COMPUTERS 2: BRAVE NEW COMPONENTS

From tapes, disks and transistors to bubbles, charge packets and supercurrents, the revolution in computer technology rushes on unabated

BY JOHN H. DOUGLAS

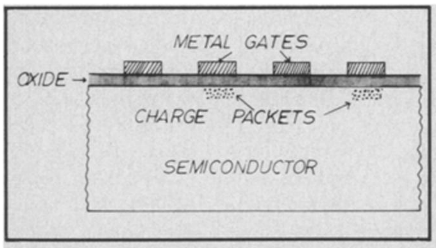
Second article of a series.

So fast have computers developed that many of the men designing today's most sophisticated machines learned their trade building versions that took ten-thousand times longer to complete a calculation, only two decades ago. Yet, before these engineers retire, electronic technology promises to pass through another revolution, changing once again the computer's fundamental components and inherent abilities.

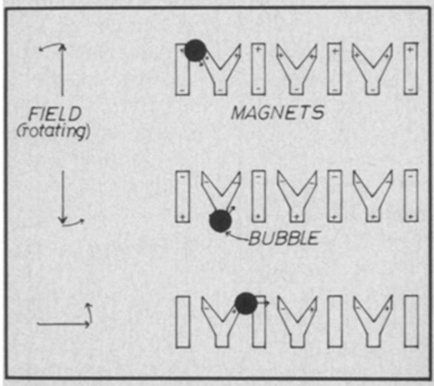
Of today's familiar devices, probably the first to go will be the bank of magnetic tape units that line the walls of most computer facilities. Not only are they bulky and intrinsically slow—since they must be read linearly by a mechanical device—but they are also the last major component of the whole computer system that requires manual intervention. Someone must physically select a tape from racks containing several thousand, then manually mount it in the reading unit. Industry sources estimate that this manual intervention may cost as much as $2.50 for every tape change, and that because material at the end of a tape takes so long to reach, 95 percent of the users fill less than half a tape.

The rapidly developing alternative for such "archival" storage is the data cartridge, a short piece of wide magnetic tape rolled on a spindle that fits into the palm of the hand. A 10-foot-long cabinet can hold 2,000 of these cartridges, replacing some 4,000 to 16,000 tapes and holding the information available for purely automatic retrieval—with an average access time of three seconds. The Control Data Corp. design just described, allows several individual "files" of information to be put on one cartridge, while an IBM unit holds a greater amount of data on a single cartridge file, with slower access time. Advent of these mass storage facilities now makes it possible to have terabit memories (one trillion binary digits) "online."

Between archival storage and the high-speed central memory of a great computer, where hundreds of millions of operations are performed on as many pieces of data each second, lies the so-called "intermediate memory." These devices—at present, whirling magnetic disks or drums—hold data retrieved from tapes for rapid entry into the central memory. But a great "memory gap" exists between the millisecond access times of the best disks and the submicrosecond operations of the central processor and memory. Three new technologies are rushing to fill this gap, with less power loss and expense than the bulky, temperamental magnetic devices.

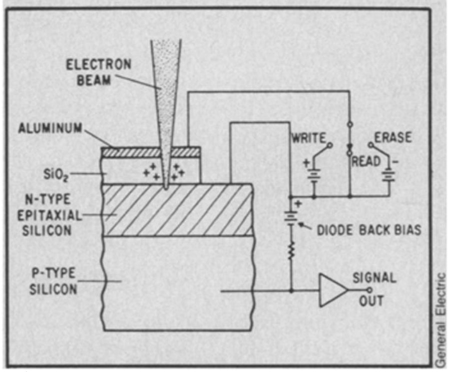


Charge packets stored in a CCD memory.



Illustrations: Douglas

Sequence of moving magentic bubbles.



General Electric

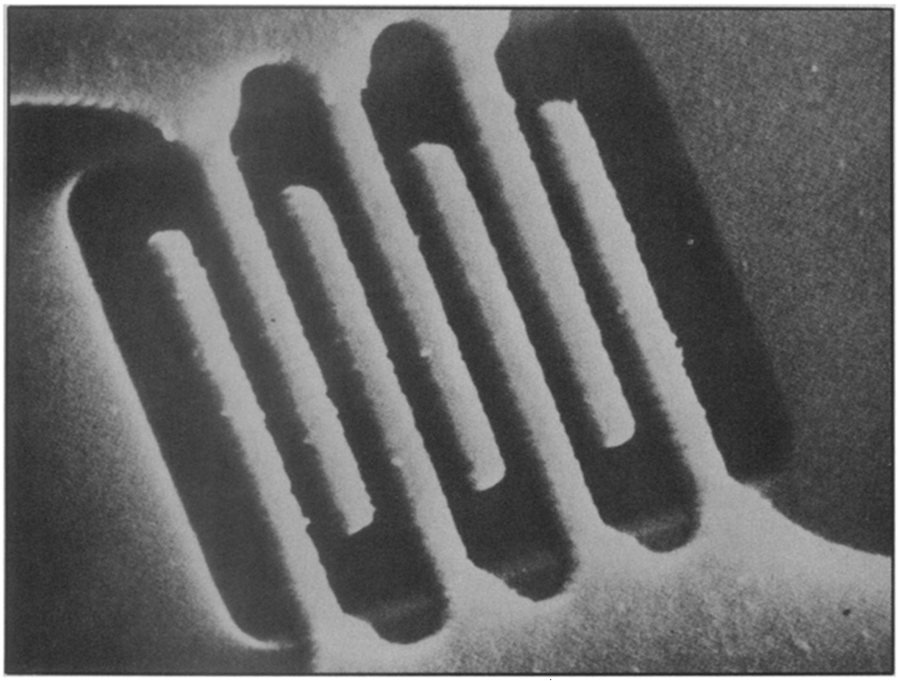
Electron interaction in an EBAM memory.

Closest to wide-scale adoption is the charge-coupled device (CCD), developed by Bell Labs—a versatile new product of metal-oxide-semiconductor (MOS) technology (SN: 9/6/75, p. 154). CCD memories have access times ranging from 25 microseconds to about a millisecond (depending on circuit configuration) and store data even more densely than the faster semiconductor devices used in central memory. Equally important, CCD's form the basis of several new non-computer devices, including completely solid-state TV cameras and filters for discriminating faint radar signals.

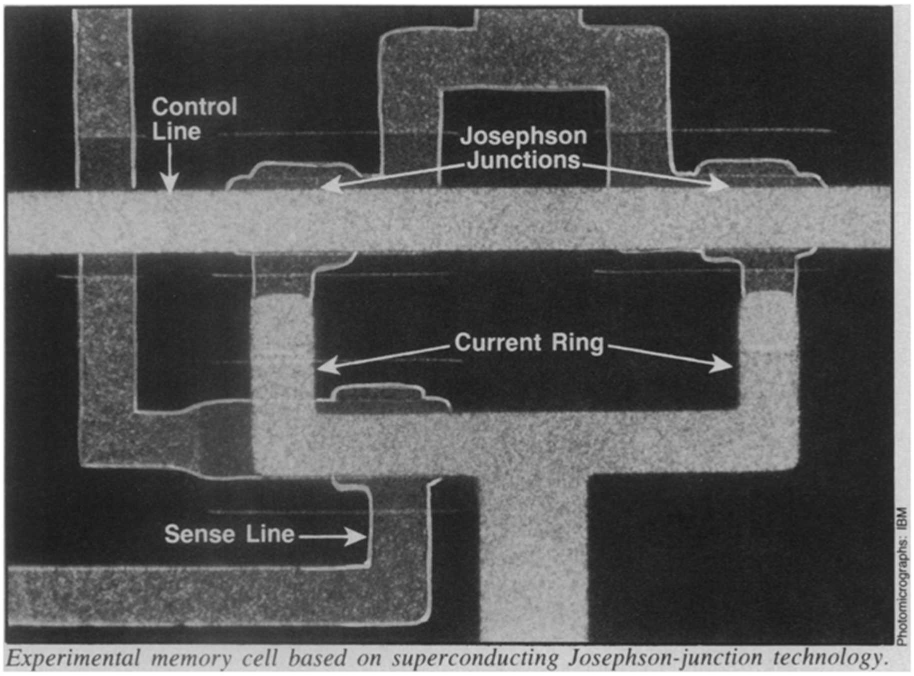
A CCD operates by shifting packets of charge trapped in its semiconductor substrate. As voltage changes along the line of metal "gates" lying above the substrate, the packets of charge below move down the line correspondingly. Bits of data are stored according to whether a particular region contains a charge packet or not, and data are read out serially at the end of the line. Access time depends on how long the particular data line is; if short access time is required, more of the expensive read/write centers must be added. ("Random access" memory is not available because there is no way of measuring whether any particular location contains a charge without running the whole string of data by.)

The serial nature of CCD memories are their main disadvantage, for not only is it intrinsically slower than random access memories, but each time the packets of charge are shifted, a little charge gets lost. Still, compared with rotating magnetic memories, CCD's offer several advantages: For comparably sized data capacities, a CCD memory has a fifth the access time and one-sixtieth the power consumption of a drum, while lasting five times as long between failures.

To cut down on charge loss, "buried channel" CCD's were developed, which move the charge packets away from the semiconductor surface. Charge mobility is higher deep within the substrate and losses are reduced, but the conventional surface CCD's are easier to make and allow greater



Electron beam fabrication: World's smallest transistor, enlarged 10,000 times.



Experimental memory cell based on superconducting Josephson-junction technology.

Photomicrographs: IBM

densities of data. General Electric scientists have been experimenting with "charge sloshing" as a way to practically eliminate loss, but this requires additional circuitry.

Next on the horizon are the "magnetic bubble" memories, now apparently ready for pilot production. They are only about one hundreth as fast as the CCD's but are potentially capable of much greater densities. The devices utilize tiny magnetic domains ("bubbles") that can move about in garnets just as the domains of charge move in the semiconductor of a CCD. They were first developed at Bell Labs during the late 1960's, but have not been accepted as quickly as the CCD, largely because of cost.

When a thin wafer of garnet is placed in a magnetic field, the naturally occurring, randomly spaced islands of magnetic anomaly (domains with field orientation opposite to that of the rest of the material) shrink into tiny round bubbles. These can then be attracted to the ends of tiny magnets deposited on the garnet surface. If the external magnetic field is rotated, the poles of the deposited magnets change and the bubbles will shift position. Through careful construction, a long string of these magnets can be created with bubbles running along its length as the external field rotates. By adding a bubble generator and detector, a serial memory is created.

The attractiveness of this apparently clumsy device is that the bubbles can be made so small that theoretically a billion "bits" of data could be stored in a square inch of material—a density approximating that of the human brain. Also, bubble logic circuits are possible, so that both storage and arithmetic operations could be combined on one tiny chip. Since the stored information is "nonvolatile" (it doesn't disappear during a power failure), early applications will probably come in situations where space, power and reliability are at a premium and cost is not so important. Not surprising, NASA has bought one of the first prototypes.

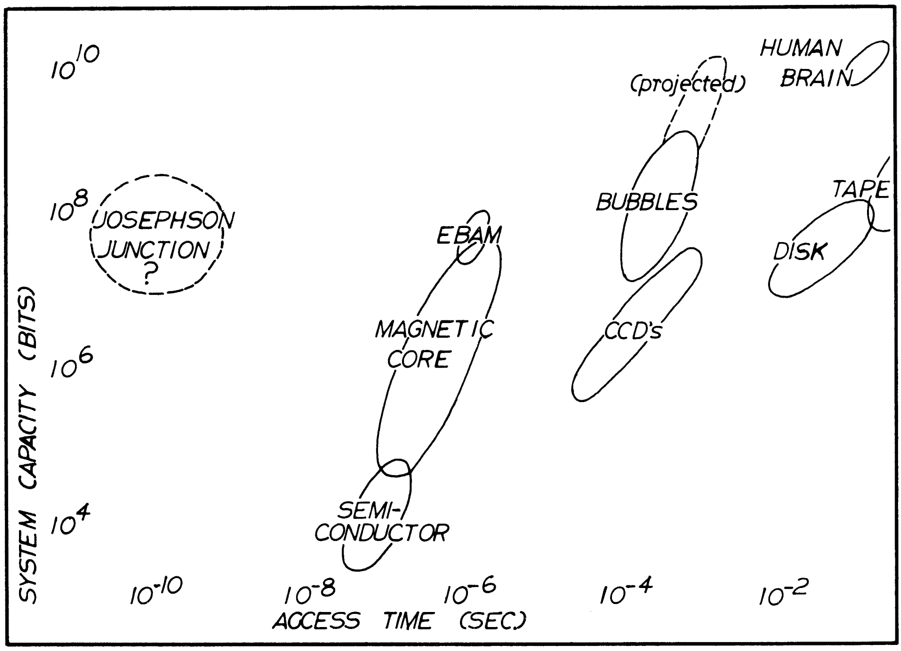
To reduce costs, IBM has developed a "sputtering" technique for creating a thin, amorphous film of garnet for use in bubble devices. This technique should provide substantial savings over present, single-crystal substrate processes. Also, IBM scientists are experimenting with ways of using bubble *orientation* as a means of storing bits, which should increase by several times the amount of data that can be stored. Bubble devices and CCD's will be in direct competition for some years, and each have their ardent supporters.

Fastest among the new intermediate-speed devices is the electron-beam-accessed-memory (EBAM). A true random access memory, with access time in the tens of microseconds, present devices can hold up to 32 million bits each, but billion-bit systems are foreseen. Some industry observers give EBAM the edge over bubbles and CCD's after a few years.

EBAM works much like a television picture tube, except that the "screen" is replaced by a set of MOS chips. Electrons from the cathode induce a packet of charge to form at the interface of the oxide and silicon layers. The presence or absence of charge at any given location can be determined by changing voltage on the chip and seeing whether a pulse is sensed when the beam passes over the desired location. A lot of bulky power supplies are necessary, but the overall cost is surprisingly small.

The Control Data Corp. is field testing an EBAM made by Micro-Bit Corp., on its new STAR computer. General Electric Co. has come out with a competitive model—called BEAMOS—that is slightly slower but has a larger data storage capacity. EBAM's have almost leapfrogged the gap between peripheral and central memory, incorporating the data capacity of a large disk unit with the speed of a slow core memory.

Other limitations aside (such as power and size), the choice among the new intermediate-speed technologies will be made on the basis of cost. Storing data on CCD's now costs about 0.15 cent per bit; bubbles cost 0.05 cent per bit; EBAM, about 0.02 cent per bit. These compare to central memory costs of about 0.20 cent per bit and disk storage at 0.03 cent per bit. It is already cheaper to store information in computer archives than on typed



John H. Douglas

Estimated capacity of various memory systems and the access times needed in each.

paper, and intermediate-memory costs are expected to drop by a factor of ten over the next decade.

One way to grasp in everyday terms just what these new technologies means is to consider that the Bible contains about a million words or roughly the equivalent of some 40 million bits. Thus the Bible could be stored on one data cartridge in less than a minute or on two BEAMOS tubes in about four seconds. Many central memories could not hold all the information, but could read through it in as little as a hundredth of a second. Using a high-speed page printer, the computer could then reproduce the Bible in about two minutes.

Looking further toward the future, two developments still in the laboratory may even more fundamentally reshape computer technology: Electron beam fabrication may create circuits so small their details will no longer be resolvable under the most powerful optical microscope, and superconducting Josephson-junction devices may replace transistors altogether in some applications, while increasing computation speeds 100 to 1,000 times.

Both technologies depend inherently on a rather abstruse concept of quantum physics—that electrons, like light, travel as waves, and that their wavelengths shorten as the electrons pick up speed. Since wavelengths of the ultraviolet light used to expose photoresists in making integrated circuits are about a 0.4 micron, the smallest dimensions of devices thus made are usually larger than 5.0 microns. (A light beam just smears out around any object about the size of its wavelength). Even slow-moving electrons have wavelengths thousands of times shorter than any possible in optical devices, hence electron microscopes can give clearer pictures of small objects, and similar devices can be used to etch surfaces with electrons, along the extremely small lines needed for circuits.

Experiments in electron beam fabrication are now being conducted at IBM's Thomas Watson Research Center and Bell Labs. The major problem with the technique, other than intrinsically expensive equipment, is the long exposure times needed to create the miniature circuits. Present research is thus concentrating on finding new electron-sensitive materials, increasing beam strength and developing computer controls for the beam so that it is concentrated on only those areas requiring exposure (rather than having to scan a whole mask). Expense will probably limit initial application of electron beam fabrication to making very fine masks, rather than circuits. Short-wavelength X-rays could then be used with the new masks to create somewhat smaller circuit patterns than are now possible. Ultimately, however, direct fabrication with electon beams should make it possible to cram tens of thousands of circuits onto a tiny chip a tenth of an inch on a side.

The wave properties of electrons also make possible an entirely new type of circuit element, orders of magnitude faster than the best transistor. In 1962, a young British graduate student, Brian D. Josephson, predicted that the phase relationships between electron waves in two superconducting metals would be coordinated if the metals were brought close enough together, so that a current would flow between them. Since classical physics (which didn't recognize "waves" of matter) said that any such gap would be an impenetrable barrier to current, the observed flow of electrons across the gap was called "tunneling." The flow across this "Josephson junction" could be stopped by an external magnetic field, so a new switch had been invented.

There are several pressing reasons for trying to adapt the new switch for practical logic and memory circuits, for not only would it improve computer performance by perhaps a factor of 100, but it would require less than a thousandth the power of an equivalent semiconductor device. Again, the work is being led by researchers at Bell Labs and IBM. (Watson Center physicist Leo Esaki shared the 1973 Nobel Prize with Josephson, for his work on tunnel junctions.)

A Josephson-junction memory cell consists of a current ring (containing two Josephson junctions), a control line above, and a sense line below. As with any superconductor, once current begins flowing around the ring it continues essentially forever without the need for any external force. If the flow is clockwise (say), the sense line reads its contents as zero; if counterclockwise, as one. Passing current through the control line applies a magnetic field to the Josephson junctions, so that the ring current direction can be changed by applying an external voltage. The sense line also contains a Josephson junction, which is sensitive to the presence of a current in the ring.

Simple though Josephson devices are in concept, and despite their potential importance, much research must be done before commercial units can be produced. For one thing, it is not yet clear just how small the devices can be made before tunneling is interfered with, so the ultimate marriage of computer technologies—subminiature Josephson devices created by electron beam fabrication—remains in question. Current research is concentrating on investigation of the basic tunneling phenomenon, while some simple devices, such as adders, are created using various fabrication technologies. (Doping materials for the junctions, for example, pushes the state of the art, and ion implantation has replaced conventional techniques.)

According to one survey, electronics experts expect Josephson-junction devices in computers sometime after 1985. IBM engineer Wilhelm Anacker says he can envision a complete Josephson-junction computer—including central processor and memory—compressed into a volume of about a cubic foot (all inside a tank of liquid helium). Others have speculated that the random access time of such a memory might be a short as tens of picoseconds (trillionths of a second) compared to current memories with access times of tens of nanoseconds (billionths of a second).

The only thing that is certain is that computers will become orders of magnitude smaller, faster and cheaper. They will require only tiny amounts of power, and their new mobility will take them into almost every nook and cranny of daily life. An assessment of the likely impact will be covered in the final article of this series. ☐