IBM Drops Superconducting Computer Project

Problems with a high-speed memory chip would delay a Josephson junction computer long enough for semiconductors to catch up

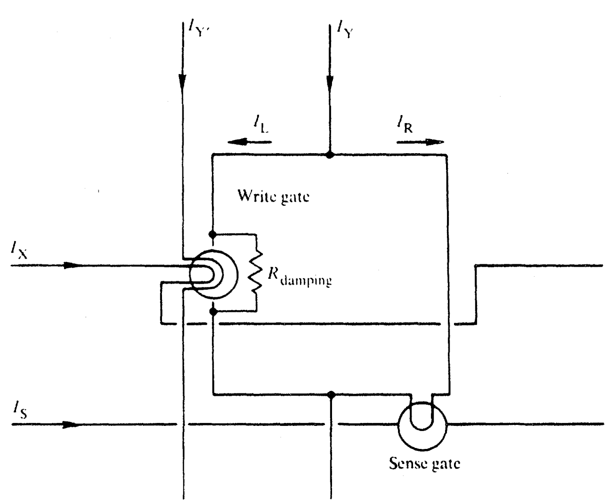
On 23 September, IBM ended its attempt to build a high-speed, general-purpose computer whose guts would be logic and memory chips made of superconducting, Josephson junction switches. At its end, IBM's project was a $20-million-per-year affair that involved 115 researchers. The reason cited for the decision was a probable 2-year delay due to difficulties in developing a high-speed memory chip. IBM judged that by the time a computer could be built, its performance would not be far enough ahead of the more traditional but rapidly advancing semiconductor competition to warrant the revolutionary superconductor approach.

Josephson junctions, named after Brian Josephson of Cambridge University, who received the 1973 Nobel Prize in Physics for his invention, hold the potential of ultrafast computer processing. One measure of processing speed is the period of a computer's internal clock. IBM has talked of a Josephson junction computer with a clock period or cycle time of 1 nanosecond. The most recent Cray supercomputer has a cycle time of 9.5 nanoseconds.

IBM disclosed its decision at a workshop on digital Josephson junction electronics held on the California side of Lake Tahoe in late September. A company spokesman confirmed to *Science* that the Josephson junction computer program has been terminated, although research on superconducting electronics will continue at a reduced level. "The basic conclusion was that IBM's resources can be better used on other high-speed technologies," he said.

Memory cell

The write gate is a three-junction interferometer. The sense gate is a two-junction device. A "1" is stored in the cell when a superconducting current circulates around the square loop in the I_Y line with no current in the line itself ($I_L + I_R = 0$). A "0" is stored when there is no circulating current ($I_L = I_R = 0$). Current pulses in the Y, Y', and X lines are used for writing and in the Y and S lines for reading. [IBM]



IBM accounted for roughly half of all U.S. research on Josephson junction electronics. The consequences of the company's pullout will be considerable. As it happens, IBM's action follows on the heels of two other significant reductions in Josephson junction research. The Sperry Corporation closed its research center in Sudbury, Massachusetts, effective 30 September. A ten-member team there chose not to accept Sperry's offer to relocate to its Computer Systems Division in St. Paul, Minnesota, and continue Josephson junction research. And last spring, Bell Laboratories dropped its level of effort on Josephson junctions from a dozen to two or three researchers.

Are Josephson junctions therefore dead? The Japanese have two large research programs aiming at Josephson junction computers, and how they will respond to the developments in the United States is not yet known. Barring their pursuing the technology and succeeding, it appears unlikely there will soon be a Josephson junction computer. Instead, the search is on for a superconducting device that acts more like a semiconductor transistor and could therefore be the starting point for a future computer development program.

At the same time, the ultrafast switching time and low power consumption of Josephson junctions continue to make them ideal for other applications in digital electronics, such as analog-to-digital converters and other high-speed signal-processing systems for military and measurement applications. Moreover, the extreme sensitivity of Josephson junctions to electric and magnetic fields makes them sensors of unparalleled responsiveness. Investigators at the National Bureau of Standards in Boulder, Colorado, Bell Laboratories, the University of California at Berkeley, Sperry (St. Paul), TRW, Westinghouse, and Hughes Aircraft all say they will continue active programs in both these areas.

Why, with all the progress in semiconductor microelectronics, would one think of building a computer from superconducting devices, which, among other things, require cooling to the vicinity of 4 K with liquid helium? The answer starts from the speed of light. The fastest electrical signals (in transmission lines) travel at about one-fourth the speed of light. This physical fact sets the ultimate limit on the speed of a computer. Even with switches that worked instantaneously, no machine could run faster than the time it takes a signal to propagate through the various logic and memory circuits called for by a particular computer instruction. In the end, the fastest computer will be the smallest.

Switches, however, generate heat during their operation, which must be dissipated. The heating problem, many researchers argue, will someday limit how closely semiconductor microcircuit chips can be packed together. Josephson junctions emit only one-thousandth as much heat as semiconductor transistors and can, therefore, be shoved into a smaller space. As an added bonus, Josephson junction switches are also faster than semiconductor transistors, although the margin is down to a factor of 2 or so for individual switches at present.

IBM began its Josephson junction studies following the mid-1960's demonstration by Juri Matisoo that the devices could serve in digital electronic circuits. A Josephson junction begins with two strips of metallic superconductor, such as lead, separated from one another by a layer of insulating material.

At the junction, the insulator thickness is reduced to a few nanometers. As originally predicted by Josephson, a superconducting current will flow from one strip to the other with no voltage across the thin insulating layer, provided that a certain "critical current" is not exceeded. Above the critical current, the behavior is no longer superconducting, and a voltage arises across the junction, while the metal strips remain superconducting. Josephson also calculated that the application of a magnetic field in the plane of the junction lowers the critical current. Matisoo's idea was to use the magnetic field generated by a current in an adjacent superconducting strip to switch the Josephson junction between its zero-voltage and nonzero-voltage states. Logic and memory circuits could be built upon this basic switching action.

In the 1970's, under Wilhelm Anacker, IBM researchers made considerable progress toward a Josephson junction computer. The high point of this effort was a so-called cross section model that served no explicit electronic function but nonetheless contained all the types of circuits a full-fledged computer would have. The module also demonstrated a packaging scheme for mounting all the logic and memory chips in a box about 10 centimeters on a side (*Science*, 1 January 1982, p. 42). No comparable achievement in high-speed semiconductor technologies has been reported.

About 2 years ago, a decisive shift in the IBM program took place. Joseph Logue replaced Anacker as Josephson junction manager. At the time, Logue told *Science* that his intention was to establish a pilot production line at IBM's East Fishkill, New York, plant. The idea was to make Josephson junction chips in a realistic pilot line atmosphere to test whether the fabrication processes developed in the laboratory could be made to yield large numbers of defect-free chips. A researcher who has seen the East Fishkill facility says it is "very large and filled with very expensive equipment."

At about the same time, IBM also made a materials switch. The Josephson junctions made with lead alloy were insufficiently mechanically stable to withstand extensive cycling between room temperature and 4 K. The company therefore adopted the refractory metal niobium for the bottom superconductor in the Josephson junction but kept a lead alloy as the top superconductor.

An additional wrinkle to keep up the switching speed of the niobium–lead alloy Josephson junctions was to make them as small as possible. IBM researchers accomplished this by covering the top of the niobium strip with a relatively thick layer of niobium oxide but with a much thinner layer on the edge of the strip. They then deposited the lead alloy on the oxide-covered niobium. Current flows only through the thin oxide on the edge. It is much easier to control the thickness of the niobium strip as it is deposited than it is to control its width by the photolithographic techniques

Editing mRNA Precursors

Ever since most genes of eukaryotic organisms were discovered in 1977 to be interrupted by noncoding sections, or introns, molecular biologists have puzzled over two major questions. First, what is the role of introns in the origin and functioning of such genes? And second, what are the mechanics of editing out the noncoding sections from RNA transcripts of these genes? No one is surprised that answers to the first question are slow in coming, as, by their nature, definitive tests are difficult to devise. The second question has been tougher to resolve than might have been expected, however, especially in view of the technical wizardry that prevails in any decent laboratory these days. But, at last, the problem is beginning to crack, as four laboratories in the United States and one in Germany are currently reporting various in vitro reaction systems from whole cell or nuclear extracts that faithfully perform the RNA-splicing function.

Only by establishing reliable test-tube reaction systems will biologists be able to both determine what components are involved in splicing messenger RNA precursors and define what specific nucleotide signals are required to ensure the fidelity of the process. The in vitro systems developed so far are still in relative infancy; nevertheless they have revealed several general points. For instance, splicing is not necessarily coupled to transcription: in vitro splicing has been achieved both in systems in which the RNA precursor is synthesized endogenously and in which it is added exogenously. The splicing apparatus almost certainly includes at least one form of small ribonucleoprotein particle (specifically a class known as U1 snRNP's), as antibodies that precipitate them in in vitro tests halt splicing. This result adds welcome support to data from intact cells.

One intriguing observation from several laboratories is a lag time of 1/2 to 1 hour between the addition of the pre–messenger RNA and the onset of splicing. Phillip Sharp of the Massachusetts Institute of Technology notes that the naïve interpretation is that a complex splicing apparatus has first to assemble itself, presumably involving the U1 snRNP's. Tom Maniatis and his colleagues at Harvard and Walter Keller and his colleagues at the German Cancer Research Center in Heidelberg see the same phenomenon and agree—in the absence of any direct data—on the general interpretation. By contrast, Carlos Goldenberg and co-workers at Washington University, St. Louis, and Ryszard Kole, formerly at Yale but now at the University of North Carolina, have not noticed a significant lag period preceding splicing.

It seems clear by now that splicing does not proceed by a simple "scanning" of the RNA precursor molecule from one end to the other by a splicing complex. An endogenous structural specificity of the splicing apparatus, including the long precursor RNA molecule, must therefore be responsible for the precise excision of introns and the ligation of coding regions in the correct order. The overall configuration might be conferred by the tertiary structure of sections of the introns or coding regions, with precise alignment between splice junctions being assured by their complementarity with a short sequence of the small RNA molecule in the U1 snRNP particle.

Efficiency of splicing in the in vitro systems varies somewhat between laboratories, though in all cases it is high enough to allow experimental dissection of the component parts. Sharp, for instance, using whole cell HeLa extracts, achieves around 15 percent splicing with added precursor, whereas Kole, using the same system, has not yet reached this level. Both the Keller and Maniatis laboratories are developing nuclear extracts from HeLa cells: Keller regularly achieves 15 percent efficiency, and sometimes much higher; the Maniatis system is consistently higher. Goldenberg reports an 80 to 90 percent splicing efficiency with a myeloma nuclear extract.—ROGER LEWIN

Additional Reading

B. Weingartner and W. Keller, *Proc. Natl. Acad. Sci. U.S.A.* **78**, 4092 (1981); W. Keller and N. Hernandez, *Cell*, in press; R. Kole and S. M. Weissman, *Nucleic Acids Res.* **10**, 5429 (1982); R. A. Padgett, S. F. Hardy, P. H. Sharp, *Proc. Natl. Acad. Sci. U.S.A.* **80**, 5230 (1983); C. J. Goldenberg, *Nucleic Acids Res.* **11**, 1337 (1983).

practiced in the microelectronics industry. Hence, the edge junctions could be made many times smaller in area (*Science*, 1 January 1982, p. 40).

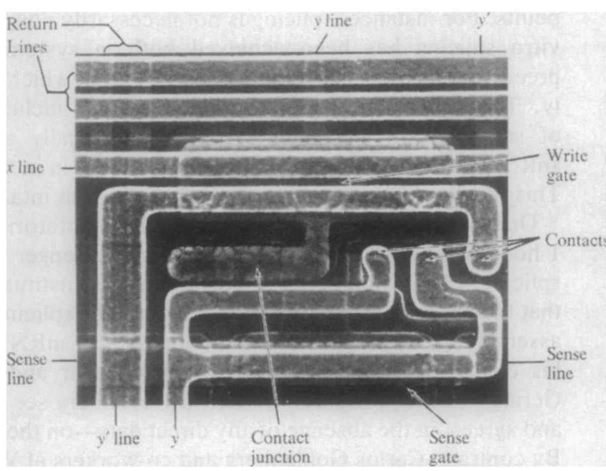
In both the old lead alloy and new niobium-edge junction technologies, single Josephson junctions themselves are not the switching elements. Devices called interferometers comprising two, three, or more junctions do the switching. Schematically, a two-junction interferometer resembles two letters Y placed top to top with Josephson junctions joining them. A three-junction interferometer looks like two tridents joined at each point by a junction.

A crucial parameter of these devices is the critical current for switching from superconducting to nonsuperconducting states. The critical current decreases exponentially with the thickness of the insulating oxide in the junction. Control of the thickness must therefore be better than one atomic layer. IBM researchers reported at the Lake Tahoe workshop that they had achieved about a 1 to 2 percent statistical variation in the critical current for both logic and memory chips containing a few to several thousand interferometers, respectively.

Participants at the workshop have uniformly said they were impressed by this performance. "What IBM has done is adequate for [our] needs," commented one researcher at a defense company where projects on analog-to-digital converters and other signal processing devices are under way. Compared to a mainframe computer, such specialized systems are relatively simple. An analog-to-digital converter might consist of only a few chips with 100 Josephson junctions each. The low number of devices makes IBM's pilot line statistics more than adequate.

Memory chips present more of a problem. In particular, IBM has been concentrating on a fast or cache memory chip that holds 4096 bits of information. Each memory cell includes two interferometers, one three-junction and the other two-junction. In addition there are logic circuits that steer information to the correct cell during writing and recall information during reading. There are well over 20,000 Josephson junctions on a chip measuring a little more than 6 millimeters on a side. For such a chip, a 1 or 2 percent variation in critical current is not good enough.

The allowable variation in critical currents is dictated by the interferometer and by statistics. If the critical current is too low, then the current coming into the interferometer will always be sufficient to switch it to the nonsuperconducting state, even without an applied magnetic field. If the critical current is too high, then it is not possible to switch the interferometer with an applied field of any strength.



Cache memory

Scanning electron micrograph of a cache memory cell. The superconducting lines in IBM's old lead-alloy technology are 2.5 micrometers wide. The cell itself is 58 × 48 micrometers square. The cell switches in 30 picoseconds. [IBM]

To take a not necessarily realistic example, suppose that a 2 percent random variation in critical current translated into a 99.9 percent chance of any particular Josephson junction having a critical current within the required range. For 100 junctions per chip, the probability that the chip will be satisfactory is then $(0.999)^{100}$ or about 0.9, which is a little lower than manufacturers would like. For 20,000 junctions per chip, the probability plummets to $(0.999)^{20,000}$ or about 2×10^{-9}. IBM researchers did, in fact, make logic chips with about 5000 Josephson junctions, which shows how well they were doing.

At the workshop, Logue asserted that it would be possible to redesign the memory circuitry in such a way that a 1 to 2 percent variation in critical current would yield a functioning chip most of the time. However, he continued, it would add almost 2 years to IBM's target date for a small prototype computer of 1986. By then, IBM projected, advances in the speed of silicon or gallium arsenide semiconductors would make computers based on such materials only slightly lower in performance than the Josephson junction machine. It would not be worth the effort to introduce an altogether new computer technology for such a modest increase in performance.

The optimistic view of IBM's decision to step back is that the company tried for a specific and ambitious product in a narrow time window and failed. This does not mean Josephson junctions are likewise a failure. The Musashino Electrical Communications Laboratory of the Nippon Telegraph and Telephone Public Corporation has, for example, reported a 1024-bit memory chip made with Josephson junctions. This chip is about 50 percent larger in area than IBM's and about three times slower, so it may not be suitable for a superfast computer. But the Japanese also used a different memory cell design. A Josephson junction computer could yet come from Japan.

In the United States, the view is tilted towards writing off Josephson junctions for large high-performance computers. IBM is maintaining a research program at least partly to look for new superconducting devices that behave more like semiconductor transistors. And a new entrant in the field, Hypres, Inc., of Elmsford, New York, is also gearing up for such a search.

Transistors have a property called gain. The current that comes out of a transistor switch can be ten or so times the current that goes into the device and initiates the switching action. In a Josephson junction interferometer switch, the current coming out is not greatly different from the current that generates the magnetic field that causes the switching. The consequent low gain requires circuit designs that do not take full advantage of the speed of Josephson junctions and makes tight control of the critical current mandatory. A superconducting switch with high gain would considerably ease these burdens. A superconducting device called a quiteron, invented by Hypres founder Sadeg Faris when he was at IBM, is a step in this direction but apparently is not the answer, at least in its present form.

Besides the heat advantage of Josephson junctions, superconducting transmission lines can shuffle electrical signals around a chip and from one chip to another at high speed and with little loss and distortion. Metal wires on semiconductor chips do worse at this as they are miniaturized. The driving force for superconductors is still there.

—ARTHUR L. ROBINSON