again one or more

Variation of bubble diameter with applied bias field in a typical garnet film

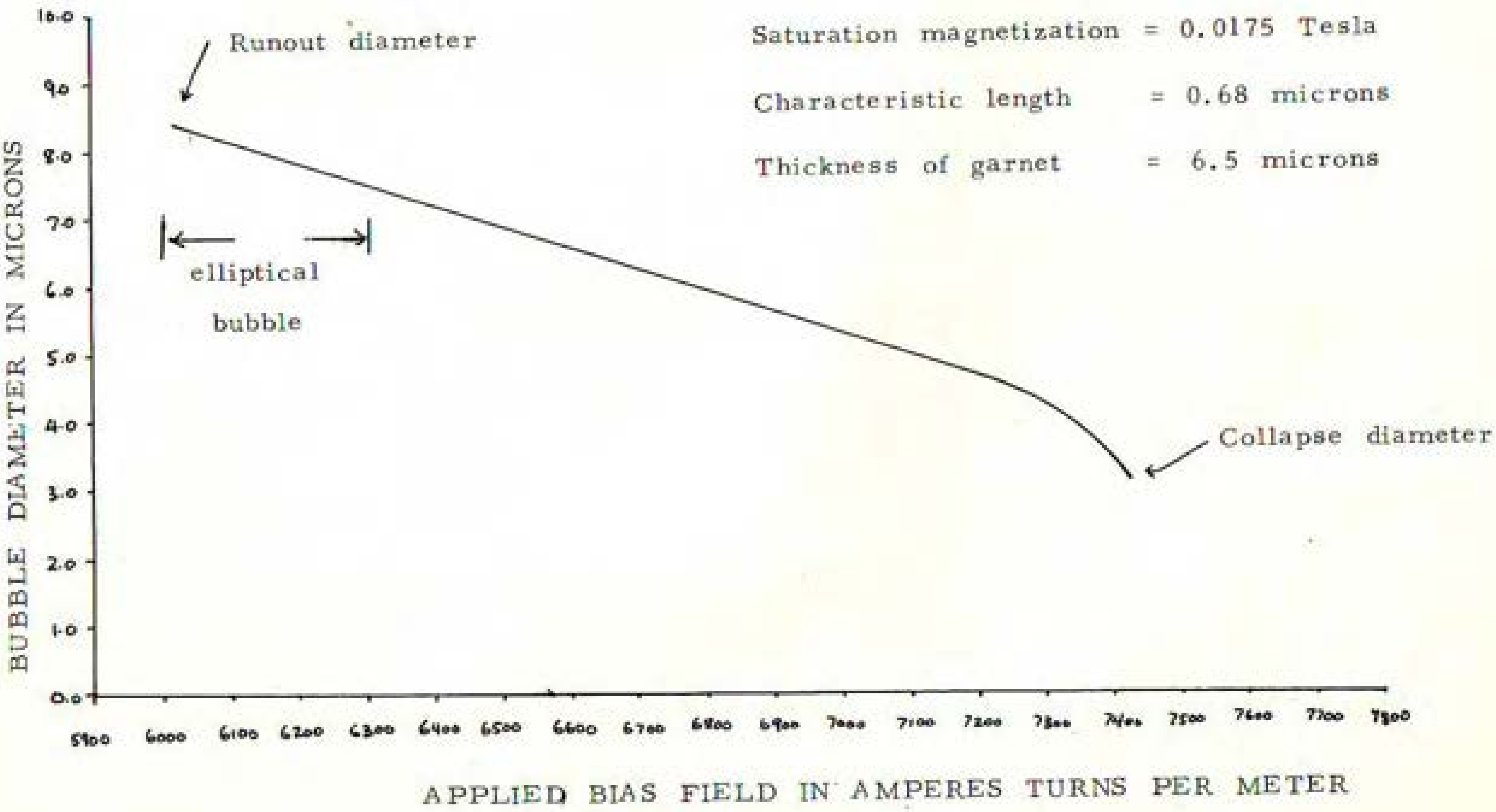


FIG : 2

of the rare-earth elements. Fig. 2 shows a typical plot of the applied field H_a against diameter of a bubble supported by a garnet film. The operating margins between which the domain is stable are typically 10 per cent of M_B/u_o. The ratio of the elliptical instability field H_e and the bubble collapse field H_{co} vary between 1.6 to 1 being dependent on the thickness of film. The ratio of the runout radius R_{ro} and the collapse radius lies between 2 and 3 for most garnet films.

Thiele[11], from consideration of the static stability of the bubble, has suggested a preferred thickness h of film with wall energy σ_w and saturation magnetization M_B to be

$$h = 4l_c = \frac{4\sigma_w u_o}{M_B^2} \quad \text{.........................(1.1)}$$

where l_c is called the characteristic length of the film. At this plate thickness, the minimum diameter attainable for this material is realised and its compliance to variation in domain boundary maximized. The operating diameter of bubble devices is generally chosen to be the geometric mean of its limiting diameters.

$$d_o = 2(R_c.R_{ro})^{1/2} \quad \text{.........................(1.2)}$$

3. THE STATIC STABILITY OF CYLINDRICAL DOMAINS

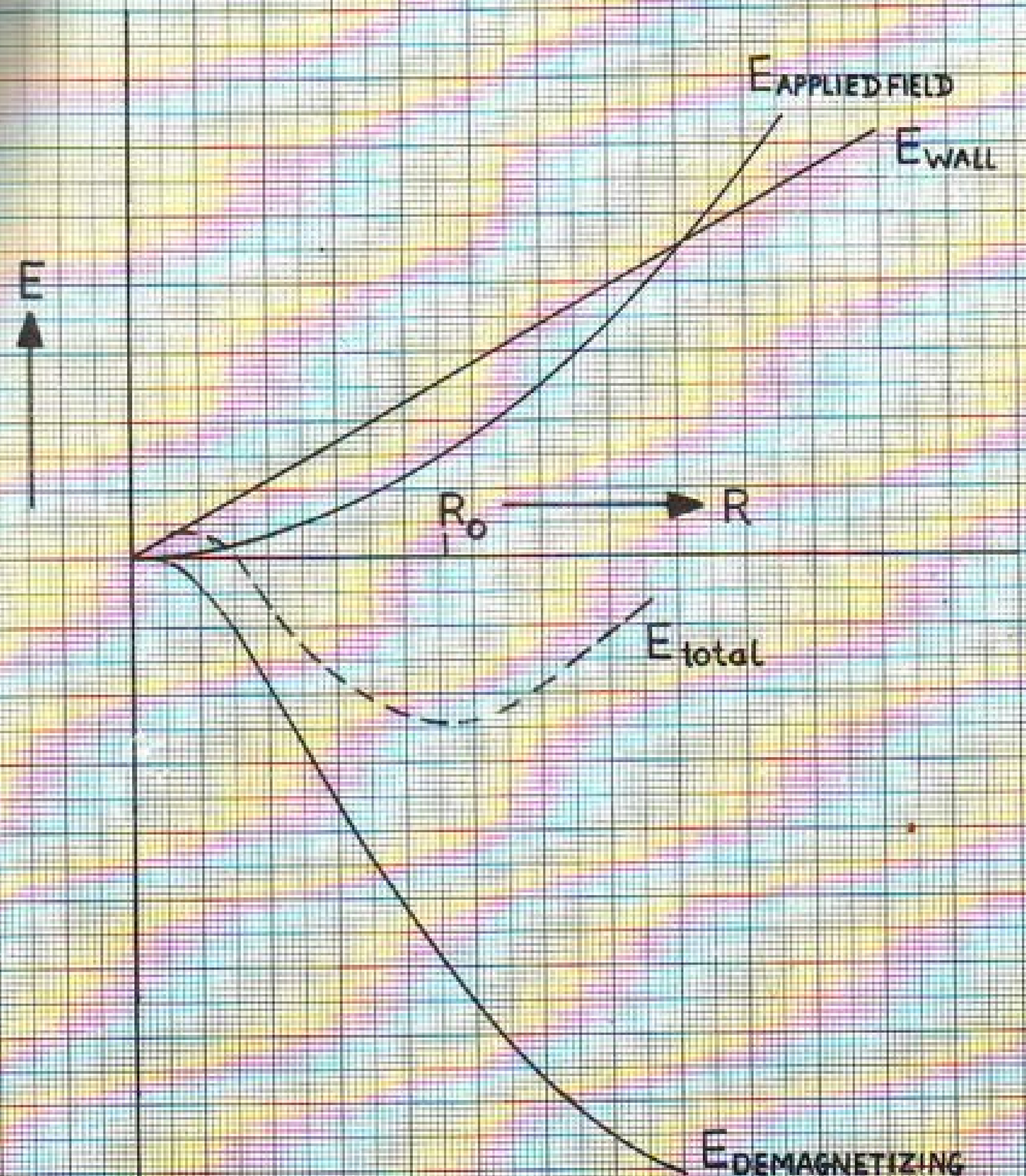
An understanding of the theory of domain stability is necessary if the limitations of a device are to be known. The static stability of a bubble can be investigated theoretically by consideration of its total energy. The total energy of an isolated domain of any shape in an infinite plane of film has three major components[12].

a. The energy associated with the domain wall often referred to as the wall energy. This term is a simple product of the wall area and the wall energy density σ_w. The wall area will of course depend on the shape and thickness h of the domain.

b. The energy associated with the interaction of the external applied magnetic field H_a with the magnetization vector of the domain M_B. This applied field energy is a function of the volume of the domain, the external field and the saturation magnetization.

c. The demagnetizing or electrostatic energy. This component of the total energy is due to the interaction of the magnetization vector with the demagnetizing fields set up by the pole concentration in the domain. Since these demagnetizing fields are a complex function of pole concentration, the electro-static energy will be dependent on the surface area of the domain.

VARIATION OF BUBBLE ENERGY WITH RADIUS



Under the influence of an external field, the domain wall tries to minimise its total energy by reducing its volume V so that the equation below is satisfied.

$$\frac{\partial E_T}{\partial V} = \frac{\partial (E_W + E_H + E_D)}{\partial V} = 0.0 \quad \ldots\ldots(1.3)$$

The applied field and domain wall energy (E_H and E_W) effectively try to reduce the volume while the magneto-static energy E_D tries to increase the surface area. Fig. 3 shows a typical plot of the variation of each of the energy components with increasing domain radius for a fixed applied magnetic field. For this applied field, the bubble will assume the radius where the total energy is minimum. Note that as the applied field is varied the energy minima will move resulting in the bubble taking up a new radius. The bubble collapses when the second derivative of the total energy $\frac{\partial^2 E_T}{\partial V^2}$ is greater than zero i.e. the solution of equation 1.3 is no longer a minima but a maxima.

As the total energy of the domain is a function of the external magnetic field and the material parameters σ_W, M_B, h, any changes in these parameters will result in a different solution of the energy equations. Consider the effects of such incremental changes on the dynamics of a bubble. The translational force F acting on a bubble experiencing gradient changes in these parameters is given by(13)

$$F = -\text{grad}\ (E_T) = -\nabla E_T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.4)$$

If the device parameters H_a, σ_w and M_B are considered independent variables, then equation 1.4 resolves into

$$F = -\left\{ \frac{\partial E_T}{\partial h} \right\}_{H_a,\, M_B,\, \sigma_w} \nabla h \; - \left\{ \frac{\partial E_T}{\partial H_a} \right\}_{h,\, M_B,\, \sigma_w} \nabla H_a$$

$$- \left\{ \frac{\partial E_T}{\partial M_B} \right\}_{h,\, H_a,\, \sigma_w} \nabla M_B \; - \left\{ \frac{\partial E_T}{\partial \sigma_w} \right\}_{h,\, H_a,\, M_B} \nabla \sigma_w \quad \ldots \quad (1.5)$$

For a device of thickness $4l_c$ and operating diameter $d = 8l_c$, the translation force equation reduces to

$$F = \frac{\pi d h M_B^2}{2u_o} \left\{ 0.238 \frac{\nabla h}{h} - 0.279 \frac{\nabla H_a}{H_a} + 0.772 \frac{\nabla M_B}{M_B} - 0.25 \frac{\nabla \sigma_w}{\sigma_w} \right\} \quad \ldots\ldots\ldots\ldots (1.6)$$

The above equation illustrates several methods that can be used to propagate the domain. It can be seen that gradient changes in any of the material parameters σ_w, M_B and h or the applied field H_a will cause motion of the bubble if the translation force can overcome the wall co-ercivity of the domain. In bubble devices, only gradient applied fields are used to propagate the domain although, recently, magnetization gradients have been used to limit the propagation path of the bubble(14) Note however that in gradient field access devices, it is imperative that gradient changes other than applied field are minimised by careful monitoring in the production of the magnetic film and of the operating temperature of the bubble device.

The velocity V_d of a bubble of optimum diameter $8l_c$ experiencing a gradient applied field H_a is given by[13].

$$V_d = \frac{u_w M_B}{2u_o} \left\{ 0.279 \left| \frac{\nabla H_a}{H_a} \right| - \frac{8H_{wc} u_o}{\pi M_B} \right\} \quad \text{......(1.7)}$$

where u_w is the wall mobility and H_{wc} the wall motion coercivity.

A condition for motion of a domain is that the term inside the bracket is greater than zero i.e. the translational force must be of sufficient magnitude to overcome the wall co-ercivity. Note that if the field gradients are not uniform with bubble position, then its velocity of motion will be non-linear. A similar set of equations may be derived for the stripe or elliptical domains that exist in the region near the elliptical instability field H_e. The velocity of the tip (in the direction of expansion) of such an elliptical domain has been calculated by Copeland[15] to be

$$V_d = u_w \left\{ 0.5 \left(H_{as} - H_s \right) - \frac{8H_{wc}}{\pi} \right\} \quad \text{.........(1.8)}$$

where H_{as} is the sum of the applied field H_a and the other local fields from the propagating elements, and H_s is the stripe to domain contraction field mentioned in the previous section.

4. DOMAIN PROPAGATION

It has been shown that a domain will experience a force in the presence of a gradient field. Various techniques to set up these gradient fields have been investigated[4]. Fig. 4a illustrates the conductor access scheme, one of the first methods used to propagate the domain. The current flowing through the conductor produces a highly localised field region. Each loop is energised in turn to propagate the bubble, the condition of motion being that the field gradients produced by this selective energisation are strong enough to overcome the wall co-ercivity. The main advantages of this method are that

a. Only a single d-c magnetic field is required.

b. A memory chip can be very simply organised into a number of shift registers each of which can be activated only when needed.

c. Very fast data rates are possible as the velocity of the domain is a direct function of the magnitude of conductor current.

Several techniques based on the modification of the conductor access scheme have been successfully demonstrated[16, 17]. However due to the complexity and large number of inter-connections required during the fabrication of the overlay, this method is not widely used.

Conductor propagation circuit

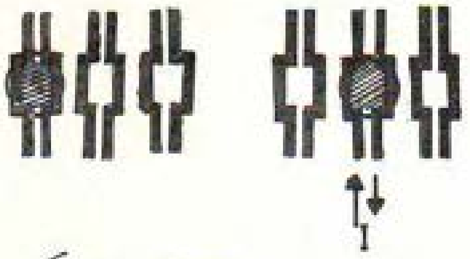


FIG: 4-a

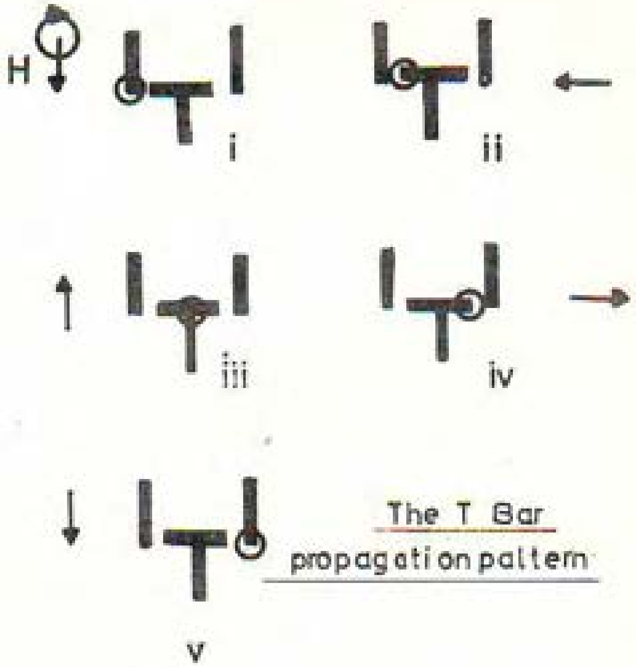


FIG: 4-b

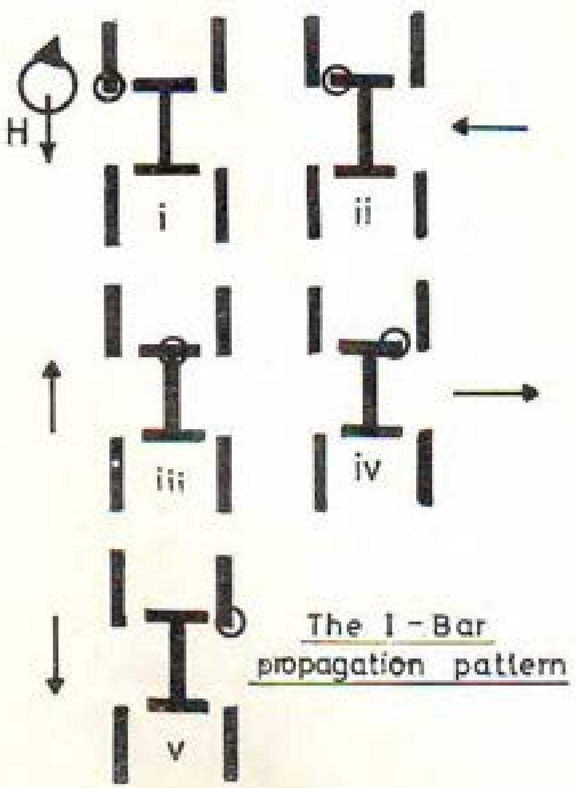


FIG.: 4-d

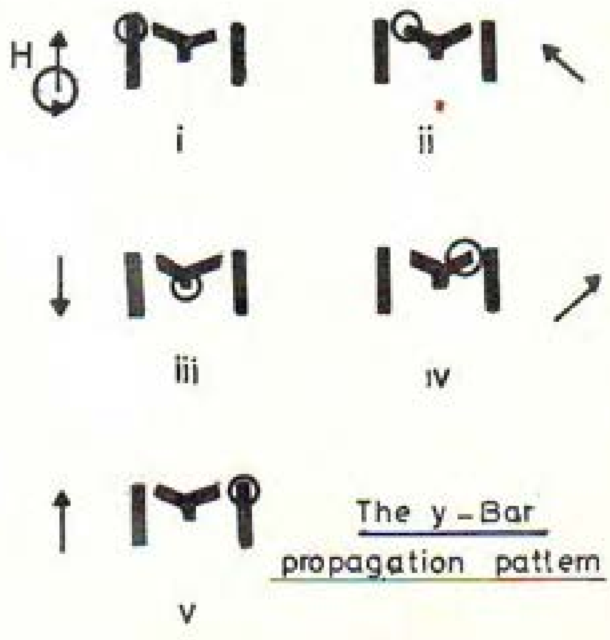


FIG: 4-C

Furthermore due to the use of large currents, these memories have rather high power per bit ratios.

Fig. 4b shows the T-Bar pattern, one of the most developed forms of propagation. The T-Bars shaded dark are fabricated out of thin soft ferro-magnetic alloys such as permalloy (Nickel Iron 83/17). These patterns are placed in close proximity to the surface of the film supporting the domains. To achieve propagation, a rotating field is applied in the plane of the film. Since the soft magnetic alloy can be easily magnetized, this rotating field creates distinct pole regions on the T-Bar elements every cycle. The operation of this structure can be easily demonstrated in terms of these induced pole positions(4). If the magnitude of the rotating fields is such that the demagnetizing fields in the short dimensions are strong enough to oppose the formation of poles, then strong pole regions will only be produced by the rotating field in the long dimensions. Since the domain is effectively a long cylindrical magnet it can be thought to be attracted towards dissimilar pole regions. As the in-plane field rotates, the motion of the bubble can be visualised as the domain follows the consecutive regions of dissimilar poles. In practice, the stray magnetic fields generated by these poles cause field gradients normal to the surface of the platelet. Hence the bubble experiences a

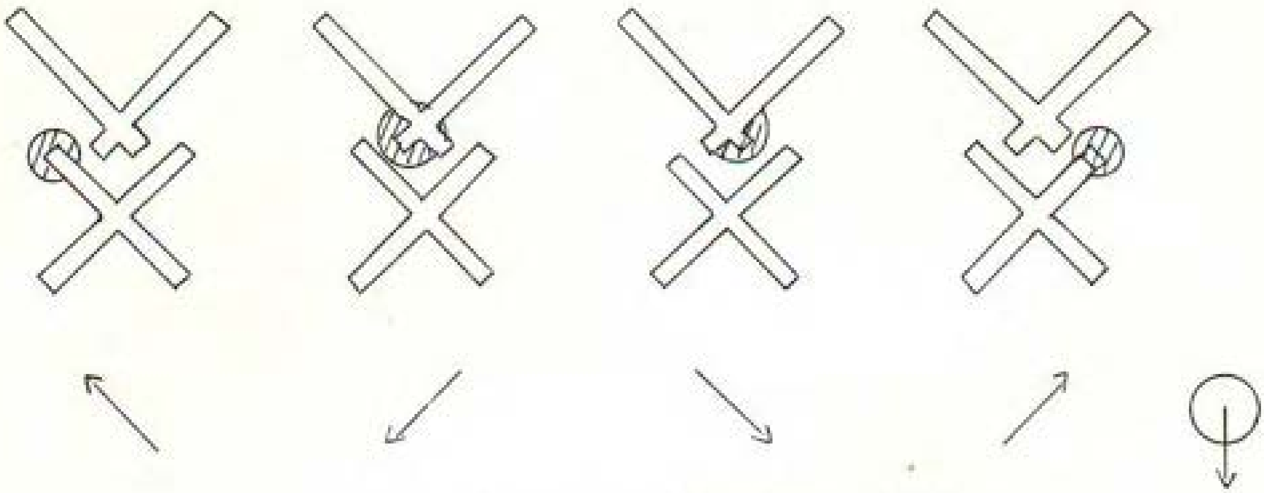


FIG: 5a

The X- Bar Propagation pattern

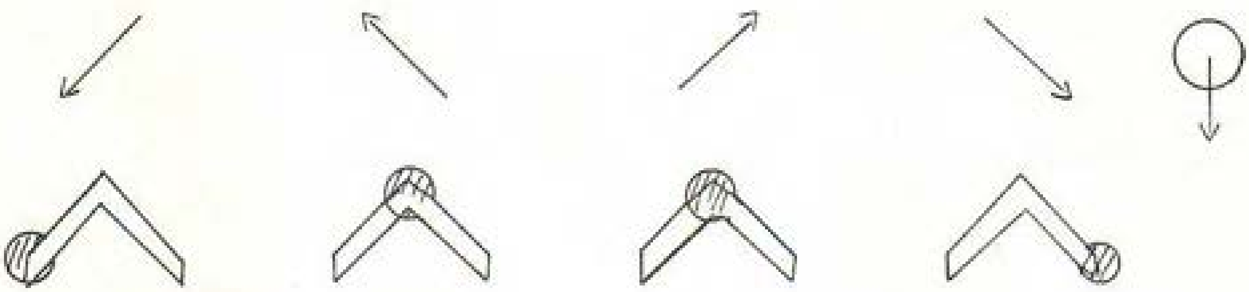
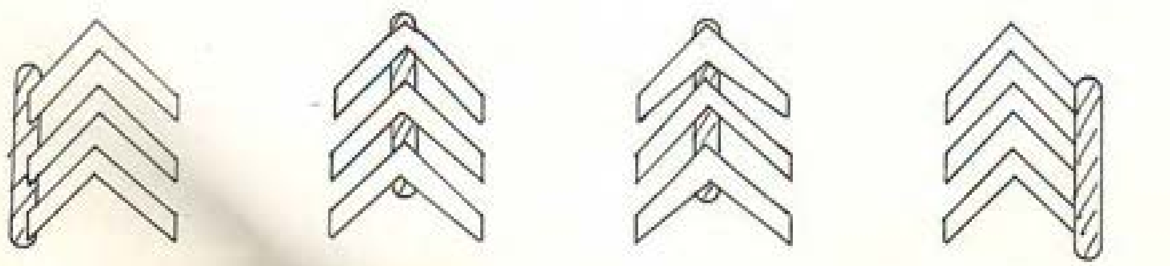


FIG: 5b

The Chevron Propagation pattern



The Modified Chevron Propagation Pattern

FIG: 5c

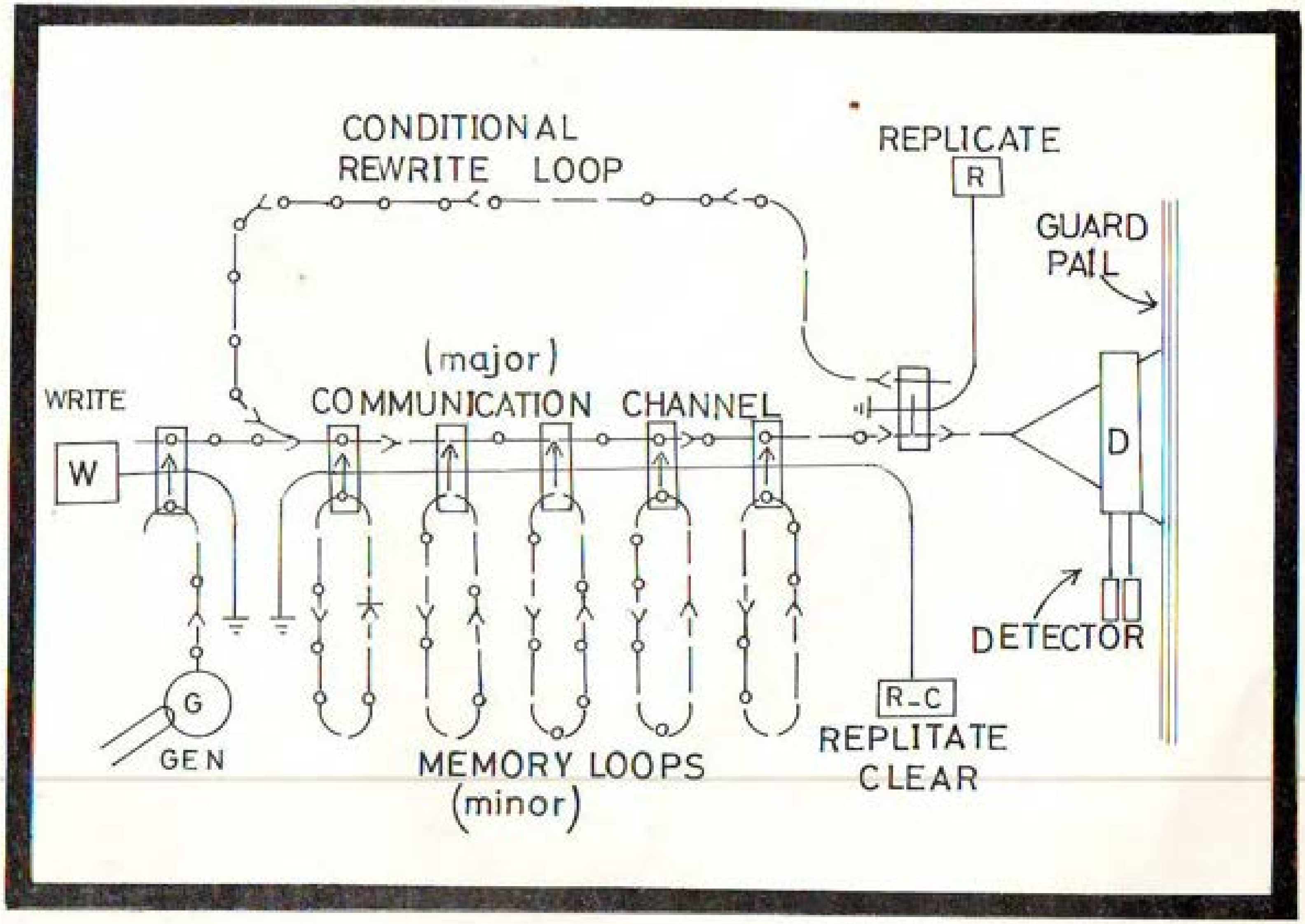
translational force and propagates towards the localised pole region in an effort to minimise its energy. Note that as the propagation of the bubble is synchronous with the external rotating field it is relatively easy to form large shift registers using such propagating structures.

Several modifications of the T-Bar circuit have been investigated with a view to improving the operating margins. Fig. 4c shows the Y-Bar circuit which has been suggested[18] as a more suitable interface as it offers a more stable position at the centre of the Y than the equivalent position on the Tee elements. Fig. 4d shows the I-Bar circuit. Here the apex of the Tee's of two consecutive propagations have been joined in an effort to increase the packing density and create a more distinct pole region at the centre of the I element. Fig. 5a shows a recently developed propagating structure[19], the X-Bar which not only has improved operating margins but can achieve faster propagation speeds. Propagation speeds in excess of 600 k bits per second have been demonstrated with this configuration.

Fig. 5b illustrates the chevron propagating structure which has been considered the successor to all other previous ferromagnetic propagate structures. The success of this element as a basis for propagation is largely due to the ease with which it is possible to pack several of these structures together (Fig. 5c). It is found that these packed structures can under certain conditions cause a cylindrical domain to assume an elliptical shape. If however the energy equations of the elliptical bubble are not satisfied, then the domain can also propagate as a cylindrical domain. The main advantage this circuit offers over the conventional circuits, is its inherent ability to propagate a domain around a small defect in either the material supporting bubbles or the propagate elements. In the T-Bar etc. circuits, a defect will result in a terminal failure in the ability of the bubble to propagate. However for the chevrons, it is possible to propagate past the defect as each element of a chevron stack is capable of propagating the domain. Hence if a defect occurs under one chevron, the other one or more chevrons should in theory aid the bubble past the defect. Note however that the packing density of chevron structures utilising this property is lower than the equivalent T-Bar structures.

Recent advance in fabrication of overlays and the production of garnets has led to an increasing use of the T-Bar element as the basis of a memory. Most bubble circuits use either the T-Bar or I-Bar as the shift register element and extend to chevron and other structures for complex operations such as generation replication, transfer and detection. In the devices being fabricated, a length to width ratio of 5:1 is used for the T-Bar elements, the width is normally made half the optimum bubble diameter. The chevrons have a length to width ratio of 6:1 with the angle subtended being 90°. As no comprehensive theory on the design of propagating elements has as yet energed, the structure of overlay elements is normally evaluated on a trial and error basis. In this paper, all further reference to the overlay structures will refer to the use of either of these structures fabricated out of Permalloy. Note that it is usual to use both types of basic elements in the design of a storage system. No difficulties in interfacing one structure to the other are encountered as both elements function on the same principle.

Since these domains follow a defined track in synchronism with an external rotating field, the presence or absence of the bubble at a fixed location on the propagating path can be considered as a basis of storage. As it is also relatively easy to move the bubble from one storage location to an adjacent location, bubble memories, unlike most other solid state memories, are normally organised into shift registers i.e. each set of T-Bar elements on the track is considered to represent a storage location. It is normal to represent each location of memory



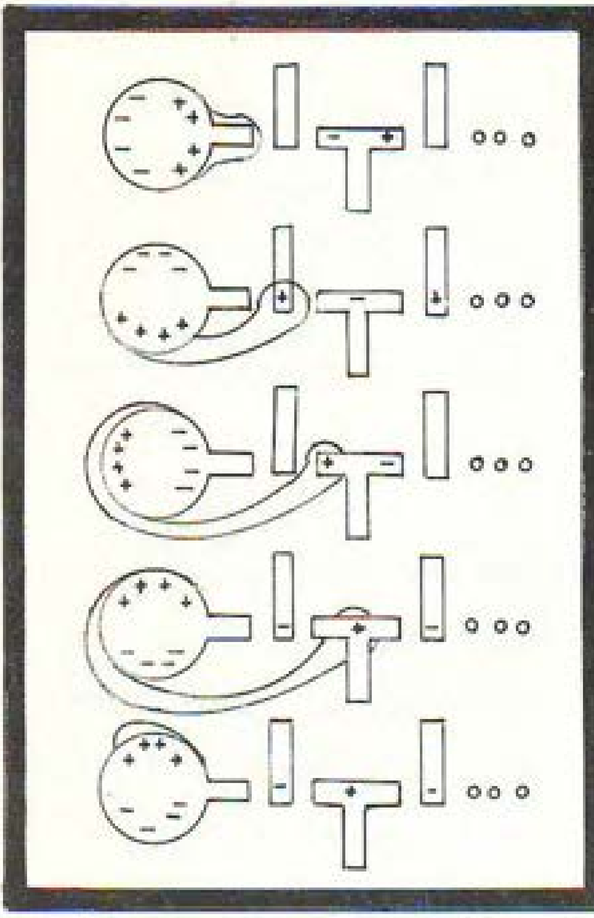
Organaisation of a bubble mass memory

Fig.: 6.

by one period of the propagating path, although in theory it is possible to pack more bubbles per period. The limit on this packing density is 3 x operating diameter. At this distance the bubble - bubble interaction leads to failure in propagation.

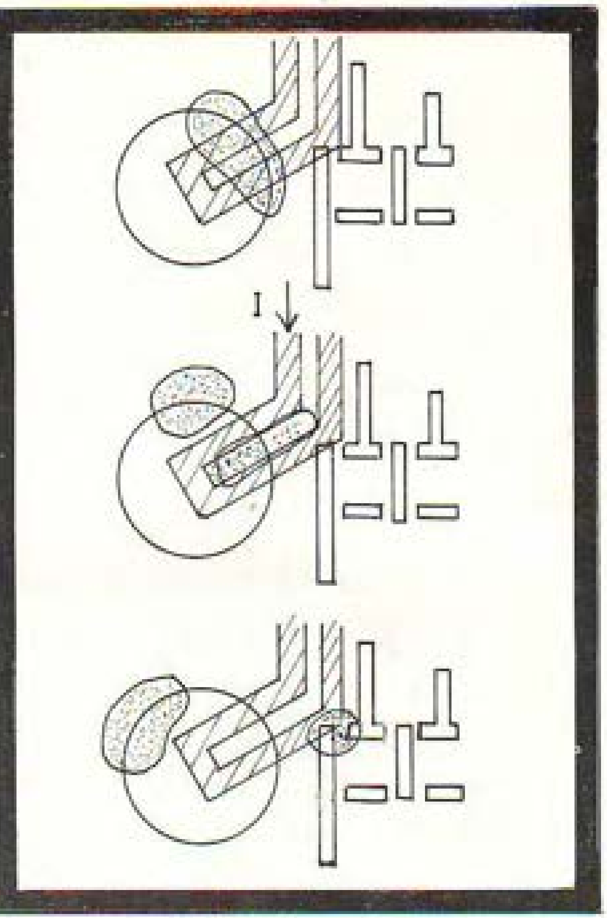
5. THE ORGANISATION AND DESIGN OF A SIMPLE BUBBLE MEMORY

The basic for any mass-memory organisation must, by fabrication and access time consideration, be endless loop shift registers. Such propagating paths feed back on themselves thus retaining all information that has been written into the loop. Registers with 10K bit locations have been successfully implemented[20]. An inter-connection of these endless loop shift registers provide the frame-work for mass memory on a single chip of garnet. Fig. 6 illustrates the organisation of a typical memory[21]. Data stored in what are called minor memory loops, can be selectively replicated or transferred into the single major loop. Data in the major loop can be read out using a bubble detector and then discarded. By selective replication before detection, the data can be either duplicated or altered before being returned into the minor loop. To write information, the selected word is cleared in the minor loops and new information, generated by the controlled generator, is transferred into the major loop. This new data is then transferred into the minor loop at the appropriate location. It is usual to store a bit of a word in each minor loop, i.e. a kilo word n bit word memory will be implemented as a minor loops each storing 1k bit of information. Hence to access a word, the replicate-transfer gates on all minor loops are energised at the same time to access the word. This process, of course, results in serial readout of the information. A similar but opposite process is used to write a word. Note that by selective energisation of the replicate function between minor and major loops, it is possible to re-write only selected bits of any word. However to avoid difficulties in fabrication and layout, it is usual to replicate and transfer all minor loop information into the major loop at the same time. The organisation of the bubble memory along these lines results in a minimum number of complicated functions such as detection generation etc. This is desirable since the failure rate of this part of a memory is expected to be higher than that of the basic propagating element[22]. Error rates of 1 per 8×10^7 operations have been reported for a major-minor loop configuration using Y-bars as basic elements[23].



The continuous stream bubble generator

FIG.:7a



The conductor stretch cut generator

FIG.:7b

The domain nucleate generator

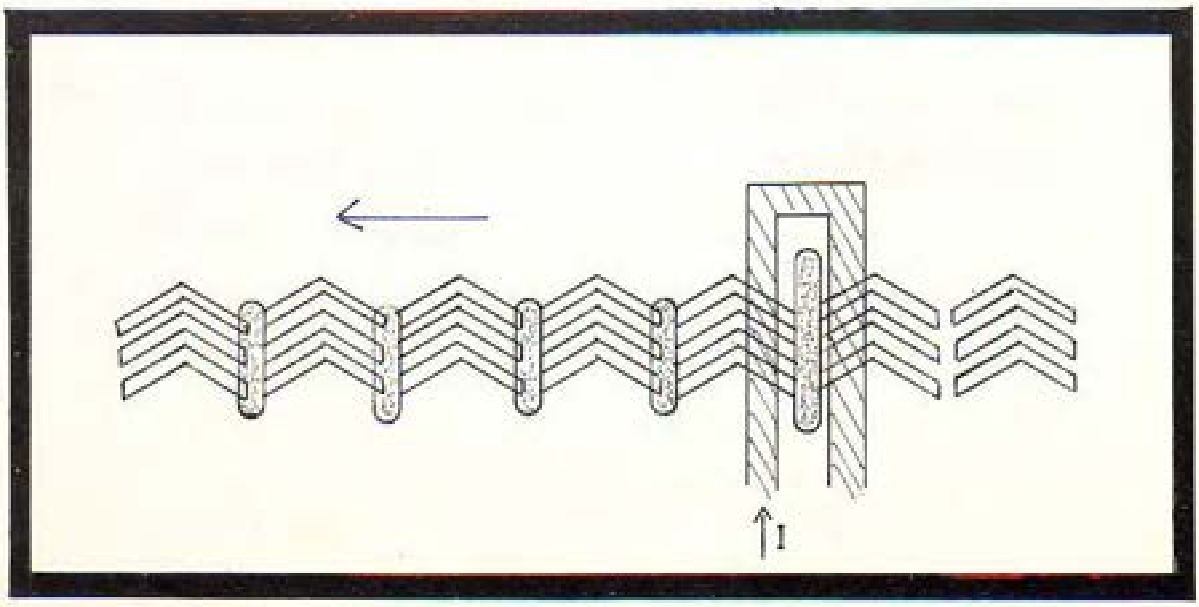


FIG.:7C

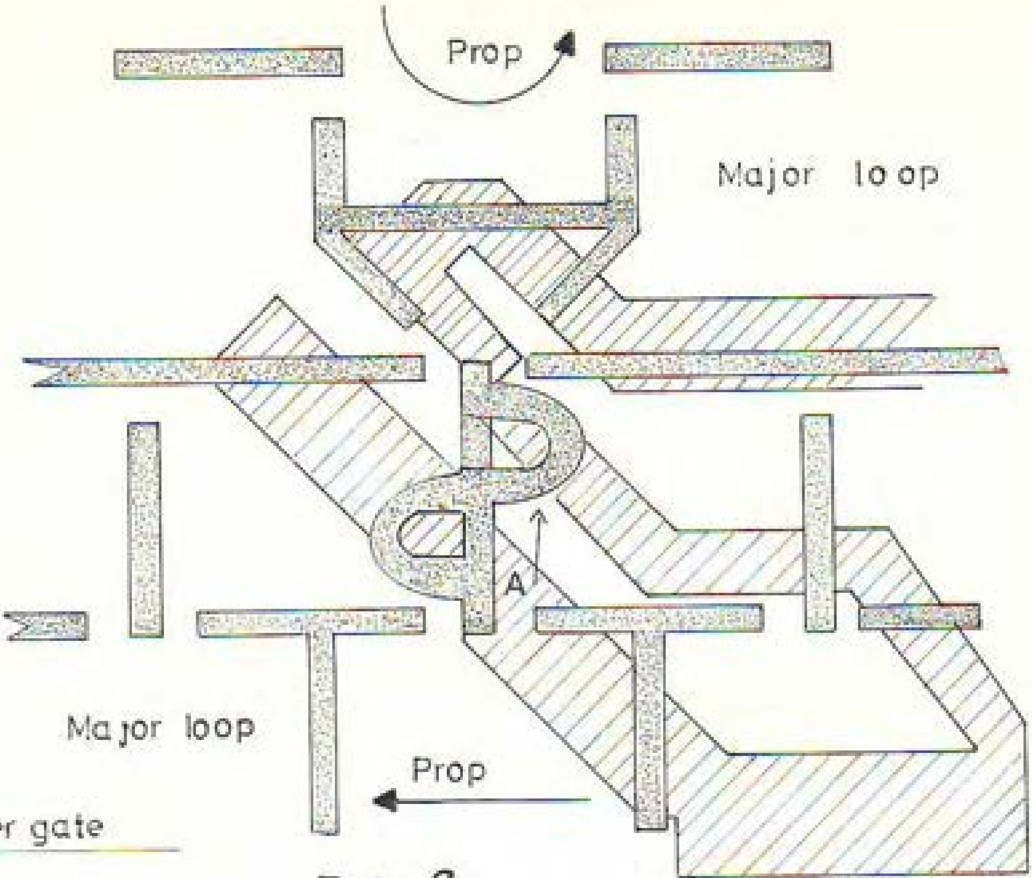
6. THE GENERATION OF MAGNETIC DOMAINS :

In any mass-memory organisation involving bubbles, the function of generation is essential, since otherwise it would be impossible to input information. Three main types of generators have been designed by various workers[4,24,25] to satisfy this requirement.

a. The continuous stream generator (Fig. 7a) is, from the view of fabrication and power-requirements, extremely suitable for mass memory applications since it requires no current for its operation. A transfer gate is normally put in series with the propagating path of the generated bubble to selectively input the bubbles into the major loop. The bubbles not required are channelled into an annihilator, which collapses the bubbles. This generator functions by stretching the seed bubble underneath the disk with the use of a suitable arrangement of the Permalloy propagating structures. The poles formed by the rotated field then cut the elongated domain into two, leaving the seed bubble underneath the dish and a bubble in the propagate path. This generator, however, has extremely small operating margins. (The range of bias and rotating fields for which a particular function operates as desired will be referred to as the operating margin). Another major problem in the mass-production of memories using this generator would be the difficulties involved in generating a seed bubble underneath the disk.

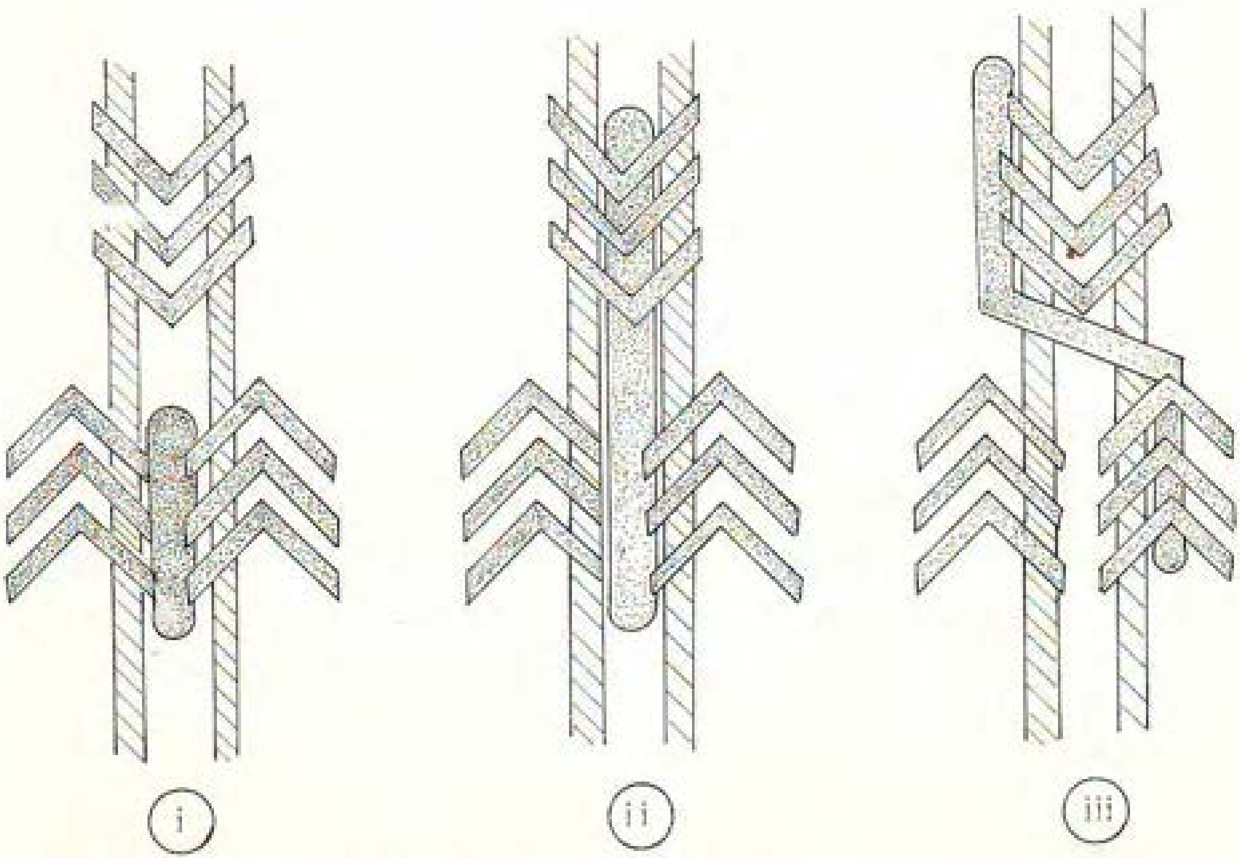
b. The stretch-cut generator (Fig. 7b) is basically a variation of the continuous stream generator in that it too splits a seed bubble that rotates under the disk. However unlike the latter, the bubble is expanded and severed by a conductor loop which is strobed at the correct phase within the rotating field cycle. For this generator to function in the designated manner, it is necessary to control not only the amplitude of the current pulse but also the exact relative phase and pulse width of the current pulse with respect to rotating field. This accuracy in the timing position is required because the bubble tends to lag the rotating field; the amount of lag being a complicated function of disk size and frequency of operation[26].

c. The nucleate generator (Fig. 7c) uses the highly localised field produced under a conductor loop to locally nucleate the film and hence generate bubble. To ensure satisfactory operation by this method, the magnetic fields produced by the conductor must overcome the nucleation field H_N. In most garnet films, this material parameter H_N is between 3 to 5 times the saturation magnetization M_B (M_B lies between 0.01 to 0.03 Tesla usually). Even though Nelson[27] has found that the magnitude of the magnetic field need only be a half of the nucleation field, it can be seen that these generators will require large currents to operate. The upper limit on the current density allowed in the conductor loop would be determined by thermal dissipation and the degree of electron migration in conductor material. To overcome these difficulties Bobeck[25] has used a laser to selectively anneal the area under the loop. This process reduces not only the nucleation and anisotropy field but the saturation magnetization of the annealed area. With lower nucleation fields it is hence possible to nucleate the film with currents of the same magnitude as that required by the stretch cut generator. Generation with currents in the range of 100 mA of duration between lus to 4us have been achieved by this selective anneal[25] Note that this generator does not require a seed bubble like the other two types. However it either uses larger currents or requires a laser anneal for satisfactory



The Transfer gate

FIG: 8a



The domain replicator

FIG: 8b

operation. The operating margins of both the cut-stretch and nucleate generators can be made larger than the operating margins of the simple propagate track.

7. THE TRANSFER GATE AND REPLICATOR

To move information into and cut of minor and major loops it is necessary to switch the propagation of the bubble from one stream to another. To achieve this aim, Smith[28] has designed the dollar transfer sign shown in Fig. 8a. The layout of the permalloy dollar sign and associated conductors is such that the magnetic field of the current is only used to modify the stray fields of the overlay that propagate the bubble. This design hence results in extremely small transfer currents (35 mA). Depending on the relative position of the current pulse in the rotating field cycle, the bubble can either be transferred into or out of the minor loop. Consider the transfer of a bubble from the major loop into the minor loop. When the bubble is at position A in the major loop, the conductor is pulsed. The magnetic fields produced by this current not only aid the bubble towards the minor loop but also magnetize the dollar sign in such a manner as to attract the bubble towards E. The current pulse is terminated and the bubble moves into the minor loop from there on without any help from the conductor. The transfer out of the minor loop is performed in a similar manner. Detailed analysis of the mode of operation of this function can be found elsewhere.[28].

Although it is possible to organise a memory using the dollar sign transfer gates, one of the main problems with this structure is the need to re-write the information back into the minor loop, sometime after any access. It would hence be advantageous if the information in the minor or major loop could be replicated and transferred by the same process. This would ensure the retention of all data by the minor loops and decrease access times for the memory. Fig. 8b illustrates a design of a conductor based replicator. The half-period shift between the two propagating streams ensures that magnetic poles in each channel are aligned parallel when the current is applied. When the loop is energised, the localised field region is sufficient to strip out the bubble. A second pulse of opposite polarity is applied at a later stage in the cycle to sever the elongated domain into two bubbles. Typical values for the stretch pulse and cut pulse are 100 mA, 3us and 125 mA, 1us respectively. The operating margins of this replicator are approximately the same as those of the propagate elements. Note that if only replication could be performed on the data, it would be impossible to delete any information in the minor loop. It is hence necessary to annihilate bubbles in minor loops. The replicator design can be used also as an annihilator, the only difference in operation being that the second pulse is applied immediately after stretching the domain. This effectively collapses the elongated domain destroying the information.

8. THE DETECTION OF MAGNETIC DOMAINS

Although detection of the magnetic domain can be accomplished by the Hall Effect, the magneto-optical Faraday Effect or the planar Hall Effect, the most developed form of detection uses the so called magnetoresistive effect. It is found that under certain conditions, the soft ferromagnetic films used for propagation of the domain also changes resistances in the order of 2% in the presence of very small fields. As the bubbles pass the sensor, the radial magnetic fields of the domain magnetizes the detector causing a resistance change. Hence, the domains presence may be sensed simply by monitoring the resistance of a thin Permalloy strip placed close to the propagation path of the film. If a constant current I was used to drive the sensor, an output signal V_o would be obtained such that

$$V_o = I \Delta R \qquad (1.9)$$

Note that this signal is superimposed on a d.c level (V_{dc} = IR). Fig. 9 shows the development of the magneto-resistive sensor as the bubble size was reduced. Fig. 9a illustrates the earliest detecting scheme designed so as to minimise the effects of the detection process on the bubble. The sensor fabricated out of permalloy was made very thin (30 nm) in order to minimise interaction with the domain and to reduce the demagnetizing fields which increase proportionally with thickness. The size and position of this type of detector were of critical importance due to the shape dependence of the demognetizing fields and the non-uniform nature of the bubble's radials fields. Patel (29) optimising the sensor properties on a theoretical model, suggested that sensors to detect domains of diameter 2R should be of length 6R, with length to width ratios of 5 and thickness 300 nm for optimum performance. Furthermore they should be positioned about 1.2R away from the propagation path. 2.3 mV signals have been obtained in detecting orthoferrite domains with 7mA input current[30].

With the increase in packing density by the use of garnet films, this design was discarded as the signal length decreased proportionally with reduction in domain size. To overcome this loss, the so-called Chinese letter detector configuration was implemented[31]. The sensor was still

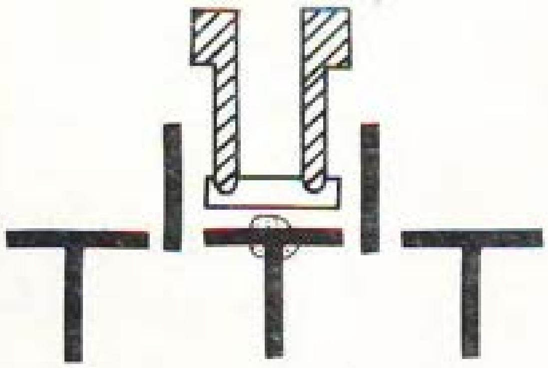


FIG: 9

The conventional magneto-resistive detector

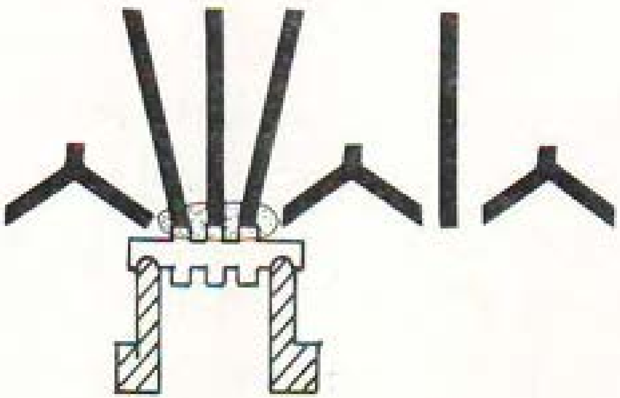


FIG.: 9a

The Chinese letter detector

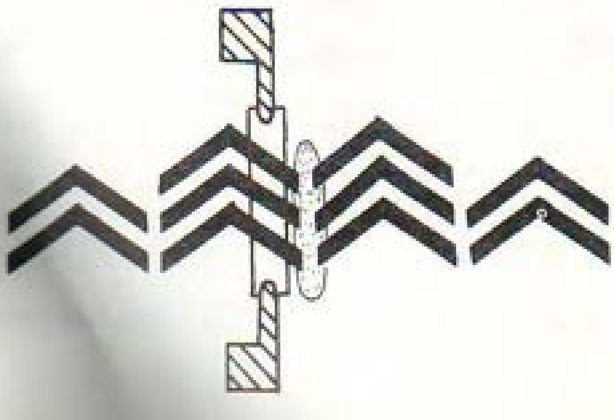


FIG.: 9b

The thin film chevron stretch detector

made as thin as possible but the overlay propagating path was modified so as to stretch the domain in the direction of propagation (Fig. 9b). The domain was normally stretched to about 3 to 4 times the operating diameter for detection. The length of the magneto-resistor could hence be increased as the radial fields of an elliptical bubble are distributed along the total boundary of the domain wall. This type of detector has been successfully used to detect domains as small as 4um at speeds in excess of 100kHz[32]. 1.5mV signals were obtained for 3mA input currents. The divergence of the detector itself from the rectangular shape of Fig. 14a is the result of an effort to reduce the demagnetizing fields that oppose the magnetization of the detector by the radial fields.

Although the Chinese letter detector has been successfully utilised at bit rates in excess of 100kHz, the inclusion of the bubble stretcher in the propagation path will lead to a reduction in the maximum obtainable device data rates. Since the bubble is expanded in the direction of propagation, the tip of the elliptical domain will have to travel at least four times the normal distance between bits in the same time interval. Its velocity must hence increase to about four times its averaged value. Since the limit on the bubble velocity is dependent on the mobility of the domain, the device can only be operated at a fraction of the maximum obtainable data rate. Furthermore due to the complex nature of the elongating process, the operating margins of the domain stretcher are sensitive to variations in bias and rotating fields.

The Chinese letter detection scheme established that it was possible to amplify the output signal by suitable expansion of the domain. The basic disadvantage of the Chinese letter detector, that of low device rate, can be overcome if the bubble is stretched orthagonal to the direction of propagation. This would ensure that the velocity of the domain in the direction of propagation is not altered when it passed the detect position. The chevron structure is ideally suited to this form of expansion since the domain can be gradually expanded over consecutive periods to the required size. Fig. 9c illustrates the principles of the chevron stretch detector first suggested by Archer[33]. The bubble from the propagating path enters the network and is gradually expanded into vertical strip domains propagating in a similar manner to a cylindrical bubble. At the point of maximum expansion, sensing occurs after which the vertical strip is gradually reduced to its original state. The amount of expansion is limited only by the area available on the chip. Bobeck[25] has used this technique to expand a 6um domain into 2400um vertical strip, an expansion of about 400 times the bubble diameter. Signals of 45mV were obtained for 6mA current.

As the bubble size is reduced some means of expansion will have to be used to amplify the size of the domain. The chevron stretch detector offers the greatest advantages since it is possible to expand the domain to any required size without drastic reductions in operating margins and data rates.

9. CONCLUSIONS

In the last few years magnetic bubble technology has developed at a rapid pace. Much of this progress was originally directed towards perfecting materials with low defect densities and high domain mobilities in order to ensure low costs and fast data rates. However, with the availability of materials with extremely low defect densities and high mobility, much of the recent effort has been orientated towards the design of the magnetic overlay that is required to move the domain. The storage medium nowadays is usually a rare-earth crystalline garnet of composition $R_3Fe_5O_{12}$ where R is one or more of the rare-earth elements. The composition of this material determines the data packing density, bit rates and the operating temperature range[5].

As bubble diameters in these materials usually range from about 1.5um to 2.0um, packing densities in excess of 10^6 bits per square inch can be easily achieved. (The separation distance between two adjacent storage locations is limited by the bubble to bubble interaction that occurs with distances less than 3 x domain diameter). Typical domain diameters in use today range between 4um and 10um, emphasis being placed on reducing the domain size with the development of this technology.

The mode of operation of a large bubble memory is based on the magnetic overlay deposited onto the garnet film and fabricated such that it provides rows or loops of storage locations for the domain. Upon the application of a rotating magnetic field under certain conditions, every domain on the chip will move one step in the location pattern for each revolution of the magnetic field. The bubble memory can hence be thought of as a miniature disc in which the stored data itself is moved instead of the material supporting the information. Domain generators are used to provide the write operation that maintains a supply of domains under these locations while a readout transducer also deposited on the film is used to sense the train of bubbles moving past the detector. It has further been shown that these domains can be transferred from one track to another on the same chip by a simple yet powerful technique. This ability to perform logic has resulted in better access times and higher reliability for large capacity memories. Domain memories are hence expected to be organised into endless circular propagation tracks from which data is selectively transferred in or out as required[6]. Besides the advantage of high packing density (10^6 bits/sq. inch) low cost (0.005 p/bit), and fast data rates (100kHz to 300 kHz), bubble memories have several other advantages over their electro-mechanical counterparts, the drum and disc. Due to the absence of mechanical moving parts, reliability of bubble memories is expected to be as high as that encountered in solid state semiconductor storage. Furthermore the energy requirements of an operational bubble memory will be exceptionally low. For example a bubble store would require 40mW to perform 10^{12} operations as compared to 10 watts required by an equivalent semiconductor store. Since these domains can be established by the magnetic field of a permanent field magnet any storage system of this form will also possess non-volatility. It has also been found that under certain conditions it is possible to perform other logical operations such as AND, NOR and ADD using bubble-bubble interaction[7]. Although these investigations are at a preliminary stage, the use of domain in this manner could lead to completely selforganised memory systems that will not only store but also operate on information in a predetermined manner. These extraordinary abilities to perform logical operations plus the added advantages of low cost, high capacity, low power consumption and small size have led to bubble memories being commercially viable.

In order to further reduce costs and increase data rates it is necessary to decrease the operational domain size. Recent developments in magnetic bubble technology have been directed towards the design of the magnetic overlays that will be required for domain sizes below 4um. It is expected that domain sizes below 1um will ultimately be used to provide packing densisties in excess of 10^8 bits per square inch at data rates approaching 1 MHz.

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