BUBBLE DOMAIN MEMORY MARKETS II:

A STRATEGIC ANALYSIS

1980-1985

VENTURE DEVELOPMENT CORPORATION

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ABOUT THE COMPANY

Venture Development Corporation was founded in 1971 by graduates of the Harvard Business School who previously had worked for many years as engineers and managers at leading electronic companies. It serves clients in four segments of the Electronics Industry: computers, components, instruments, and consumer electronics. The firm provides custom consulting services and publishes in-depth reports dealing with marketing strategy and technological trends of interest to the management of electronic companies.

VDC specializes in analyzing the strategic aspects of building businesses, marketing new products, and financing the growth of new enterprises. We welcome difficult tasks where no easily-obtainable data exists and where the research and pioneering can be done jointly, in close cooperation with our client's personnel.

All staff members are skilled in analyzing and forecasting the impact of new technology on the client's marketing, engineering, financial, and manufacturing plans. Each has had extensive "practical" technical management experience in his area of specialization.

Leading electronic companies the world over call on VDC for assistance in formulating their product and business strategies. We are proud of the reputation we have earned for providing our clients with practical, innovative, incisive, and thorough analytical research. Services we provide for clients include:

<u>STRATEGIC PLANNING</u>

- Formulating business plans at corporate, divisional, or departmental level
- Developing strategies for internal growth or growth by acquisition
- Conducting acquisition or divestiture searches
- Performing industry analyses
- Evaluating technological trends.

MARKETING

- Conducting in-depth market research
- Developing marketing strategies
- Recommending product and/or pricing policy
- Evaluating channels of distribution
- Conducting competitive analyses.

FINANCIAL SERVICES

- Formulating financial policies
- Developing pro forma cash flows, income statements, balance sheets, and budgets
- Raising debt or equity capital
- Selecting investment banking firms
- Valuation of securities of privately-held companies.

VDC's special strength is its ability to bring multidisciplinary capabilities in technology, economics, marketing, finance, engineering, and manufacturing to bear on a client's problems. In the changing competitive environment of the electronics industry, management decisions cut across boundaries of all these disciplines.

VDC is able to augment its client's capabilities with the resources, skills, and perspectives necessary to deal systematically with the interrelated problems of technological, market, economic, and social change. Most important -- we are staffed by professionals who are aware of evolving electronic technologies and have the ability to work with clients in developing imaginative and workable business policies and strategies.

The key to a successful consultant/client relationship is the availability and responsiveness of competent staff consultants. We welcome your inquiries and would be pleased to discuss our services with you.

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EXECUTIVE SUMMARY

- VDC believes that shipments of bubble memory devices by United States companies will grow from 138,000 units in 1980 to 1,446,000 units in 1985. The annual rate of increase will average 60 percent over this period.

- Shipments of bubble memories will increase in value from a 1980 level of $18.4 million to $226 million in 1985. The average yearly dollar market growth will amount to 68 percent.

- The precipitate price reductions in bubble memories, predicted by leading bubble memory manufacturers, did not occur. In 1977, VDC had questioned the industry leaders' predictions, finding them unrealistic for a radically new technology. VDC believes, in 1980, that the more modest but still impressive goal of 45 percent average cost-per-bit reductions can be attained.

- We believe that shipments of ¼-megabit and smaller capacity chips will constitute 99 percent of the units shipped in 1980, and 92 percent of the value, declining to 7 percent of the unit market and 3 percent of the value in 1985. The one-megabit chips which are now considered high capacity, but will be medium capacity in 1985, will make up 1 percent of unit shipments and 8 percent of dollars in 1980, and will increase to 71 percent of units and 69 percent of dollars in 1985. Large-capacity chips of between 2 and 4 megabits will be introduced in 1983, and by 1985, will have a 22 percent share of the unit shipments and 28 percent of the dollar value.

- We regard it as probable that patterned ion implantation techniques will be used before 1985, but not dual conductor access propagation, although the latter is potentially a very exciting discovery which could increase data rates to disk-competitive speeds and simplify bubble production.

- Numerical control (N/C) is an ideal application for bubble memories; already General Numerics is committed to bubble memories at the rate of 15,000 bubble packages per year. American N/C producers, including General Electric, will be utilizing bubbles in the near future. We believe that shipments of bubble memories for N/C, robotics, and other machine control applications will amount to $20 million in 1985. Process control is another excellent use for bubble memories; 1985 shipments will be $15 million.

- The bubble memory will never eliminate the floppy disk because the diskette is an ideal removable medium. Bubbles will, however, find important applications in such applications as word processing, where one of a pair of floppy disk drives could be replaced. In 1985, shipments of bubble memory devices for word processors will be valued at $37.5 million.

- Bubble memories can serve a similar function in small computer systems. We believe that by 1985 shipments for this application will total $37.5 million. The bubble is particularly attractive for desktop and portable computers for reasons of size, weight, and reliability.

- Military and aerospace markets have been seriously curtailed by the failure of bubble memories to meet military temperature specifications. Temperature ranges are being extended, but the bubble memories are not expected to meet full military specifications for semiconductors by 1985. Even with limited operating temperature ranges, we believe that the aerospace market for bubble memories will grow to $32 million in 1985.

- Shipments of bubble memories for telephone applications will total $30 million in 1985. Telephone Announcement Systems manufactured for AT&T by Western Electric utilizing serially configured bubble chips are working out well. Plans to use bubble memories for telephone switching applications have not been successful, and disk drives are being used instead. Other telephone applications for bubble memories are being worked on and include a call recorder used with PBX's.

- We believe that Texas Instruments, with 74 percent of the market, is the leading supplier of bubble memory devices to the open market.

- Our research indicates that users have become skeptical concerning the predictions made by bubble memory producers. Users do not want to devote the time and money required to test and incorporate bubble memories into their products if prices do not fall to reasonable levels, making their use economically viable.

- By offering ancillary circuits for its megabit bubble device which reduce component count by a factor of ten, Intel has made the bubble much easier for customers to use. To remain competitive, other bubble producers need to make similar advances in ancillary IC's.

- VDC does not believe that the computer industry can gain much by "IBM-watching." IBM's motivation to replace rotating memories in its systems may be lacking; independent companies, to whom maintenance is more a headache than a source of revenue, will take the lead in bubble equipment.

- One of the brightest spots in the bubble picture has been their performance in the field. Except for some temperature problems in exacting military applications, bubbles have met the high standards predicted for them; they have proven rugged, reliable, and error-free.

- Although the bubble memory industry has made substantial progress in the last three years, growth has been slower than many had hoped. Shipments are not as high as forecasters had projected because bubble prices, although below 1977 levels, are nowhere near the levels originally promised by the industry participants.

- Because their prices are still high in comparison to competing technologies, bubble memories are now used primarily in applications such as machine tool and process control, and in portable terminals where their special qualities of ruggedness and small size give them advantages which override their high cost. Hopes have faded that bubbles will be competitive with large-scale disk memories in the foreseeable future. Lattice file memories, which were thought the most promising method of attaining very high density chips at low cost, have not proven a successful subtechnology.

- Competing memory technologies are continuing to evolve. CCD's have faded as a threat, but the development of the sealed, fixed disk drive, known as the "Winchester," has solidified the position of the moving head disk as the preferred memory for large amounts of data at low cost per bit. Although the disk probably cannot equal the bubble in reliability and requires some maintenance, it will provide cost-per-bit ratios that will remain far superior to that of the bubble, at least through 1985.

II

INTRODUCTION

Bubble domain memory markets are still in their infancy, but when VDC published its original bubble domain memory industry study in 1977, the bubble memory business was embryonic. Bubble Domain Memories II was developed after many subscribers to the first study asked "When are you going to do another bubble report?"

Bubble memory technology is new, and radically different from previous memory technology. It involves movement of magnetic bubbles rather than material, as is the case with disks or tape. Bubble memories are not semiconductors, although similar techniques are used in their fabrication. Applying bubble memories in usable circuits requires new capabilities on the part of circuit designers.

The computer industry has long been seeking a device to fill the "memory gap" between high-speed, high-cost random access memories and low-cost mass storage. Industry participants' hopes that bubbles will provide the solution have alternated with fears that bubbles will suffer the fate of technologies such as plated wire and planar thin-film memories, which were highly touted in the past and subsequently faded into near-oblivion.

The purpose of this report is to bring hopes and fears in line with the realities of the present situation, and to plot the most probable future course of this technology.

In the three years since the publication of VDC's original bubble domain memory study, the industry has not moved as fast as many had hoped. Bubble memory is still a promising new technology, however, as this report will point out.

Tens of thousands of bubble domain memories have been produced to date, but most of them have been used in "captive" applications (for voice recorders in the Bell system and for Texas Instruments' own Silent 700 terminals). In the past three years, some production runs have been made, and bubble domain memories shipped to users in 1977 are still functioning. These facts attest to the bubble's viability as a commercial product.

On the other hand, sales volume is below that originally projected by VDC, and much smaller than the less conservative forecasts which were apparently based on the opinions expressed by spokesmen from Texas Instruments and Rockwell International, the first commercial suppliers. Prices are lower than they were in 1977, but nowhere near the level that had been promised by the suppliers at that time.

Research is still proceeding on bubble devices. Contiguous disk propagation techniques are a possibility for the future, as are current access devices which would eliminate field coils. Current access devices would improve transfer rate phenomenally, but the timetable for this development is uncertain. The lattice method of propagation seems stymied at present.

RAM costs continue to improve on one side of the memory gap, while "Winchester" disk drive technology is improving mass storage cost and performance on the other. Squeezed in between, the bubble memory is not "out of the woods" yet. The bubble has virtues of its own, including non-volatility, ruggedness, and reliability, but it must be sold at lower prices in order to become a prime factor in large-volume applications.

Intel has joined Texas Instruments and Rockwell International as a supplier of bubble domain memories for the commercial market in the U.S. Motorola and National Semiconductor are definitely committed to joining them. In Japan, Hitachi and Fujitsu are bubble producers, as are Siemens in Germany and Sagem in France. Western Electric is producing bubble domain memories for AT&T, while Bell Laboratories continues development of new bubble technologies. IBM has continued its sizable development program but has not announced a product with bubble memory. Several other companies are waiting to see "which way the bubble bounces" before committing themselves to bubble production.

III

METHODOLOGY AND SCOPE

In 1977, when we completed our first study on bubble domain memories, only a handful of users were in the development stage. VDC had to rely on information supplied by bubble domain memory manufacturers and scientists, and on potential users who understood the bubble's functions. For the present study, we used not only data and opinions of the industry participants who research and manufacture bubbles, but we also were able to obtain information from actual users of products incorporating bubble memories. Comparisons were made between the 1977 responses and predictions and the 1980 realities.

At a very early stage in the study, bubble memory industry participants were queried on what they considered to be the principal strategic issues which would be facing them in the coming years. Based on their responses, VDC constructed an interview guide designed to elicit responses dealing with these specific issues as well as such general issues as market size, growth, competition, and market shares.

Interviews were conducted by telephone and in person. Mail questionnaires were not used because in-depth interviews with very knowledgeable respondents were essential, and there is not yet a large number of users who would make good mail respondents.

Senior consultants with engineering or physics degrees performed the interviews because of the technological nature of the product and the necessity for projecting market growth on the basis of performance characteristics and attitudes of engineers at user companies.

In addition to interviews with manufacturers of bubble memories and competitive memories, and with memory users, VDC also made use of its extensive data base of published information on the computer and instrumentation industries and information gathered in previous VDC reports, including:

* The Hard Disk Industry: A Strategic Analysis
* Floppy Disk Markets
* The Small Business Computer Industry: A Strategic Analysis for Industry Participants
* Desktop Computer Markets
* CRT Graphics Terminals and Systems
* Alphanumeric CRT Terminals: A Strategic Analysis for Industry Participants
* Data Acquisition Systems
* Data Acquisition Subsystems
* Data Recording Industry II.

Emphasis was placed on assessing the viability of the bubble memory as a product and on determining the best strategies to satisfy the needs of prospective bubble memory customers based on their long-term requirements. Given the uncertainties surrounding any new technology, our market forecasts are based on our best assessment of what is most likely to occur in bubble technology and competitive memory technologies, and on our analysis of customer demand based on extensive interviews.

In the History section of this report, we trace the evolution of the bubble memory and look at parallel developments in other memory technologies.

In the Industry Structure section, we analyze the position of the magnetic bubble business in the hierarchy of the computer industry.

The Technology section presents bubble memory technology in a manner which can be understood by an operating executive without expertise in the field.

Trends in Technology discusses the expected changes in bubble memory prices and specifications.

The Market section analyzes present and future bubble memory markets in terms of total market and markets by application, size of memory, and bubble domain organization. Growth in bubble memory markets is dependent on technological and price improvements in bubble devices and competing technologies.

Marketing Strategy discusses the means by which bubble memory suppliers can best adapt to the requirements of users and compete in memory markets against other technologies and within the bubble arena.

Finally, The Competition describes the major producers of bubble memories and their market positions.

IV

HISTORY

EVOLUTION OF MEMORY DEVICES

The memory gap between random access memories and mass storage has existed since the introduction of the digital computer.

In the late 1940's two devices revolutionized random access storage techniques. The first device, the magnetic core, was invented in 1947. By the early 1950's it had replaced the electrostatic storage tube as the random access memory (RAM) of choice. The second device was the transistor, invented in 1948. In the early 1960's transistors replaced the vacuum tubes previously used for logic operations. Semiconductors, however, were not effective competitors to magnetic cores until the mid-1960's, when integrated circuit RAM's were developed.

On the other side of the memory gap, mass storage techniques were improving also. Early digital recordings were made on steel tape coated with iron oxide. This recording medium was replaced by polyester-backed tape in the early 1950's. Although tape has been greatly improved over the years, magnetic tape by its very nature will always be a serial data storage medium. Large amounts of data can be stored at low cost per bit, but access time remains slow.

Magnetic drums and disks are much faster than tape. The IBM 1311 disk pack was introduced in 1962, and the 2314 in 1964. The disk firmly occupied a portion of the memory gap by 1970.

In 1970 the floppy disk made its first appearance as a low-cost recording mechanism, in the diagnostic system of the IBM 370 Series computer. More expensive on a per-bit basis than hard disk drives, and slower in access time and data transfer, the floppy disk drive offered the advantages of lower cost per device and easily-removable media.

When the magnetic bubble domain memory first appeared, industry was still seeking a device which would be closer in speed to the core or semiconductor memory, and comparable in cost to the disk.

DISCOVERY OF BUBBLE TECHNOLOGY

The history of the bubble domain device is brief, but years of research into magnetism and magnetic material preceded its invention. Domains in ferromagnetic materials had been studied for more than 50 years. Bubble domains were observed in ferromagnetic garnets at Bell Telephone Laboratories in 1956. Experiments were performed in shifting domains in the late 1950's and early 1960's.

Andrew Bobeck and co-workers at Bell Labs applied for the first patent on a bubble device in 1967. Other companies were quick to see its possibilities. IBM, Texas Instruments, and Rockwell funded programs because magnetic bubbles offered a non-volatile storage medium with many of the same capabilities as tapes and disks, but without the wear and tear of mechanical motion and with the potential for small size and low cost. After Bell Labs' disclosure of bubble domain memory devices, sizable sums were spent on research in foreign countries as well as in the United States. In 1977 commercial devices were announced by Texas Instruments and Rockwell in the United States, and by Fujitsu in Japan.

Since then bubble memories have proven satisfactory as non-volatile, maintenance-free memory storage peripherals.

Prospective users of bubble memories have been disturbed by the failure of prices to fall as rapidly as bubble producers had forecast. In 1977, Texas Instruments executives informed their customers and the trade press that prices would fall from approximately 500 millicents per bit to between 20 and 25 millicents per bit in 1978 and 10 millicents per bit in 1980. This is about one-tenth the actual 1980 price for the Texas Instrument 92-kilobit chip and controller. Prices for large chips have been even more disappointing; instead of the anticipated reduced cost per bit, prices per bit for megabit chips have been higher than those of smaller bubble memories.

Research continues into ways to reduce costs, increase bubble density, and speed up transfer rates; IBM and Bell Labs continue to lead in bubble domain research.

PARALLEL DEVELOPMENTS OF MEMORY DEVICES

Charge-coupled devices (CCD's) have been linked together with bubble domain memories in news articles and in the minds of the readers. CCD technology was first announced three years after bubble domain memories, and it was also invented at Bell Labs. Faster than the bubble by a factor of 10, it was aimed at roughly the same portion of the memory gap. The most obvious disadvantage of the CCD is its volatility; data is lost when power is removed. On the other hand, CCD's are less complicated to use than magnetic bubbles, which require new techniques in manufacture and application.

Despite industry predictions that CCD's would come into widespread use before bubble memories, this has not been the case. VDC's predictions that CCD's would not prove adequate for mass storage have proven correct. CCD's could not be produced consistently with the high quality required for long-term mass storage.

Magnetic disk drive technology has continued to develop. In 1973, IBM introduced a disk drive in which the disk, head, and moving arms were contained in a sealed module. Known as "Winchesters," drives of this type increasingly dominate the mass memory market. Small drives of 8-inch and 5½-inch diameter are now available, reducing the minimum cost for a hard disk system. Although "Winchester" disk drives represent an improvement in reliability over previous drives, they are not maintenance-free; bubbles are. For large amounts of storage, gigabyte sealed fixed disk drives are now available which offer lower cost-per-bit ratios than bubbles seem likely ever to approach.

RAM's have been reduced in price to a point where bubbles must fight to be cost-competitive with them. Bubble memories have the advantage of non-volatility, but they are slower, have higher entry cost, and are more difficult to use.

Further discussion of the merits of competing memory technologies will be reserved for the Technology and Trends in Technology sections. For now, it is sufficient to point out that bubble memory history is still in the making, as the bubble memory attempts to establish its position before the memory gap closes.

V

INDUSTRY STRUCTURE

Although the bubble memory industry is young, relationships among material suppliers, manufacturers, and users have started to develop. It is now becoming possible to see what the mature industry structure will look like.

To place the bubble memory in proper perspective in the computer industry, we must look at the complete structure of the bubble memory industry, which is divided into five tiers: (See Figure 1.)

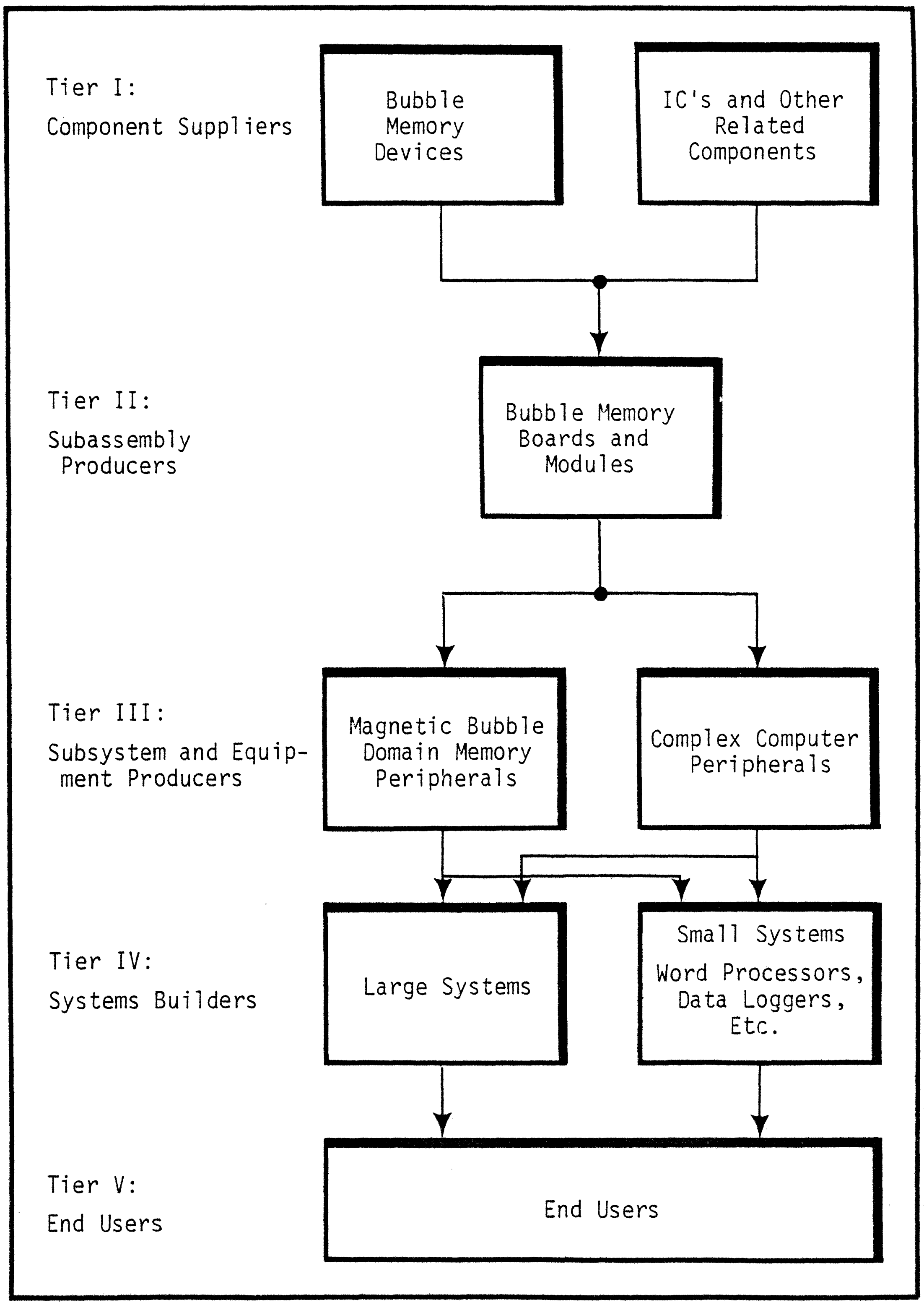
1. Component suppliers
2. Subassembly producers
3. Subsystem and equipment producers
4. Systems builders
5. End users.

COMPONENT SUPPLIERS

We classify the bubble domain memory device as a component. We define a component as the smallest piece of apparatus which is capable of performing a specific electrical or mechanical function. The simplest commercial bubble memory package is more complex than many other electronic components; it contains a bubble chip surrounded by coils of wire with bias magnets over the coils.

FIGURE 1

BUBBLE MEMORY INDUSTRY STRUCTURE



Materials used in bubble memory manufacture are relatively common and readily obtainable. Garnet used for bubble chips is available from Union Carbide and Allied Chemical, among others. Although more expensive than the materials used in semiconductor chips, it is readily available, as are the other materials, such as permalloy, magnets, wire, etc.

Bubble memories require ancillary circuits. (See Figure 2). Functional circuits such as bubble controllers, timing generators, coil drivers, function drivers, and sense amplifiers must be designed especially for bubble use. When ancillary circuits are produced in volume, these functions can be performed at lowest cost by integrated circuits. Most bubble manufacturers produce semiconductors as well. It is logical that they should build both the memory and its ancillary integrated circuits. Eventually, large users may design their own ancillary circuits, but in the next few years, they will have to be supplied by the bubble manufacturers.

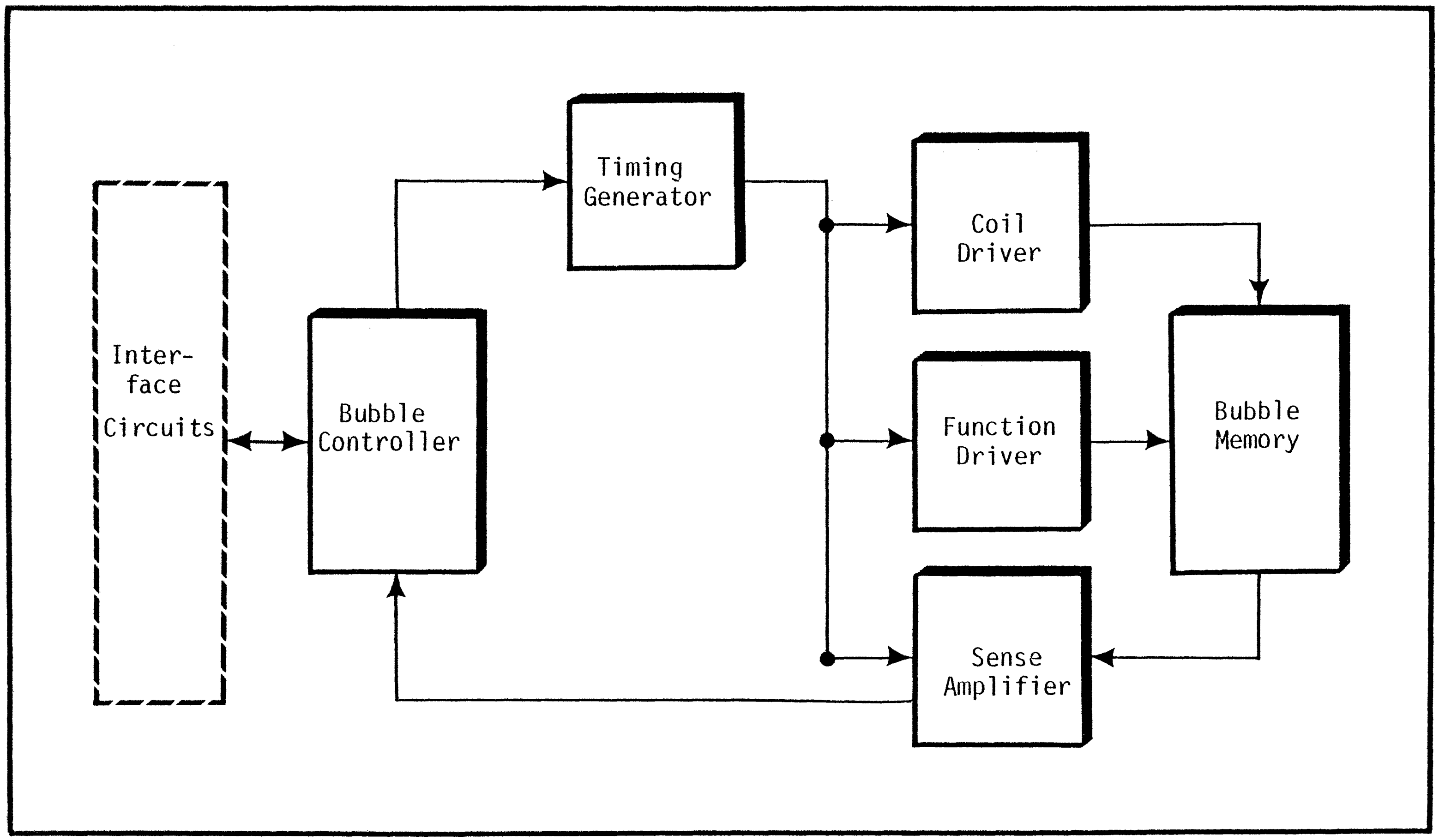
Texas Instruments and Rockwell International offer bubble memories commercially. Intel has delivered some bubble chips, and National Semiconductor and Motorola have efforts underway. Western Electric, a subsidiary of AT&T, has produced bubble memories in quantity, but does not sell on the open market.

In Japan, Hitachi and Fujitsu are active in bubble memories; NEC also has a bubble program. Siemens, in Germany, is planning to produce bubble memories under a license agreement with Rockwell, and Sagem in France, under agreement with National Semiconductor. Other companies with strong interest in bubble memories include Digital Equipment Corporation, Hewlett-Packard, Philips, and Plessey, but we believe that they are not planning to produce bubble chips at this time. Entrance into bubble memory production involves substantial monetary investment, amounting to about $5 million to produce the bubble chips and the required ancillary circuits. For the time being, at least, Sperry Univac has

FIGURE 2

MAJOR BUBBLE MEMORY CIRCUIT COMPONENTS

(Simplified Block Diagram)



dismantled its bubble program, while Burroughs, NCR, and others in the computer industry watch and wait.

It is noteworthy that the two leading companies in bubble memory research and development, IBM and AT&T, do not sell to industry at the component level.

SUBASSEMBLY PRODUCERS

In order to be useful as a memory, one or more magnetic bubble devices must be incorporated into a subassembly. There must be included on this circuit board or modular subassembly a controller, coil drivers, and the interface circuits to make it possible for the bubble to communicate with other equipment. Because bubble memory application techniques are not familiar to most design engineers, most users want to avoid working with the bubble chips. For this reason, participation at two levels -- Tier 1 (Components) and Tier 2 (Subassemblies) is much greater for bubble memory producers than for most other computer industry participants.

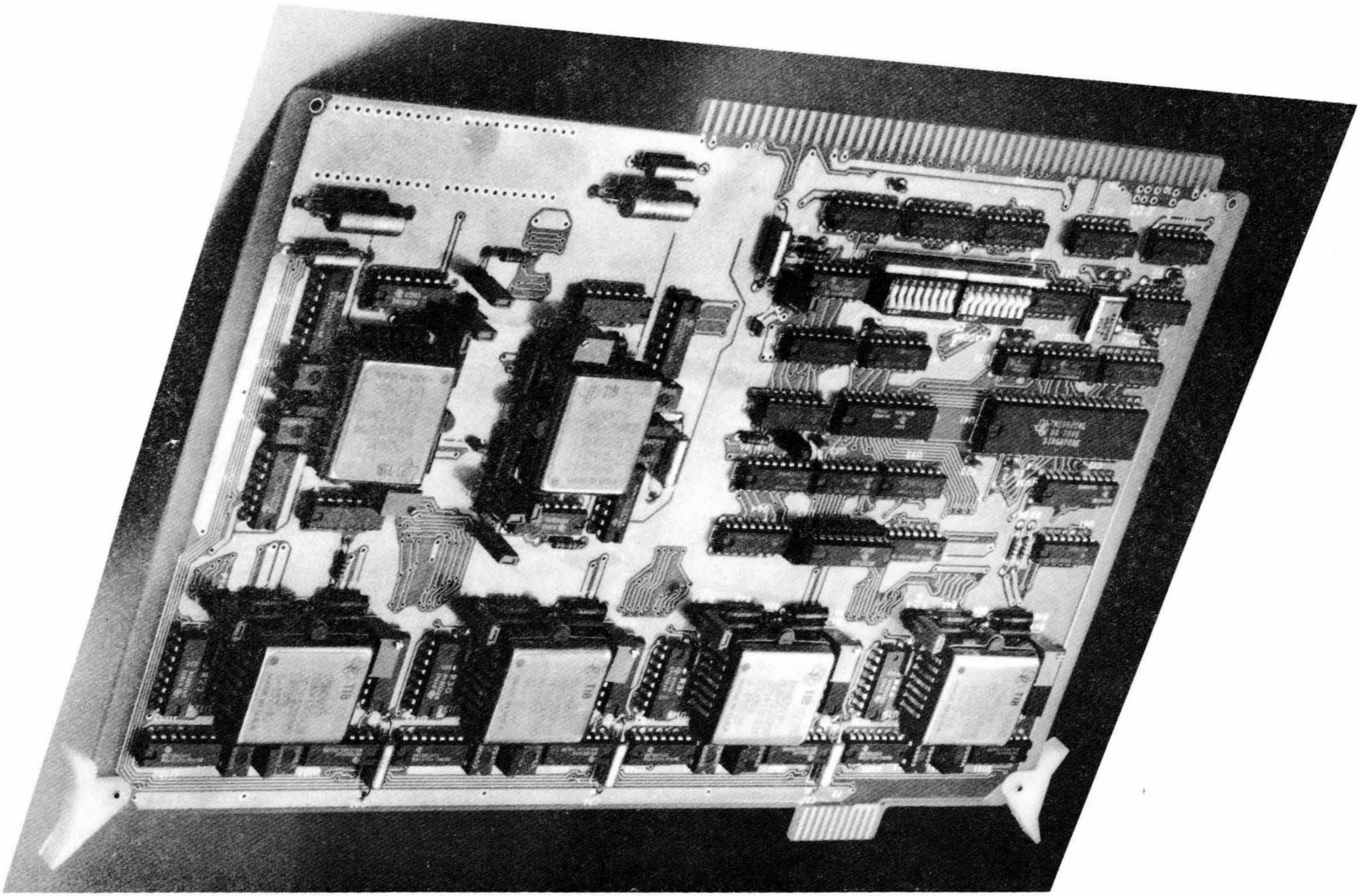
All of the manufacturers of magnetic bubble memory devices will produce subassemblies incorporating their bubble memories. An example, the Texas Instruments 69-kilobyte bubble memory module TM 990/210, is illustrated in Figure 3. A number of factors will determine whether the user of subassemblies chooses to purchase the basic packages and build the system, or buy a subsystem. These factors include:

1. The size of the application. The large OEM user is more apt to choose to make the subsystem boards, or modules, himself for reasons of cost and improved control. A small user will not want to develop his own designs or set up his own production.

2. The sophistication of the user. OEM's with strong electronic design capabilities are more apt to buy the separate memory components and build them into their own subsystems.

FIGURE 3

TEXAS INSTRUMENTS 69-KILOBYTE BUBBLE MEMORY MODULE TM 990/120
CONTAINING SIX 92-KILOBIT BUBBLE MEMORY DEVICES



3. The specificity of the application. The more unusual the application, the less likely the OEM is to find an off-the-shelf module that suits his requirements.

4. The quality and service of the bubble subassembly supplier. If the user is unsure of satisfactory delivery, he is more likely to build memory boards or modules himself.

An analogous situation may be seen in the microprocessor industry. Microprocessors are purchased either as individual components to be built into subsystems or as functioning subassemblies. The cost of entering the microprocessor business as a manufacturer of the CPU itself is high, but the entry cost of manufacturing circuit boards utilizing microprocessors is relatively low. The latter involves circuit design, procurement, and assembly of printed circuit boards. A similar situation will exist in the bubble domain memory business where initial costs of manufacturing the magnetic bubble package itself are high, but set-up costs for modular subassemblies using the bubble package and standard integrated circuit ancillary packages are low.

This means that, in addition to the magnetic bubble subsystems offered by bubble makers themselves and those manufactured by OEM users, there will also be a myriad of small manufacturers making magnetic bubble subassemblies. Specializing in circuit design, they will provide custom designs where the applications are too specialized for the magnetic bubble device manufacturers to offer packages, and too small for OEM's to design their own. Digital Interface Systems and Bubbl-Tec already supply modular bubble memory packages.

Present suppliers of bubble memory chips offer subsystem modules. We believe that all manufacturers of bubble memory devices who plan to sell to OEM's must also offer memory subassemblies as well as bubble chips, if only to make it easier for their customers to utilize their bubble memory devices in prototype systems.

SUBSYSTEM AND EQUIPMENT PRODUCERS

Our definition of the subsystem or equipment manufacturer is a purchaser of bubble memory devices or modules who incorporates them into a piece of stand-alone equipment which contains all of the auxiliary electronics to enable it to perform a specific function in an operating system. By definition, products in this tier are not fully operational systems that could be of value to an unsophisticated end user.

Two classes of products comprise this group:

* Magnetic bubble domain memory peripherals
* Complex computer peripherals.

Magnetic Bubble Domain Memory Peripherals

We believe that bubble memories will soon appear as stand-alone "black boxes" which will perform the sort of functions now performed by disk packs, floppy disk storage systems, or computer add-on memories. We think it is logical for those who fabricate bubble memory devices to offer such equipment. Small manufacturers of bubble memory modules will be technically capable of designing this equipment, but many will not be capable of producing them economically in volume, will not have the funding to prepare the interfaces necessary for broad appeal, or will not possess the marketing know-how to sell them effectively.

Complex Computer Peripherals

Bubble memories will be used in terminals, which must be classified as subsystems even though they may be quite complex, because they perform an input-output function rather than operating alone.

Computer terminals represent a sizable potential market for bubble memory devices. In the past, terminals have used floppy disk and cassette drives for mass storage. Semiconductor delay lines and RAM's were used for the internal data base and refresh functions.

Bubble memories are candidates to replace floppy disks in some applications, to replace the internal data storage in others, and to add new capabilities for internal storage to terminals that do not now provide data storage beyond what is actually displayed on a CRT.

Already, Texas Instruments has replaced floppy disks in its major line of portable terminals. Other portable terminal and computer manufacturers who offer bubble memories are:

* Computer Transceiver Systems
* Findex, Inc.
* Telcon Industries
* Teleram Communications.

Leading producers of terminals are IBM and Teletype, the latter a subsidiary of AT&T. These companies represent captive markets for bubble memories. Other important terminal producers who are potential users of bubble memory include:

* Ann Arbor Terminals
* Applied Digital Data Systems (ADDS)
* Beehive
* Bunker Ramo
* Burroughs
* Conrac
* Control Data
* DEC
* DatagraphiX
* Datamedia
* Datapoint
* Delta Data
* ECCO
* Evans and Sutherland
* Four Phase Systems
* Harris Corporation
* Hazeltine
* Hewlett-Packard
* Honeywell
* Informer
* Infoton
* ITT/Courier Terminal
* Intertec Data Systems
* Lear Siegler
* Lee Data
* Lundy

* Memorex
* Mohawk Data Sciences
* Ontel
* Nixdorf Computer
* Northern Telecom Systems
* Perkin-Elmer
* Pertec Computer
* Ramtek
* Raytheon
* Research, Inc.
* Sanders Associates
* Soroc Technology
* Sperry Rand
* Tektronix
* TeleVideo
* Telex
* Texas Instruments
* Trivex
* Visual Technology
* Westinghouse
* Zentec.

SYSTEMS BUILDERS

The function of the systems builder is to provide the end user with equipment that is fully operational. The systems builder assembles the various equipments that are necessary to make the system work: computer, terminals, recorders, printers, etc.; sees that they are interfaced; and provides operating instructions, training programs, and repair and maintenance services.

Companies that function as systems builders include such diverse participants as the large computer mainframe manufacturers which operate on Tiers I through IV, producers of small business systems, small systems houses which cater to specialized market segments, and interface houses which provide sophisticated end users with operating hardware interfaced to a system, but with a minimum amount of software and technical assistance.

Whether the assembly of system components is accomplished by the computer mainframe maker, a systems house which operates exclusively on this level, or a sophisticated end user or hobbyist, it is a necessary step in bringing the magnetic bubble domain memory to the end user.

Large computer companies have always provided fully operating systems. Minicomputer manufacturers have operated only on the OEM level in the past, but, motivated in part by the minicomputer's declining percentage of total system cost, these manufacturers have gone into systems and peripheral production in a big way.

Large computer manufacturers who operate in this tier include:

* Burroughs
* Control Data
* Honeywell
* IBM
* NCR
* Sperry Univac.

Minicomputer companies active in systems building include:

* BTI
* Computer Automation
* Data General
* Digital Equipment Corporation
* General Automation
* Harris
* Hewlett-Packard
* Microdata
* Perkin-Elmer
* Prime Computer
* Texas Instruments.

Small business systems are one of the most promising areas for bubble memories. Leading manufacturers of small business systems, in addition to companies already mentioned as large computer and minicomputer manufacturers, include:

* Basic/Four
* Datapoint
* Display Data
* ICL
* Minicomputer Systems
* Programmed Control Corporation
* Qantel
* STC Systems
* Wang Laboratories
* Xerox.

Not only will bubble domain memories be used in the above-mentioned systems, but they may be used in the types of systems listed below, some of which may be as small as a portable calculator. In smaller systems, there are many applications for bubble memories. Some of these applications and leading systems producers are:

Word Processing

* A.B. Dick
* AM Jacquard
* Basic/Four
* Burroughs/Redactron
* CPT
* DEC
* Dictaphone
* IBM
* Lanier Business Products
* Lexitron
* Qyx
* Vydec
* Wang Laboratories
* Xerox.

Data Loggers

* Accurex
* Datel Systems
* Doric Scientific
* Fluke
* Gould
* Kaye Instruments
* Monitorlabs
* United Systems/Monsanto.

Home/Hobby Computers

* Commodore
* Digital Group
* Intelligent Systems Corporation
* Pertec Computer
* Radio Shack.

Programmable Calculators

* Hewlett-Packard
* Monroe/Litton
* Olivetti
* Sharp
* Tektronix
* Victor Comptometer
* Wang.

END USERS

End users are the purchasers of the word processors, small business computer systems, data loggers, etc. which will incorporate magnetic bubble domain memories. End users will not usually attempt to influence the selection of one bubble memory over another. In most cases they will not concern themselves with the internal hardware of the machine at all -- only with the price and performance of the complete system.

There are some situations in which the end user will be influenced by an internal design feature because it indicates that the systems builder is utilizing the latest technical developments. However, the end user is generally more concerned with software and applications than with hardware.

End users will hardly ever buy bubble memory components, with two possible exceptions: first, in the home computer market, the hobbyist tends to regard the difficulties of do-it-yourself design as a challenge to be welcomed; second, in the R & D market, sophisticated researchers in university, government, industrial, and medical laboratories may buy bubble memory components for much the same reasons.

VI

TECHNOLOGY

Bubble domain technology has advanced from the laboratory to the field, where it has performed reliably, as expected. This chapter will describe the technology and how it has evolved.

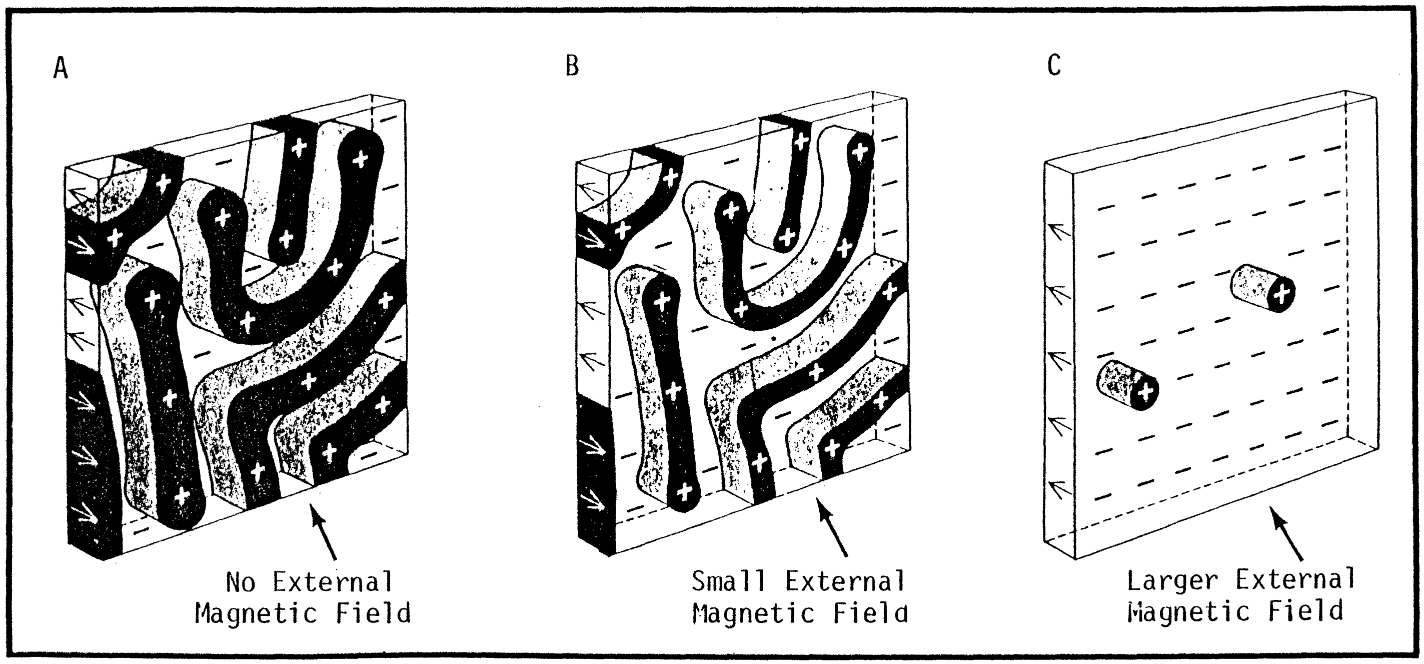
We do not believe that it is necessary for the reader of this study to know the theory of ferromagnetic crystals or the subtleties of domain magnetization, but we think that it is essential to understand the fundamentals of bubbles in order to understand the inherent advantages and limitations of the technology.

WHAT IS A BUBBLE?

A "bubble" is a cylinder of reverse magnetization in a film or wafer of magnetically anisotropic material. Anisotropic films have the characteristic of being magnetized in a direction perpendicular to the plane of the material. If no external field is applied to the wafer, bubbles are not formed. Instead, about half of the material is magnetized in one direction perpendicular to the wafer's surface, and the other half is magnetized in the opposite direction. Each half of the material takes on serpentine patterns, as shown in Figure 4.

FIGURE 4

DOMAIN PATTERNS



In order to form bubbles, a magnetic field must be applied perpendicular to the surface of the wafer. When such a field is applied, more magnetic domains become aligned in the direction of the field than in the opposite direction. (See Figure 4B.) As the field is increased to a certain strength, only a few random areas remain magnetized in the reverse direction. These areas tend to be round in shape as viewed from the surface and have become known as "bubbles." (See Figure 4C.) Actually, these bubble domains are cylindrical, extending through the wafer. If the external field is made too strong, the material will become entirely magnetized in the direction of the field, thereby eliminating the bubbles altogether.

Why is this tiny magnet whose diameter is measured in microns called a "bubble?" The term "bubble" comes from the little magnet's behavior. It appears to float in a sea of magnetic material polarized in the opposite direction. It does not necessarily stay in one place, unless it is held there by a separately applied magnetic influence. Bubbles have extreme mobility and may be easily "herded" across the wafer by moving a fine magnetized wire across its surface. The bubbles maintain their integrity over a considerable range of magnitude of the applied external polarizing magnetic field, neither proliferating nor disappearing. Because the bubbles are all of the same polarity, they repel each other, thereby maintaining fairly uniform spacing.

When a gradient in the bias field is created along the film, bubbles move in the direction where the polarizing bias field is diminished because the bubbles are magnetized in the direction opposite to the field. They are therefore attracted to the area of lesser bias.

Bubble domains can be moved along the film or wafer, creating a condition in some ways equivalent to other forms of magnetic recording. However, magnetic tape and disk recording and readback are accomplished by physically moving the magnetic media past recording and readback devices. The bubble wafer, on the other hand, remains stationary, while the magnetic domains, or "bubbles," move within the wafer.

IMPLEMENTATION OF BUBBLE DOMAIN TECHNOLOGY

In order to perform the memory function, the bubbles must be made to behave in disciplined fashion. They must appear on command, move in desired patterns, report their presence or absence at an appointed detection point, and disappear when required to do so. When there is no command to perform, they must remain in their places indefinitely until called upon.

Figure 5 provides a representation of a practical bubble memory module. The basic bubble package includes a non-magnetic substrate, an epitaxial layer of uniaxial anisotropic magnetic material, permalloy guide patterns, orthogonal coils, permanent magnets, a magnetic shield, and various interconnections. In addition, coil drivers, power supplies, and controllers are required which are external to the package and may serve a number of basic packages. Figure 6 illustrates an actual bubble memory, the Rockwell XBM 256 ¼-megabit bubble memory device, on a magnified permalloy pattern. The chip itself is also illustrated. The Intel 7110 one megabit bubble memory package is shown in Figure 7.

To attain bubble stability, an external magnetic field of proper magnitude is required. This bias field is provided by permanent magnets placed on either side of the module. They are magnetized so that the poles are on the flat surfaces, and they produce a field applied across an epitaxial layer containing the bubbles. The strength of the permanent magnet is selected so that bubbles which are present remain, but unwanted bubbles are not created.

A magnetic shield (not shown) encircles the package, preventing stray magnetic fields from affecting the bubbles and providing a path for the magnetic flux between the exterior poles of the permanent magnets.

FIGURE 5

VARIOUS COMPONENTS NEEDED FOR BUBBLE MEMORY OPERATION

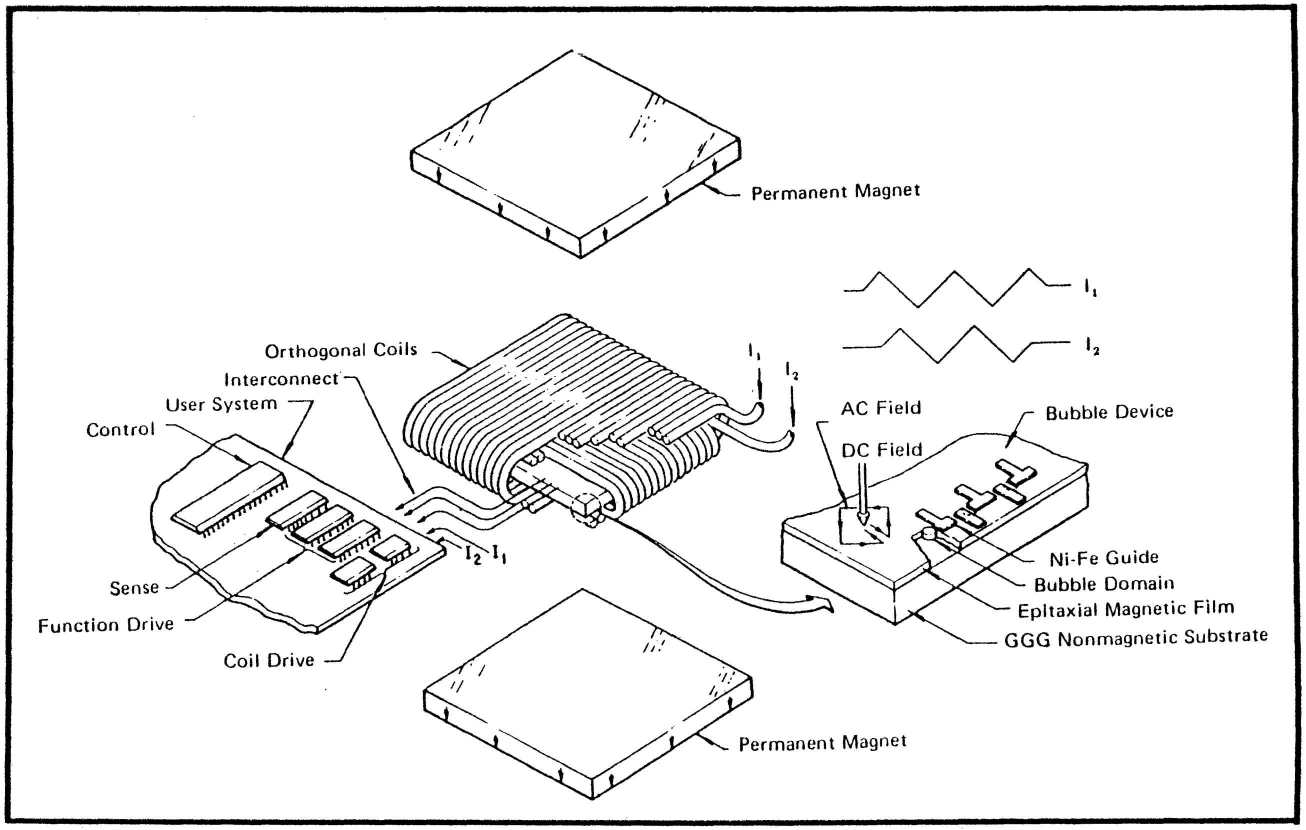


FIGURE 6

ROCKWELL RBM 256 ONE-QUARTER MEGABIT BUBBLE MEMORY DEVICE

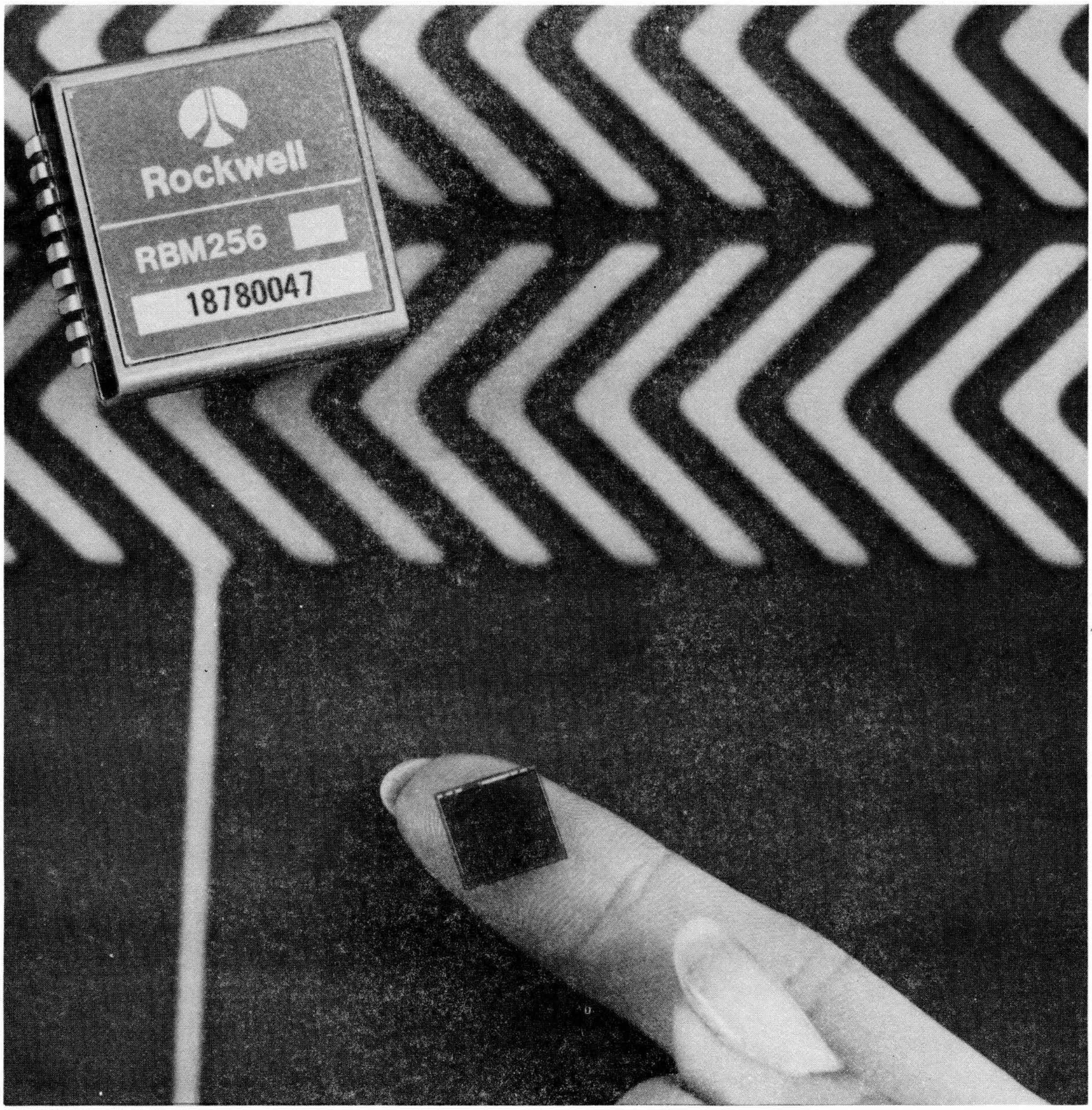
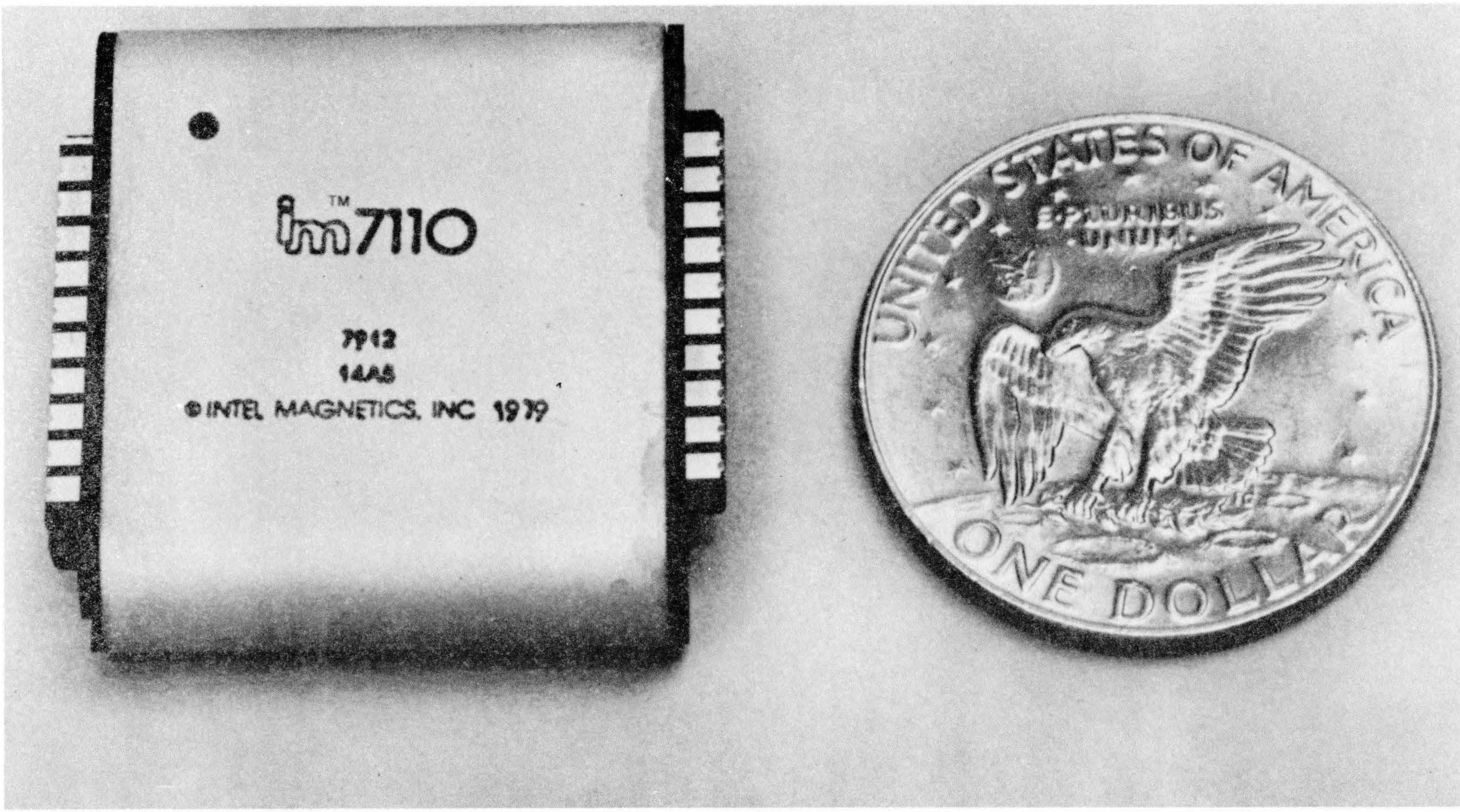


FIGURE 7

INTEL MAGNETICS 7110 ONE MEGABIT BUBBLE MEMORY PACKAGE



In bubble memories today, a binary datum is recorded by the presence or absence of a bubble at a particular location. Therefore, bubbles must be generated when and where they are needed. In the previous subsection, we discussed randomly-placed bubbles which remained in the wafer, or epitaxial layer, after the magnetic field was increased to the point where the serpentine patterns had disappeared. Bubbles which appear at random are obviously not suited to data recording.

A new bubble may be generated by neutralizing the bias field created by the permanent magnets at the point on the bubble chip where the new bubble is desired. A short pulse of current is sent through a small loop placed on the surface of the chip. The field produced in the loop counteracts the bias magnetic field at that point, causing a bubble to form. Bubbles may also be created by dividing a bubble already in existence.

Once bubbles have been formed, it is necessary to move them about the chip to store the information and retrieve it when it must be read. Previously, we discussed the herding of bubbles with a magnetized wire. Such a mechanical means of bubble propagation is not feasible for large-scale bubble movement; a large part of the bubble's appeal lies in having no moving parts.

In present commercial devices, the force to move bubbles is provided by a rotating magnetic field in the plane of the wafer. This field does not affect the permanent bias field which maintains bubble integrity, because the two fields are at right angles to each other. The rotating field is applied by orthogonal coils wound around the wafer and its substrate.

"Field access propagation" designates use of a rotating external field to drive the bubbles. All of the present commercial bubble memory devices use this method. To harness the force supplied by the rotating field, guide patterns of highly permeable magnetic iron and nickel material, known as permalloy, are deposited on the surface of the wafer. The rotating field induces magnetism in the patterns. The bubble is attracted toward the induced poles which are opposite to the magnetization of the field. By proper pattern selection, the bubbles are moved in desired directions.

Figure 8 illustrates the manner in which a bubble moves along a T-I bar pattern of the type utilized in the popular Texas Instruments 92-kilobit bubble memory chip. As the direction of the field rotates from the "1" direction of the arrow to the "2" direction, the bubbles which are assumed to have their negative poles in the position toward the permalloy pattern move toward the right side of the T-bars, in which the field has induced positive poles. When the field rotates to the "3" direction, the positive poles in the I-bars pull the bubbles away from the T's onto the I's. When the field rotates to the "4" direction, the bubbles are pulled onto the positive T poles which have now moved to the left side of the T's. After that, the bubble is pulled across the T's, and the cycle begins again. In order to allow the bubbles to move from bar to bar, spacing between the I and T bars is not greater than one-half of the bubble width.

The T-I bar permalloy method is not the only way of propagating bubbles. Other methods are described subsequently in the paragraphs on "Methods of Bubble Domain Propagation."

Patterns may be deposited on the wafer in a number of configurations. Like railroad tracks, they conduct bubble streams around the chip. A chip containing a single long pattern is used much like a tape recorder; it is a serial access device. (See Figure 9.) It is also practical to arrange the patterns in the form of a major loop and minor loops. (See Figure 10 .) In that case, the bubble device functions as a block serial device, as does a disk recorder.

Bubbles may be routed around the wafer along the permalloy patterns like trains on tracks. If the system has more than a single loop,

FIGURE 8

T-I BAR PATTERN

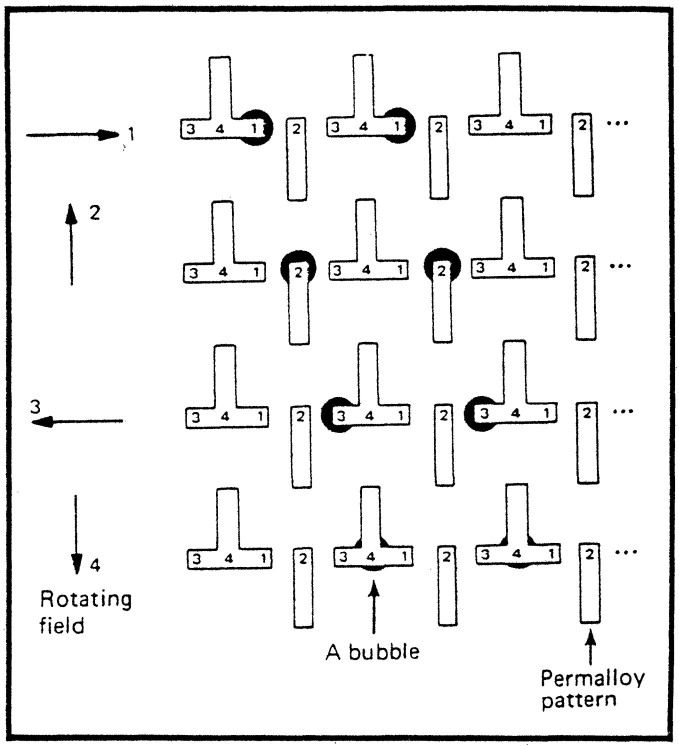


FIGURE 9

SERIAL LOOP CHIP

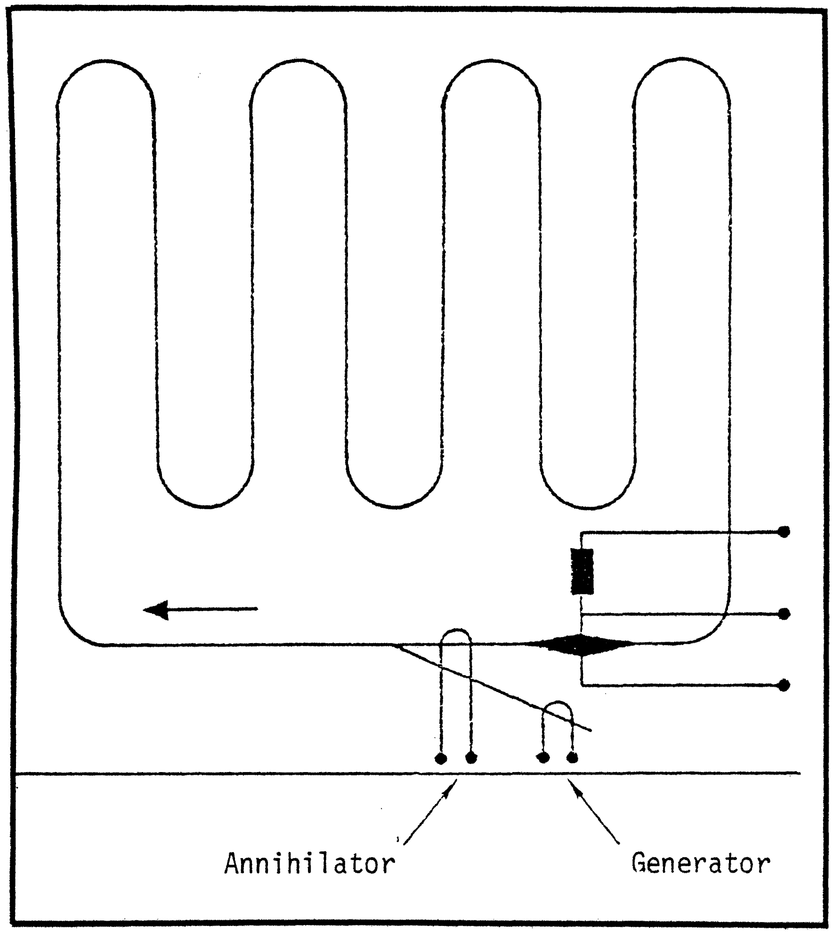
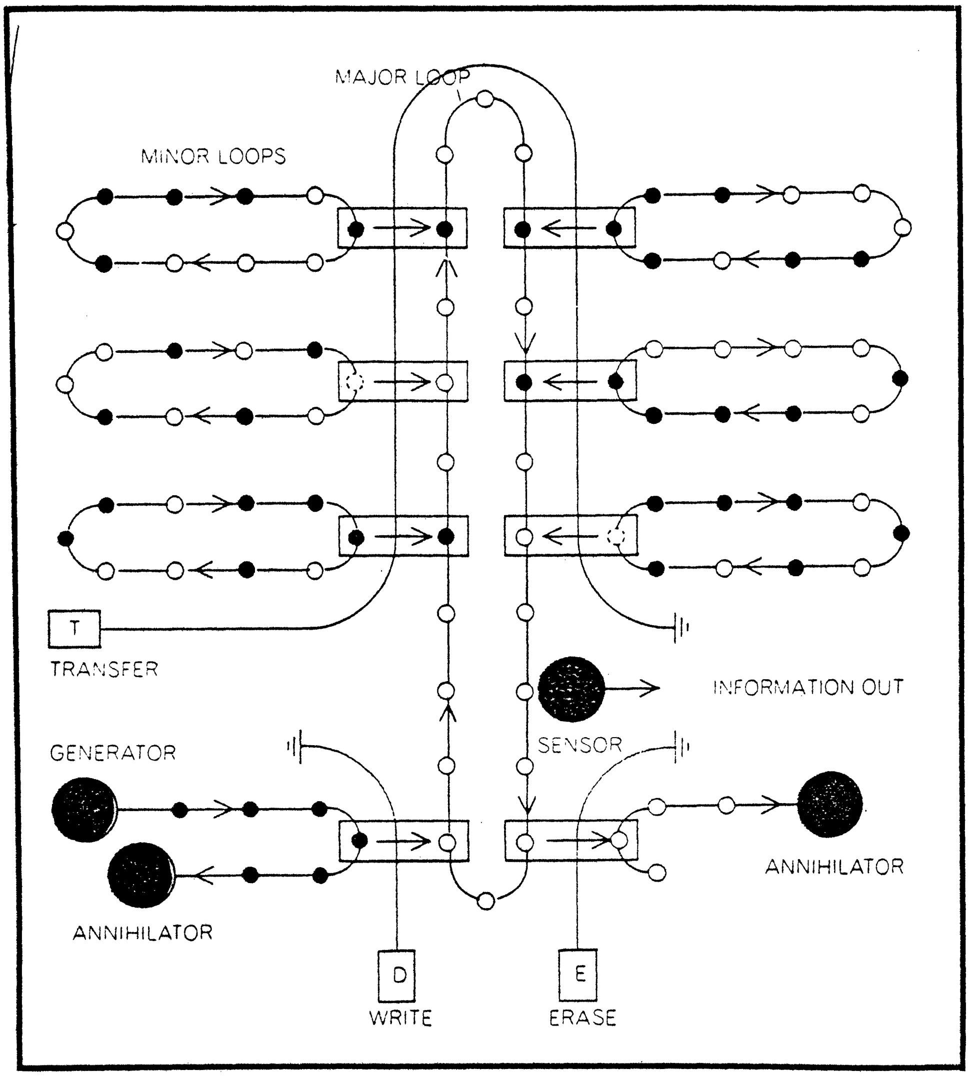


FIGURE 10

BUBBLE MEMORY SCHEMATIC, SHOWING MAJOR AND MINOR LOOPS



bubbles must be switched from track to track. As in a railroad system, switching must be controlled externally because the bubble has no ability to select a track itself. Bubbles may be switched in a number of different and complex ways. Bubble streams may be merged, a bubble stream may be separated into two streams, and a bubble may be gated by the presence of another bubble. It would be possible to design complete logic systems entirely from bubble technology, but there is little economic justification for doing so.

In one method of switching, propagation channels are radially arranged around a central disk. Only when a domain is enlarged will it be able to reach a T-bar in order to move it along. At other times it will remain in the disk. Enlargement may be achieved by using a small current loop which counteracts the bias field, allowing a bubble to grow larger at that point.

Another method of switching is to energize a current loop which will hold a bubble in place when the rotating field would otherwise move it on. When released, the bubble moves on in a different direction and proceeds along a different channel.

Data must be read out of a memory device, so the presence or absence of bubbles must be detected. Usually, the first step in detecting a bubble is to expand it. Because a larger bubble carries more charge, it becomes easier to detect. The bubble may be expanded by decreasing the bias field acting on the bubble or by designing a portion of the permalloy pattern so that it stretches the bubble. Methods used to detect bubbles can rely on electromagnetic induction, the Hall effect, or magnetoresistance. They may be non-destructive -- that is, it is not necessary to destroy data during detection.

When information is rewritten, previous bubbles must be annihilated. Permalloy subpatterns may be designed so that bubbles switched onto them will disappear. A very efficient "bubble eater" can be designed using a current loop which reinforces the bias field, causing the bubble to disappear.

INHERENT ADVANTAGES OF BUBBLE DOMAIN TECHNOLOGY

The bubble module is a non-volatile, mass storage, solid-state memory device. Most of its proven advantages derive from this combination of characteristics. No major competitive technology provides all three qualities.

Because data stored in bubbles is not volatile, electrical power is not required to retain data. Standby power is not needed when the equipment is shut down, and data is not lost because of power failure. Semiconductor RAM's and CCD's, on the other hand, are volatile. Core memories are not volatile and are solid-state, but because of cost and power requirements, they are not as well suited for mass memory applications as are bubble devices.

Disk and magnetic tape equipment have moving parts which wear out. Cost per bit is low, and they are not volatile, but they require maintenance. Bubble memories do not wear out because they do not have moving parts. This feature also gives them an inherent advantage in access time. With major-minor loop organization, the bubble memory provides faster access than disks. Even fixed head disks have an average latency of about 8 milliseconds, while the desired data rotates to the "read" head. Moving head disks require additional time for head movement.

The minimum cost for a small bubble system can be lower than a tape or disk system, but it is higher than a minimum semiconductor system.

Most of the bubble memory's virtues result from combinations of qualities which are not, in themselves, unique. However, one claim has been made for bubbles from the beginning; they are said to be ultra-reliable. On the basis of performance so far, the claims are holding up. Of course, bubbles require semiconductors in their support circuits, which limit the reliability of the total bubble system, but compared with other methods of storage, the error rates are commendably low.

Bubble memories have proven rugged and reliable in factory use, withstanding shock and vibration incalculably better than disks and tape, and proving impervious to dust and most chemicals.

Because bubble devices inherently accept incremental inputs, they are capable of low transfer rates. This simplifies interfacing and reduces buffering requirements.

INHERENT LIMITATIONS OF BUBBLE TECHNOLOGY

As we discussed in the previous subsection, the inherent advantage of the bubble lies in a combination of qualities. Most of the parameters are not exceptional. Access time and cost are intermediate; bubbles will essentially be less expensive than RAM's but will always offer much slower access time.

As long as field access is used as the propagation method, the transfer rate will be slower than any of its competitors. By operating a number of bubble paths in parallel, the transfer rate can be improved, but as more bubble paths are used, the electronics become more complicated. All of the present devices use field access, but current access bubble memories are under development which might be able to provide bit rates of at least a million bits per second in future years. Current access is discussed later, in the subsection entitled Methods of Bubble Domain Propagation.

Cost is still high in 1980 compared to other storage methods. Although improvements are expected, it appears that the inherent cost per bit is higher than for moving head disks.

The bubble memory is not an ideal removable medium, although it is possible to physically remove a bubble module with data preserved on it. In fact, Fujitsu does offer a bubble cassette. (See Figure 11.) However, the costs will always be an order of magnitude higher than for a diskette. The bubble can only compete with the floppy disk on price when it is not necessary to physically store data external to the system, or where there is also a floppy disk drive in the system which can perform this external storage function. Otherwise there must be an environmental problem, such as dust, chemicals, shock or vibration to justify using bubble memory despite the price disadvantage.

In comparison with disks and tape, bubble memories' temperature characteristics are generally good, but bubbles are more temperature limited than military semiconductors, thereby inhibiting their use in military applications for which they would otherwise be ideal. Temperature stability is improving, but the 125^{o}C military requirement may not prove possible to meet. The problem is that the magnetic bias required to keep bubbles stable varies with temperature.

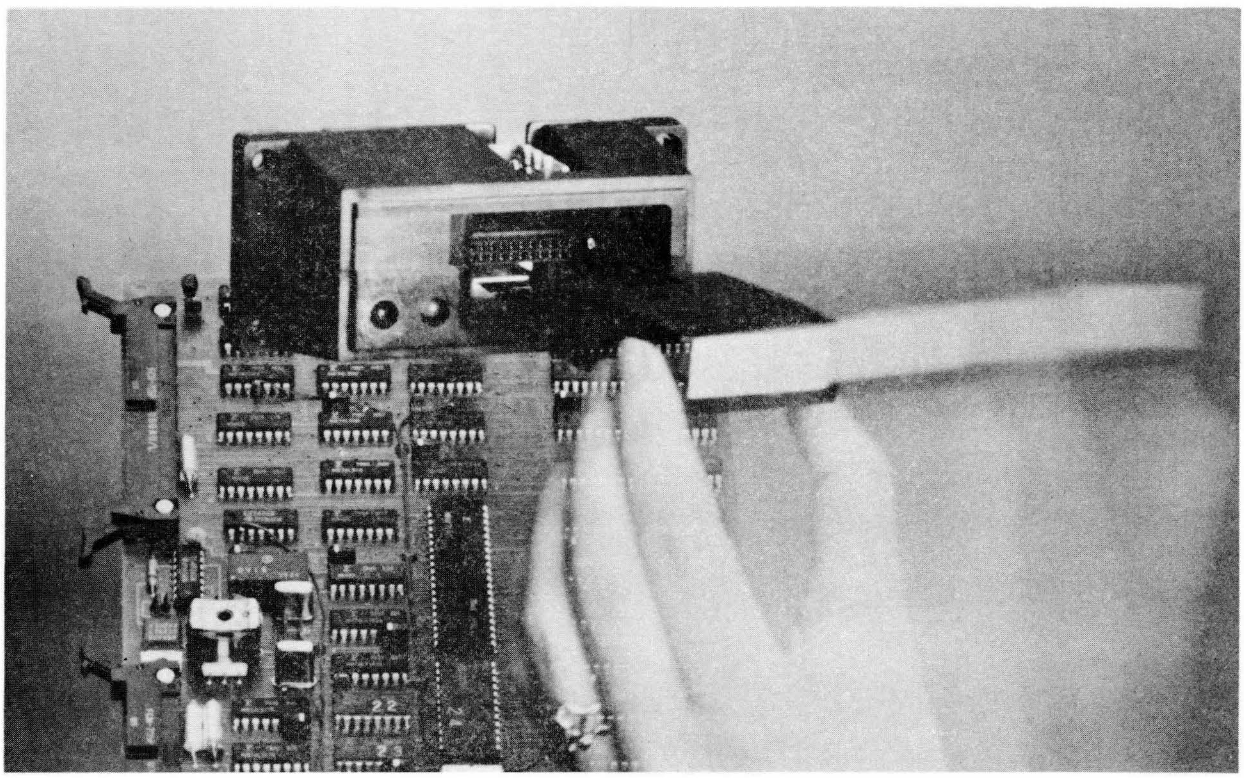
BUBBLE ORGANIZATION

Bubble organization may be simple or complex. The simplest arrangement is a single loop, as described previously in Implementation of Bubble Technology. (See Figure 9 .) The other configuation is the major-minor loop which incorporates a major loop and minor loops. (See Figure 10.)

The main reason for utilizing chips with complex patterns is to improve the access time. For example, if a single-loop chip contains 100,000 bits, it will take an average time of at least 0.5 seconds to gain access to desired data if the rate is 100 kHz. This compares well with tape cassettes, but not with disks. Major-minor loop design offers the advantage of reducing access time to a few milliseconds. On the other hand, with major-minor loop

FIGURE 11

FUJITSU BUBBLE MEMORY CASSETTE SYSTEM



design, interfacing is more complex, more leads are required, the package is larger for the same amount of data, and there are more chances for error.

With the single loop organization, there is less to go wrong. However, if there is a defect, all of the information in the loop is affected, whereas a minor loop error affects only its own loop. If redundant minor loops are included in the design, it may be possible to improve manufacturing yields by using alternate loops in place of defective ones.

Both types of bubble memory organization will be used, but we believe major-minor loop configurations have more market potential and will be offered by all bubble domain device manufacturers.

As already mentioned, transfer rate can be improved by running loops in parallel, either within the same package or using several single-loop bubble memories. For example, eight single loops run in parallel will produce a parallel 8-bit byte at the data output. This allows faster data transfer as well as a simple interface.

Serial Loop Organization

The serial loop bubble device performs the same functions as single-track magnetic tape. In most applications, the cost per bit of bubble memories is so much greater than that of tape media, whether ½-inch tape, cassette, or cartridge, that bubble devices are not competitive. Where ruggedness and reliability are of paramount importance, and/or if there is no need to remove the media, the serial loop bubble device is a viable alternative. Satellite recorders and military recorders in difficult environments are two promising applications.

If rapid access is not necessary, the serial loop organization has advantages. Size and weight are reduced because most of the chip is used for data storage rather than control functions. Reliability is greater because there are fewer loops and fewer circuits to develop faults. Interfacing is simpler with a single data loop. Blocks may be any length, or data may be continuous. On the other hand, the chip may be more difficult to make because there is no way to include redundant loops; any defect in the single long loop makes the device unusable.

Major-Minor Loop Design for Block Access

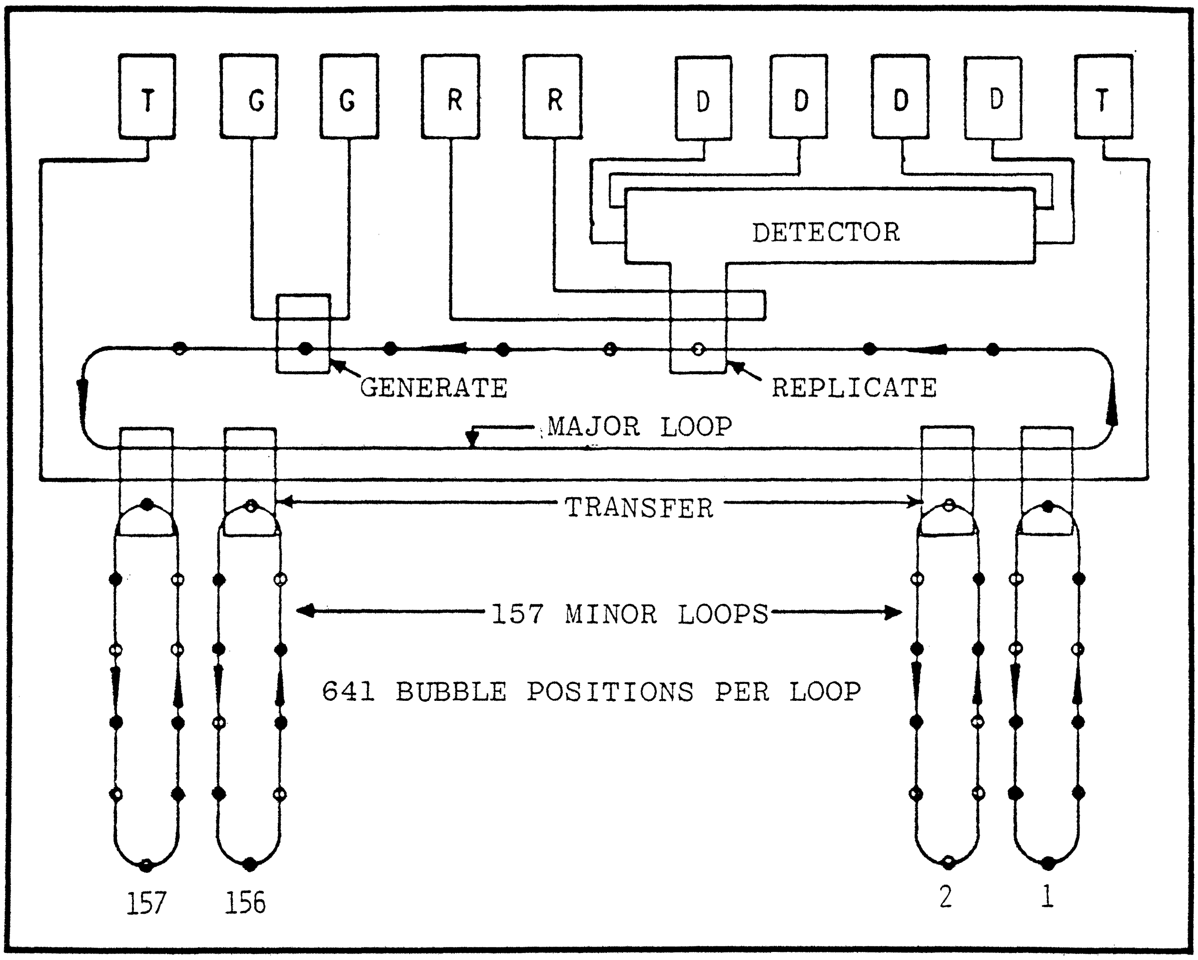
The principal reason for using minor loops is to improve access time. Instead of having to seek through every bubble position on the chip, it is possible to use the major loop as a "collector" loop, serving groups of minor loops. Access time varies inversely with the number of loops.

Figure 12 represents the Texas Instruments TBM 0101 single chip bubble memory, a major-minor loop device now offered for sale. In this system, information is exchanged when bubbles are transferred between minor loops and the major loop. There are 157 minor loops, and each minor loop has 641 positions. Thirteen of these loops are extras, provided in case of faults in the minor loops, leaving 144 minor loops to be used. The access time comprises the amount of time to read the bubble positions transferred to the major loop, plus the latency in selecting the right position in the minor loops. In the TBM 0101, information is incremented in 144-bit blocks, corresponding to the number of usable minor loops, and the number of blocks is 641, corresponding to the number of positions in each minor loop. Many other configurations are possible.

If access times are to be competitive with fixed head disks when bubble chips with larger capacities are used, it will be necessary to design more complex organizations. The chips will have to be broken down into smaller arrays, each organized into major and minor loops.

FIGURE 12

TEXAS INSTRUMENTS TBM 0101 SINGLE CHIP BUBBLE MEMORY



Bubble memories are not true random access devices. In major-minor loop configurations, they provide rapid access to blocks of data, the characteristics being similar to those of a fixed head disk memory.

METHODS OF BUBBLE DOMAIN PROPAGATION

Today, the method of bubble movement, or "propagation," in practical bubble memory devices is the permalloy bar file. A common form of this method is the T-I bar file, already described. There are other variations in use.

The T-I bar, like other permalloy bar files, uses a rotating magnetic field to drive bubbles along the pattern. For each rotation, a bubble crosses two gaps. Newer bubble memories made by Texas Instruments, Rockwell, and Intel use asymmetrical half disks or chevrons. (See Figure 13 .) The half disks and chevrons move the bubble in a manner similar to the T-I bar but require only one gap to traverse per cycle. Another advantage over the T-I bar is that they do not require long, thin bars which are more likely to result in faults during manufacture.

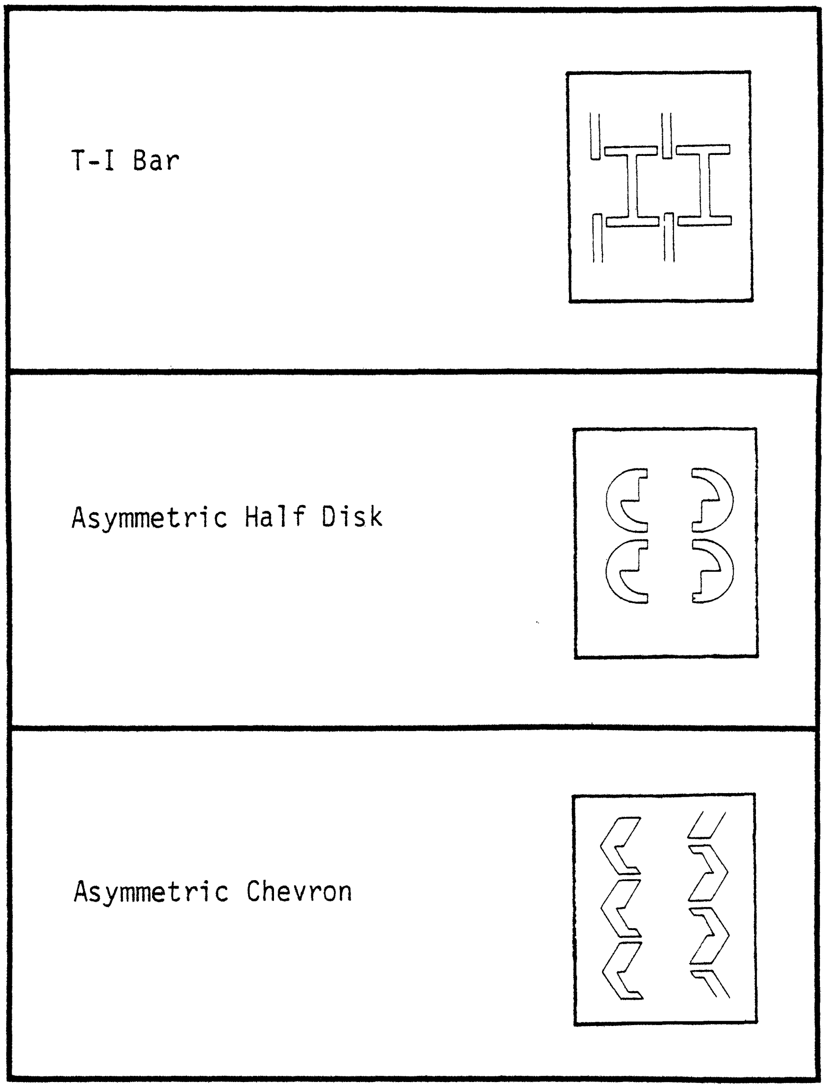
Contiguous Disk (Patterned Ion Implant Structure)

A pattern which eliminates the gap altogether, and also the need to lay down thin patterns, is the contiguous disk. Bubbles can be very small, allowing better packing densities. We believe that in the future there will be a shift to gapless devices as higher densities are required. Strong research and development efforts on contiguous disk memories are reported at Bell Labs and IBM. Ion implantation seems likely to replace permalloy.

The contiguous disk approach can offer higher bubble densities, and therefore more storage, than T-I bars or chevrons. The density possible with permalloy bar files is limited by lithography. Bar widths are critical, and the gaps must not be more than half of a

FIGURE 13

TYPES OF PROPAGATE STRUCTURES



bubble diameter, which fixes a minimum bubble size. Bubble diameter can be reduced in a gapless configuration, and the contiguous disk pattern has no very critical widths. (See Figure 14 .) Bubble density can be increased by a factor of four over chevrons and an order of magnitude over T-I bars. In addition, it should be possible to move bubbles in opposite directions on each face of the contiguous disk.

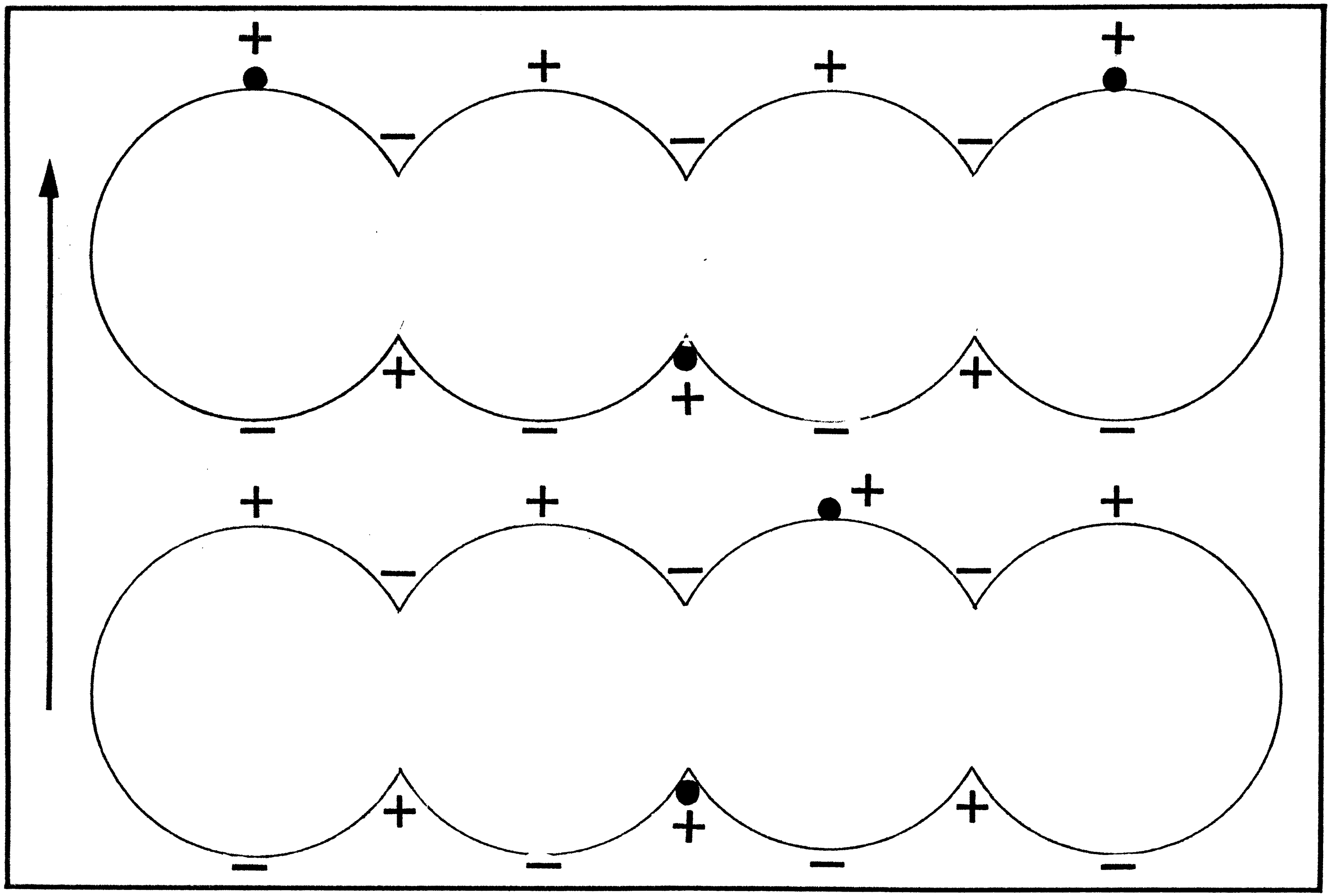
Originally, permalloy contiguous disk files were researched, but there were serious problems with propagating the bubbles. The idea with the contiguous disk is to move the bubble around the semicircle during 180^{o} of the rotation of the magnetic field and have it remain in the cusp between two disks for the remaining half of the cycle. The polarity of the cusp with permalloy disks is such as to repel the bubble during the 180^{o} when it is supposed to remain in the cusp. Bubbles tended either to jump across the permalloy and continue to follow the attracting pole around a single disk or else to drift away from the permalloy.

The permalloy guide method was therefore replaced by ion implantation. If the surface of the garnet is bombarded with helium ions, the top layer of garnet will have its direction of magnetization changed, so that it runs parallel instead of perpendicular to the plane of the film. If the disk pattern is covered with gold, which absorbs the helium ions, only the garnet between the disk patterns has implanted ions. Under the influence of the rotating magnetic field, the boundary between the disk and the interdisk space becomes a charged wall which changes polarity as the field rotates. The cusp and the top of the disk semicircle are of opposite polarities on the same boundary so that the bubble finds itself attracted to the cusp during the 180^{o} of the cycle in which it remains stationary.

In practice, a clearly-defined cusp is unnecessary. A sinusoidal charged boundary, or wall, is at least as effective. For this reason, "disk" is really a misnomer; a better definition is

FIGURE 14

CONTIGUOUS DISK PROPAGATION USING ION IMPLANTATION



"patterned ion implant structure." The absence of critical dimensions further improves the possibility of reducing the size of the patterned ion implant structure compared with the permalloy bar files. Improved lithography methods will make it possible to shrink the permalloy bar file in the future, but the patterned ion implant structure has an inherent advantage which may offset the cost of some extra manufacturing steps.

Dual Conductor Access

Magnetic fields may be introduced not only by an external magnetic source, but also by electric currents. In fact, the first experimental magnetic bubble devices utilized electric currents passing through metallic conductors on the chip to cause bubble movement. The complexity of the bubble patterns and the large power dissipation required caused the industry to turn to field access as a better alternative.

At Bell Labs, Andrew Bobeck, who is generally regarded as the chief inventor of the bubble, heads a group which is working on a new form of current access, called "dual conductor," which would improve the transfer rate of bubble memories. The limitation on propagation speed of field access devices is the main technical weakness of the bubble memory in comparison with disk memories. Bell Labs' experimental dual conductor current access device is driving bubbles at a rate of one megabit per second, and appears capable of much higher rates in the future. An additional improvement is the elimination of the access coils which are required with field access devices.

The dual conductor access bubble memory is not close to being a commercial device. The bubbles can be seen to move under polarized light, but at this time they cannot be sensed at operating speeds.

In a dual conductor bubble memory device, two conductor films separated by a non-conducting layer are superimposed on the garnet layer which carries the bubbles. An additional non-conducting layer may be included, as in Figure 15 , between the second conducting layer and the garnet. Each conducting layer has patterns cut out, the number of holes being equal to the number of bubble periods on the chip. The holes in the two conducting layers overlap by one-quarter of a period, as illustrated symbolically in Figure 16 .

When a current passes through a conducting sheet, it is deflected around each hole, and a magnetic field is thereby created; bubbles are attracted to one side of the hole and repelled by the other side. The polarity may be rapidly reversed by reversing the current. Figure 16A through C illustrates one cycle of bubble movement, when the conductors are pulsed by currents, as in Figure 17 . As indicated in Figure 16 , the bubble is propelled upward in each successive phase from A to E as it follows the attractive edge of the holes. If the current sequence is reversed, the bubble motion is reversed, and the bubble proceeds downward from e to a.

The dual conductor access bubble memory may be able to provide fast data transfer rates and would eliminate the need for access coils. It is not yet entirely clear what the cost of manufacture would be compared with permalloy guides. In 1980, it appears to be a device worth watching, but as no working prototype memory has yet been demonstrated, it may have a long way to go and seems unlikely to impact the business before 1985.

MANUFACTURING TECHNOLOGY

Although the bubble memory is not a semiconductor device, its manufacturing techniques have much in common with those of semiconductors.

Materials

Present devices which are in production use a garnet film, grown epitaxially on a gadolinium-gallium-garnet (G-G-G) non-magnetic

FIGURE 15

DUAL CONDUCTOR BUBBLE MOVEMENT, CROSS SECTION

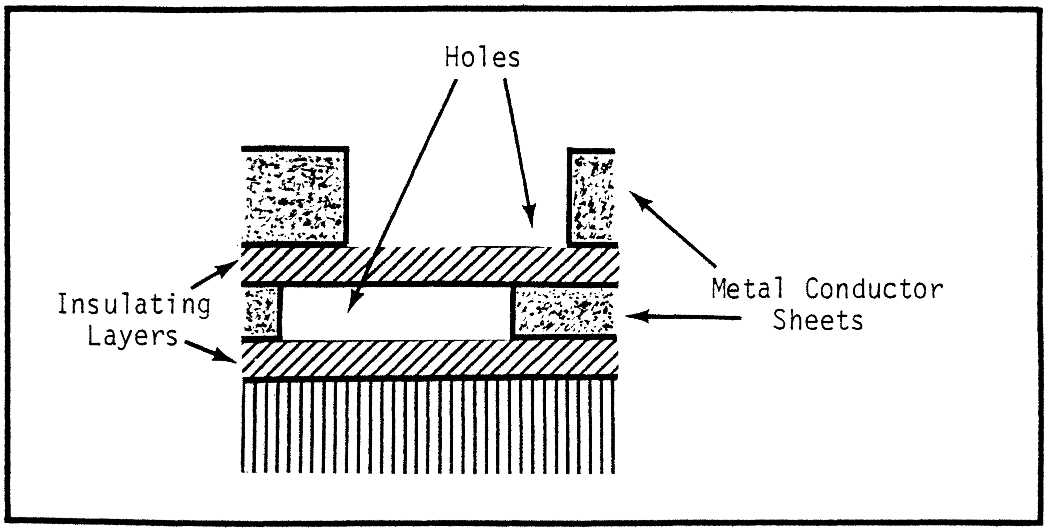


FIGURE 16

DUAL CONDUCTOR BUBBLE MOVEMENT, TIME SEQUENCE

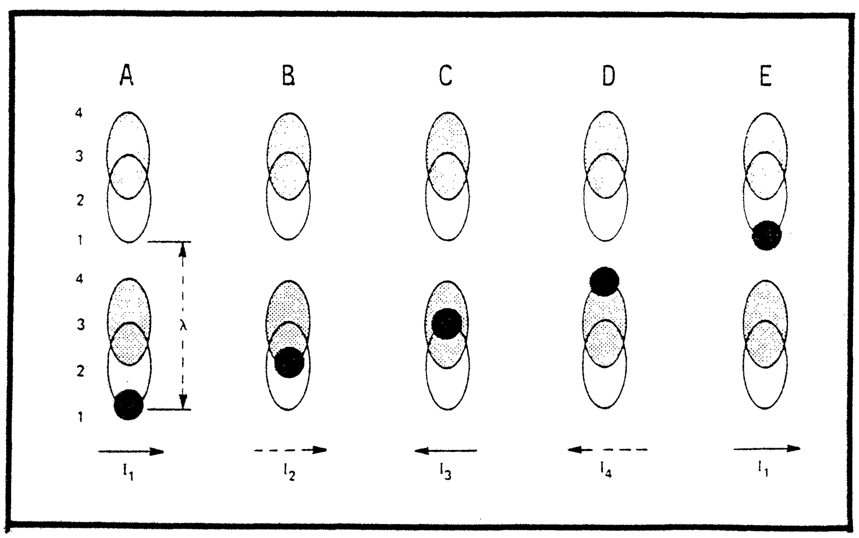
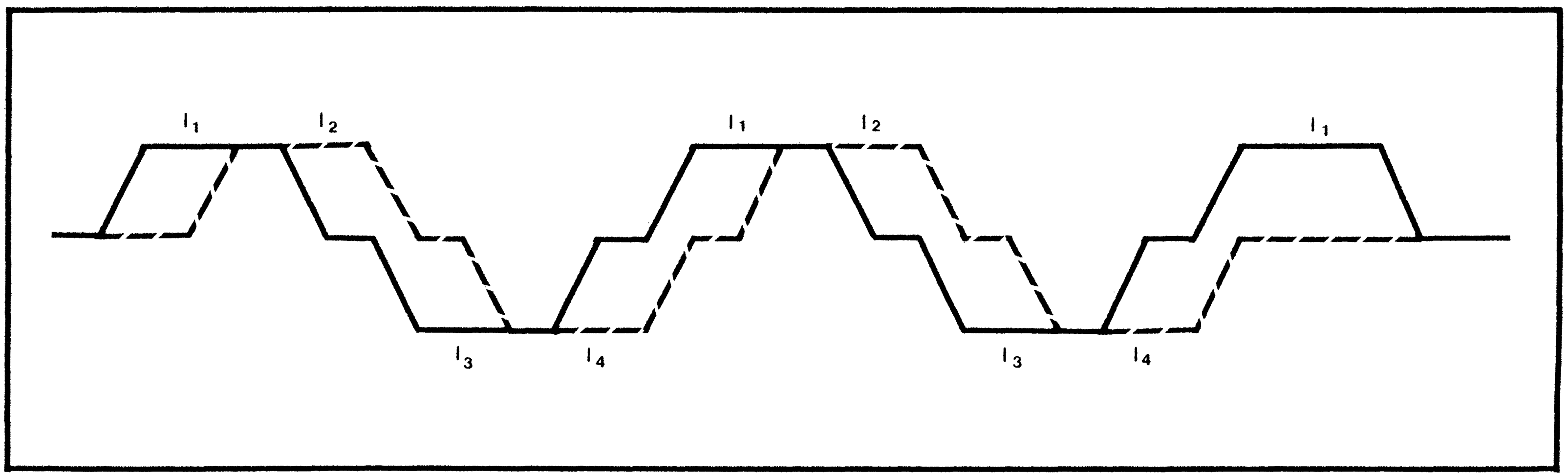


FIGURE 17

CURRENT PULSE SEQUENCE FOR DUAL CONDUCTOR ACCESS



substrate. The film which carries the magnetic bubbles is a uniaxial garnet of the class $A_3Fe_5O_{12}$, in which A is Yttrium or another rare earth. One of the most successful methods for depositing the garnet layer has been dipping in a super-saturated solution. Evaporation techniques are also used. The bubble sizes and properties may be varied by using different rare earths and by introducing non-magnetic ions into the crystal structure. Research is proceeding with amorphous metal films.

Construction

Bubble domain devices are manufactured utilizing techniques which are identical to some semiconductor manufacturing steps, similar to others, and different from still others. The epitaxy, photolithography, metallization, and passivation steps are identical, while the electroplating steps are not commonly employed. Much of the equipment used in semiconductor device manufacture is likely to be usable in bubble manufacture. However, there are sufficient differences between the two processes to make it necessary to become familiar with the intricacies of bubble device manufacture.

The manufacturing steps for a three-mask-level bubble domain device are illustrated in Figure 18 and listed in Table 1.

In the future, we expect that the number of steps will be reduced until only one mask level is required. This should increase the yield and lower production costs. Of particular importance will be the elimination of the problem of mask registration, which becomes severe with the high storage densities that will be used in the future. (See Figure 19 .) X-ray lithography and electron beam masking will be used for high-density devices in the future.

COMPETITIVE TECHNOLOGY

All memory devices are competitive to some degree. All store and retrieve data. Some of the parameters which are used to select the

FIGURE 18

THREE MASK LEVEL BUBBLE CHIP

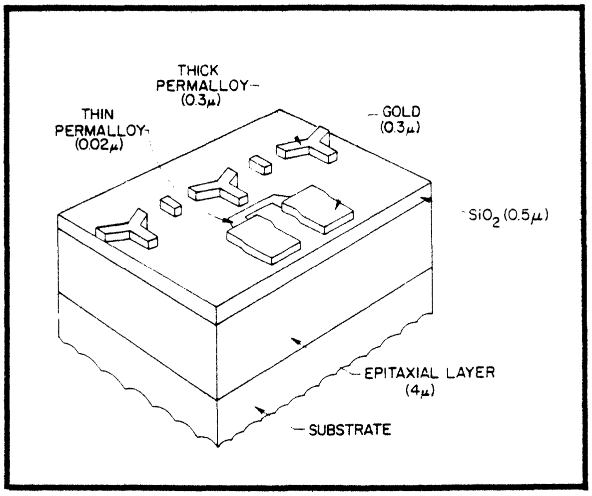


FIGURE 19

SINGLE (CRITICAL) MASK LEVEL BUBBLE CHIP

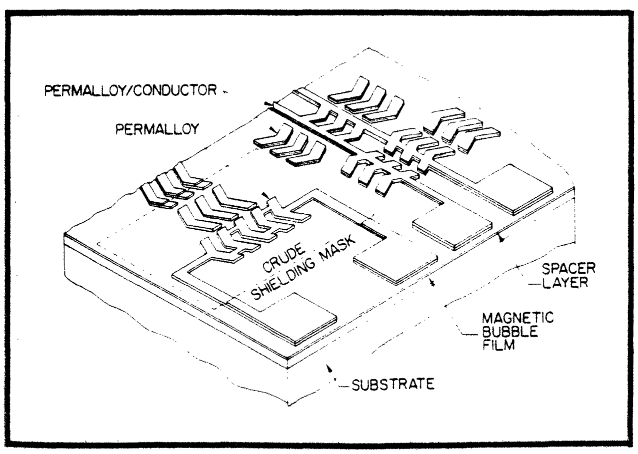


TABLE 1

SUMMARY OF OVERLAY FABRICATION STEPS
Three Mask Level Devices

1. Substrate cleaning	
2. Space (2K-3K A SiO_2)	Evaporation
3. First permalloy sheet (200 A NiFe) - base for electroplating in Steps 5 and 8 - sensor in Step 11	Evaporation
4. First photoresist	Spin resist, exposure, and removal of exposed resist
5. Permalloy propagation structure (2K-3K A NiFe)	Electroplate through photomask
6. Clean off first photoresist layer	
7. Second photoresist	Spin resist, alignment, exposure, and removal of exposed resist
8. Control and access conductor structure (5K A Gold)	Electroplate through photomask
9. Clean off second photoresist layer	
10. Third photoresist	Spin resist, alighment, exposure, and removal of exposed resist

most desirable storage method for a particular application include:

* Price per bit for the system
* Price per bit for the media (where the media is removable)
* Entry cost per system (minimum cost for the smallest system)
* Minimum size of system
* Maximum size of system
* Speed of access
* Speed of data transfer
* Reliability in terms of error rate (long or short term)
* Reliability from the standpoint of mean time between failures
* Volatility of data
* Destructive vs. non-destructive readout of data
* Power requirements
* Size and weight.

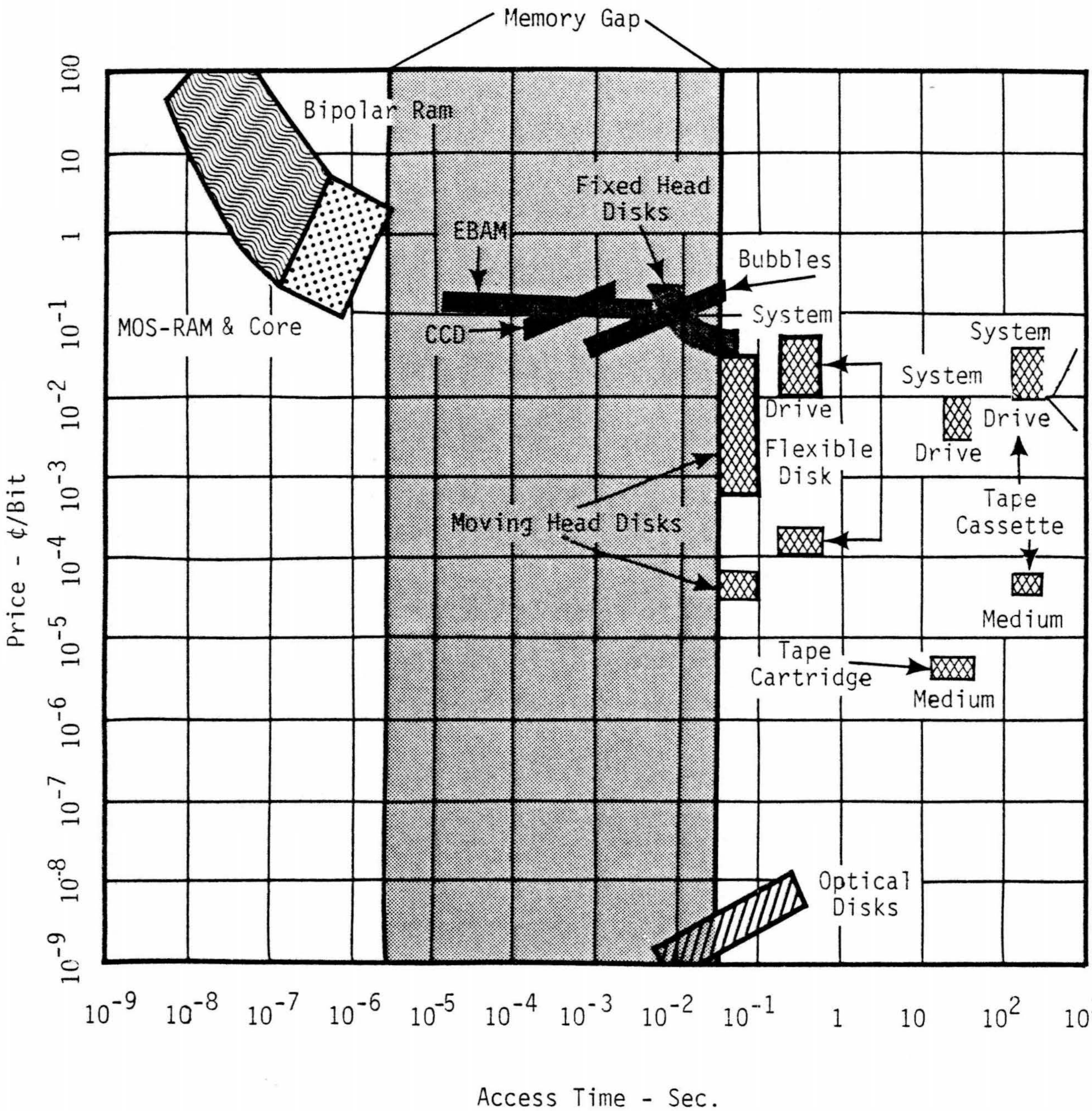
In addition to these parameters, there will also be special requirements for some applications, such as radiation hardness, ruggedness, etc. Two qualities which are important in nearly all applications are price and access time.

Price vs. access time is plotted in Figure 20 for the leading competitive memory devices. In the gap between moving head disks and RAM's lie bubbles, CCD's, and fixed head disks. These devices compete quite directly in terms of price and access time. Other parameters make one or the other preferable for a particular purpose.

This section discusses the interaction between bubbles and each major competitor, both with regard to opportunity for the bubble to capture business from the competitor, and with regard to the impact that bubble memories will have on that technology's market.

FIGURE 20

PRICE VS. ACCESS TIME FOR PRESENT TECHNOLOGIES



CCD's (Charge-Coupled Devices)

CCD's have often been thought of in association with bubble memories because they occupy similar positions in the memory hierarchy, and they were developed at about the same time. They both originated at Bell Labs, and both have been strongly promoted by Texas Instruments.

Unlike the bubble memory, the CCD is a true semiconductor device. Regions of charge are stored and transferred to adjacent locations by applying external voltages. The charge in each region represents digital information. As in the bubble memory, information may be channeled along a single path, or a major-minor configuration may be employed.

In its capabilities and applications, the CCD is not a twin of the bubble memory by any means. Usage of CCD's is not limited to memory applications since their high transfer rate permits them to be used for imaging and signal processing, while all of the practical applications for the bubble domain devices involve memory.

The most conspicuous advantage of the bubble over its CCD rival is non-volatility. The CCD requires the application of power or it will lose its data. Volatility is a serious disadvantage when long-term data storage is required. Standby power can be made available, but it is certainly an extra expense not required with bubbles.

Perhaps an even more important advantage of the bubble over the CCD is its superior reliability. Even for short-term storage, the bubble is probably superior. CCD's have proven difficult to be produced with adequate reliability. CCD data must be continually recirculated while it is not being used. Each recirculation brings the possibility of new errors. If data contained in mass memories were only stored for a short period of time, then the CCD might represent serious competition.

Bubble memories are likely to be producible at lower cost per bit than CCD's, an advantage which we believe will increase over time as greater bubble density is obtained and yields are improved. Power dissipation is also lower for bubbles than for CCD's.

The most significant advantage of the CCD is higher transfer speed. The bit rate is better by a factor of ten. Bit rates of several megabits/second allow the CCD to compete on even terms with hard disks, something the bubble cannot do with the technology now available.

The CCD package fits easily on a semiconductor circuit board. The bubble requires permanent magnets and orthogonal coils surrounding the chip. Minimum systems cost for CCD's is lower than for the bubble, a big advantage when low price is a major consideration and when not much memory is required. Interfacing CCD's is simpler.

In summary, bubbles will compete successfully against CCD's in those applications that require long-term storage of sizable amounts of data. It is a telling point that the Bell System, which invented both CCD's and bubble domain memories, has chosen the latter for most of its applications.

Rotating Magnetic Memories

Tapes, drums, and disks are examples of magnetic memory systems in which a magnetized surface is moved past a recording head. Drums and disks permit much faster access to data than tapes because the magnetized surface is continuously rotated. Data is accessed either by a single magnetic record/playback head to a particular track or by selecting one of a number of heads positioned at each track. By contrast, it is necessary to traverse the entire length of a magnetic tape to get from one block of data to another if the blocks are located at opposite ends of the tape. Disks, rather than drums, are the preferred method of rotational memory storage because they offer greater capacity.

Disks may be divided into two main categories: fixed head and movable head. Movable head disks are further divided into rigid disks and flexible or "floppy" disks. Floppy disks have very different characteristics from hard disks.

All rotating magnetic memories represent a compromise between the true random access of a semiconductor RAM or magnetic core on one hand, and the serial access of the magnetic tape on the other. For fixed head disks, the time required to access data is the interval required for the disk to turn until the desired data location passes the magnetic heads. The average access time for the fixed head disk is equal to half the period of rotation, known as the "latency" time. For movable head disks, the access time is the latency plus the time for the head to move to the proper track and to settle.

Fixed head disks are the most expensive rotating magnetic memory because they require a head-per-track. They allow much faster access than moving head disks, although access time is still very slow compared with RAM's. Floppy disks cost the least and require the most time to access data.

In the major-minor loop configuration, the bubble memory organization is roughly equivalent to that of rotational memory systems; however, all rotating memories are mechanical devices, by definition. All are apt to require maintenance at some time, and all are subject to mechanical failure. The bubble memory has the advantage of having no moving parts.

Fixed Head Disks - Fixed head disks are more competitive with bubble memories than any other memory peripheral. Both bubble domain memories and fixed head disks are non-volatile. An advantage of the fixed head disk is its high transfer rate. The transfer rate should not be confused with the access time, which is the time is takes to find the desired data location; the transfer rate is the speed at which data can be transferred into or out of the memory.

The total time required to retrieve data involves both access time and data transfer time.

Advantages of bubble technology over fixed disks include the following:

1. Reliability of equipment. The bubble memory has no moving parts to wear out. It requires no servicing or maintenance. (Failures in ancillary electronics are possible, of course.)

2. Ruggedness. One of the principal reasons for utilizing fixed head disks has been their resistance to mechanical shock and vibration. They are superior to moving head disks, but all rotating memories are subject to failure when operated under severe mechanical stress. Bubble memories, on the other hand, are not affected by extremely high levels of shock and vibration which would prevent operation of any disk memory. Unlike bubble memories, disks, with their exposed recording surfaces and tight tolerances between surface and magnetic head, are subject to contamination from dust and impurities.

3. Smaller size and weight. This is especially important in airborne applications.

4. Lower cost. Eventually bubble memories are expected to cost less.

Moving Head Rigid Disks - The technology for moving head disks is much the same as that of fixed head disks. The fixed head disk is superior with regard to access time and resistance to environmental stresses, but it is much more expensive. The multiple heads required by head-per-track disk files render very large systems cost-prohibitive. Unless especially rapid access or unusual ruggedness is required, small systems also use movable head disks for price reasons.

If bubble memories could achieve approximate equality with movable head disks on a cost-per-bit basis, the disk would go the way of the dinosaur. It appears extremely unlikely that price reductions of that order can be achieved for bubble memories during the period covered by our forecasts. In fact, with continued improvements in disk technology, it is not clear that the bubble can ever compete in large systems. The lattice file research at IBM that was to have made very high bubble capacities possible is now considered unpromising.

Flexible Disks - The flexible disk, or "floppy," is a movable head disk drive. Instead of the magnetic head being held close to, but not touching, a rigid disk, the head maintains physical contact with a disk made of flexible Mylar-based material similar to magnetic tape. The disk remains within a cardboard envelope with openings for access, but the whole package is easily removed. The access time, transfer rate, and storage capacity of the floppy disk are not as good as for other types of disks. It has been widely predicted that the bubble memory will soon compete with the floppy in terms of price. While the system cost will be similar, the floppy disk or "diskette" itself, in its package, costs only agout $4. The bubble memory will be price competitive only in applications where the floppy disk does not have to be removed. The great majority of floppy disk applications require the capability of recording and retrieving data on media which can be removed from the drive and stored in a cabinet or other remote location. Many systems, such as word processors and small computer systems, use more than one floppy disk drive. The bubble can replace one of the drives; the other will be used for backup and archival storage.

Because the floppy disk has been the only low-cost, rapid access mass memory available, it has been used in applications for which it is far from the ideal solution. The floppy is not a good memory system in applications requiring continuous usage of the same diskette. Disks are in physical contact with the recording head when in use. They wear out, and the heads are also gradually eroded. Floppy disk drives are not rugged. They do not perform well as portable devices, and they are susceptible to damage from dust and other contaminants. Bubbles are clearly superior in rugged environments or where heavy duty use is required. Portable terminals, numerical controls for machine tools, and process control are natural applications for bubble memories, and not for floppy disks.

Semiconductor Memories (RAM's)

There is not much head-on competition between semiconductor RAM's and bubble memories. It is something like the rivalry between a jet aircraft and a freight train.

The access time of RAM's is in the microsecond/nanosecond range, while bubble access is in milliseconds. If access time or transfer rate is important, bubbles cannot compete. RAM's are volatile; bubbles are not. In extremely small memory systems, RAM's may be preferred over bubbles, even if access time is of no importance, because interfacing is easier, and they have a lower minimum system cost. There is a psychological factor, however. Users tend to resist paying more for bubble memory, with its slower access, than for RAM's, setting an effective upper limit on bubble prices.

Core Memories

Cores are used in high-speed, random access memory systems. Core memories were the dominant main memory systems until semiconductor RAM's were developed. Like semiconductor RAM's, magnetic cores are not really competitive with bubbles. Core memories are not volatile, although reading the memory does destroy the data. Mass storage core memory systems are available, but at much higher prices than those projected for bubble memories.

EBAM (Electron Beam Addressable Memories)

The first random access storage method used with computers was an EBAM system. Electrostatic storage tubes, which were electron beam addressable memories, served as computer main memories until cores replaced them in the early 1950's.

EBAM has enormous theoretical potential. Although it is too slow to compete against modern random access memories, it allows faster data access than any other device competing in the memory gap between disks and RAM's. Unlike its memory gap competitors, EBAM offers the future possibility of very large storage capacity in the region of 10^{12} bytes at lower cost per bit than any other memory technology.

We do not believe, however, that EBAM will offer serious competition to bubble memories. Long-term storage appears to be EBAM's weak point. Data is subject to deterioration over time, which places the reliability of bubble memories beyond the reach of EBAM technology.

EBAM seems to have some technological disadvantages to overcome before it can be a satisfactory memory technology. Analog circuitry is required for the deflection circuits, which introduces a possible source of trouble. The system has high entry cost for a minimum system, compared with bubbles or CCD's. It has the additional disadvantage of requiring a high-voltage power supply. Advanced EBAM technology is still not proven in production. We believe that bubble memory growth through 1985 will not be inhibited by EBAM's.

Domain Tip Memories (DOT's)

Bubble memories are not the only magnetic domain memory technology. Domain tip memories (DOT's) also make use of reverse-magnetized domains.

Instead of garnet, the anisotropic layer in which the domains occur is a very thin (0.1 micron) layer of cobalt permalloy. The "tips" which are propagated through the media are elliptical rather than round at the film surface. Like the round bubble cylinders, the DOT's can be propagated along channels, performing functions that are roughly equivalent to those of bubble memories.

Originally developed at LFE Company under contract from the Air Force, the main American proponent of DOT memories has been CAMBEX (formerly Cambridge Memories, Inc.) in Waltham, Massachusetts. The DOT development actually predates the development of garnet devices.

The main advantage claimed for DOT's over bubbles is higher transfer rates which are now in the 500 kHz range. The main theoretical disadvantage is the much lower densities that can be achieved. DOT's with memory size of 48,000 bits have been produced. DOT's, of course, are non-volatile.

Proponents of the DOT claim that it has never received the publicity or the funding that Bell Labs has given to the bubble, but whatever its essential merits, DOT's do not appear to be a significant competitor to bubble memories in the near future.

<u>Magnetic Tape</u>

There is really no head-on competition between bubble memories and magnetic tape. Bubble memories lie in the memory gap between fast access RAM's and slow access (by comparison) rotating disks. Tape, which is even slower than disks in access, does not fit in the gap. Magnetic tape excels in terms of cost per bit. Media cost for large systems is in the microcent-per-bit range.

From a cents-per-bit standpoint, cassettes are much more expensive than ½-inch tape systems, but less expensive than bubble devices. The cassette media cost is more than two orders of magnitude cheaper than bubble cost.

Bubble cassettes which allow a portion of the memory to be physically removed are now offered by Fujitsu. The cost of a removable bubble memory is so much greater than that of a tape cassette or cartridge that it is doubtful there will be much market for it except where price is not an object. On the other hand, the price of tape recorders that will meet space and special military requirements is so high to begin with that bubble expenses will pose no problem.

Non-removable endless loop tape recorders, such as are used in the IBM "memory" automatic typewriters, will be candidates for replacement by bubble memories. However, the main body of the magnetic tape market will not be menaced by bubble memories.

VII

TRENDS IN TECHNOLOGY

Bubble technology is new, and it is still evolving. Most of the competitive technologies, although now well established, are changing too. Any market forecast must deal with what will happen in the future in price and technology of both bubbles and their competitors.

Price is especially important. In the past, some industry participants have been wildly optimistic about anticipated procedures. As a result, predictions were seriously overinflated. Bubble manufacturers speak in terms of "the chicken or the egg" (volume must build up before prices can come down, but prices must come down before volume can build up). An increase in sales volume, however, does not automatically guarantee a low price; the technological capability to move down the "learning curve" must be there. Technology is directly related to price, since density is a key factor in determining chip capacity and consequently price per bit.

In this section, we will discuss the following bubble parameters:

* Price
* Access time
* Chip capacity

* Bubble density
* Bubble diameter
* Data transfer rate.

PRICE

Potential users consistently referred to price as the prime determinant of whether they would use bubble memories, and present users emphasized that price would determine their volume of use.

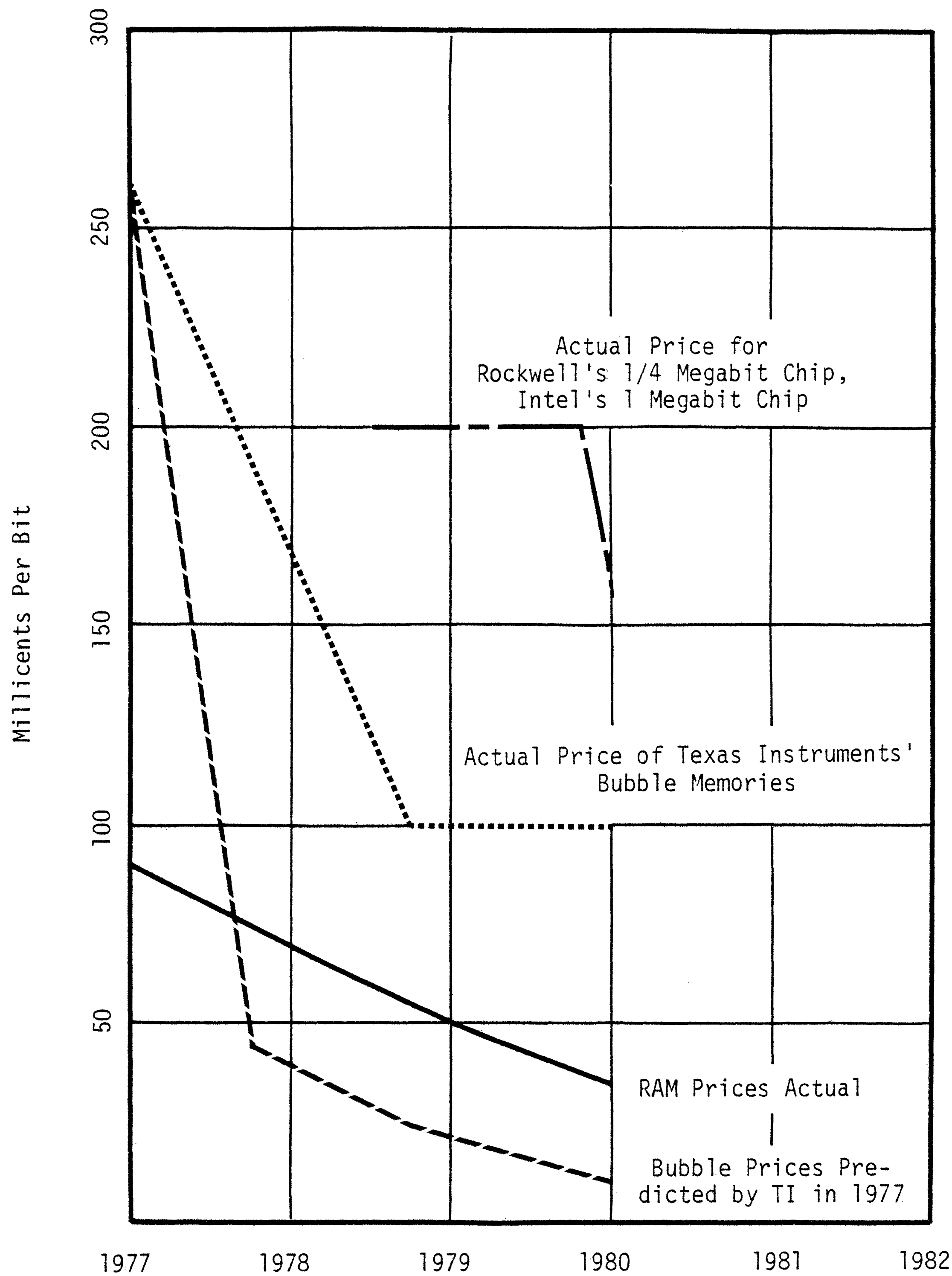
In 1976, spokesmen for Texas Instruments informed the trade press that their 92-kilobit bubble memory would sell for approximately $50, or 40 to 50 millicents per bit, in 1977. In 1977, TI announced the system at $250 for the chip and $150 for the controller, but assured would-be users that the price would fall to 50 millicents per bit by the end of the year, to 20 to 25 millicents per bit in 1978 and to 10 millicents per bit in 1980. Burroughs agreed that bubble memories would be priced at 20 millicents per bit by 1978 or 1979. (See Figure 21.)

By 1978, Texas Instruments had dropped the price, not to 20 to 25 millicents per bit, but to 100 millicents per bit; this is still the price in 1980, not the 10 millicents per bit which had been predicted three years ago.

Prospective users eagerly awaited the larger-capacity chips which were expected to reduce the cost per bit drastically. In 1978, Rockwell brought out the ¼-megabit bubble chip for $500, or 200 millicents per bit. This was twice the cost per bit of the 92-kilobit TI device. In 1979, Intel introduced a one-megabit Bubble Prototype Kit at a cost of $2,280, which contains the bubble chip and several ancillary IC's. A functioning bubble board costs $3,900, or 390 millicents per bit. Potential users were struck by what seems to be a "through the looking glass" situation where increased cost-per-bit is obtained by buying in quantity. There are other advantages to large-capacity chips (compactness, for

FIGURE 21

BUBBLE MEMORY CHIP PRICE PER BIT
ACTUAL COMPARED WITH PREDICTED



example), but the main reason for interest in megabit chips was lower cost per bit; so far it has not been achieved.

Bubble industry participants have become more reticent about predicting future bubble costs. In 1979, a National Semiconductor executive offered an opinion that "in the mid-80's" bubbles would cost one millicent per bit, which is a generality and avoids pinning the forecast to a particular year.

Intel has offered estimates of future prices, but with a difference. The company's sales force has been instructed that Intel will take quantity orders for future deliveries of its one-megabit chip at prices under $1,000 in 1980, $500 in 1981, and $210 to $300 in 1982. If Intel accomplishes these reductions, bubble memories will cost in 1982 what Texas Instruments in 1977 said they would cost in 1978.

RAM prices are continuing downward at a more or less linear rate as larger RAM's are introduced. According to current predictions of industry participants, bubbles will continue to cost more than RAM's for some time to come, which is not in line with what the bubble industry was expecting. Our respondents predicted that bubble prices would drop to between 5 and 10 millicents per bit by 1984 or 1985.

No one seems to feel that bubble memories will ever compete with moving head hard disks on price. Floppy disk drive system prices are in the area of 5 to 30 millicents per bit, hard disks in the millicent range and under. For off-line storage, media cost for floppy disks is approximately one-tenth of a millicent per bit.

ACCESS TIME

Access time is the time required to recall a portion of data recorded on a device. Usually average access time is used for randomly-placed data.

No significant improvement in access time is expected during the next five years. There is more likely to be an increase in access time as chips attain larger data capacities. Access time is dependent principally on the data transfer rate of the bubbles. If, for example, a minor loop contains 4,000 bits and the data transfer rate is 100 kilobits per second, it may take as much as 40 milliseconds to position the loops to the desired data. Access time can be reduced by shortening the loops, but then the major loop must be made longer in order to obtain the same total storage. Multiple major loops might be provided, but the circuitry then gets more complicated.

Intel's one-megabit device, the only one which will be delivered in quantity in 1980, has access time in the 40 millisecond range. Access time to the TI and Rockwell one-megabit chips are in the 8 to 10 millisecond range. Proposed 4-megabit capacity chips may be slower.

Access time will not be appreciably faster unless data transfer rates are improved, which does not appear feasible until current access devices become a commercial reality, possibly in the late 1980's.

CHIP CAPACITY

Chip capacities have been increasing much as predicted. From the 92-kilobit Texas Instrument chip introduced in 1977, we have progressed through the ¼-megabit stage to Intel's one-megabit chip in 1979. Some bubble manufacturers plan to have 4-megabit chips in production by 1983, and possibly by 1982.

With the lattice approach stymied, at least for the time, giant bubble memories of 100 to 256 megabits are not foreseen for the period of our report.

Bell Labs is reported to have built 11.5-megabit chips using contiguous disk propagation, but the access time is long. IBM reports the possibility of multi-layer bubble devices which would allow high capacities. For the next five years, however, 4-megabit chips are likely to continue as the practical limit for commercial bubble devices.

BUBBLE DIAMETERS AND DENSITIES

Bubble density is the number of bubble positions that can be included in a given area. The chip capacity is determined by the bubble density and the size of the storage area on the chip.

The minimum size of the period of the conductor pattern determines the maximum density. The minimum period size is limited by lithographic capabilities in laying down the pattern, and by the design of the pattern. A pattern which does not require narrow strips of permalloy and critical gaps can be made smaller. If lithography and pattern design improve sufficiently, the bubble size itself may be a limiting factor; bubbles of .1 micron have been produced, but it is still not clear whether bubbles of that size can be controlled.

The T-I bar pattern used with the 92-kilobit Texas Instruments chips contains bubbles of 5 micron diameter. The newer products, ranging in chip capacity from ½ to one megabit, use bubbles of 2 to 3 micron diameter.

By using X-ray or electron beam lithography, it will be possible to use smaller patterns. In addition, patterned ion implant structures will allow smaller bubbles to be used in relation to pattern size.

Data densities of as high as 25 megabits per square inch have been achieved in the laboratory. For the next five years, however, it seems likely that the commercially-available bubbles will be designed with maximum densities in the order of 12 to 15 megabits per inch, using bubbles of one to 1½ microns in diameter.

DATA TRANSFER RATE

The bubble memory has been generally assumed to have an inherent fault; its data transfer rate (presently 50 to 100 kilobits per second) is slower than any of its competitors.

Engineers at Bell Labs created widespread interest when they announced that a bubble memory chip had been constructed using dual conductor current access propagation which offered a data rate of 1.5 megabits per second. However, there is also some resistance to the idea. Considering that each of the bubble memory makers has invested millions of dollars on making bubble chips and ancillary integrated circuits and gotten very little, if any, of it back yet, the idea of making obsolete most of what has been done in order to embrace a brand new technical approach is decidedly unwelcome.

When the bias field is eliminated, it appears that data rates of at least 10 megabits per second can be achieved. As we pointed out earlier, there is still no actual working prototype, so that even if there should be a major government program, or the requirement by a major computer company for a high-speed bubble memory, several years would pass before the dual conductor device would be a commercial reality. Given the psychology of the bubble producers and the absence of a major program requiring it, we would be astonished if it were a commercial device before 1985. Yet, it is an exciting technique. Improvement in data speed would result in shortening of access time. The "latency" of the minor loop and the speed of the major loop constitute the major delays that make up the access time.

Price is still the major concern for most potential users of memories. It is too early to estimate the probable cost, but certainly the field access technique will be years along the learning curve before the current access technique makes its debut, so that current access can be expected to cost more initially.

TEMPERATURE RANGE

The bubble memory's operating temperature limitations on the upper end have been a serious concern of the military. If the bubble memory could operate over the full military range, up to +125°C, it would certainly make it easier to sell bubbles to the military. Although bubble memory scientists feel the +125°C limit may well be attained someday, in their view it is not likely to happen by 1985.

Texas Instruments' 92-kilobit chip was specified to operate to +50°C; the Rockwell chips are specified at +70°C. The lowest maximum operating temperature that can be accepted by the U.S. Air Force is +71°C, which is about the limit for military disk memories. Tests of samples by the Navy seem to indicate that the Rockwell RBM 256 ¼-megabit chip does operate to +75°C. Intel also specifies one model of its one-megabit chips to +70°C. Even for a fixed head disk replacement, however, there is still some customer doubt that the bubble can meet the +71°C specification in production quantities, and they desire a greater margin of safety. Other military applications require high temperature ranges, and some customers insist on the full +125°C.

The difficulty at high temperatures is caused by "self-nucleation," or the spontaneous generation of unwanted bubbles, and by problems in magneto-resistive sensing circuits.

Some producers of bubble memories feel that by 1982 a temperature of +85°C is achievable and that by 1985 +100°C may be possible.

VIII

TOTAL MARKET

FORECASTING THE MARKET

If we could get a look at next year's newspapers today, we could buy all the right stocks and bet on the future winners of all the sporting events. Oracles who can foresee the future in spite of any random occurrences have always been in demand, but in short supply.

Forecasting is never an exact science. A mature market can be predicted with accuracy, but a new market can behave like a particle in Brownian motion, being buffeted continually in new directions. A forecaster's job is to predict the most probable course of events, using all the knowledge available to him and explaining the assumptions he made in preparing the forecast. A forecaster cannot always foresee every possible contingency. For example, a sports forecaster who predicted in 1979 the number of gold medals to be won by U.S. athletes at the Moscow Olympics did not discuss the possibility of zero gold medals, but when the United States decided to boycott the games, that result was inevitable.

As we stated in the 1977 Bubble Domain Memories report:

> "There are significant differences in developing forecasts for markets which do not presently exist and for more mature markets. First, estimates must be made based on what the researcher perceives users ought to want rather than on users' needs which have already been demonstrated in the marketplace. Second, dollar shipments must be based on estimates of future prices made by technologists/researchers rather than on data developed by manufacturing/marketing personnel on economies of scale and increased demand. Finally, it is more difficult to estimate the timing of market penetration for a device which cannot easily be designed into existing equipment and, in fact, will create many new and presently unforeseeable applications.
>
> "The question, then, might be asked, 'Why make a forecast at all? Why not wait two years and then make one?'
>
> "The answer is that decisions need to be made now. It is not too early for the manufacturer of fixed head disks to assess the impact of bubbles on his business and to make plans to ensure his survival. A company planning to make a floppy disk drive or diskette must make a decision now as to whether he should turn back. The bubble memory manufacturer must make plans on the basis of the best analyses available rather than on uncertainties.
>
> "It is not unlikely that our figures will require revision in the future, but it is our hope that in performing our in-depth research, in analyzing the data, and in reaching our conclusions, we will assist industry participants in making informed business judgments.
>
> "We intend to update this report as the market grows and matures in the same manner as we have done with our other industry reports -- for example, Data Recording was followed by Data Recording Industry II, Floppy Disk Markets was followed by Floppy Disk Markets II, etc."

This report is Bubble Domain Memories II.

THE TOTAL MARKET

The industry has not grown as rapidly as we had expected, for two principal reasons:

* Prices failed to decline as anticipated; none of the industry experts predicted a higher price per bit than 40 millicents in 1977, and most thought it would be much lower; the actual 1980 price is 100 millicents.

* The telephone switching application failed to develop; increased need for storage has made the "Winchester-type" disk the preferred mass storage for telephone switching centers.

Military spending cutbacks also slowed market development in the government area.

Our original report, which had seemed pessimistic in 1977, was more accurate in its predictions than other forecasts. Texas Instruments had officially predicted a $100 million market in 1980, Small Business Systems $92.4 million in 1979, and Gnostic Concepts $328 million in 1981. Our more restrained original estimate of $58 million for 1980 was closer to the mark, but still high; our 1979 projection was $11 million.

Still, the bubble market has begun to develop. Unlike plated wire memories, EBAM, planar thin film, and apparently CCD's, the bubble memory is a product which, as we indicated in our original report, is here to stay. Most new technologies have technical problems in the early stages of production; bubbles have not. Whatever troubles the bubble makers had with yields and however this may have affected their ability to lower prices, the bubble memories which have been shipped out have worked well.

Bubbles have outperformed their associated circuitry; any problems have generally been with ancillary semiconductor circuits. This situation contrasts with that of floppy disks and digital cassettes at the time of their introduction when their low cost and convenience attracted buyers in spite of their reliability and error rate problems. Except for some temperature problems, mainly in military applications, bubbles have lived up to their advance notice in performance and reliability. It is clear now that bubble prices will decline. Many users who have samples or are merely watching bubbles with interest will be ready to proceed as prices permit bubbles to be used in their applications. Nevertheless, bubble memories have lost some ground; some applications where Winchesters, ROM's or RAM's are now used have been permanently lost. The telephone switching market was destined to be mainly captive in any case, and need not unduly concern independent bubble makers.

VDC believes that shipments of bubble memory devices by U.S. companies will increase from 138,800 units in 1980 to 1,446,000 units in 1985, an average annual increase of 60 percent over the period. (See Table 2 and Figure 22.) Over that time period, we anticipate that the dollar value of shipments will increase from $18.4 million in 1980 to $226.0 million in 1985, an average yearly gain of 65 percent. (See Figure 23.) The more rapid increase of dollar sales over unit sales will result from increased data capacities of chips. We have assumed that the cost per bit will drop by an average of 45 percent per year for most bubble memories. Exceptions are in the military, telephone, and some industrial markets where temperature stability will be pushed to the limit and prices will remain high.

In 1977, we did not believe that bubble memory manufacturers would meet their forecasts of precipitate price declines, but in 1980, we believe that they can meet the more modest but still impressive price reductions now being forecast. Bubble memory producers are now more cautious in their forecasts, and more knowledgeable about semiconductor manufacturing technology. The result is improved yields, and as the industry moves further along the learning curve, prices will fall.

TABLE 2

SHIPMENTS OF BUBBLE MEMORIES 1980-1985

	1980	1981	1982	1983	1984	1985
Dollars (Millions)	18.4	24.1	41.8	103.9	179.1	226.0
Units (Thousands)	138.8	181.5	292.2	475.0	915.5	1,446.0

FIGURE 22

SHIPMENTS OF BUBBLE MEMORIES 1980-1985

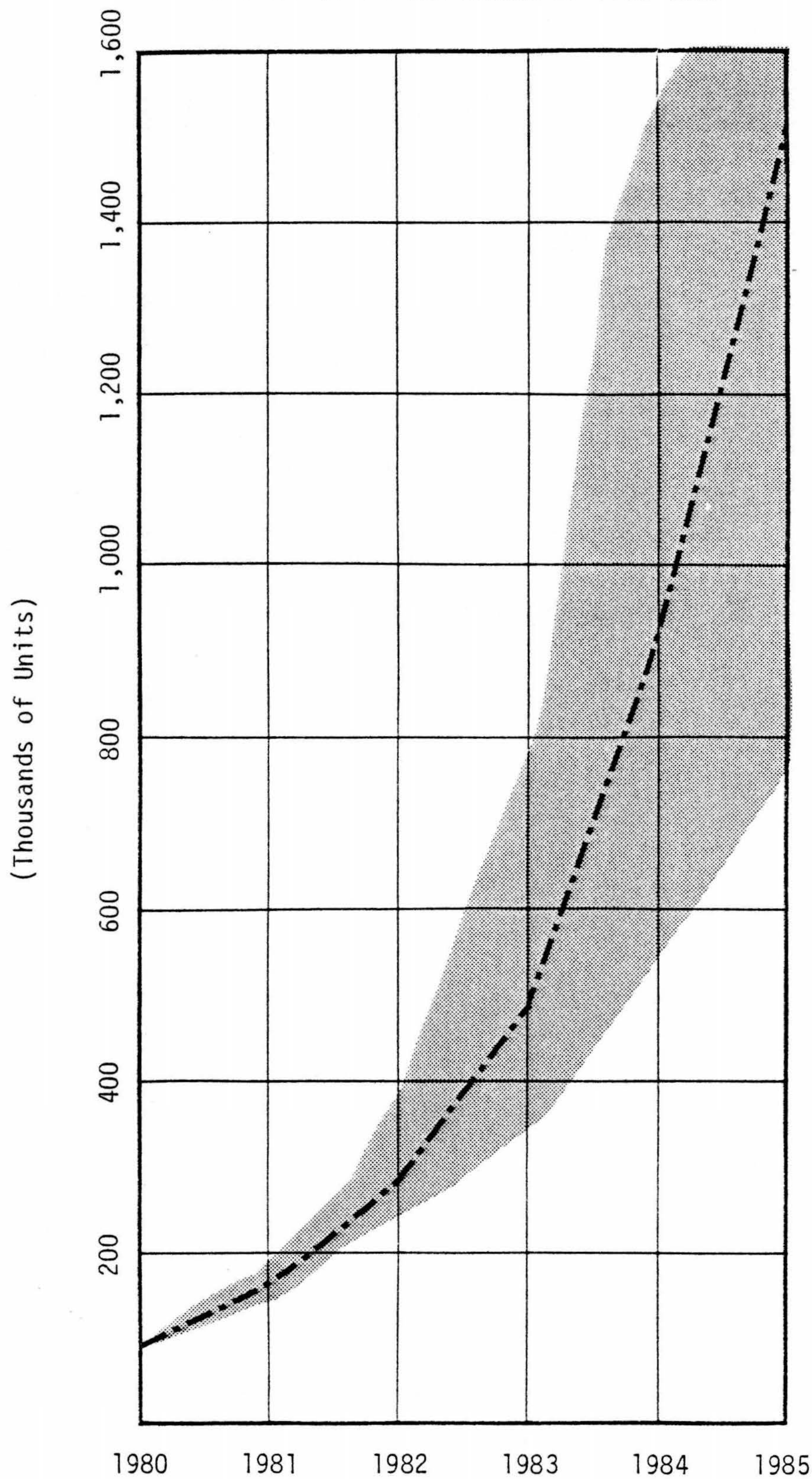
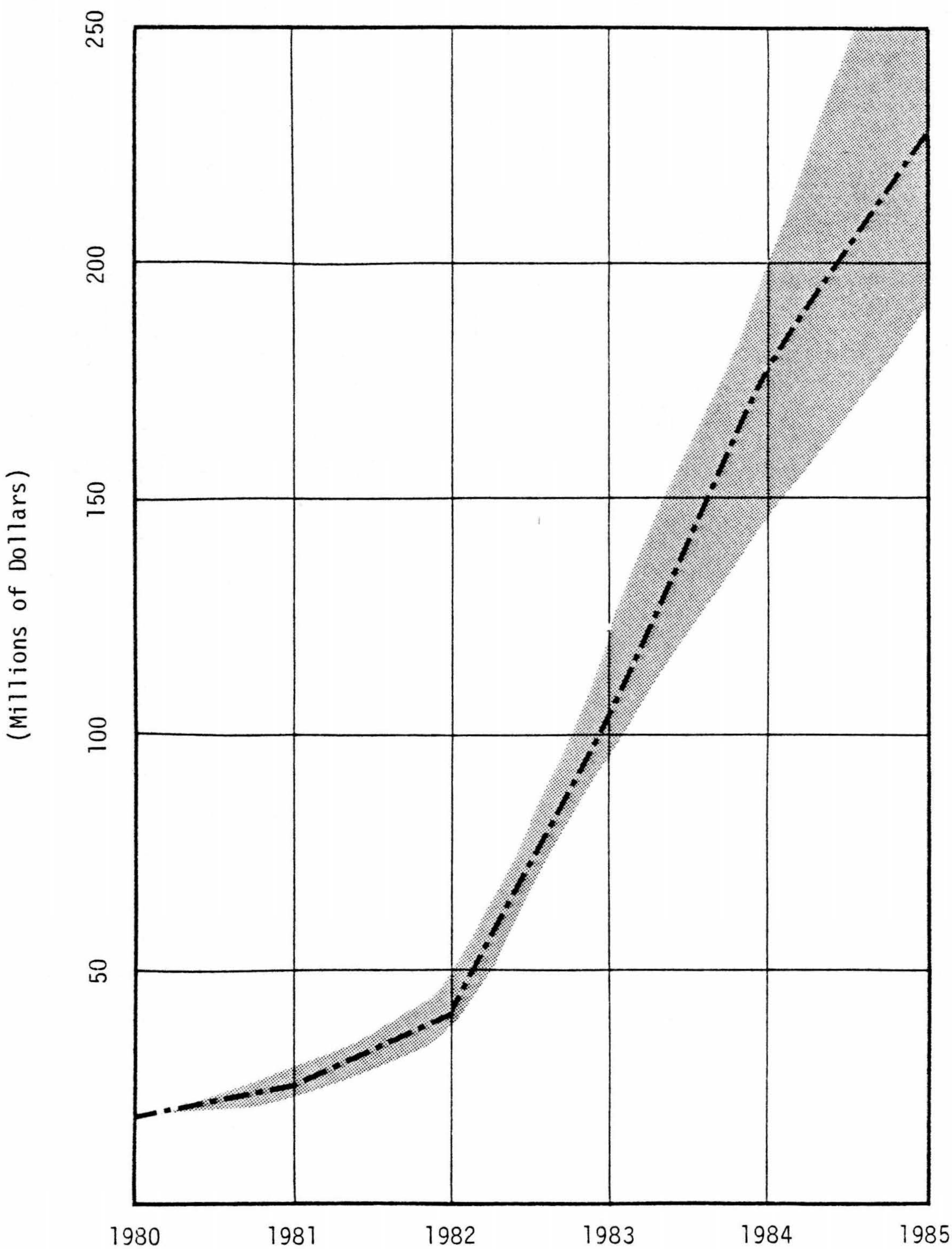


FIGURE 23

SHIPMENTS OF BUBBLE MEMORIES 1980-1985



In Figures 22 and 23, the area of uncertainty is shaded. With so many technical and price uncertainties, there is more likelihood of deviation from prediction than there would be with a more mature product and market. The probable percentage of deviation is greater for units than for dollars because future bubble prices are uncertain. In some segments, such as numerical controls for machine tools, the demand for bubbles will be comparatively price inelastic because bubbles have special qualities of ruggedness which these manufacturers require. In some segments, such as office equipment, the demand is very price dependent. Therefore, a sharp reduction in prices would increase unit sales volumes greatly, but would have less effect on dollar volume.

MARKETS BY TECHNOLOGY

In analyzing the bubble domain memory markets by technology, there are three logical divisions:

* Chip organization: Whether a serial loop configuration or a major-minor loop configuration is employed.

* Data capacity: Whether the device is relatively small in data capacity, as were the earlier chips, containing a quarter of a megabit or less; medium-sized, as the one-megabit chips introduced after 1978; or large-sized, as the two- to four-megabit chips which are predicted for 1983.

* Propagation pattern: Whether permalloy bar files, patterned ion implant structures, or current access propagation will be used.

We have segmented the bubble domain memory market by the first two categories, but not by the third because there is insufficient data at this time.

Chip Organization

The serial loop configuration in which all of the bubbles on a chip are conducted along a single long path is the simplest configuration, but it will constitute a very small portion of the total bubble memory market. (See Figures 24 and 25 .) From 28 percent of unit shipments in 1980, it will decline to only 3 percent in 1985, and in dollar value from 26 percent to 6 percent. The present serial devices are mostly used in AT&T's telephone message units, where dollar values are dependent on the internal transfer rate of the Bell system, which we do not know.

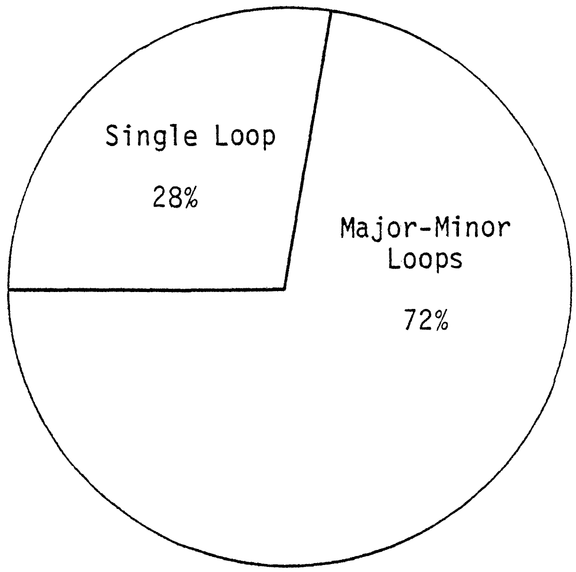
It used to be thought that the price per bit would be lower for serial loop configuration devices, but this appears to be so only in applications where the error rate is unimportant, such as voice recording. The problem is that a single defect at any position can invalidate all of the digital data on a loop. Whereas major-minor loop configured devices can include redundant minor loops, allowing only the good loops to be selected for use, no such option is possible for the single loop chip; it needs to be perfect. Most industry participants believe that it is more cost-effective to push density to its extreme limit than to try for zero defects.

Even if there were no problem with obtaining zero defect chips, however, the single loop configuration would still be a small part of the market because the access time would be too long. Only voice recording and replacement of some instrumentation recorders seem likely candidates for single loop configured memories.

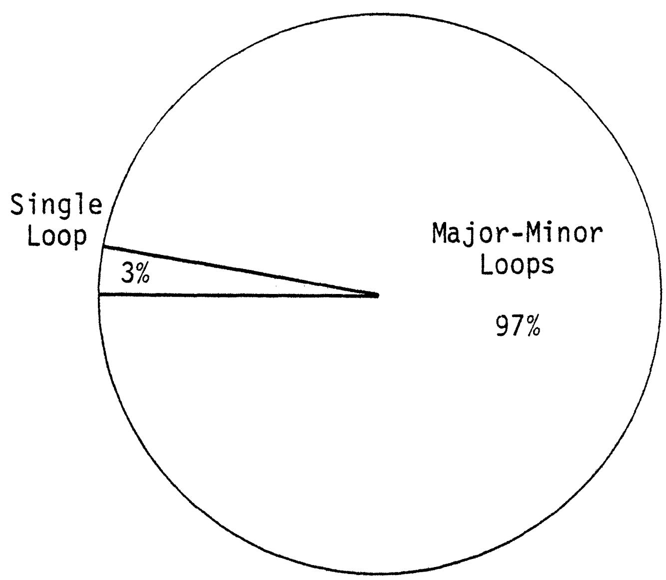
The Fujitsu 64-kilobit bubble memory cassette demonstrates that defect-free single loop recorders can be produced, but the price per bit is more than twice that of the Texas Instruments 92-kilobit major-minor loop device. In 1980, all of the standard bubble devices offered by American companies use major-minor loop configurations. Only Fujitsu offers a standard single loop device.

FIGURE 24

MARKETS BY CONFIGURATION
(Units)



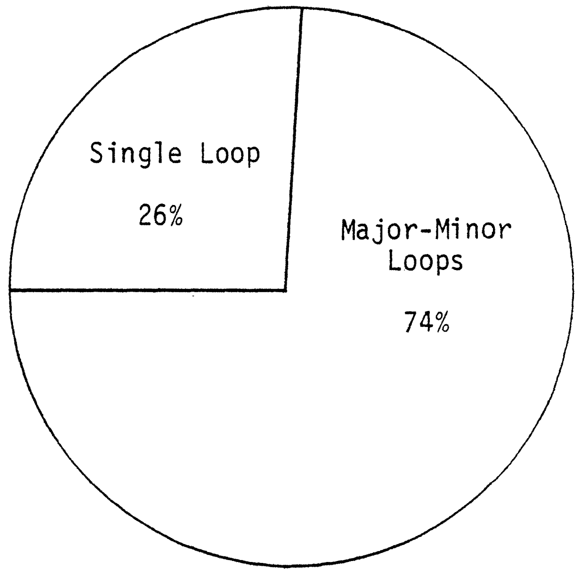
1980



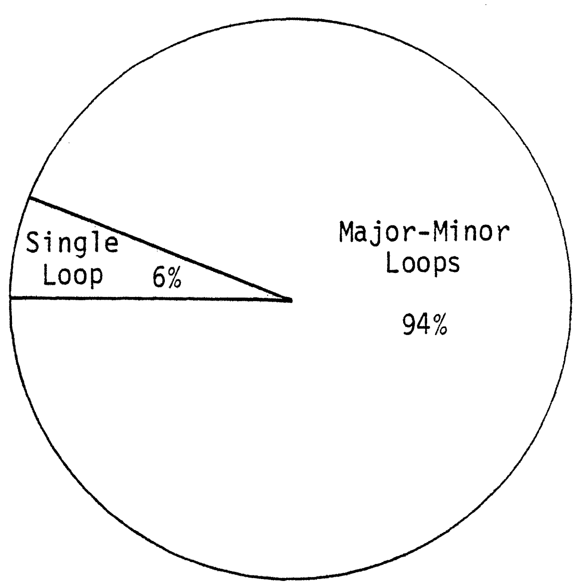
1985

FIGURE 25

MARKETS BY CONFIGURATION
(Dollars)



1980



1985

Data Capacity

Bubble memories in 1977 were small in capacity by today's standards. In 1980, Texas Instruments' 92-kilobit chip, which uses bubbles with a diameter of 5 microns, is still in production. The Intel one-megabit device is representative of the next generation of bubble memories. It uses bubbles 2.7 microns in diameter. Texas Instruments, Rockwell, and National Semiconductor have announced one-megabit chips, although none is actually in production.

In the next stage, four-megabit chips are planned, with production likely in 1983. As bubble densities increase, new devices which capitalize on the concomitant cost advantages will be introduced.

In the low-capacity area, RAM's, PROM's, and EPROM's provide competition. In the future, we expect ½-megabit and larger bubble chips to be in much greater demand. When four-megabit chips make their appearance, a single bubble chip becomes price competitive with a double density 8-inch floppy disk system for on-line storage; growth of this market will be rapid.

In 1980, we believe that shipments of bubble memory devices with ¼-megabit and lower capacities will total 137,000 units and will increase to 305,000 units in 1983. After that, we believe that shipments of these devices will decline to 105,000 units in 1985, a net average decline of 5 percent per year over the five-year period. (See Figure 26 and Table 3.) The share of market will decline from 99 percent in 1980 to 7 percent in 1985. (See Figure 27.)

In dollar value, the low chip capacity market will increase from $17 million in 1980 to $30.2 million in 1983, and then decline to $6.3 million in 1985, an average annual decline of 18 percent over the five-year period. In dollars, the small capacity chip will decline from 92 percent of the market to 3 percent in 1985.

TABLE 3

SHIPMENTS OF BUBBLE MEMORY DEVICES BY CHIP CAPACITIES
(Thousands of Units)

	1980	1981	1982	1983	1984	1985
¼-Megabit and Less	137.7	172.7	256.1	305.0	135.0	105.0
More than ¼-Megabit; Less than 2 Megabits	1.1	8.8	36.1	164.5	650.5	1,023.0
2 Megabits and Over	--	--	--	5.5	130.0	318.0
TOTAL	138.8	181.5	292.2	475.0	915.5	1,446.0

FIGURE 26

SHIPMENTS OF BUBBLE MEMORY DEVICES BY CHIP CAPACITIES

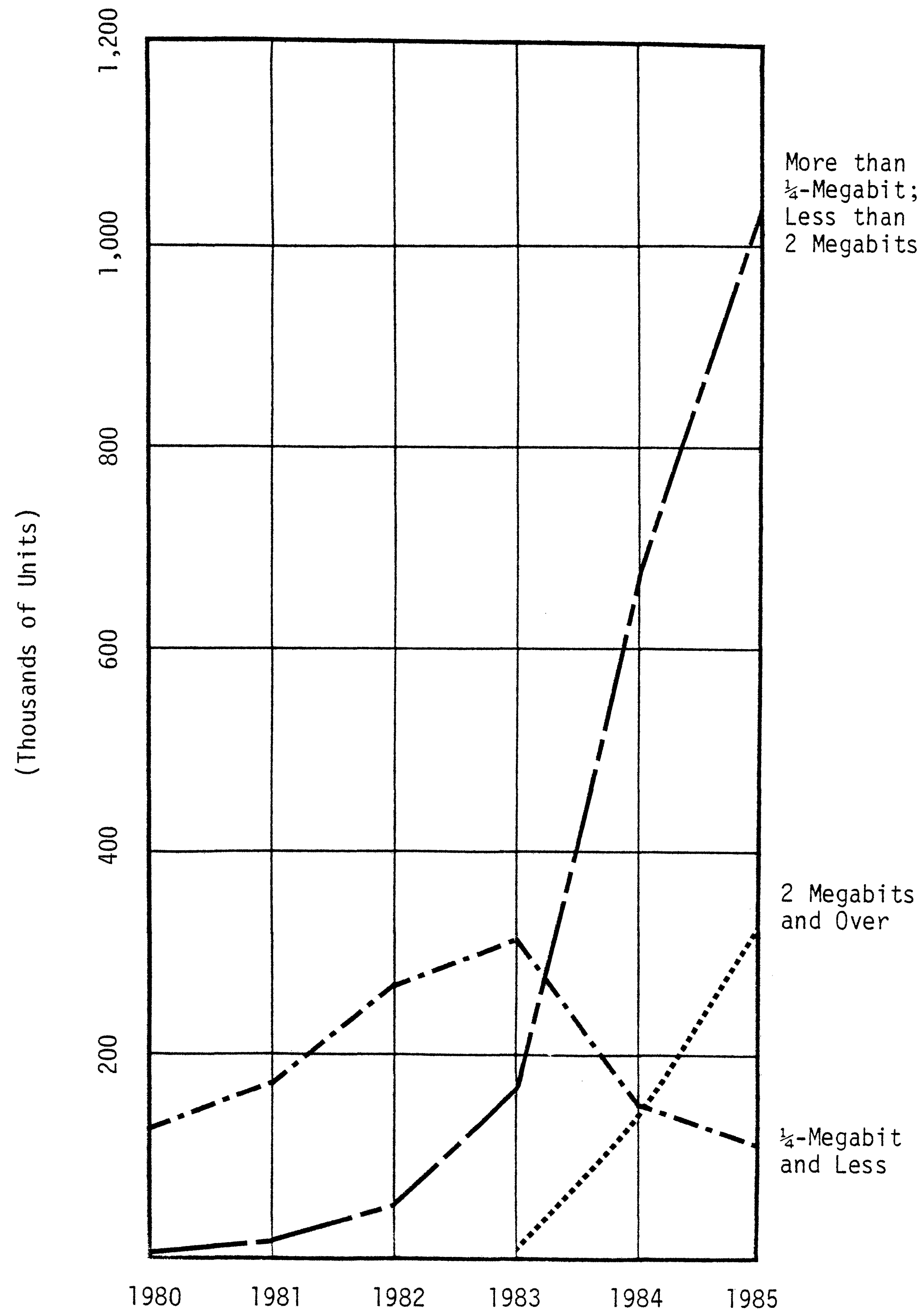


TABLE 4

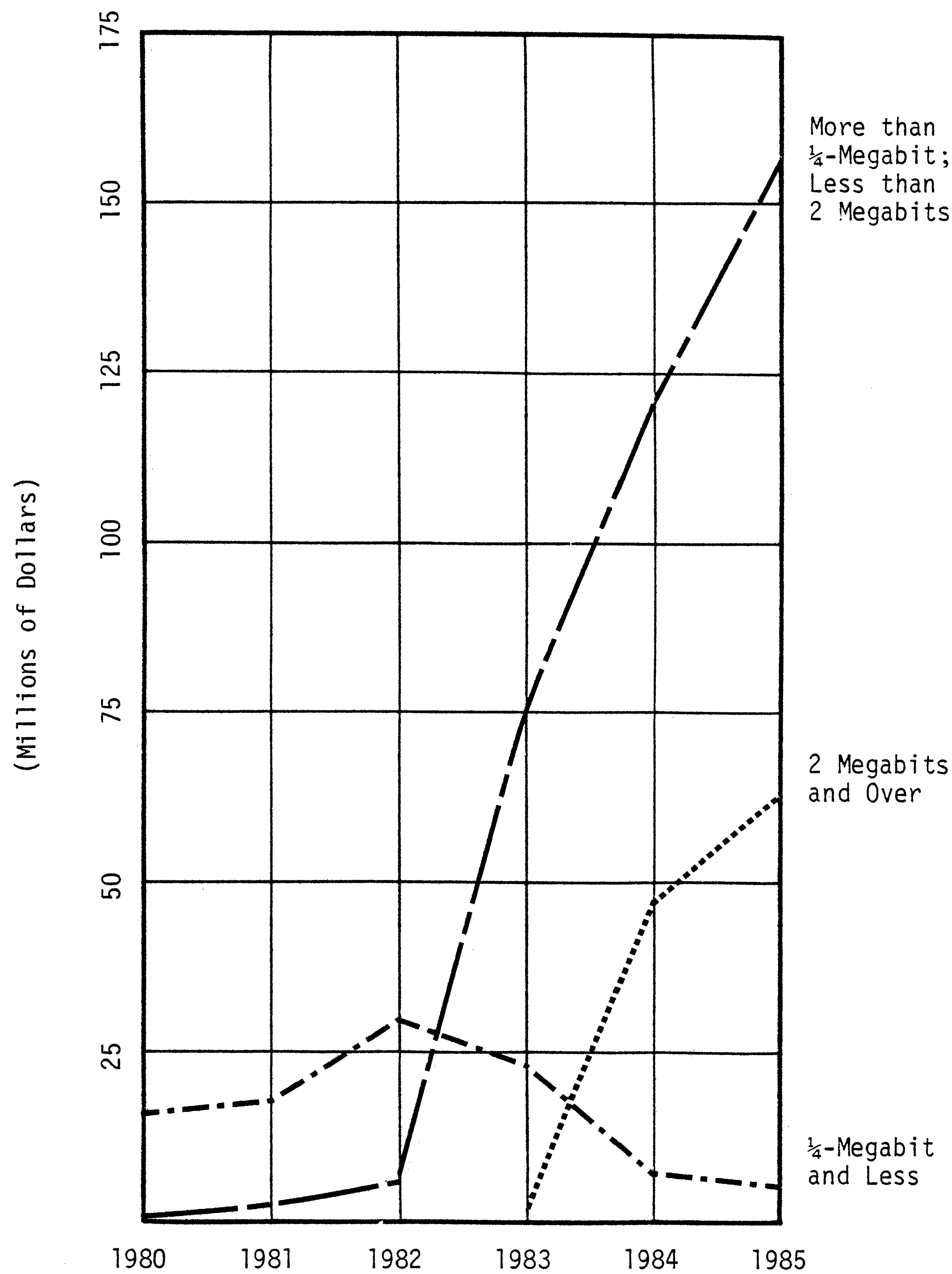
SHIPMENTS OF BUBBLE MEMORY DEVICES BY CHIP CAPACITIES

(Millions of Dollars)

	1980	1981	1982	1983	1984	1985
¼-Megabit and Less	17.0	19.2	30.2	23.5	9.5	6.3
More than ¼-Megabit; Less than 2 Megabits	1.4	4.9	11.6	76.8	122.8	156.1
2 Megabits and Over	--	--	--	3.6	46.8	63.6
TOTAL	18.4	24.1	41.8	103.9	179.1	226.0

FIGURE 27

SHIPMENTS OF BUBBLE MEMORY DEVICES BY CHIP CAPACITIES



What is now a high-capacity chip at one megabit will be a medium-capacity device in three years; these chips will constitute only one percent of the unit shipments in 1980, but 71 percent in 1985. Shipments will increase from 1,100 units in 1980 to 1,023,000 units in 1985, an average yearly growth rate of approximately 400 percent. Dollar shipments will grow from $1.4 million in 1980 to $156.1 million in 1985, an average growth rate of 160 percent.

Large-capacity chips may be introduced in 1983. There is always considerable uncertainty in predicting timetables for products not yet in production. Companies will try to produce four-megabit chips in volume by then. If this should be unfeasible, they are likely to turn to two-megabit chips.

We expect to see 5,500 large-capacity chips shipped in the first year, increasing to 318,000 units by 1985, for a 22 percent market share. In dollars, we expect that shipments will grow from $3.6 million in 1983 to $63.6 million in 1985, for a 28 percent share of the market. (See Figures 28 and 29.)

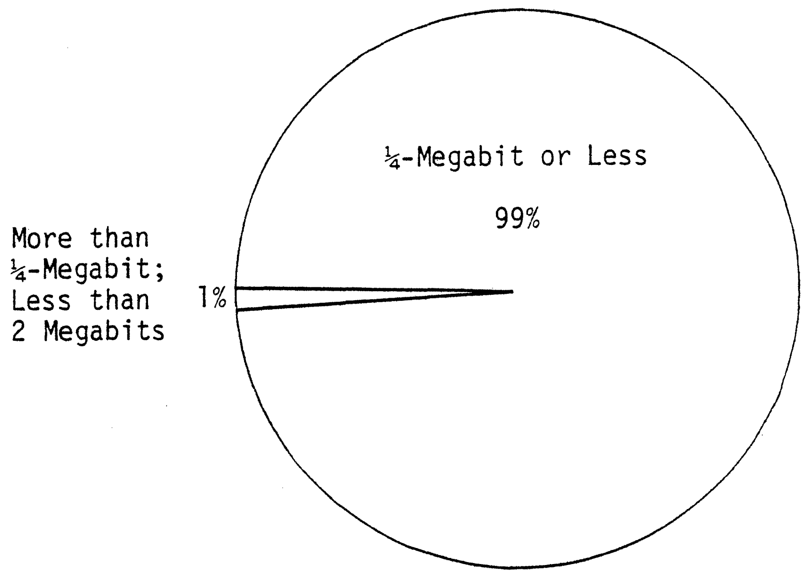
Propagation Pattern

All present commercial devices utilize the permalloy bar file. The chevron design has begun to replace the T-I bar, but these technologies are very similar.

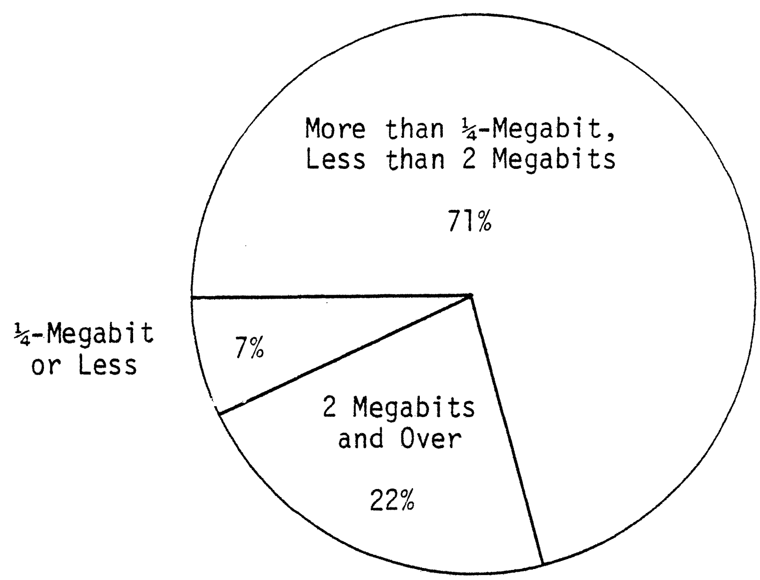
In terms of technology, patterned ion implant structures are a quantum leap, and current access is an even greater one. We believe that patterned ion implant structures (contiguous disk) are near to becoming a commercial reality, but for reasons already discussed in Technology, the current access devices are not apt to appear commercially until late in the 1980's. At this time, we are not able to make a reasonable forecast of ion implant structure device shipments; we are sure that efforts are underway to introduce large-capacity chips using this technique before the end of our forecast period.

FIGURE 28

MARKET SHARE BY CHIP CAPACITY
(Units)



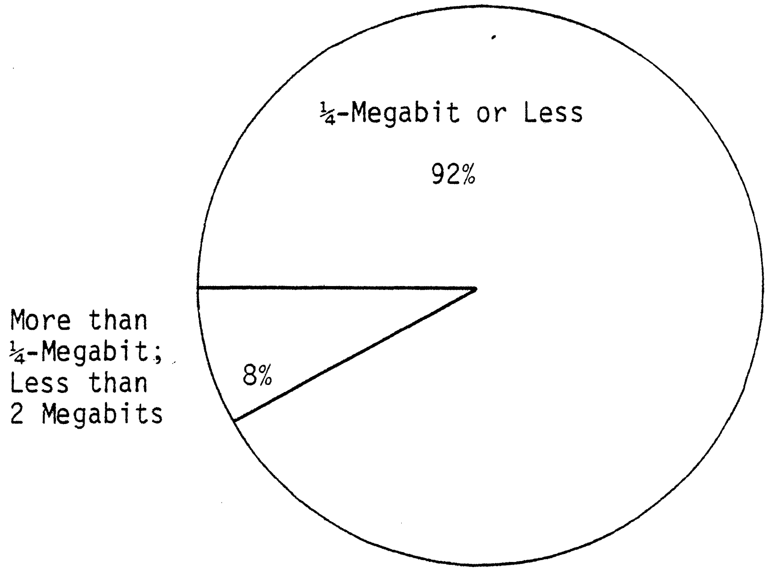
1980



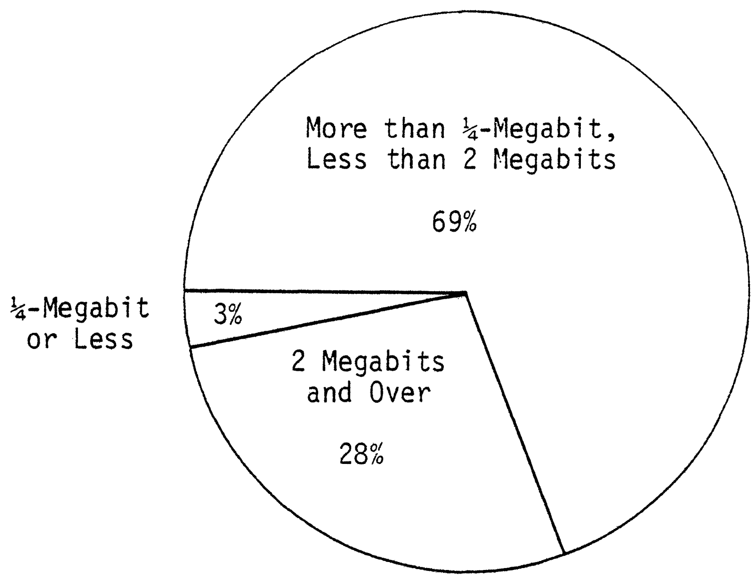
1985

FIGURE 29

MARKET SHARE BY CHIP CAPACITY
(Dollars)



1980



1985

MARKETS BY APPLICATION

At a significant price disadvantage, OEM's need to have a clear reason for using a new technology: portability, ruggedness, reliability, etc.

Bubble memories do not have the potential for revolutionizing the electronics and computer industries, as did the transistor, the integrated circuit, and the microprocessor. Bubble technology is new and different, but the applications are old. As research continues, new and unforeseen applications may develop, but for now bubble memories compete for only a portion of the memory market. Current access propagation, with its promise of high-speed operation and possible savings in cost and space, may bring on a whole new era in bubble memories, but not in the timespan of 1980 to 1985.

Tables 5 and 6 and Figures 30 and 31 illustrate the growth of the major market segments. In 1980, the bulk of shipments will be captive, as Texas Instruments and Western Electric ship to other branches of their own companies. Together, shipments for terminal and telephone applications will account for 98 percent of unit sales and 89 percent of dollar value in 1980. Intracompany strategy undoubtedly affected the promotion of Texas Instruments' bubble memory terminal and the telephone voice recorder. In 1985, however, terminals will continue to be the largest single bubble application, accounting for 35 percent of unit sales and 22 percent of dollar sales; most of this business will not be captive. (See Figures 32 and 33 .)

In 1985, we believe that small computers and word processors will follow terminals in both units and dollars, each accounting for 17 percent of units and dollars. Military and space applications will constitute 14 percent of the dollar value of bubble memories, but less than 1 percent of the units.

TABLE 5

SHIPMENTS BY APPLICATION 1980-1985
(Thousands of Units)

	1980	1981	1982	1983	1984	1985
Machine Control	0.8	1.8	6.0	25.0	100.0	200.0
Process Control	0.7	1.5	3.0	30.0	100.0	150.0
Terminals	130.0	150.0	200.0	250.0	300.0	500.0
Word Processors	--	20.0	50.0	100.0	150.0	250.0
Small Computers	0.1	1.0	25.0	50.0	200.0	250.0
Dictating Machines	--	--	--	1.0	20.0	40.0
Military and Aerospace	0.2	0.2	0.2	4.0	5.5	6.0
Telephones	7.0	7.0	8.0	15.0	40.0	50.0
TOTAL	138.8	181.5	292.2	475.0	915.5	1,446.0

FIGURE 30

SHIPMENTS BY APPLICATION 1980-1985

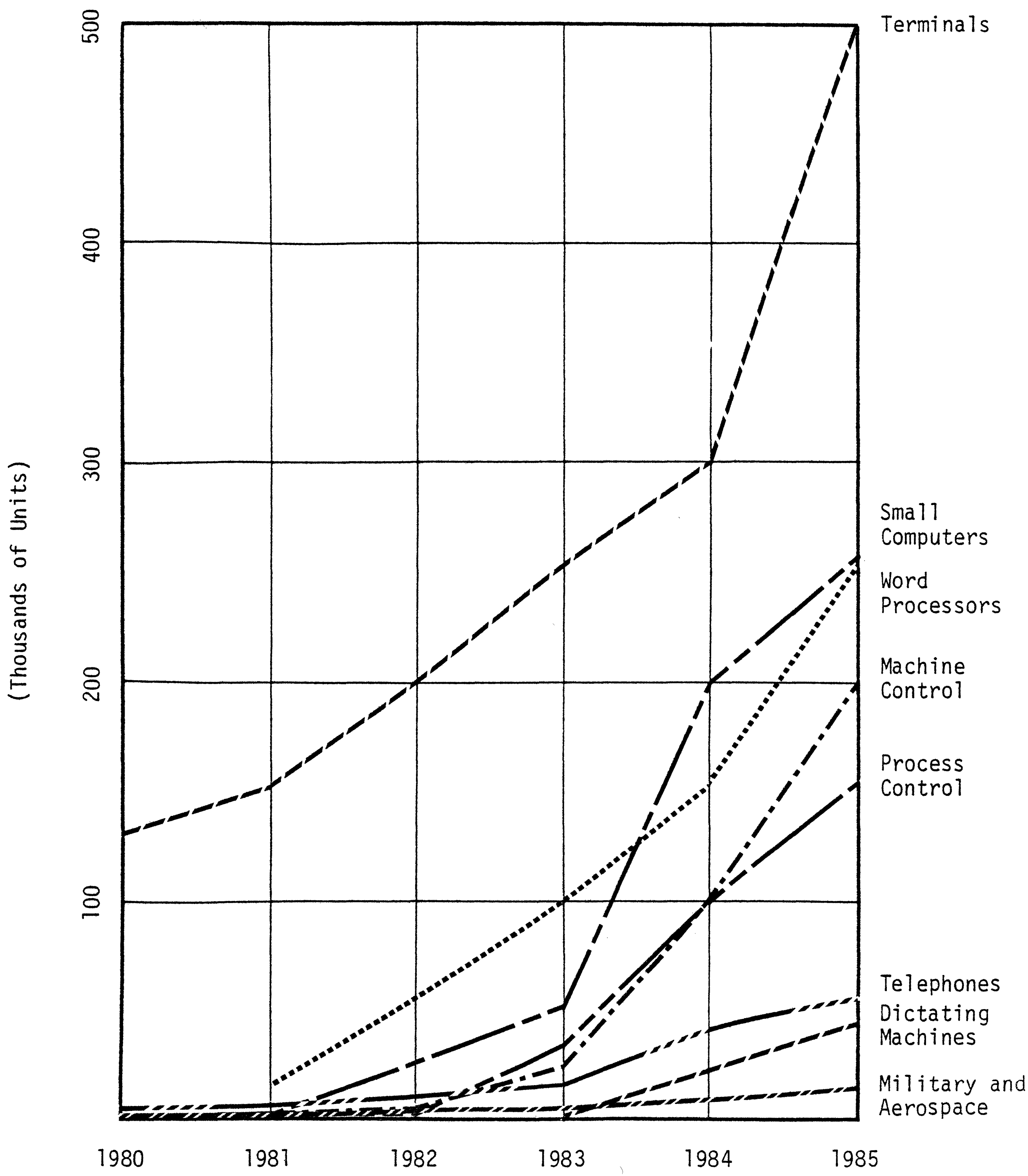


TABLE 6

SHIPMENTS BY APPLICATION 1980-1985

(Millions of Dollars)

	1980	1981	1982	1983	1984	1985
Machine Control	0.5	0.8	1.8	5.5	14.4	20.0
Process Control	0.5	0.6	1.8	6.5	14.2	15.0
Terminals	11.4	14.1	20.0	38.8	48.0	50.0
Word Processors	--	2.0	4.0	10.0	19.5	37.5
Small Computers	0.4	1.0	7.5	10.9	26.0	37.5
Dictating Machines	--	--	--	0.2	2.0	4.0
Military and Aerospace	0.6	0.6	0.7	22.0	30.0	32.0
Telephones	5.0	5.0	6.0	10.0	25.0	30.0
TOTAL	18.4	24.1	41.8	103.9	179.1	226.0

FIGURE 31

SHIPMENTS BY APPLICATION 1980-1985

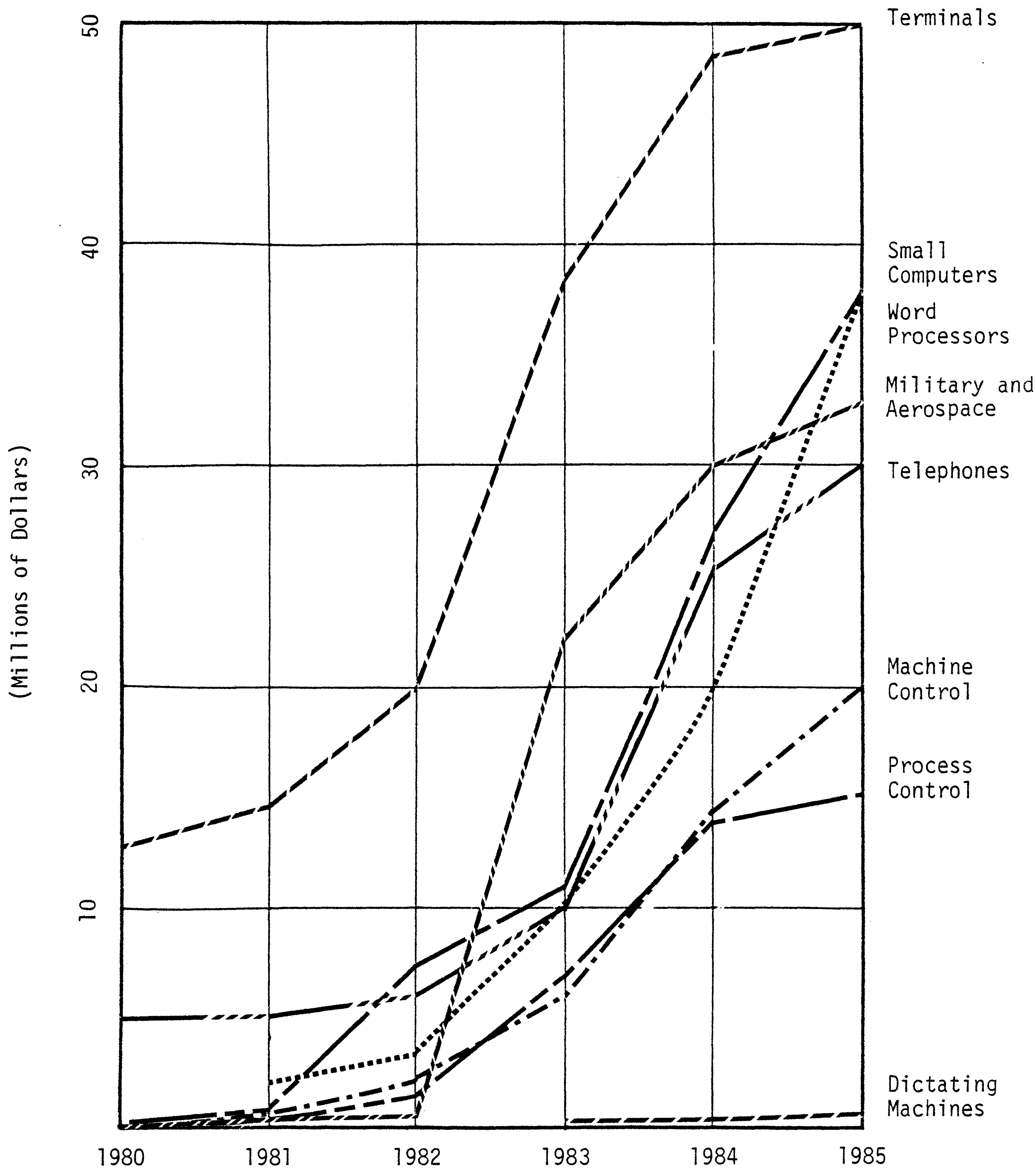
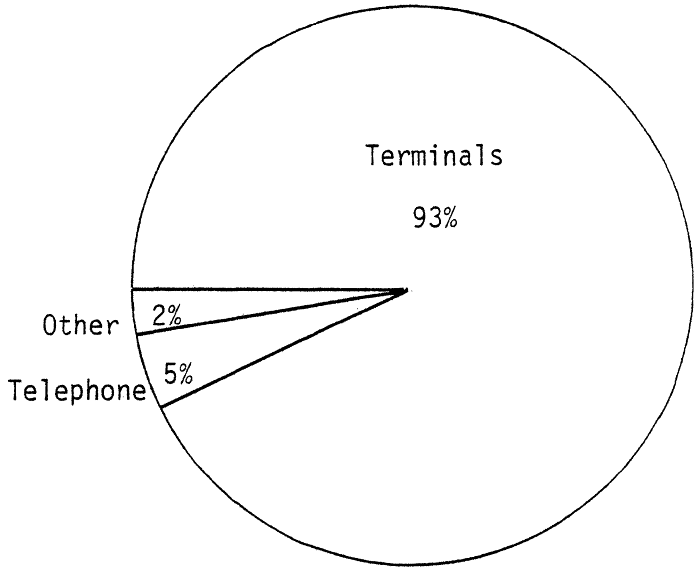
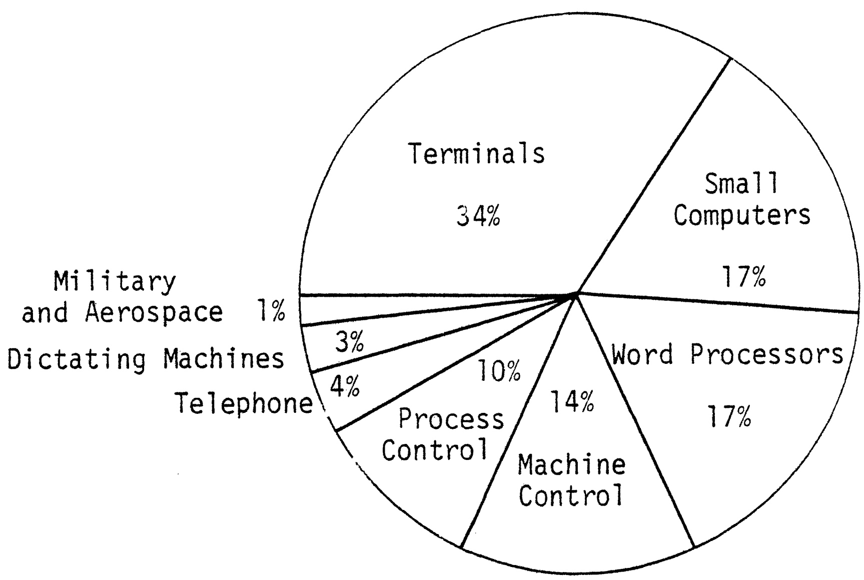


FIGURE 32

MARKET SHARE BY APPLICATION
(Units)



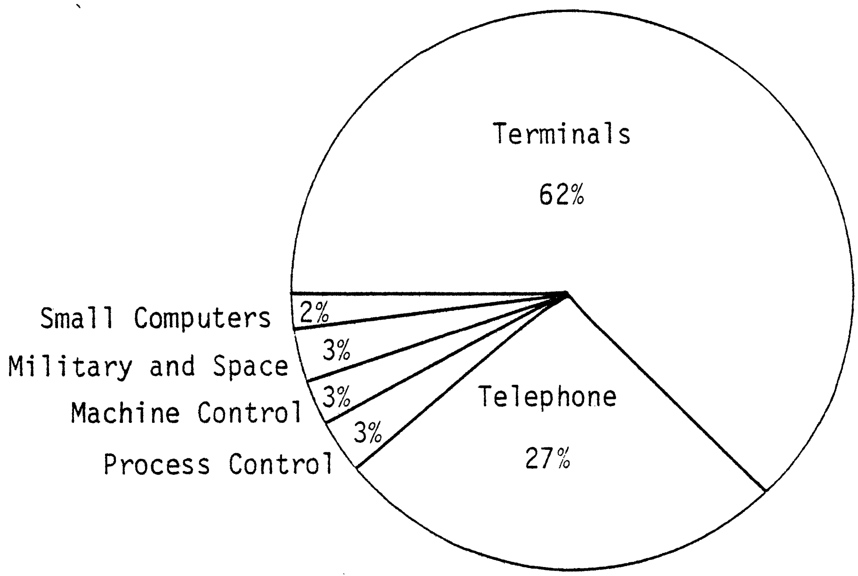
1980



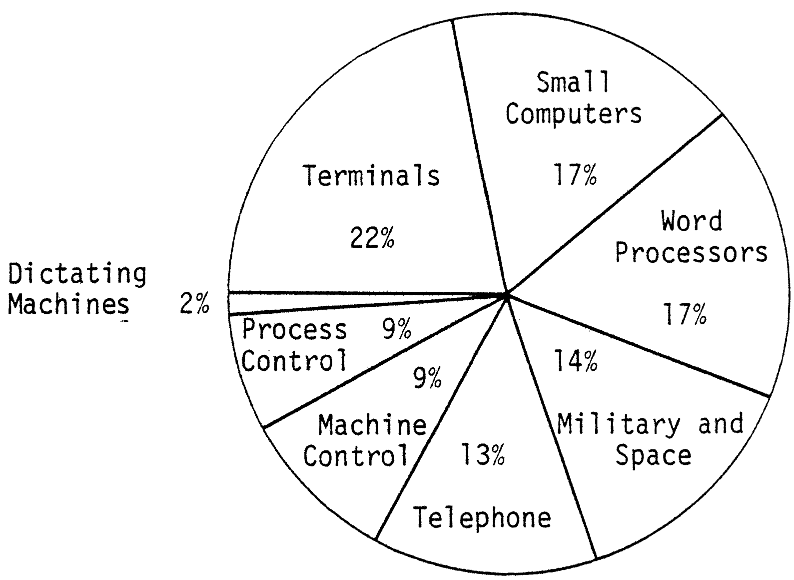
1985

FIGURE 33

MARKET SHARE BY APPLICATION
(Dollars)



1980



1985

Machine Control

Market penetration of a new technology such as bubble domain memories is aided greatly if one or more "ideal" applications can be found. Numerical control of machine tools is such an application. Although the machine tool business tends to be one of the most conservative industries regarding new engineering methods, the bubble memory promises to catch on rapidly with the N/C market. This market is not large in comparison with commercial computer equipment; it consists of approximately 10,000 systems produced in the U.S. in 1980. Within three years, however, we expect virtually all new N/C machines to be equipped with bubble memories.

Already, General Numerics has incorporated bubbles into its N/C machines. A composite of German and Japanese interests owns this company, which is the largest producer of N/C machines in the world. The Japanese portion of the company will turn out 3,000 N/C machines in 1980. Production models contain an average of three bubble memory devices, which are made in Japan.

The German machines will use four bubble devices per machine, but are not yet into production. Prototypes use Rockwell devices; in production the bubble devices will be manufactured by Siemens, one of the owners of General Numerics, under license from Rockwell. Quantities will initially be in the range of 7,000 to 8,000 per year.

American manufacturers are watching carefully. We believe that the largest U.S.-based N/C producer, General Electric Company, will soon equip more than 2,000 units per year with bubble memories, and Sundstrand has announced plans to use the Intel megabit chip.

We expect total shipments of bubble memory devices used in numerical machine tool control to increase from less than 1,000 units in 1980 to 200,000 units in 1985, and from less than $1 million in

1980 to $20 million in 1985. Of this, less than half will be numerical control as we know it now, but the N/C application will introduce the bubble memory to control builders who will use it in the growing robotics industry as well as in improved factory control. With increasing emphasis on productivity, we think it likely that the U.S. over the next five years will regain some of the ground we have lost to the better-automated Japanese industry.

The N/C application itself is worth examining as an illustration of just where the bubble memory can perform better than anything else. N/C machines are characteristically used for a medium-length run of machine parts. They are not ordinarily used for one-of-a-kind parts or for extremely large runs. Historically, the memory system which performed the function now being handled by the bubble memory was a combination of a paper tape punch and a paper tape reader. The machine was controlled during its operations by a loop of paper tape which was in motion while the machine operated, the holes being sensed by mechanical fingers or by light beams. For a run of 1,000 pieces, the tape travelled through 1,000 times and tended to get badly worn. Some improvement has been obtained with mylar, but the tape punch and reader caused more trouble than anything else in the N/C system. Magnetic tape is even worse; particles of metal, dust, coolant, and other contaminants destroy the tape, temperatures vary widely at the drive, and in some applications there can be shock and vibration problems. For these reasons, recent advanced N/C designs have replaced the paper tape devices with RAM's, which are improvements over paper or mylar tape in every way except volatility.

Moving magnetic memories will still be used in N/C at remote locations in conjunction with computers that control the equipment, but the amount of storage required at each machine is well suited to bubble memories.

Use of bubble memory in numerical control and robotics applications will greatly boost its credibility.

Process Control

Use of bubble memories in process control will parallel that of machine control. We believe that shipments will increase from fewer than 1,000 units in 1980 to 150,000 units in 1985. At this early stage, the average annual growth rate is bound to be very high; it will be close to 200 percent per year. In dollars, we expect sales to increase from approximately $500,000 in 1980 to $15 million in 1985.

Process control makers are attracted to the bubble memory for reasons similar to machine control manufacturers. In both applications, contamination militates against the use of floppy disks. In process control environments, the problems may be powdered sugar, lint, soap powder, or any of a number of other substances.

Although the applications of process and machine control have much in common, there are differences. Machine control deals primarily with manufacture of discrete parts, whereas process control deals with flow of materials. Process control systems are very large, and a single system can use hundreds of bubble memory devices. Manufacturers of process controls include such companies as Foxboro, Fisher Controls, and DuPont, the last of which is also an important user.

There is no single ideal application for bubble memories in process control, but the overall reliability of the bubble memory is even more important than in machine tool applications. Whereas a machine tool failure may damage a valuable workpiece, a process control failure can be catastrophic. Although processes are designed with fail-safe features which prevent life-threatening situations by shutting down the line, the stoppage can be extremely costly. Initially, process control systems will use bubble memories where serious environmental problems exist.

The process control industry is even more conservative than machine tool control, because the stakes are larger. Design decisions are made by the builder of the controls, the customer for the process, and especially where the probability of catastrophe is great (as in nuclear power plants), by consulting engineers. This means that bubble memory suppliers have to convince not just one organization, but several, to design bubble memories into their systems. It also means that price sensitivity is not as great as in many other areas because of the critical nature of the application.

Terminals

The rapidly-expanding computer terminal industry seems destined to be an important user of bubble memories. We believe that 130,000 bubble devices will be shipped for use in computer terminal applications in 1980, expanding to 500,000 units in 1985, an average yearly growth rate of 31 percent. In dollars, we expect shipments valued at $11.4 million in 1980 to grow to $50 million in 1985, an average yearly increase of 34 percent.

The bulk of the 1980 shipments will be Texas Instruments' bubble memory devices used in the TI "Silent 700" terminals, which employ two per system. Other portable terminal makers offering bubble memories include Computer Transceiver Systems, Telecon Industries, and Findex.

Not only portable terminals will use bubble memories. Terminals intended to be stationary can also benefit from the small size, quiet operation, and dependability of the bubble memory. AT&T had a contract for a large number of non-portable terminals, most of which were expected to use bubble memories; the rest would use floppies. The contract was cancelled after the vendor, Digital Equipment Corporation, failed to make timely deliveries. The cancellation had nothing to do with the bubble memories, which were reported to be performing well. Close to 1,000 sample units were delivered to AT&T, although most of these did not contain bubbles. The bubble was to have been an option which would have cost the user $175 per month for a memory package of 22 kilobytes, using two TI 92-kilobit devices. With three units, it was to have cost $185. They would have been slightly less expensive than a floppy disk option which provided a much larger memory.

It is improbable that bubble memory sales will have a critical impact on floppy disks. As previously stated, floppy disks will be preferred where there is no intention of physically removing stored data. The bubble will be preferred for remote terminals that will transmit their information to the computer at the end of a period of time.

Bubbles will also be used to replace one of a pair of floppy disk drives. Where large amounts of data need to be stored cheaply, a fixed disk drive will be preferable, but where the requirements for data storage are moderate, a bubble memory system will be more appropriate.

The market will be extremely price-sensitive for non-portable terminal applications. The bubble memory's price must drop sharply over the next five years to make the terminal market application grow as predicted.

Word Processors

We believe that the number of bubble memory devices shipped for word processing applications in 1985 will amount to 250,000 units, valued at $37.5 million.

The bubble memory will not replace the floppy disk drive in a single disk system, but will certainly be able to replace one of two floppy disk drives in a dual system. In word processing, diskettes provide excellent removable media for storing letters and manuscripts off-line, and large numbers of diskettes are often stored; however, one floppy disk drive often serves as a backup memory for the other in a dual floppy disk system. In this case, the bubble memory will be able to replace one of the two floppy disk drives. Bubble memory's smaller size and weight, and increased reliability, make it attractive as a floppy disk replacement. In the future, cost will also be a plus.

In addition to the floppy disk replacement, bubble memories will be used in other capacities in word processing equipment. For example, the bubble memory can replace the endless tapes used on some IBM automatic typewriters, with a clear gain in performance, reliability, and, in the future, cost.

The first word processing system using bubble memories will be introduced by Xerox in 1981.

Small Computers

Small computers, or small business systems, are referred to as "small" less because of their physical size than their small price in comparison with other computers. As the price becomes smaller, the cost of the component parts must be lower. Thus, the small computer application is price-sensitive almost by definition.

Small business system manufacturers who have used bubble memories find excellent results from a technical standpoint, but there are few takers of the option among end users. This is not surprising because when a bubble memory is used the cost of the memory is 25 percent of the entire system, and the amount of storage is smaller than for a floppy disk drive costing one-third as much. From the point of view of reliability, however, the bubble is very attractive for this application. Floppy disks used continuously tend to be less reliable, and at least one of a pair of floppy disks will receive heavy usage.

The floppy disk will remain as the primary removable backup and archival storage medium for small systems. Larger systems will more often use hard disks. Intermediate size systems will use "Winchester" fixed disk drives, which, like bubble memories, are not removable.

Because price is so critical, we see large-scale usage occurring in 1984, at which time bubbles will attain a cost of 10 millicents per bit. We believe that usage in 1980 will be limited to the "toy market" where computer companies buy samples to play with. By 1984, we believe that 200,000 units will be shipped for small computer use at a dollar value of $26 million. By 1985, shipments will reach 250,000 units at a value of $37.5 million.

The bubble will be especially attractive with desktop and portable computers for reasons of size, weight, and reliability.

Dictating Machines

Price is the issue in dictating machine applications for bubble memories. A megabit chip will record approximately three minutes of speech. It seems hard to imagine a commercial dictating machine company being interested in such a device at present prices.

It seems possible, however, to make voice recorders, which do not have to be as error-free as computer memories, at lower costs than other bubble memories for the number of bits stored. It is probable that bubble memories will find use in dictating machines by the end of the forecast period. We believe that in 1985, 40,000 bubble memory devices will be shipped at a value of $4 million.

Military and Aerospace

Growth of the military market for bubble memories has been seriously retarded by temperature problems which were not fully comprehended in 1977.

Although most industry participants believe that it is impossible for bubbles to operate over the full military temperature range to +125^{o}C by 1985, they do feel that +100^{o}C is likely to be feasible. Because of the bubble's superior reliability in more restricted temperature ranges and its great ruggedness, it is otherwise an ideal military memory device. At +71^{o}C operating capability, some military applications are satisfied; others require higher temperature, and some need the full range. Not all of the high temperature specifications really need to be met for equipment to work in some applications, but if other memory devices meet the specification and bubbles do not, generally the specifications are not waived.

We believe that military and aerospace shipments of bubble memory devices will increase from sample quantities for test and experiment in 1980 through 1982, to 6,000 units valued at $32 million in 1985.

The largest application will be for airborne computers, where head-per-track disks have been used in the past. In this application, problems of vibration and shock preclude the use of moving head disks.

Satellite tape recorders are still a real application; it was one of the first for which bubble memories were proposed. Budgetary considerations have cut back the number of satellites which are planned, so the market will remain limited.

Much computer equipment purchased by the military establishment is of the ordinary commercial type, and for purposes of this report is considered as part of the commercial market because the special military characteristics do not apply. The bubble memory is ideally suited for rugged applications requiring extremely reliable equipment.

Military and space markets have unique characteristics which will influence bubble domain memory usage. Chief among these characteristics are:

1. The ability of the user to spend money. For the right product, the government will not only pay the necessary purchase price, but will also fund substantial developments by the supplier, under contract. Millions of dollars have been paid to Rockwell and TI for bubble memory device development.

2. The requirement for reliability. For example, where a tape recorder in a satellite has an MTBF (mean time between failure) of 10,000 hours and the rest of the satellite components have MTBF's of 100,000 hours, almost any additional money paid for a more reliable recorder will be well spent.

3. The requirement for ruggedness. Equipment is mounted on vehicles which must traverse rugged terrain on dirt roads or no roads at all; shipboard equipment must be able to withstand the hazards of the sea; and airborne equipment will be subjected to considerable mechanical stress and vibration. A wide range of climatic conditions will be encountered.

4. The time-consuming process of obtaining government approval. Military/aerospace usage of new computer technology usually follows rather than leads commercial usage. Standards must be established for new types of equipment; budgets must be established; and the approval process is complex and unwieldy. When a new development is vitally necessary to further an essential product, red tape can be cut and procedures waived. In such cases, military/aerospace usage is likely to occur early in the product's life cycle. In the case of bubbles, acceptance has been delayed by temperature problems.

Because of the temperature problems, we believe that military and aerospace bubble memories will turn out to be much more expensive than had been expected originally. The tendency will be to push the units to the limit of their capabilities whatever their expense.

In addition to airborne computer and satellite recorder replacement applications, which are funded, there are numerous other applications which are still not funded. One of the likely near-applications for bubble memories is as a replacement for special rugged cassettes used for program loading and data acquisition. Fully-sealed cassettes with the magnetic heads inside cost about $5,000 each. This application, too, has been slowed by the difficulty of meeting temperature specifications.

Apart from production quantities to be shipped, military and aerospace markets have been an important source of funding for research projects and will continue to be. The knowledge gained in this way can be put to commercial use as well.

Telephone Systems

As has been the case with so many other components, including transistors and CCD's, the bubble memory was invented by "the" telephone company at Bell. Possibly more than any other user, AT&T is interested in the ultra-reliability of the bubble domain memory. The telephone company must provide 24-hour service, using a variety of equipment at widely-separated locations. The public has grown to expect that their telephones will always operate. Bell people measure equipment life, not in hours as missile engineers do, but in decades.

Moving magnetic storage devices do not truly meet Bell's life requirements, although they are used both for digital and voice storage because nothing superior has been available. Real applications for bubble memories have already been developed by the telephone company in two product areas: telephone "announcement systems" and electronic switching systems.

Most of the bubble markets in telephone applications are captive; Western Electric can be expected to supply the Bell system. However, the independent telephone companies, including GTE and Continental Telephone, represent a market for independent producers of bubble memories.[1]

We believe that shipments of bubble memories for telephone applications will increase from 7,000 units in 1980 to 50,000 units in 1985, an average yearly growth rate of 50 percent. The value of shipments will grow from $5 million in 1980 to $30 million in 1983, for an average yearly increase of 43 percent.

Audio Applications - The first practical audio application of bubble memories will be used in telephone "announcement" systems. Announcement systems deliver messages to the user such as "The number you have dialed is not in service; if you need assistance . . . " etc.

In the past, motor-driven magnetic drum-based systems were used to deliver a variety of messages. These drums have proven to be reliable by most standards, but not by Bell's, since they have found that the quality of the recording deteriorates with time.

As a result, the Bell system intends to gradually replace the motor-driven drum devices with a bubble memory-based device called the "13A Announcement System." After a trial run in the Detroit switching office of Michigan Bell Telephone, bubble memory announcement systems were put into production at Western Electric.

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[1]According to a recent VDC study, Retail Telephone Markets, independent (non-Bell) companies will continue to account for about 19 percent of the telephones installed in the U.S.

For each of the many messages contained on the motor-driven drum, there is a bubble package replacement containing four chips. Each chip contains 68,121 bits which will record 12 seconds of speech in serial digital form. No use is made of the bubble's fast access capability, since each bubble package implements a single loop. Although the cost of the "13A" system is expensive in comparison to its predecessor, the telephone company prefers it because it contains no moving parts, is expected to be trouble-free, and the recorded message will not deteriorate with time.

Telephone announcement systems will not be a large market for bubble memories. Past usage of the magnetic drum recorder was approximately 100 per year. Gradual field replacement will take place, and other applications for audio bubble recorders are likely to be developed. We believe that 10,000 four-chip bubble packages per year will be used by 1983, since each system will contain multiple packages, one for each 12-second message.

Switching Applications - In telephone switching systems used in central offices, the potential applications for bubble memories are digital, rather than audio. They will be used to replace fixed head disks in some applications, especially for mobile use.

The switching system application is a very logical use for bubble memories. Several 26-megabit systems are actually in use in Japan. A portable bubble-based electronic switching system has been manufactured by Nippon Electric Company for Nippon Telephone. NEC was founded by Bell in 1899, although it is now separate from the American company. NEC manufactures equipment for Nippon Telephone as Western Electric does for AT&T, but it is not a captive supplier.

Portable systems are especially suited to bubble technology since they are less likely to be adversely affected by being driven around in trucks than are mechanical systems. For stationary switching systems, the bubble memory seems destined not to be employed by the Bell system during the time period of this report. Although moving head disk files had been considered too error-prone to be used in AT&T's central offices, forcing the use of very high cost-per-bit fixed head disks, the "Winchester" fixed disk drives have changed the situation. The high volumes of data at low price, combined with the improved reliability of the "Winchester" disks, have precluded the use of bubble memories in most of AT&T's applications.

Other Telephone Applications - There are a number of other telephone applications, among them a call recorder used with PBX's, which polls a day's calls. A potential application is a local charge calculator. When installed at coin boxes, it would tell the caller the toll charges without the necessity of communicating with a distant office. A block access bubble memory could retain the information regarding rates and distance. Another bubble memory could provide information to the consumer in audio form.

Variations on this product could be used by businesses to keep track of their telephone costs by project in order to bill clients for expenses or to aid with internal accounting.

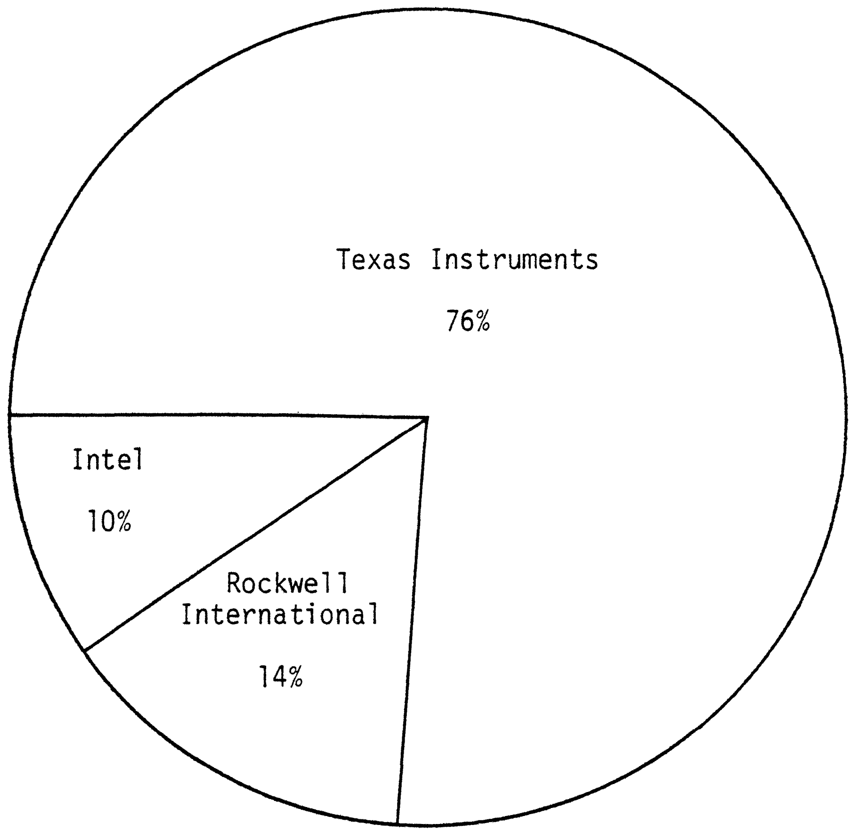
MARKET SHARE BY COMPANY

Any market share figures are transitory in 1980, as the market is changing rapidly. Of companies who are now selling commercial bubble memories, we believe that Texas Instruments supplies 76 percent in dollars, including captive business; Rockwell 14 percent; and Intel 10 percent. (See Figure 34 .) National Semiconductor and Motorola are not yet in production. Western Electric, by company policy, will probably never sell on the open market.

We believe the situation will change rapidly. Intel's share will increase significantly as soon as the ancillary support chips are in full production. TI's business is now made up of the 92-kilobit device; one-megabit chips are scheduled for the near future.

FIGURE 34

BUBBLE DEVICE MARKET SHARE BY COMPANY
(Dollars)



Not included are government research contracts which make up a major portion of Rockwell's bubble business and are important to TI as well.

IX

MARKETING STRATEGY

In this very early stage in the life cycle of the bubble memory industry, it is not possible to examine all of the aspects of marketing policy which could be discussed if the product were mature. There are four items, however, that are particularly important at this time. They are:

* Pricing Policy
* Product Policy and Ancillary Circuitry
* Marketing Policy and Organization
* Strategy Relating to IBM.

PRICING POLICY

Bubble memories, while revolutionary from the point of view of technology, are not revolutionary from an applications standpoint. They must compete with disks, tapes, and RAM's -- all viable memory technologies. There must be an economic reason for users to switch from these technologies to bubbles.

As mentioned in the section Trends in Technology, the relationship between bubble prices and industry growth is a "chicken or the egg" problem. Producers say they cannot lower prices until sufficient volumes are purchased, and equipment makers refuse to design bubble memories into their products while prices are still high.

Bubble memory manufacturers are hesitant to take the first step because, at this stage, the manufacturing costs at various production volume levels are not known with certainty. VDC's skepticism in 1977 regarding bubble manufacturers' predictions of early and drastic price reductions was occasioned by the unwillingness of manufacturers to take firm orders on future large quantities at low prices, which indicated to us that they were less certain of their costs than they were willing to admit. Users are still reluctant to pay high prices for small quantities, not so much because they object to the initial high prices, but because they fear that prices will stay up. They will then have spent the time and money to design a bubble memory into their product and will not be able to afford to use it.

Intel acted aggressively by starting to take firm orders, in large quantities, for future delivery. They will have acted wisely if they actually meet their predicted cost goals; or perhaps their strategy is to build market share even if they do not earn a profit now. Buyers will be more fully convinced to use bubbles when prices from a number of suppliers are lowered.

We have heard the statement from bubble manufacturers that "We have sunk so much money into bubble memory R & D that we have to charge high prices initially in order to get our investment back." Sunk costs are sunk, however. The issue is how to maximize future profit. It is hard for us to see that charging high prices for "samples" will have a substantial influence on long-term profits. Certain semiconductor and IC products have enabled their suppliers to earn high profits on samples because the customer could not solve his application need as economically by other means. As a result, there were many customers who would pay well for a chance to try the new device, and the additional cost kept out those who were not serious.

The capabilities of the bubble, on the other hand, are now well understood. Some users are suspicious about the prices ever coming down to feasible levels for their applications. Texas Instruments 92-kilobit memory, for example, has not been lowered even though it is now in quantity production. Intel's decision to accept volume orders at low prices was a step in the right direction from the OEM user's viewpoint, but they know that no company will deliver quantity orders indefinitely at a loss, so the lingering doubt persists. The company's reduction of its megabyte bubble price to 100 millicents per bit in small quantities in the fall of 1980 helped.

PRODUCT POLICY AND ANCILLARY CIRCUITS

One picture is worth a thousand words! Figure 35 illustrates the Intel 7110 one-megabit chip mounted on a 4" x 4" circuit board along with all of the auxiliary control and driver circuits to make it work. The large boards behind the 4" x 4" circuit board are the previous Intel circuits which the new board replaces. The bubble memory boards (which mount the bubble chip and all of the ancillary circuits) made by Intel's competitors tend to resemble one of the earlier Intel boards, with many discrete components required.

Bubble memory manufacturers must make it easy for OEM equipment companies to use their products. Intel has shown the way. Competitors must provide ancillary IC circuits which reduce the need for additional discrete components. Good application notes and instruction are also a must.

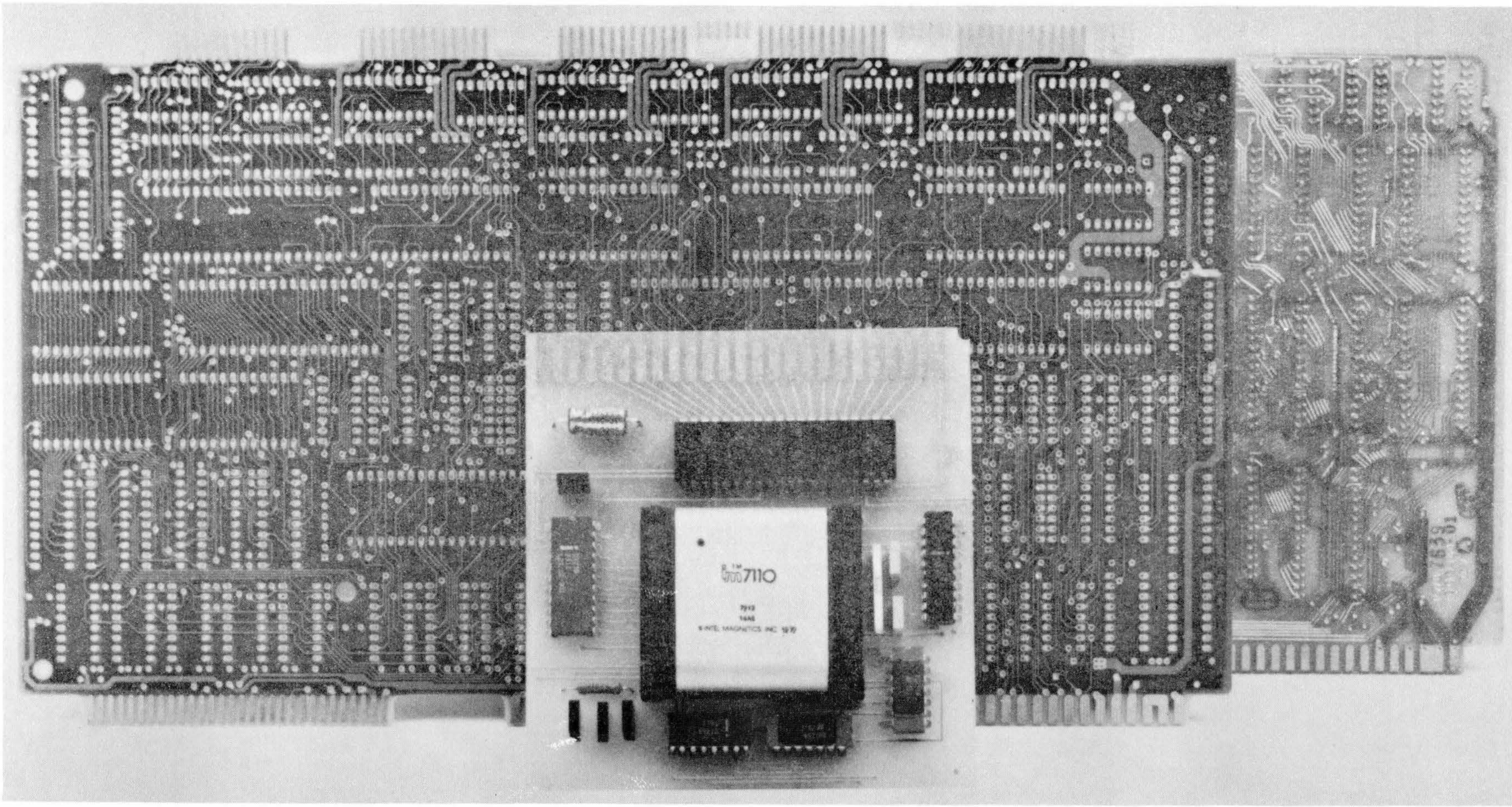
MARKETING POLICY AND ORGANIZATION

Up to this time, bubble memory producers have had more problems related to production than to sales. Real selling efforts will be required in the future.

We have found, in the past, that there are dangers in selling new products through established channels. The problem tends to

FIGURE 35

INTEL MAGNETICS BUBBLE MEMORY AND ANCILLARY LSI FAMILY
OF CONTROL AND DRIVER CIRCUITS



result from the much higher level of effort required to see that new products are designed into new equipment. Salesmen tend to sell the products that they know.

Semiconductor sales personnel can be trained to sell bubble memories, but field salesmen are evaluated and compensated according to sales volume. A new product requires extra effort that they may not be able to give. If established marketing organizations are used to sell bubble memories, it is necessary to employ bubble memory applications engineers to back them up and help customers with their designs as well as to furnish written application notes.

It is essential for a manufacturer to get its own bubble memory circuits into the customer's design at an early stage. After a competitor is "designed-in" and quantities build up, it is likely to be too late.

STRATEGY RELATING TO IBM

In many computer areas, it is customary to wait until IBM moves, and then do what IBM has done but charge less. We believe that the industry should not wait to see what IBM does.

IBM has put large amounts of money and effort into bubble memories; some estimates indicate that their investment in R & D has approached $100 million. Yet, IBM does not always use its developments and is under no pressure to pioneer the bubble memory market.

Bubble memories, unlike disk and tape drives, require no maintenance. Maintenance and leasing have always been, and still are, important sources of revenue for IBM. Why would IBM want to displace their large installed base of disk and tape drives with a lower-cost product not likely to be leased separately or to require much maintenance? It is not reasonable to expect IBM to take the lead in pushing bubble memories.

If IBM should bring out products with bubble memories, it would certainly boost interest in bubbles throughout the computer business. It is most likely that IBM will use bubble memories in small, "stand-alone" products. We believe that IBM is more likely to follow than lead in pioneering the bubble domain memory business.

X

THE COMPETITION

AT&T Company

The bubble domain memory was invented at Bell Labs by Andrew Bobeck and co-workers. They are still conducting extensive research into new approaches to bubble memories, including patterned ion implant structures and current access propagation techniques. Western Electric is manufacturing audio message devices which use bubbles for AT&T. Other telephone uses as in terminals and call recorders are under consideration, but bubbles appear not to be in the company's plans for switching systems any longer. AT&T will license their bubble technology, but by company policy they will not sell bubbles on the open market.

Fujitsu

A broad-based electronics company with worldwide sales of more than $1 billion, Fujitsu was Japan's first computer manufacturer. Fujitsu began as a manufacturer of telephone exchange equipment, and that business will provide a large internal market for bubble memories. In addition, bubbles will make a convenient addition to Fujitsu's integrated circuit product lines. Fujitsu has introduced a bubble cassette system which contains removable packages. At 200 millicents per bit in sizable quantities for the removable package alone, it has limited commercial appeal, but is reported to be exceptionally reliable.

Hitachi

With sales in the region of $7 billion, Hitachi is Japan's largest electronics manufacturer and one of the largest in the world. At Hitachi's Central Research Laboratory, bubble devices have been developed for use in Nippon Electric's telephone equipment. Hitachi could well prove to be a substantial competitor in U.S. and world bubble memory markets.

IBM

This $23 billion United States computer company is leading the bubble industry in quantity of research and money expended on bubble technology. From the intensity of their effort, it can be surmised that IBM has important plans for the bubble. As always, IBM is secretive about its intentions. Historically, IBM has not sold, in the open market, any of the considerable volume of components it has produced. Instead, the entire volume has been used internally.

Intel Magnetics

Set up by Intel Corporation to make bubble memories, Intel Magnetics moved directly to production of a one-megabit chip, bypassing the smaller bubble memories already offered by competitors. They offer a complete set of integrated circuits to perform all of the ancillary functions required for bubble memory operation. The system is very attractive to users, but there has been some delay in getting the IC controller chip into production.

Motorola

By an agreement with Rockwell to provide IC's for bubble memory operation in exchange for bubble memory technology, Motorola is preparing to move into the bubble memory field, second sourcing Rockwell to their mutual advantage. Other manufacturers have widely differing approaches that do not lend themselves to interchange. Motorola's bubble know-how was abetted by personnel obtained from Sperry Univac after Sperry Univac decided against in-house bubble manufacture.

National Semiconductor

National Semiconductor, a leading manufacturer of integrated circuits, has announced a line of bubble memories including one-quarter and one-megabit chips, and will offer a full line of supporting IC's in early 1981. An agreement has been made with the French company, SAGEM, to second source the National Semiconductor bubble line.

Rockwell International

Rockwell, along with Texas Instruments, pioneered bubble memories for open market sales. Rockwell has worked closely with NASA and the Air Force on supplying satellite recorders and airborne disk drive replacements, but temperature problems with bubble memories have slowed military markets for bubbles. Commercial users of Rockwell's bubble memories tend to feel the military background makes the company "act like a job shop." Rockwell has formulated an agreement with Motorola to exchange bubble technology for IC know-how. This appears to be a wise move, because Rockwell is in competition with bubble makers who are producers of semiconductors, and good ancillary integrated circuits are an essential ingredient of bubble memory product planning.

SAGEM

This French company has concluded an agreement with National Semiconductor to produce bubble memories which are interchangeable with the American company's products. Production is planned for 1981.

Siemens

A German electronics company with sales of $14 billion, Siemens has licensed bubble technology from Rockwell International. Part owner of General Numerics, the world's largest manufacturer of numerical control equipment, Siemens will have a ready market of 7,000 bubble memory packages per year for General Numerics in Europe.

Texas Instruments

Aided in its entry into the bubble memory industry by government contracts, this $2.5 billion manufacturer of semiconductors, computer peripherals, etc. produces more bubble memories than the rest of the industry combined. A large captive market for bubble memories is provided by TI's portable terminals which use 92-kilobit bubble devices. A one-quarter megabit device was discontinued; a new family of one-quarter, one-half, and one-megabit chips has been announced.