Toward the Realization of a Josephson Computer

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High-quality Josephson junctions, with both electrodes made from niobium and with an aluminum-oxide insulating barrier, were introduced in 1983. This niobium junction is very stable, reliable, controllable, and reproducible. Because of these excellent characteristics, these junctions can be applied to large-scale integrated (LSI) circuits, such as microprocessors having a few thousand gates and a few kilobits of memory. These circuits operate much faster and consume less power than any semiconductor circuit now available. Integrated Josephson circuits are now being tested in a closed-cycle refrigerator. The next step is to design a special-purpose, small-scale Josephson computer and to demonstrate its high performance.

SWITCHES AND GATES ARE THE BASIC ELEMENTS OF DIGITAL computers. As they have evolved, the performance of each successive element has improved; switching speeds of today's transistors are 1 billion times as fast as those of the relays of 50 years ago. However, even though the rate of progress in computers has far exceeded that in other technologies (for comparison, today's ultrasonic planes move only 100 times as fast as the horse-drawn stagecoaches of the past), this rate is becoming harder to maintain. Some applications, such as weather forecasting, protein design, and astronomical simulation, will never be satisfied by the speeds of today's computers. To satisfy the need for higher speeds, researchers are now developing new transistors made from materials other than Si (such as GaAs and InP). Many researchers fear, however, that the switching speed of transistors will saturate in the near future. Thus, completely new switching elements, such as superconducting devices, optical devices, and bioelectronic devices, are also being investigated. Among them, the Josephson junction, a superconducting device, has made remarkable progress. Current LSI circuits built with Josephson junctions are much faster than semiconductor circuits, although their integration density is still much smaller than that of semiconductor LSI circuits.

Characteristics of Josephson Junctions

The Josephson junction is an electronic device that uses superconductivity. Superconductivity is the material property of having zero resistance; at present, this property occurs only at low temperatures. For many years the highest transition temperature (T_c) for superconductivity was about 23 K, but after Bednorz and Müller discovered a high-T_c superconductor (*1*), interest in new materials and devices increased.

Josephson junctions can be applied to a variety of fields of electronics; however, the operating temperature has to remain in the material's superconducting regime. Today's Josephson junctions mostly operate at the temperature of liquid He (4.2 K); if the available high-T_c superconducting materials could be used to fabricate reliable junctions, the operating temperature would jump to the temperature of liquid N_2 (77 K).

The physical principles of the Josephson junction were first discussed by Josephson in 1962. He predicted that superconducting electrons could flow through a thin insulating barrier sandwiched between two superconductors (*2*). The structure (Fig. 1A) incorporates an insulating barrier that can be as thin as a few nanometers. The Josephson effect was verified by experiment in 1963 by Anderson and Rowell (*3*).

The Josephson effect is produced by superconducting electrons, which can be described by macroscopic quantum-mechanical wave functions. The wave functions penetrate the thin insulating barrier, causing electron-pair (Cooper-pair) tunneling, which, in the absence of an applied voltage, takes the form of a superconducting current (supercurrent) flowing across the junction barrier. If the current exceeds a certain threshold (I_c), a gap voltage (V_g) builds up across the junction (Fig. 1B). The *I-V* curve is symmetric about the origin. The straight vertical line represents the supercurrent at 0 V.

Figure 1C is an actual *I-V* curve. When the current exceeds an I_c of 1.2 mA, a V_g of 2.8 mV appears across the junction. The threshold current is determined by the thickness of the insulating barrier, and the gap voltage is determined by the junction electrode materials. The gap voltage is 3 mV for a Nb junction. As shown in

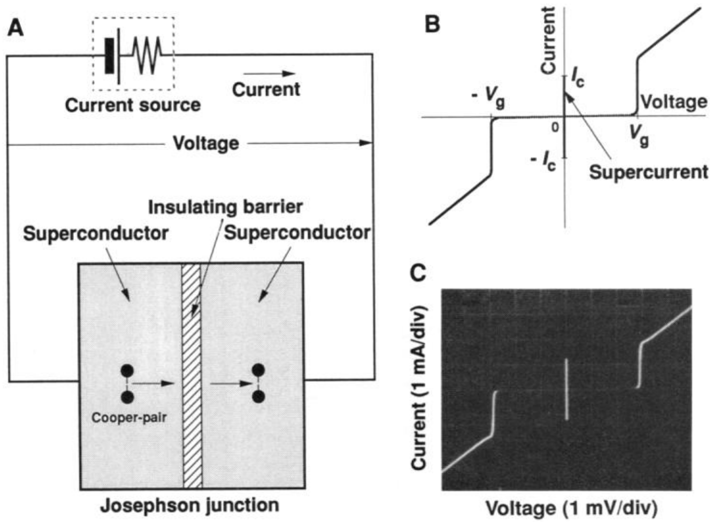

Fig. 1. (**A**) Basic Josephson junction structure. The insulating barrier is a few nanometers thick and is constructed from several atomic layers. (**B**) Schematic *I-V* curve of the junction. (**C**) Oscilloscope *I-V* curve of a typical Josephson junction (div = division).

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the *I-V* curve, two distinct voltage states exist: 0 V, which is assigned logic 0, and 3 mV, which is assigned logic 1. Because of this bistable behavior, the Josephson junction can be applied to digital circuits.

Josephson junctions can be applied to a variety of fields. Most of the current application research focuses on four areas: magnetic sensors called superconducting quantum interference devices (SQUIDs), electromagnetic detectors, voltage standards, and computers. One research goal is the construction of an ultrahigh-speed computer. To construct such a computer, one needs switching elements that are fast and that consume little power. Fast switching is not sufficient for ultrahigh calculation speeds. The propagation delay time between individual elements must also be minimized. To reduce the delay, one must reduce the device spacing, which requires a low power consumption to prevent the switching element from generating excessive heat. As an example, a large-scale computer having a central processing unit (CPU) of 50 by 50 cm might consume a few kilowatts of power. To increase the clock rate by a factor of 10, one must increase both the switching speed by a factor of 10 and decrease the board size to 5 cm by 5 cm. If a conventional cooling system were used, a computer of these dimensions would melt when turned on. To prevent this, the power consumption must be small enough to closely pack the LSI chips without increasing the operating temperature so much. The Josephson junction is able to fill this requirement.

Figure 2 shows the relation between switching time and power consumption for various high-speed devices. The switching speed of the Josephson junction is one order of magnitude faster than conventional bipolar-transistor logic or emitter-coupled logic (ECL). In addition, the Josephson junction consumes one-thousandth of the power that ECL consumes. Thus, by more densely integrating these faster devices, one can develop an ultrahigh-speed computer.

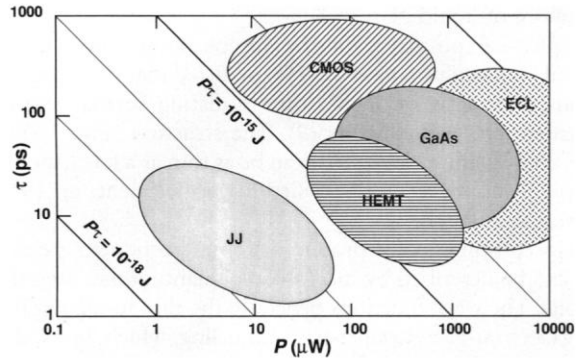

Fig. 2. Relation between switching delay time, τ, and power consumption, P, for the Josephson junction (JJ), the high electron-mobility transistor (HEMT), the gallium-arsenide field-effect transistor (GaAs), the Si ECL, and the CMOS logic. The $P\tau$ products shown in the figure denote the switching energy necessary for one logic operation.

High-Speed Circuits

Until 1983, it was difficult to make a Josephson junction LSI circuit because no high-quality junction was available. A high-quality junction, suitable for being applied to an LSI circuit, was developed by M. Gurvitch *et al.* in 1983 (*4*). They reported the fabrication of a new Josephson junction with both electrodes made from Nb and with an aluminum-oxide insulating barrier. Junctions made from Nb are very stable and reliable, with little scattering of characteristics. Owing to these excellent properties, a variety of LSI circuits can be fabricated.

A Josephson LSI circuit is constructed of basic logic gates in the same manner as a semiconductor LSI circuit. Because the characteristics of the basic gate determine the performance of LSI circuits, the design of the gate is very important. A large number of Josephson logic gates have been proposed. Among them, the fastest logic gate, faster than any semiconductor logic, is the modified variable-threshold logic gate, or MVTL gate (*5*). Figure 3, A and B, show an equivalent circuit and a micrograph of the MVTL gate.

A Josephson logic gate operates differently than a semiconductor gate. The Josephson gate switches like a latch and does not return to its initial state after the input signal is turned off, whereas a semiconductor gate changes state only while the input signal is applied. The current for a Josephson logic gate, which is called a bias current, is supplied by pulses rather than by dc power. The frequency of the pulses determines the speed of computation, so this is called the clock frequency.

A schematic cross section of the MVTL gate is shown in Fig. 3C. Niobium is used for junction electrodes, ground planes, and wiring layers. Molybdenum is used for resistors and SiO_2 for insulating layers between wiring layers. The Josephson junction is made by sequential deposition of a $Nb/AlO_x/Nb$ junction structure in a vacuum chamber without breaking the vacuum. This is the most important fabrication process for Josephson integrated circuits. First, Nb electrode is deposited by dc magnetron-sputtering in an Ar-gas atmosphere, and Al (6 nm thick) is also sputter-deposited.

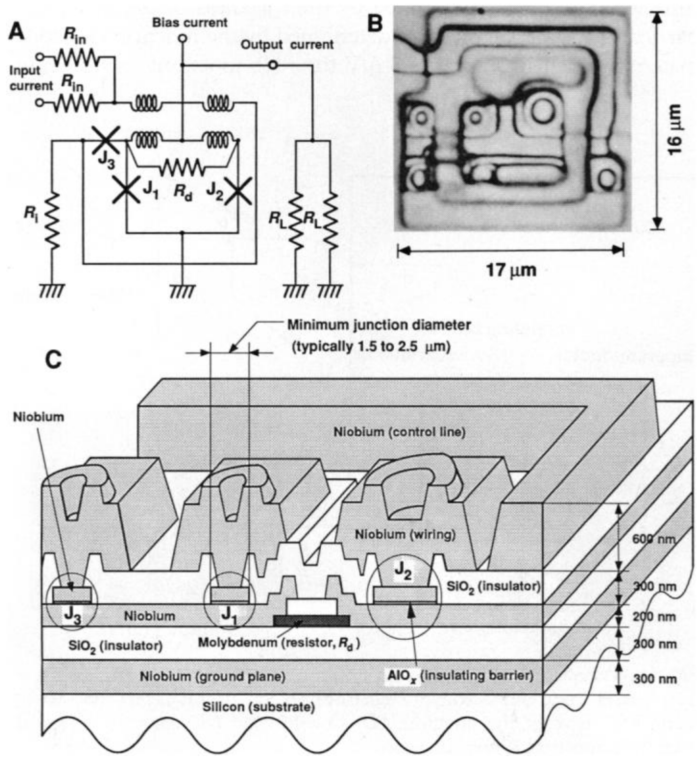

Fig. 3. (**A**) An equivalent circuit of the MVTL gate. When input current is applied, Josephson junctions J_1 and J_2 switch to the resistive states and output current flows from the bias current. Josephson junction J_3 also transfers to the resistive state and input current flows to the ground through the isolation resistor R_i. Consequently, output current is isolated from input current. R_L and R_d are the load resistor and the damping resistor. (**B**) A micrograph of the MVTL gate. Circles are Josephson junctions. Outer circles denote the junction, and inner circles show a contact hole to connect the wiring line to the junction. (**C**) Schematic cross section of the gate. The sandwiched structures (in circles) are Josephson junctions. The horizontal scale is exaggerated to emphasize the junction structure.

Table 1. Comparison of four-bit microprocessor performance for Si, Ga As, and Josephson-junction versions of the Am 2901.

Device	Clock frequency (MHz)	Power dissipation (W)
Si	30	1.4
GaAs	72	2.2
Josephson	770	0.005

Then the surface of the Al is exposed to O_2 gas introduced into the vacuum chamber; thus, the insulating barrier is formed. The upper Nb electrode is deposited by sputtering. After the deposition of the $Nb/AlO_x/Nb$ structure, the junction areas are delineated by reactive ion–etching.

The fastest switching time of the MVTL gate is 1.5 ps with a power consumption of 12 μW (*6*). The design rule, which is the minimum size of the patterning in LSI circuits, for the fastest MVTL gate is now 1.2 μm in junction diameter. In semiconductor manufacturing, patterns of this size are routinely fabricated and are widespread commercially. So for semiconductor fabrication, 1.2 μm is very large, yet the Josephson junction is still quite fast. If the design rule were stricter, that is, in the submicrometer regime, subpicosecond switching times could be obtained.

Circuit fabrication requires stable, uniform, high-quality, controllable, and reproducible junctions. Niobium junctions satisfy these requirements, and thus they can be applied to LSI circuits. In the present circuits, junctions with a diameter of 1.5 μm are usually used for a circuit of a few thousand gates. But to increase the integration density for the circuits with 10,000 or more gates, one must develop a fabrication process with submicrometer junctions. Although making a single submicrometer junction is not so difficult, it is very difficult to fabricate a large number of uniform submicrometer junctions. This is because I_c is proportional to the area of the junction, and an area with a submicrometer size largely scatters because of the scattering of the photolithography.

A Josephson microprocessor that used MVTL technology was fabricated in 1988 (*7*). A total of 1841 MVTL gates was integrated on a 5 by 5 mm chip that functions in the same way as the Am 2901 microprocessor (*8*) manufactured by Advanced Micro Devices, Incorporated (Sunnyvale, California). The Am 2901 is considered the world's standard four-bit microprocessor. A GaAs version of the Am 2901 microprocessor has also been developed (*9*). Table 1 compares the performance of the Am 2901 microprocessors for the three different materials. The Josephson microprocessor can be operated up to a clock frequency of 770 MHz and has a power consumption of 5 mW. Comparing these characteristics with those of the microprocessors constructed of other materials, one can see that the Josephson microprocessor operates at much faster speeds and with much less power than semiconductor circuits. Recent semiconductor microprocessors have improved in performance, and they can be operated around 100 MHz (*10*); thus, it may be slightly unfair to compare Am 2901 processor performance. But the Am 2901–type processor is an example that can be compared for three different materials with the same function.

The largest scale Josephson LSI chip at present is an eight-bit digital signal processor (DSP), fabricated in 1990 (*11*). The DSP is useful in areas such as image processing. A photograph of the chip, which includes 6300 MVTL gates, is shown in Fig. 4. The chip operates 100 times as fast as its complementary metal-oxide semiconductors (CMOS) logic counterpart. High-speed four-kilobit cache memory circuits with an access time of only 500 ps have also been developed, although the integration is not as dense as that of semiconductor cache memory, and these circuits are not yet fully functional (*12, 13*).

Even though microprocessors and memory have been fabricated, another circuit is important for Josephson computers. An interface circuit is needed to connect the Josephson circuits and semiconductor peripheral circuits. Because Josephson circuits operate at low voltages, typically 3 mV, the interface circuit must amplify the signal from the Josephson circuits to a power great enough to drive semiconductor circuits. Another interface circuit should decrease the clock frequency to drive the room-temperature circuits. However, just decreasing the frequency will cause the room-temperature circuits to miss a substantial portion of the information being passed by the Josephson computer. So the high-frequency signal output from the Josephson circuits should be multiplexed into a low-frequency parallel signal. Both of these interface circuits have already been built and tested (*14, 15*).

Josephson technology is now at a level such that LSI circuits, such as microprocessors having a few thousand gates and a memory of a few kilobits, are possible. These circuits have been demonstrated by Hitachi (*16*), NEC (*13*), and Fujitsu (*7, 11, 12*). Electrotechnical Laboratory (ETL) has fabricated a prototype four-bit Josephson computer and confirmed its functional operation (*17*).

Toward the Development of a Josephson Computer

Josephson circuits have been envisioned as replacing conventional semiconductor circuits for the future generation of computers. A partial replacement with present technology would be meaningless, however, because the long connection cables between the room-temperature and liquid-He–temperature circuits would cause a propagation delay much longer than the Josephson circuit's calculation cycle. The present visualization of the Josephson computer has the whole system (that is, CPU, cache, and main memory) integrated in a cryogenic environment. Yet, although such an image is heartening, the technology has not matured enough to manufac-

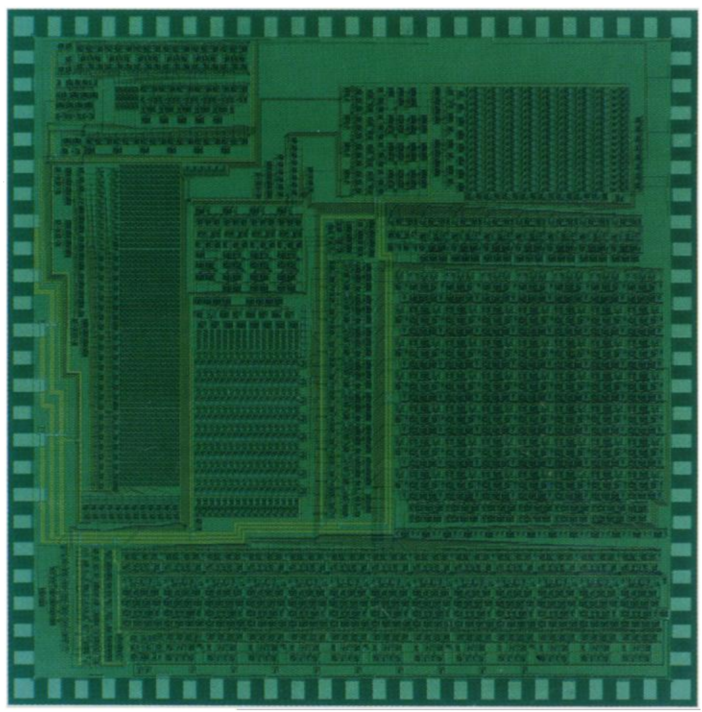

Fig. 4. Chip photograph of the eight-bit DSP. The chip is 5 by 5 mm.

ture a practical computer. The Josephson LSI chips discussed above are still only experimental and will have a long development period before they can be mass-produced. Until the concept of a Josephson computer and its associated cooling system becomes marketable, the massive investment needed to start production will be delayed.

However, a compromise could be practical, consisting of a hybrid system that uses both Josephson and semiconductor devices. Figure 5 shows the cryostat for a possible hybrid system. A cryostat is an insulated container (similar to the thermos that coffee is kept in) that can hold a low-temperature liquid such as liquid N_2 or He. The major consideration is minimizing the propagation delay time between the room-temperature circuits and liquid-He–temperature circuits. In conventional cryostats, the signal lines are inserted through the top of the chamber, requiring about 1 m of cable. This would cause a delay of several nanoseconds, making the computer useless. However, a newly designed cryostat passes flexible cables through the insulated wall of the chamber, shortening the signal propagation distance to 24 mm. This cryostat relieves the transmission bottleneck between the superfast Josephson circuits and the room-temperature peripherals.

The cryostat, developed by S. Kotani of Fujitsu in collaboration with Toyo Sanso Company Limited and Shinko Electric Industries Company Limited, was connected to a refrigerator and operated in a closed cycle as shown in Fig. 6 (*18*). Flexible, laminated, Cu-plated polyimide film cables containing a total of 60 signal lines connect the packages and are fixed in place by epoxy adhesive at the slits cut into the fiber-reinforced plastic (FRP) wall of the vessel. We tested the system in the closed-cycle operation without supplying liquid He for more than 2 weeks. After cycling the cryostat between 300 K and 4.2 K more than 20 times, we confirmed no trouble occurred.

The key developmental problem that had to be overcome was passing the cables through the chamber wall while retaining the insulating vacuum and minimizing heat conduction. The preparation of epoxy adhesives was very important to maintain the insulating vacuum. To reduce the heat conduction, a polyimide film cable with a thin Cu layer had to be developed. The thickness of Cu in the conventional film cable is a few tens of micrometers. Thus, if the conventional cables were used, heat conducted through the cables would exceed 100 W, which is much larger than the cooling ability of a small refrigerator. Consequently, we have developed a film cable with a Cu thickness of 0.3 μm for the ground plane and 2.5 μm for the signal line. The width of the signal line is 0.1 mm. The heat conducted through the cables totals 1.2 W, and heat lost through the cryostat wall totals 1.5 W. The cryostat was combined with the 3-W refrigerator. Because typical Josephson chips dissipate between 5 and 20 mW, a 3-W refrigerator is sufficient to keep a good number of Josephson chips at liquid-He temperature.

The propagation delay through the 24-mm package of connecting cables was measured to be 130 ps, two orders of magnitude lower than that for cables connecting a conventional cryostat. To verify the operability of the entire integrated system, a microprocessor installed in this cryogenic system was operated up to a clock frequency of 1.1 GHz. Thus, the electrical noise from the refrigerator is suppressed enough to allow reliable operation of integrated chips.

This cryostat system makes possible the integration of Josephson devices and semiconductor electronics. Josephson LSI chips and conventional semiconductor LSI chips can be installed on the same circuit board. Even though the integration density of Josephson chips remains low, this is more than compensated for by the high speeds at which the system operates.

Interconnecting the circuits with high-T_c superconducting wires would enable the operation of a hybrid computer that integrates Josephson devices at 4.2 K with low-temperature CMOS at 77 K. In such a computer, parallel computation would relegate large-volume processing to the CMOS processors and calculation-intensive processing to the high-speed Josephson processor. This computer system would be a springboard to developing the technology needed for a completely superconducting computer.

Some might speculate that Josephson junctions made from high-T_c materials could be used as components of high-speed computers. Unfortunately, in my calculation the power consumption of a high-T_c junction is more than two orders of magnitude larger than that of the Nb junction (*19*). Thus, high-T_c junctions could never be used as the basic elements of large-scale computers, although such

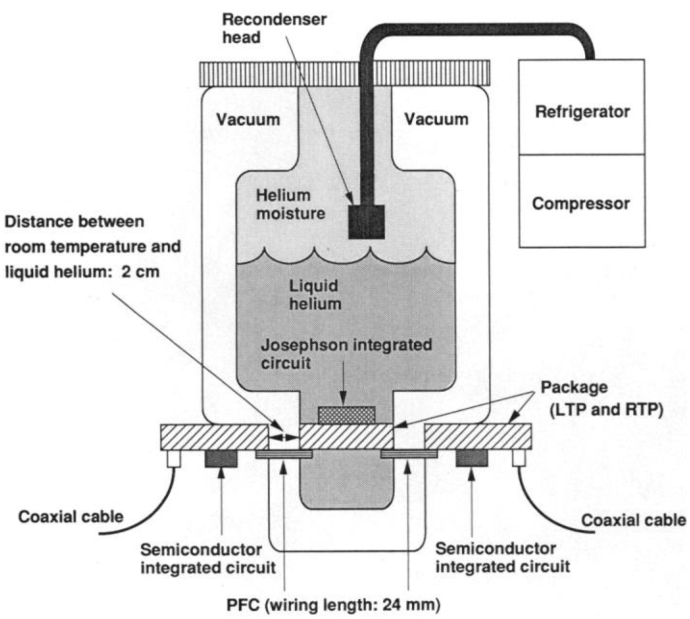

Fig. 5. Schematic cross section of the cryostat. Signals are transmitted through a polyimide flexible cable (PFC), which penetrates the vacuum wall between the low-temperature and room-temperature packages (LTP and RTP). When the cryostat is connected to a refrigerator, He that is evaporated because of heat generation in the cryostat is liquefied again by the cooled recondenser head. Thus, the cryostat can be operated in a closed cycle without being supplied with liquid He from the outside.

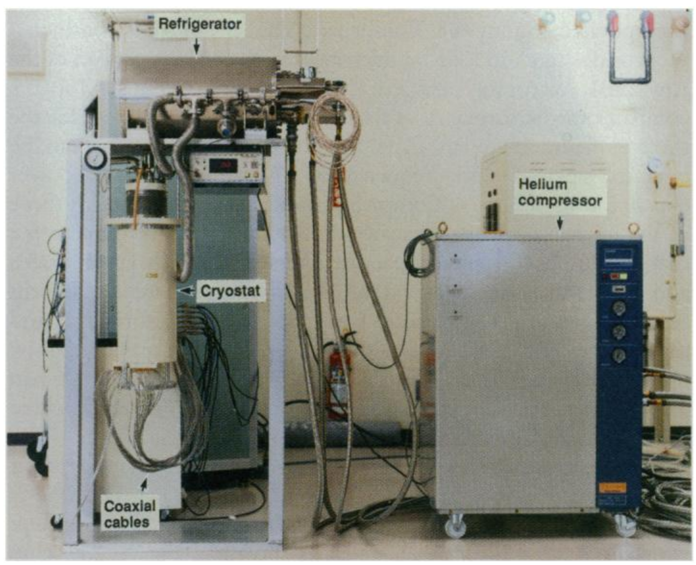

Fig. 6. Prototype cryostat system for a Josephson computer. It is connected to a refrigerator and operates in a closed cycle. The Josephson integrated circuits are installed in the cryostat, and their performance is evaluated through coaxial cables connected to the room-temperature package.

junctions might be very useful for small-scale applications such as SQUIDs.

Future Directions

The basic element of computers has evolved from the relay to the transistor. Transistors have become smaller, and integration densities have increased from small-scale integration (SSI) to ultralarge-scale integration (ULSI). Furthermore, many high-speed transistors are now being developed that are made of materials other than Si, such as GaAs field-effect transistors (FETs) and high electron-mobility transistors (HEMTs). However, both the density and speed of transistors will saturate in the near future, independent of the material. Alternatives such as bioelectronic or optical computers will be developed, but at present they are still primitive. The Josephson computer will most likely be the solution.

Commercially, the development of the Josephson computer relies on finding a market for a special-purpose Josephson computer having a limited number of functions. If a full Josephson computer having powerful processors could be developed soon, a large market would be available. However, because the technology is not yet mature, intermediate hybrid systems must be developed that will appeal to niche markets within the next few years. A possible solution would be to develop computers for fields such as radio astronomy or medicine.

A processor for a multichannel SQUID system, currently being developed for medical applications, could be useful. If each element in a 1000-channel SQUID system had to be connected externally, an unrealistic number of cables (several thousand) would have to be inserted into the cryostat that maintains the SQUIDs. If a Josephson processor with several thousand logic gates were integrated with the system, all processing could be done inside the cryostat's chamber, reducing the number of cables to one. If such systems could be established in niche markets and could prove the effectiveness of the Josephson processor, the door would open to the general marketplace.

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