MAGNETIC BUBBLE MEMORIES AND THEIR APPLICATIONS

by

W. Kinsner
University of Manitoba

Based on an address given at the 16th Annual Actuarial Research Conference, University of Manitoba. Points raised in the discussion which followed the original paper are included here.
1. **INTRODUCTION**

Magnetic bubbles are small magnetic domains residing in a thin magnetic film. The bubbles can be generated, moved from one location to another, detected, and destroyed selectively. If the presence or absence of such a domain at a specific location represents a binary 1 or 0, then the collection of domains provides the basis for a computer memory. The domains are used in this and other schemes as serial computer stores.

Since the domains are very small (approximately 10 micrometers, μm, and below 1 μm), the total bubble memory capacities may be very large (presently 1 to 16 million bits, Mbits, per chip). Even larger modules (100 Mbits) have been developed for specific applications, such as data recorders for satellites, where very high reliability and so called "graceful degradation" are mandatory. Such bubble data recorders replace the usual magnetic tape recorders which are slower, less reliable and more difficult to maintain because of their electromechanical moving parts. Since they have moving parts, tape recorders are known to fail. For example, this presentation was recorded on an analog tape for the purpose of helping the authors in the preparation of the written form. My tape playback unit cannot move the tape properly and I have to write this paper from memory. The failure of the tape unit could be called catastrophic; there is nothing graceful about it. If my talk had been recorded digitally on a solid-state bubble recorder, using a speech compression technique such as linear prediction coding done in real-time, then I could have reconstructed my presentation with much less effort and in a shorter
time. Even if a portion of the bubble recorder had failed, redundant bubble tracks could have provided the graceful degradation of the recorder's performance.

Magnetic Bubbles acquired their name from the circular shape and free movement that can be observed under an optical microscope with light polarizing and analyzing capabilities. Indeed, the visual observation of magnetic domains in magnetic crystals, so thin that visual light can pass with only little attenuation, has helped significantly in the initial research and development of magnetic bubbles. Although the bubbles are cylindrical with a circular cross-section, and not spherical, the name has been universally accepted.

The first significant paper by Kooy and Enz [1] described magnetic domains in magnetic crystalline films with unusual properties. Unlike any other domains in thick and thin magnetic materials, the domains in uniaxial magnetic films could be oriented perpendicularly to the surface of the films. This orientation results from a very strong uniaxial anisotropic magnetic field due to the crystalline structure of the magnetic material such as orthoferrite, garnet and amorphous material. If the crystal is either cut or grown, so that easy direction of magnetization is perpendicular to the surface of the film, then the uniaxial magnetic field forces the magnetic domain to orient its magnetization along the easy axis and, therefore, be perpendicular to the surface. The importance of such a configuration is that the domains are not only stable within a broad range of magnetic fields applied perpendicularly to the bubble material, but also can become very small and cylindrical. Magnetic domains in other non-uniaxial soft magnetic materials, such as permalloy, orient their magnetization
along the surface of a film and, therefore, are large and cannot exhibit the same stability.

The original study prompted many innovative ideas at the Bell Laboratories. In 1967, Bobeck [2] published a paper with the concept of utilizing the cylindrical domains (bubbles) as a digital storage medium. The full theory of such bubbles was given two years later by Thiele [3]. Major device developments continued through 1973 and beyond. The developments occurred not only at the Bell Laboratories but also at IBM, Texas Instruments, Rockwell International, Burroughs, Hewlett-Packard, Plessey, Fujitsu, Hitachi — to name a few. Some of the developments are described in several books [4-14] and perhaps more than a thousand papers.

The first commercial bubble device was announced by Texas Instruments less than a decade after Bobeck's suggestion of using the bubbles for computer storage. The device had a capacity of 92 Kbits, several times larger than the capacity of semiconductor devices at that time. This rapid development was indeed remarkable, considering the use of new magnetic materials unknown before 1970, the new precision fabrication and packaging techniques never attempted on an industrial scale, and the successful solution to many physical problems not anticipated by the original investigators. Considerable credit for the rapid development goes to the cumulative knowledge gathered from the 20 years of semiconductor technology development preceding the bubble era.

Bubble devices with capacities of 1 Mbit (binary million bits), 4 Mbits, and 16 Mbits, have been either introduced or announced. They are larger than the present semiconductor memories (16 Kbits of
static and 64 Kbits of dynamic random access memories, RAMs). Their size is expected to grow.

Not all is well with bubbles, however. Major companies, such as Texas Instruments, Rockwell International, Motorola, and National Semiconductors, have recently left the field without warning. Weekly newsmagazines tried to calm present users by pointing to economic times and financial difficulties of the companies. Why then have other companies like Intel, Canadian Mitel and others with no names, rushed to fill the gap or take the lead?

One of the reasons for the difficulty may be the incorrect use of completely new technology for old applications. For example, bubbles are being promoted as an ideal replacement for fixed or moving head hard disks or floppy disks. As it will be seen, this approach is fundamentally weak. The floppy disks are inexpensive and widely used. Nobody replaces them with magnetic bubbles which are expensive and irreplaceable at present.

Magnetic bubbles may be less expensive when their sales volume increases. This may occur if new applications of bubbles are formulated and implemented. It is, therefore, imperative that the digital and analog designers, as well as system architects, search for new applications of the new bubble technology. The problem is hardly new. Other new technologies, such as the charge coupled devices, CCDs, have either evolved or declined because of their misuse or missed use.

This paper first reviews the physical basis of the bubble phenomenon, followed by its utilization in bubble memories and logic.
2. THE BUBBLE BASICS

Magnetic bubbles are formed in uniaxial magnetic materials such as orthoferrites and garnets, whose easy magnetization direction is perpendicular to the plane of a layer formed either by cutting the orthoferrite into thin platelets or growing the garnet into thin film or sputtering a layer of an amorphous magnetic material.

Figure 1 illustrates the formation of the cylindrical domains in such films. Note that the "shaded" and "white" domains have their magnetization vectors perpendicular to the plane, but opposite in direction.

Under normal conditions (room temperature, no mechanical stress and no external magnetic field), the two domains are nearly equal in volume and form a random serpentine configuration (Fig. 1a) in order to minimize the total energy of the host material.

If a magnetic bias field $H_b$ is applied to the material along the z axis, then the "white" domains expand at the expense of the "shaded" domains. The process will continue until a critical value, $H_r$, of the bias field is reached, at which the serpentine domains disappear and some assume the cylindrical shape (Fig. 1b). The cylindrical shape is stable, except for the reduction in diameter, even if the bias field is increased. The bubble shrinks with the increase in $H_b$ until another critical value, $H_c$, is reached, at which the bubble collapses very rapidly.

Stable bubbles require a bias field which should be uniform over the entire area of the bubble film. The above process of bubble formation is presented here for illustrative purposes only. Practical
Fig. 1: The formation of bubbles: (a) Random serpentine stripe domain for low bias fields and (b) cylindrical circular bubble domains for higher bias fields.
bubble memories require bubble generation, propagation, detection, annihilation and other functions - all done in an orderly manner. Circuits used for these functions will be described next.

3. BASIC BUBBLE FUNCTIONS

In general, there are several different methods of bubble generation, propagation, detection, annihilation, and transfer gates. The methods have evolved over the last 15 years to match the development of new bubble materials, leading to smaller bubble diameters in quest for larger and faster memories. We shall review some of the methods.

3.1 Generation

Bubble domains can be generated by either bubble cutting [15] or nucleation [8]. In the first method, a seed bubble is subjected to a strong local magnetic field originating either from a magnetic material such as permalloy overlaid on the bubble material, or a current carrying conductor also positioned on the bubble material. The local field splits the seed bubble in two, one of which remains a seed and the other is propagated away from the generator.

Nucleation does not require a seed bubble. Instead, a strong local field reverses the magnetization of the bubble material and a new bubble is generated. The local field is again generated by an electric current or external magnetic field, or both. Other techniques have also been employed with lesser success.
3.2 Propagation

Propagation of magnetic bubbles is inherent in all present serial memories and is required in future random access memories (RAMs) or bubble logic devices. There are two major methods of propagation: the field access and current access. Both methods rely on the magnetic nature of a bubble acting as a small magnet. If the bubble is subjected to a local field, it is either attracted or repelled. These forces move the bubble from one place to another. Since there is no transfer of matter, but only a displacement of the bubble walls, which is formed by the rotation of spins from the +z direction to -z direction, the process is almost frictionless and consumes little power. In a certain region of the field gradient (force) responsible for the bubble motion, the velocity is proportional to the gradient. Above a certain peak velocity, the bubble slows down and may exhibit very complex behaviour [14].

Both methods may propagate bubbles in unison over the entire area of the bubble material. This is the key to the small number of pins on bubble modules. Unlike in semiconductor RAMs, bubble memories have a fairly small number of pins which are independent of the bit capacity.

The field access method uses a rotating field whose direction is perpendicular to the bias field. The rotating field induces magnetic poles in a pattern formed from a soft magnetic material overlaid on the bubble material. The moving poles can displace a bubble over a basic memory cell during each in-plane field rotation. Each memory cell is approximately four bubble diameters in size in order to avoid any appreciable bubble-bubble interaction. Each cell
can contain a single bubble whose motion is fully synchronized to the overall rotating field. Under normal conditions, all bubbles move as long as the rotating field is present. If the field is interrupted, all bubbles stop on a bit—a feature not available in disks or tapes, where a stop on a block is often difficult to achieve. The bubbles can also be restarted on a bit. The bubble motion may be symmetrical, depending on the in-plane field rotation direction.

Figure 2 shows typical propagation circuits using permalloy and ion-implanted patterns. The T-bar, Y-bar, chevron stack and half-disk, are all symmetrical and can propagate the bubbles either to the right or left. The asymmetric half-disk and asymmetric chevron cannot propagate bubbles in both directions. The contiguous disk is effectively unidirectional. These circuits are well described in any of the books [7-13] and [16], which describe a novel propagating circuit based on an alternating rather than rotating in-plane field. The result is a selective bubble propagation to facilitate logic functions. The evolution of bubble circuits from the T-bar to the continuous disk and others, was prompted by the need to handle smaller bubbles without the need for very high resolution circuit fabrication techniques, as well as to increase the stability of the propagating domains.

The second class of bubble propagators uses current access. Electric current flowing through conductors overlaid on the bubble material also causes local field gradients capable of moving the bubbles in a well defined manner. Some older techniques based on multi-wires, have been replaced by an aperture current sheet technique.
Fig. 2: Permalloy and ion-implanted patterns for field access propagation
These techniques have not found widespread applications for reasons discussed elsewhere [7-14].

3.3 Detection

Most of the serial bubble memories acting as shift registers, utilize a pair of detectors in order to minimize the number of pins. When a sequence of bubbles is passed under the detector, electric signals are generated which correspond to the bubble (bit) pattern of interest. The signals are generated by the stray magnetic field associated with each bubble, regardless of the detector construction. Again, there are two classes of detection techniques [17]: the passive and active detectors.

The passive detectors use the flux from a bubble and its change to induce a voltage in a loop or a piezoelectric-magnetostrictive element. The active detectors require external energy to activate the detectors. Various active detectors have been investigated, such as the optical, galvanomagnetic, and acoustic and magnetoresistive. The latter technique is used in practical devices. The acoustic detector is, however, suitable for sensing stationary bubbles.

Since the magnetic flux from a single bubble is relatively small, various detectors utilize a flux amplification method by stretching the bubble many times prior to detection. The larger flux generates a larger signal, thus increasing the signal-to-noise ratio. Such stretched bubbles are normally annihilated.
3.4 **Annihilation**

Bubbles can be destroyed by the following three bubble "eaters": hairpin conductor, permalloy disk and guardrail [8]. The circuits are designed so as to collapse any bubble that is propagated into its vicinity. Bubble annihilators simplify the design of bubble memories.

3.5 **Transfer**

This basic function is called for by the bubble memory organizations used in any practical devices. Since all these memories use multi-loop structures, it is necessary to transfer the bubbles from one loop to another. The transfer is usually achieved by a local magnetic field generated by an electric current, combined with a suitable permalloy element. The transfer may also be accomplished by a replicator which splits the bubble residing in a storage loop into two, one of which remains there and the other is propagated towards a detector and finally annihilated.

These fundamental operations of generation, propagation, detection, annihilation and transfer, are all used in bubble memories.

4. **Bubble Memory Organizations**

Most of the commercial bubble memories are serial. The simplest organization is the shift register, as shown in Fig. 3. There are two major problems with such a long shift register: a slow access time and a high susceptibility to fabrication and material failures. The latter problem arises whenever a single memory cell fails within
Fig. 3: Serial bubble memory organizations: (a) Long shift register; (b) Major-minor loop; (c) G-loop, and (d) Block replicate
the shift register. These problems can be minimized by subdividing the long shift register into smaller shift registers. The object of all improvements in bubble memories, is to reduce the access time and increase their reliability through redundancy inherent in their architectures.

4.1 The Major-Minor Loop Structure

This organization has many counterparts in other data communication systems, and constitutes the simplest multi-loop hierarchical structure. As shown in Fig. 3b, many shorter identical shift register loops provide the storage and a single loop serves as the assembly line for a block of bubbles to be either written into the minor storage loops or read from them.

A generator creates the void (0) - bubble (1) representation of a binary word. The bubble stream is moved into the position facing the minor loops and transferred into them in parallel, by using the transfer (swap, S) gates. The bits rotate within the minor loops. The position of each block (word) in the storage is known by counting the cycles of the rotating field responsible for the simultaneous movement of all bubbles. If the minor loop has N cells, the N cycles are required to move a bit around the loop.

A read operation requires that a specific block be positioned at the S gates and transferred into the major loop in parallel. The block is then moved along the loop and replicated. One copy is detected and destroyed, the other is moved back into the storage loops. If the block is no longer needed in the memory, the replicator changes its function and steers the block towards the annihilator. Note that
the effective length of the major loop must be the same as the length of a minor loop, in order to write the block just read back into the same location. This is a major limitation of this organization. Another is the inherent mismatch between bit densities on the major and minor loops. Since the density on the major loop is two times smaller than the full density on the minor loop, the data transfer rate is two times smaller (e.g. 50 kbs) than that implied by the frequency of the rotating field (100 kHz).

The major-minor loop organization does provide the graceful degradation by utilizing redundant loops. If one loop fails, another can be substituted. The organization has a bottleneck in throughput, however, due to the necessary read/restore (swap) operation and loop mismatch, this bottleneck has been removed by the block replicate organization, combined with interleaving.

4.2 The Block Replicate Structure

Figure 3c shows how the bottleneck can be eliminated by breaking the assembly loop and introducing another set of transfer gates. Although the mismatch is eliminated and the data rate may be increased, the swap still requires that upon power failure, the system must assure the return of all bubbles from the C-loop into minor loops.

The true block replicate, shown in Fig. 3d, has one assembly line for the write operation and another for the read operation. The block to be read is replicated, rather than removed from the minor loops. This eliminates complex power failure handling. Furthermore, the data transfer rates can be doubled by merging two streams of bubbles prior to passing them through the detector. One of the streams
contains all even bits and the other contains all odd bits. The latter
scheme is used in commercial devices.

4.3 Bubble Lattice

Bubbles may be propagated and manipulated by circuits other
than those described earlier. For example, the permalloy propagators
required cells with spacing of four bubble diameters. If the
propagator is eliminated completely, the bubbles can be brought closer
together, thus increasing the memory capacity. Such closely packed
bubbles, called bubble lattice, can either be moved simultaneously as a
large block, generated, detected and annihilated.

Since bubble memories based on this scheme have bubbles
everywhere, their information bits cannot be naturally quantized by
themselves using the previous void-bubble representation. The two
states must be coded in the bubble domain wall - a technique more
difficult than the generation of bubbles. Both representations are,
nevertheless, nonvolatile.

4.4 Non-Serial Memories

Research is being carried out on non-serial bubble memories.
The serial memory organizations have been considered natural for
magnetic bubbles, and established as electronic disks. Random access
bubble memories are less natural because of their physical properties
and the lack of appropriate technologies. For the bubble RAMs to
become viable, new solutions to generation, propagation, detection and
annihilation, must be found. This provided the motivation for the
search of new circuits, as reported in [15-17]. For example, one of
the prerequisites for bubble RAMs, is the ability to read stationary (non-moving) bubbles. All existing detection techniques require the bubble to move under a detector. The new acoustic detector [18] is capable of detecting not only moving but also stationary bubbles. This detector is used in a bubble RAM proposed in [19].

This new concept of a universal bubble memory cell [19], allows not only a regular binary storage but also a non-binary storage for multi-valued computers. Unlike any other semiconductor multi-level storage element, this cell produces the same signal-to-noise ratio for any level.

The above review concentrated on the organization of bubble modules only. Each module requires many electronic circuits to perform the rudimentary operations such as write, read, assemble bytes into blocks, keep track of current memory location, and rotating field generation. Such circuits have been implemented by bubble memory manufacturers in order to simplify the design of systems. Unfortunately, there is very little standardization of such VLSI (Very Large Scale Integration) circuits among the manufacturers at present.

5. BUBBLE LOGIC

Magnetic bubbles repel when they approach one another within four bubble diameters. This natural interaction can be used to perform all logic operations. A thorough critical review of bubble logic is given in [10, 11]. We shall only highlight some of the ideas that may lead to major developments in magnetic bubbles. For example, logic functions may be implemented directly in memory, thus eliminating the
necessary read-write operation sequences [20]. This concept is not new and equally applies to any semiconductor device, such as a microprocessor with on-chip memory.

Magnetic bubbles can, however, provide a means to an entirely new approach to computing integration. The von Neumann computer architecture relies on the processing unit and a separate memory linked through a data/instruction bus. Non-von Neumann architectures also use separate processor–memory configurations. Magnetic bubbles may integrate the processor and memory into one unit, whereby the processor has the function of memory and the memory has the function of processor. This concept provided the motivation for work reported in [19] and is given here for the first time.

Other non-von Neumann architectures could include systolic arrays [21] and systolic queues [22]. The very nature of magnetic bubble propagation, forced by the global magnetic field, could provide the key to the bubble systolic array processing. Work is being done by an author on simpler structures of systolic bubble queues and stacks, which utilize both bubble–bubble interaction and the natural pipelining property. The natural pipelining means that at every bit-time a new set of inputs is accepted and a set of corresponding outputs emerges.

A detailed review of bubble logic architectures for data-stream steering, such as text editing and sorting, is presented in [11]. The use of bubble logic in information retrieval and associative memories is also covered there.
When magnetic bubbles first appeared in literature, microprocessors and microcomputers were not available. Although the obvious application of that new storage technology was to provide large memory for mainframes and minicomputers, the nature of magnetic bubble memory organizations induced developments towards replacing disks and tapes. The reason for such an approach can be found in Fig. 4 [25].

Figure 4 shows the price per bit of various storage devices, against the time required to access data stored in those devices. The chart is not very accurate, but is intended to illustrate the basic relationship between the devices. The semiconductor memories can be accessed in less than 1 μs because they are electronic. They cannot be used for very large archival memories, because of their cost and volatility (power is required to store data). Magnetic recording media can provide such large storage at a lower cost. The electromechanical, slow storage devices like disks and tapes, are very slow. It is seen that there is a gap between the semiconductor devices and electromechanical devices. Magnetic bubbles can bridge the gap.

The use of magnetic bubbles as replacement for disks and tapes has resulted in some problems. The price of semiconductor memories is being reduced, while their size is increased. Low power memories (CMOS) are becoming faster. In addition, major developments have occurred in the area of semiconductor read-mostly memories (RMM), such as the electrically erasable read-only memories (EEROM). The memories are nonvolatile and their capacity per chip is increasing. Therefore, the old gap between the semiconductor and electromechanical
Fig. 4: Price/bit of storage devices vs. access time
memories is narrowing, and the original applications of bubble memories
are no longer attractive. New uses of bubble devices and new bubble
devices will have to be developed. Some of the developments are
described in the next section.

Bubble memories can be used, and are used, in microcomputers. They provide such systems with higher storage density than any other
type of serial memory, and reliability due to lack of moving parts. The memory is usually used as a file directory memory [26]. A designer
of such memories can now use tested boards with all the electronics
necessary to control the bubbles and communicate with the
microcomputer. The boards are, however, expensive and considerable
knowledge is required to make the bubbles operational in systems.

7. NEW APPLICATIONS

We emphasize that the success of magnetic bubbles may depend
on new applications, not attainable with any other technology. This
will not preclude their application in special areas, such as
terminals, word-processing systems, office and home electronics, tele-
communications, industrial process-control, instrumentation and
military applications.

An example of new applications is the use of existing bubble
modules in a new system architecture [25]. In order to improve the
mean time between failure (MTBF) of a mechanical floppy disk memory, a
bubble memory buffer (BMB) system can be designed to buffer data
transactions with a host computer. Such a BMB system has been
implemented and uses a design technique referred to as transparent
memory system inclusion to facilitate the incorporation of the buffering memory layer into an existing floppy disk-based computer system. A paging memory management technique is then used within the BMB system to reduce the usage of the disk memory, while maintaining a transportable copy of data on the diskette.

Other studies are being carried out to utilize bubble logic, in-memory counting and code translation procedures, and a new concept of very high-speed data acquisition systems [27].

8. SUMMARY

With current designs, serial bubble memories are intermediate in access time and cost per bit between random-access semiconductor memories and moving-head disks. If the frontiers of bubble technology move as anticipated, the density will become more comparable to large disks, while the access time will be considerably shorter, thus bridging the gap even closer.

Magnetic bubbles should be used, not only as replacement of disks and tapes, but in new applications requiring most of the characteristic features of magnetic domains. Research is being carried out in such areas as data acquisition, monitoring, control, pattern recognition, and signal processing, which can use the magnetic bubble in a novel way.

REFERENCES

1. C. Kooy and U. Enz, "Experimental and theoretical study of the
domain configuration in thin layers of $\text{BaFe}_{12}\text{O}_{19}$", Philips Research Reports, Vol. 15, 1960, pp.7-29.


