

postulated by Ya. B. Zel'dovich (Institute of Applied Mathematics, USSR).

Steinhardt noted to us that the inflationary models enable calculations of galaxy formation that are independent of any assumptions about the nature of the universe at the time of the Big Bang. The exponential expansion smooths and spreads any inhomogeneities and has the effect of erasing the previous history. At first glance, one might have felt that special initial conditions were required for our observable universe to evolve to its present state. With the inflationary universe, this evolution is insensitive to initial conditions.

One disappointment in the inflationary model is that it does not explain

why the cosmological constant in Einstein's equations is at present very small. All versions of the inflationary and standard cosmologies have to assume that this basic constant is negligible. It would be far more satisfying for the value to emerge from the theory in a natural way.

A peculiarity of this new picture of the universe is that during its inflationary period, the universe has a negative pressure that essentially drives the expansion. The work done by the expanding universe pumps energy into it. We asked Guth about the implications for conservation of energy. He said that, if one could define any such concept for this period of rapid expansion, it would imply that matter energy

is growing while the gravitational energy is becoming more negative. Guth describes this infusion of matter as the "ultimate free lunch." —BGL

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Quiteron superconducting switch acts like a transistor

With the advent of very-large-scale integration of microelectronic circuits comes the promise of enormously powerful computers; 10^4 circuits or 10^6 bits of memory per chip are reasonable prospects. What is required of circuit elements if we are to advance by one or two orders of magnitude beyond the 10^7 instructions per second that characterize today's most powerful general-purpose computers?

Present VLSI technology offers us semiconductor transistors with switching speeds (on the order of 20 picoseconds) and dimensions (a fraction of a micron) apparently adequate to the task. But the power dissipation of such room-temperature transistors appears to present a severe limitation to the design of general-purpose computers capable of executing several hundred million instructions per second. Crowding so many semiconductor devices into a space small enough to make signal propagation times sufficiently short would generate too much heat.

Superconducting devices would seem to offer a promising alternative. With intrinsic energy gaps measured in millivolts, as compared with semiconductor gaps on the order of a volt, superconducting switches dissipate three orders of magnitude less power than ordinary transistors. At the Applied Superconductivity Conference in Knoxville last December, Sadeg Faris and his IBM colleagues Stanley Raider, William Gallagher and Robert Drake reported the successful demonstration of "the first three-terminal superconducting switch possessing true transistor-like characteristics." This "quiteron," so called because it is based on the quasiparticle-injection tunneling effect, is claimed to provide adequate power gain and binary separation of on and off states for eventual use in digital computers.

Josephson switches. The quiteron is not the first attempt at exploiting superconductivity for digital computers. Considerable work has been done at IBM and elsewhere on the development of Josephson-junction switches (PHYSICS TODAY, June 1978, page 17). Such devices also have low power dissipation, and somewhat faster switching speeds (on the order of 10 picoseconds) than the first quiterons, and they are particularly attractive for memory applications. But, Faris explains, they lack several important features that make the semiconducting transistor—and now the quiteron—especially attractive for digital logic switching.

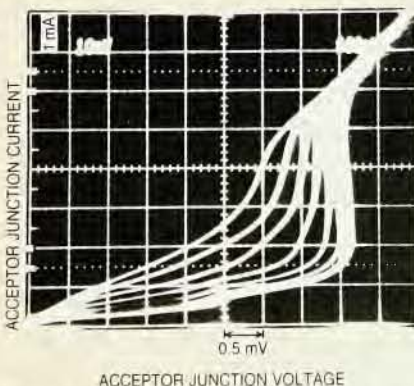
Although the area of the Josephson junction itself can be made as small as that of the transistor or the quiteron

(about a square micron), a practical Josephson switch requires an area on the order of a square mil. This large increase in area is required because the most straightforward Josephson switch lacks the sensitivity and input-output isolation needed for computer applications. One must link a pair of Josephson junctions to an external control current in an inductive transformer configuration. The two Josephson junctions effectively form a SQUID interferometer. The greater the inductive linkage between the control current and the SQUID loop, the more sensitive is the switch. But this induction is purchased at the cost of device size.

This size-sensitivity tradeoff is not the only problem presented by Josephson switches. For computer logic circuits one wants a three-terminal transistor-like switch with the input and output signals well isolated from one another. The simplest Josephson switch, by contrast, is a two-terminal device in which the switching current flows through the same junctions as the output current; input and output are not isolated. The alternative transformer configuration is a four-terminal network, with the switching now done by exceeding a critical magnetic field rather than a critical current. This does indeed isolate output from input; but again the cost is greatly expanded size.

An early Josephson switch, the Josephson cryotron, developed by Juri Matisoo at IBM in the late 1960s, was indeed a three-terminal device with good input-output isolation. But it was found to yield insufficient gain.

The ideal logic element for a digital computer, Faris asserts, is a three-terminal inverting switch. Inversion means that a binary input of "one" produces a "zero" output and *vice versa*. An inverting switch permits one to



Transistor-like family of current-voltage curves is exhibited by the acceptor junction of the quiteron as a function of quasiparticle injection power across the injector junction. With no injection (rightmost curve), the junction shows the abrupt and steep onset of current characteristic of an S-I-S junction when the voltage bias is large enough to break up Cooper pairs. At the highest injection power (47 μ W, leftmost curve), the junction behaves more like an N-I-S junction.

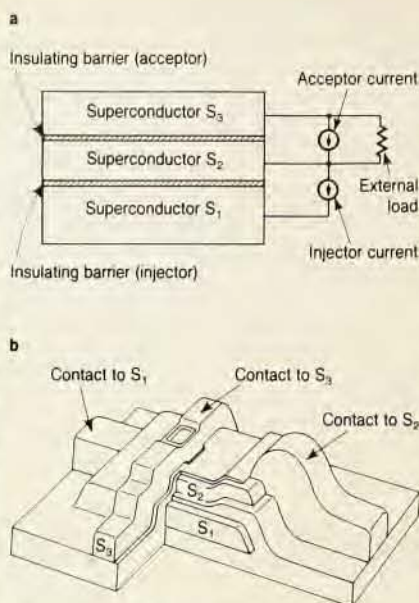
design all the required logic circuits in the most straightforward manner. The quiteron, like the semiconductor transistor but *unlike* the Josephson junction, is an inverting switch. With a Josephson switch one needs to add additional inverting circuitry.

Furthermore, one wants the logic switch to be nonlatching—its output polarity should revert to zero when the input signal is removed. This occurs naturally in a transistor or a quiteron. A Josephson switch, on the other hand, remains latched; once a positive input has killed the Josephson supercurrent through the junction, the junction retains indefinitely the resulting voltage bias that characterizes output "one." To return the junction to its zero-voltage state one must supply a reversing bias current after each clock pulse of the computer. This must be done rather slowly—several hundred picoseconds—lest the switch "punch through" its zero state to the on state of opposite polarity. Thus the latching character of the Josephson switch slows it down significantly in practice.

The quiteron. Faris had set himself the task of finding a transistor-like device suitable for the design of a next generation general-purpose computer capable of processing 5×10^8 instructions per second. He concluded that such a device must be capable of ultrahigh packing density—with dimensions on the order of a micron and power dissipation of only a few microwatts—and switching times on the order of 20 picoseconds. It must also be a three-terminal, inverting, nonlatching device, he concluded, with good input-output isolation, high nonlinearity, clear discrimination between binary states and enough power gain so that the output of one device can activate the next in a sequence of logic circuits.

The result of this search is the quiteron. Whereas the Josephson switch functions by means of a supercurrent of Cooper-paired electrons tunneling through a thin insulating layer or a narrow constriction between two superconductors, the quiteron only involves the tunneling of unpaired electrons across insulating tunnel barriers between superconductors. This is referred to as quasiparticle-injection tunneling because the electron emerges from the tunnel barrier into a mixed electron-hole eigenstate—"a quasiparticle state"—in the single-particle continuum above the superconducting energy gap. One imposes a magnetic field of sufficient strength on the device to kill any Josephson tunneling of Cooper pairs.

The current-voltage curve of such a quasiparticle tunnel junction between superconductors exhibits an extraordi-



The quiteron (a, schematic circuit; b, physical arrangement) is a three-terminal, two-junction sandwich of three superconducting layers separated by two ultrathin insulating barriers. With no quasiparticle injection across the injector junction (input zero), the acceptor junction shunts most of the output power to the external load (output one). With high injected power (input one), the superconducting gap of S_2 goes to zero and the acceptor junction passes much more current, diverting very little to the load (output zero).

narily abrupt discontinuity (PHYSICS TODAY, August 1980, page 19). So long as the voltage across the tunnel barrier is less than twice the superconducting gap Δ ($2e\Delta$ is the energy required to break up a Cooper pair), almost no current will flow. When the bias voltage reaches 2Δ , however, the current sets on abruptly and increases very rapidly as more voltage is applied.

The quiteron configuration is a two-tunnel sandwich of three superconducting films separated by two ultrathin (20 Å) insulating oxide layers. When a bias voltage of more than 2Δ is applied across the first or "injector" junction ($\Delta_1 + \Delta_2$, to be more precise, because the three superconductors 1, 2 and 3 are generally made of different materials), an intense quasiparticle current can be made to flow from the first to the middle superconductor. With a bias across the second or "acceptor" junction kept below $\Delta_2 + \Delta_3$, very little current flows into the third superconductor so long as the middle layer remains superconducting.

Nonequilibrium superconductivity. The quiteron switching trick is to reduce the superconducting gap of the middle layer (about 300 Å thick) very rapidly to zero by nonequilibrium means. The superconducting gap between the energy level of the Cooper pairs and the

allowed quasiparticle continuum is a function of temperature, current and magnetic field. One can reduce the gap to zero and thus render the material normal by raising the temperature, current or magnetic field above their critical values for the particular superconductor. But to do this under conditions that do not depart radically from equilibrium—with quasiparticles, Cooper pairs and lattice phonons all at roughly the same temperature—is a relatively slow process. It is known, however, that one can reduce the superconducting gap to zero much more rapidly (a few tens of picoseconds) by nonequilibrium means—injecting sufficient energy to break up enough Cooper pairs without significantly heating the lattice. The material is then said to be in a nonequilibrium superconducting state, behaving in many respects like a normal metal, but without the high power dissipation a truly normal state would generate.

In the quiteron, the energy required to reduce the superconducting gap of the middle superconductor is supplied in a nonequilibrium manner by the intense injection of quasiparticles across the injector junction when the voltage bias between the first two superconducting layers (the input signal) is raised above $\Delta_1 + \Delta_2$. As the superconducting gap vanishes in the middle layer, the acceptor junction is effectively converted from a superconductor-insulator-superconductor junction to a normal-insulator-superconductor junction. Such an N-I-S junction behaves much more like a normal resistor, with current increasing more or less linearly with voltage. This sort of change in the current-voltage characteristics of an S-I-S junction under quasiparticle injection was predicted by Douglas Scalapino and his coworkers at the University of California, Santa Barbara, who developed a theory of nonequilibrium superconductivity during the 1970s.

Transistor-like behavior. With little quasiparticle injection across the injector junction (input "zero"), therefore, the acceptor junction is an S-I-S barrier, passing very little current because its bias voltage is below $\Delta_2 + \Delta_3$. If a nonlinear load (a second quiteron, for example) is put in parallel with the acceptor junction, almost all the current and power applied across the terminals attached to the second and third superconducting layers will be shunted through the external load (output "one"). If, on the other hand, one injects an intense quasiparticle current through the injector junction (input "one"), the acceptor junction takes on N-I-S character, permitting most of the current applied across the output terminals to flow through it,

with almost no power delivered to the external load (output "zero").

The IBM group has fabricated a number of experimental quiterons with lateral junction dimensions ranging from 2.5 to 7.5 microns, exploiting processes developed for Josephson-junction fabrication. The power gain of the quiteron is given by the ratio of the current densities in the acceptor and injector junctions. Thus it depends only on the tunneling barrier heights and thicknesses, not on their lateral dimensions. Therefore one could presumably reduce the size of the quiteron still further without reducing its gain.

For digital switching in computers one requires clear discrimination of binary states and adequate large-signal power gain so that the output of one quiteron can drive the next in a logic-circuit cascade. The group has shown that with appropriate nonlinear loads the quiteron exhibits inversion, with very sharp threshold values of input current and power above which the output drops abruptly to the zero state—very much like an ordinary transistor. The slope of this sudden drop defines the gain of the device. Thus the group finds current gain factors of 30 to 100 and power gains from 6 to 10 in the large-signal regime of interest for digital applications, with power dissipation levels of 10 to 50 microwatts. Faris expresses confidence that the large-signal characteristics of the quiteron will prove adequate for computer applications. The group has also found comparable gain factors in the small-signal regime appropriate to analog applications.

Faris and his colleagues have demonstrated that the quiteron switching time is at most 300 ps. But this speed determination, he points out, is limited by the room-temperature measuring instruments. He estimates that the true switching speed of these early quiterons is about 50 ps. "These are of course our first experimental devices," he adds. "There is much optimization still to be done." The quiteron has yet to be tested in logic circuits.

In addition to switches, a superconducting computer will also need memory elements. John Clarke (Berkeley) points out that Josephson memory elements have the attractive property of dissipating no power except in transit from one binary state to the other, whereas a quiteron memory would seem to involve continuous power dissipation. One might consider making a hybrid superconducting computer, he suggests, with quiteron switches and Josephson memories.

The physical origin of the quiteron gain can be understood by considering the semiconductor-like energy levels of the two superconducting films adjoining

the acceptor junction. With a bias of less than $\Delta_2 + \Delta_3$ across the barrier, electrons from the filled band below the superconducting gap of the third superconductor (S_3) cannot tunnel into the middle layer (S_2) because the top of the filled band of S_3 lies within the forbidden superconducting gap of S_2 . But as soon as one begins intense injection of quasiparticles across the injector junction into S_2 , its gap begins to shrink, exposing the top of the S_3 filled band to the allowed, unfilled band above the shrinking gap and thus permitting a torrent of current to flow across the acceptor junction.

This scenario illustrates a fundamental difference between quiterons and transistors. In both cases the input signal alters the transport properties of the middle layer (the base in a transistor), but only in the quiteron does the input actually alter the forbidden-gap structure of the material; the semiconductor gap of the transistor base remains fixed, but the superconducting gap in the middle layer of the quiteron is shrunk to zero.

Earlier work. The three-layer, two-junction superconducting configuration exploited by the quiteron is not new. It has been used for some time in experiments investigating the physics of nonequilibrium superconductivity. In 1978, Kenneth Gray, who had been doing such experiments at Argonne, built a "superconducting transistor" of essentially the same configuration as

the quiteron. But the physical mechanism by which it achieves gain is somewhat different. Whereas the quiteron employs intense quasiparticle injection to shrink the S_2 gap to zero by driving it far from equilibrium, Gray's amplification involves a much lower intensity of quasiparticle injection. The middle layer remained close to equilibrium, with very little gap shrinkage.

The acceptor current in Gray's work does not result from the conversion of the acceptor junction to an effective N-I-S barrier. Rather, it achieves current gain by a cyclic process across the acceptor junction in which a single injected quasiparticle initiates the breakup of several Cooper pairs. Although the original device was much slower than the quiteron, Gray believes it could be made significantly faster by using materials with shorter Cooper-pair recombination times. The demonstrated current gain of the original device was limited to the small-signal regime. Gray told us that his device has not yet demonstrated the kind of large-signal power gain and nonlinear switching "that make the quiteron an attractive prospect for computer applications."

—BMS

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Panel on new particle-physics facilities

A new-facilities subpanel of the High-Energy Physics Advisory Panel has been formed at the request of DOE; it is headed by Stanley Wojcicki of Stanford. The subpanel is to consider and make recommendations for scientific requirements and opportunities for a "forefront" US high-energy physics program in the next five to ten years. It is to make specific recommendations for possible new construction for fiscal year 1985. Specifically, the subpanel is asked to include a definite recommendation concerning the proposed Colliding Beam Accelerator at Brookhaven; a formal proposal was to be ready in April. For its recommendations the subpanel is to make cost estimates and to give relative priorities.

The subpanel met in February and is making visits to Fermilab (23-24 April), Brookhaven (10-12 May) and SLAC (20-22 May). High-energy physicists are invited to express their views to the subpanel at a special session during each of the site visits. In addition Wojcicki has asked for written comments from interested particle phy-

sicists.

The week of 5-11 June the subpanel will meet at Woods Hole to conclude its work. The subpanel's report will be reviewed by HEPAP 29-30 June at its meeting in Washington, and HEPAP will then make comments and recommendations to DOE. In July DOE will make its own decisions concerning the FY 1985 budget request.

The subpanel members are: John Adams (CERN), Thomas Appelquist (Yale), Charles Baltay (Columbia), Mary K. Gaillard (University of California, Berkeley), J. David Jackson (Lawrence Berkeley Laboratory), Denis Keefe (LBL), Arthur Kerman (MIT), Lee Pondrom (University of Wisconsin), John Rees (SLAC), Carlo Rubbia (Harvard and CERN), Frank Sciulli (Columbia), Maury Tigner (Cornell), Sam Treiman (Princeton), John Vander Velde (University of Michigan), H. H. Williams (Penn), Bruce Winstein (University of Chicago) and Wojcicki. The executive secretary is Earle C. Fowler (DOE High-Energy Physics). □