Vortexes are creating a stir in the superconductor field

Researchers are developing new types of memories, transformers and logic devices by controlling the magnetic-field penetration of superconductors

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For years physicists have been intrigued by the effects of vortexes—tiny cylinders of normal (nonsuperconducting) metal that pass magnetic flux through superconductors. Superconductors, which have practically no resistance to current at or near absolute zero, are usually a barrier to magnetic flux.

Control of vortexes could mean development of new types of direct-current generators, motors and transformers, computer memories and logic elements. Revolutionary devices analogous to the transistor could spring from this peculiar magnetic excitation.

Vortexes are quantum mechanical in nature, localized in space and can maintain their identity indefinitely. Variations in the applied magnetic field can make vortexes appear and disappear, move, and annihilate each other.

Computer memories that would exploit vortexes in superconducting storage mediums have been under development for several years.[1] Studies indicate potential for a faster, more compact, random-access computer memory that could store up to a billion bits of information, about 100 times the capacity of present memories. Switching would be accomplished by forming pairs of vortexes of different polarities, which can be made to move in prescribed ways by applying current.

Controlling the relocation of vortexes that represent information bits could enable both storage and logic operations to be performed at the same location in a superconducting memory.

A device analogous to a drum memory is another possible application. Bits in the form of vortexes would be written onto a drum with pulses and would travel around the drum's circumference while the drum remained stationary.

A d-c generator that takes advantage of vortex motion has been built. It has no brushes and operates at cryogenic temperatures with an efficiency of about 9%.

Superconductive vortexes behave like charged particles in many respects. For example, while the transport of electrical charges produces a steady magnetic field, the transport of vortexes is analogous to a current of magnetic monopoles and produces a steady electric field. Electric charges accelerate along the electric field lines, while vortexes accelerate along the magnetic field lines (produced by the transport currents). Superconductors seem to be the first known medium in which the similarity between electric and magnetic charges has found a physical embodiment. This similarity could be exploited by engineers to yield devices like the vacuum tube and the transistor, operating by transport of magnetic monopoles instead of electrons.

The mixed state

Besides complete loss of electrical resistance, a basic property of superconductors is their ability to expel magnetic fields from their interior. This phenomenon is known as the Meissner effect.[2] Ordinarily magnetic fields cannot penetrate a superconductor. However, if the field is raised above a

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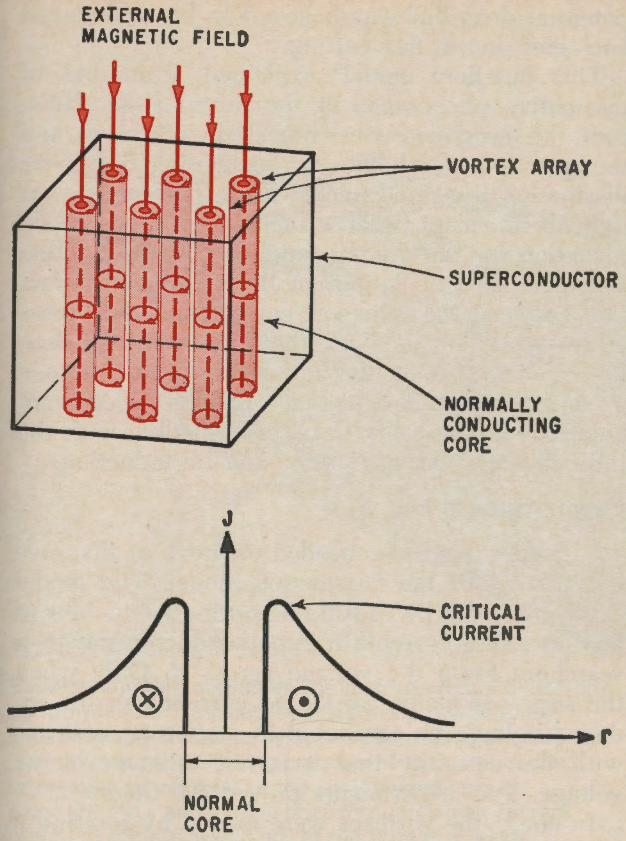
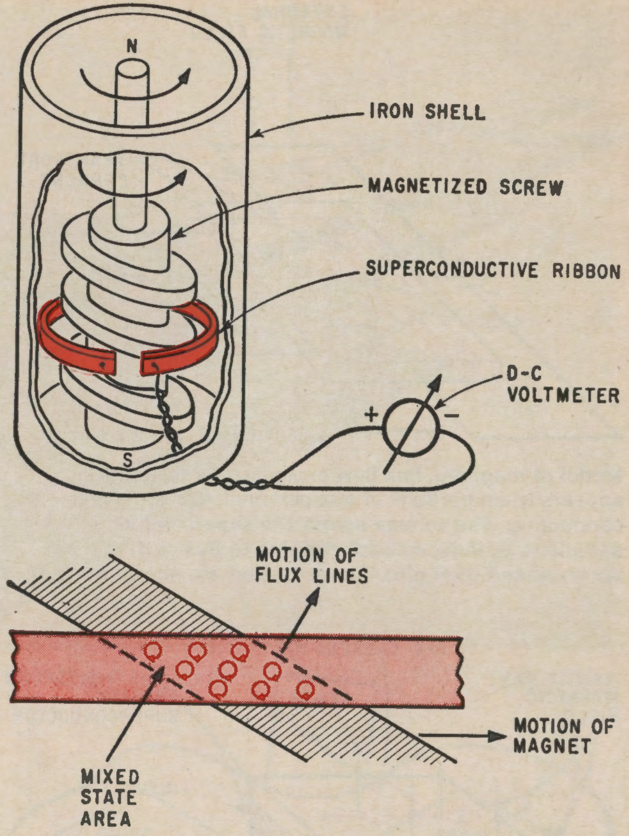


Abrikosov's vortex model, showing partial field penetration through cylindrical volumes, or flux tubes, of normal material, in color, within a superconductor. The structure of an individual vortex, directly above, shows spatial distribution of circulating currents around a normal core whose radius is a few hundred angstroms.



Experimental arrangement which could be used as a generator. Magnetized screw rotates inside coil of superconducting ribbon, in color, producing a d-c voltage across the ribbon as the lines of flux are cut. A magnified view of a portion of superconductive ribbon shows motion of the mixed state area, in color, and motion of the flux lines.

certain level, it will drive the superconductor into the normal state, and immediately penetrate it.

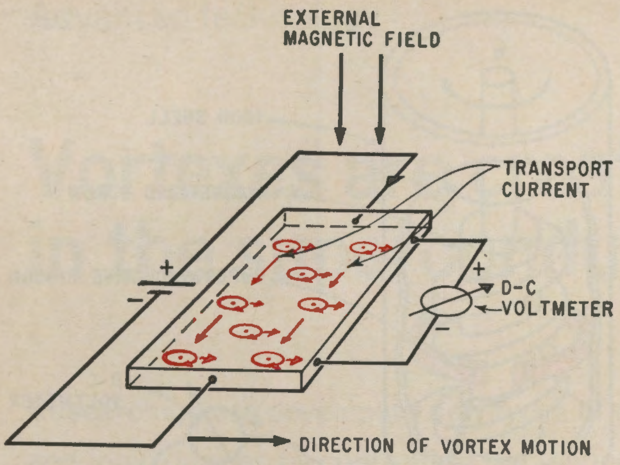
Certain metals, on the other hand, do not exhibit this effect, but are partially penetrated by magnetic fields even while in the superconducting state. At first, partial penetration was attributed to defects and impurities in the metal, but investigation[3] shows that the Meissner effect is incomplete in certain metals and would remain incomplete in a highly pure and defect-free state. These materials were named type II superconductors; the designation type I characterizes superconductors that exhibit a complete Meissner effect.

How magnetic fields partially penetrate superconductors was analyzed by A. A. Abrikosov in 1957.[4] According to his model, shown above, external magnetic fields can penetrate type II superconductors in the form of a periodic array of flux tubes, or vortexes. A vortex's cylindrical core of normally conducting metal has a radius, r, of about a few hundred angstroms. The magnetic flux is sustained in a vortex by persistent currents that circulate around the core, shown above, where J is the density of the superconducting current. Vortexes are also believed to exist in thin films of type I superconductors in perpendicular fields, where the geometrical shape of the film forces a premature field penetration.

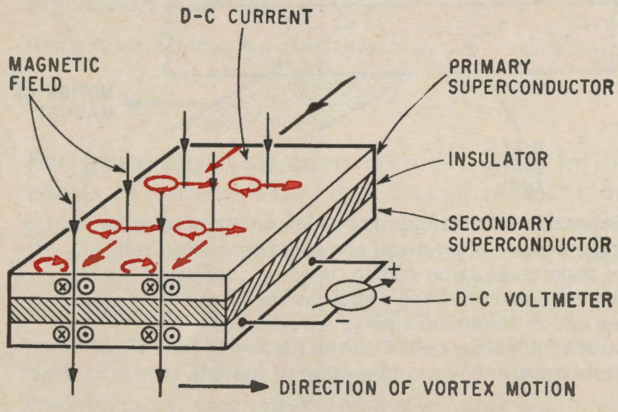
Fact or theory?

Abrikosov's vortex model of the mixed state (partially superconducting and partially resistive) of superconductors has a wealth of experimental verifications. Among the most significant of the experiments are magnetization measurements, neutron diffraction,[5] and experiments on microscopic geometries.[6]

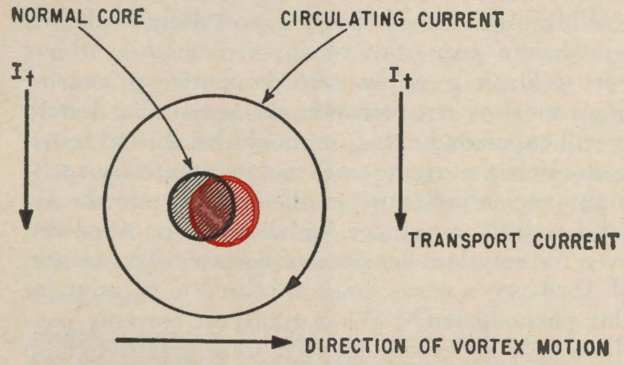
While Abrikosov's theory successfully explained equilibrium properties of superconductors, it has been difficult to apply it to dissipative processes. Since most of a superconductor in the mixed state is still superconducting, it should be able to transport electric currents with no resistance. Surprisingly, superconductors in the mixed state do exhibit a little resistance, or dissipation of power, even for very low densities of vortexes. The motion of Abrikosov's vortex lines appeared to account for this phenomenon.[7,8] When transport currents pass through a superconductor, a force is exerted on the vortexes that causes them to move uniformly at right angles to the current flow, top of page 102. The continuous motion of flux lines cutting the sample should produce an induction type of electromotive force in a direction perpendicular to the vortex motion. So, the voltage appearing across the sample was not considered an ordinary ohmic



Model of magnetic flux flow explains why resistance appears when portions of a superconductor are superconducting. The voltage across the superconductor sample is an induced back emf due to flux cutting. Vortexes and their direction of motion are shown in color.



Direct-current electrical energy can be transferred from the primary to the secondary circuit as in an ordinary transformer. Because the vortexes in the two strips, in color, are magnetically coupled, current-induced motion of vortexes in the primary results in motion of vortexes in the secondary, demonstrated by the appearance of a d-c voltage across its length. Such a transformer could be used to charge superconducting magnets.



Vortex motion can be explained by examining the critical transitions at the core boundary. The vortex position shifts because the transport and circulating currents add at the right of the core, driving more material there into the normal state. Some of the material at the left reverts to the superconducting state. The net effect is motion of the vortex to the right. The shifted position is shown in color.

potential drop but was believed to be an induced back emf due to flux cutting.

This flux-flow model[9] explained a number of dissipative phenomena of the mixed state. However, the basic ideas were repeatedly criticized, and the question of whether vortex motion did cause dissipation remained unanswered. The model was difficult to accept because there is no apparent explanation for the driving force (called the Lorentz force). Exact calculations of the magnetic interaction between the transport current and the vortex currents do not yield the force given by the flux-flow model. Second, the induction of a d-c voltage in a stationary circuit that encloses a constant magnetic flux appears to be incompatible with the fundamental laws of electromagnetic induction.

Experimental proof

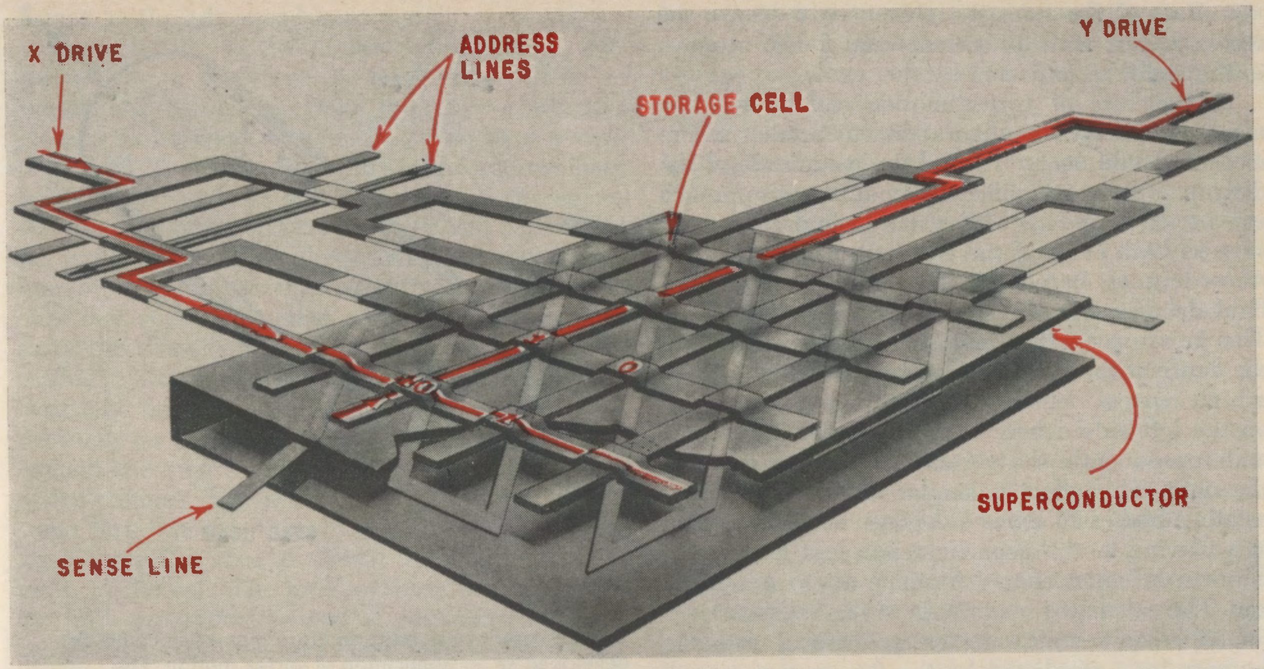
An experiment was needed to prove or disprove the validity of the flux-motion model. The model can be tested[10] by causing a continuous motion of flux lines in a currentless superconductor and then searching for a d-c voltage across it. Only when the superconductor carries no current can the induced voltage be attributed to motion of vortexes with the certainty that it is not ordinary ohmic voltage. Two experiments proved the theory.

In one,[11] the vortexes were moved by rotating a magnet near a superconductive ribbon as on page 101. A permanently magnetized screw is coaxially inserted in a coil made of 150 turns of the ribbon (only one turn is shown in the figure). A cylindrical iron shell provides an easy return path for the magnetic lines, and forces the magnetic field at the ribbon to assume a radial direction. This arrangement is actually a superconductive version of a d-c generator.

At regions of high field intensity, the magnetic field penetrates the ribbon and forms a mixed-state area aligned with the spiral threads, lower right figure, page 101. As the screw rotates, the mixed-state area tends to stay aligned with the threads, since this constitutes the lowest energy state for the vortexes. The vortexes follow the screw motion because a force is exerted on them in the direction of the energy gradient. The vortex motion has a component transverse to the length of the ribbon, and so, a continuous motion of flux lines is established across the ribbon.

A unique feature of the spiral magnetic arrangement is that vortexes are forced to move while the mixed-state area extends across the entire width of the strip. Also, there is no change in the total flux linking the coil, since the ribbon is wrapped symmetrically around the screw.

These are also the conditions in the flux-flow model used to measure resistance, shown at the top. According to this model, there should be a d-c voltage across the ribbon. Rotation speeds ranging from one to five revolutions per second were used, and d-c voltages roughly proportional to speed and as high as 100 microvolts were observed. The polarity of the voltage agreed with that predicted



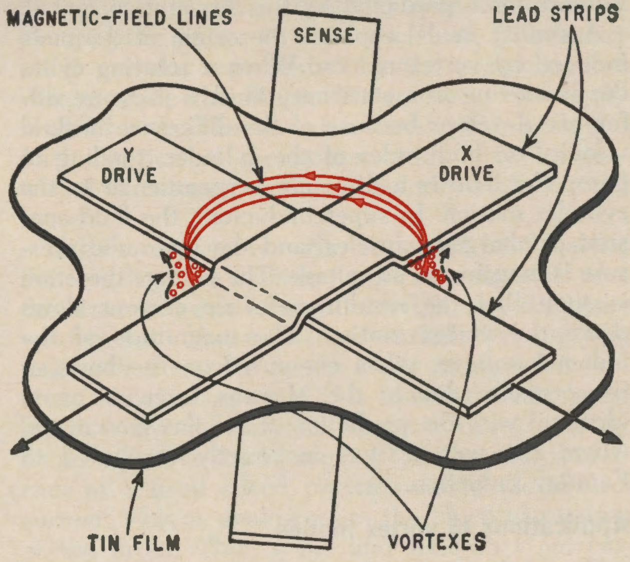
Superconducting memories could store up to a billion bits of information. This model consists of a continuous sheet of superconductor with two perpendicular grids of lead drive lines. Switching consists of the annihilation or creation of vortexes at the x-y intersections. In color are the x and y drive lines through which current is sent to initiate switching. At the right is a single memory cell showing vortexes, in color, formed by the magnetic field at the drive lines' intersection.

on the basis of the flux-flow equations and could be reversed by reversing the direction of rotation. As the temperature increased to the point where the vortex structure disappeared, the induced voltage also vanished.

According to the flux-flow model, if current were passed through the ribbon, a force would be exerted on the vortex lines which could cause them to move and drag the magnet into continuous rotation. This would correspond to operating the generator in the top right figure, page 101, as a d-c motor. With proper modification of the design, motor action can be demonstrated.

Another experiment[12,13] combines the motor and generator actions to form a d-c transformer. Two superimposed superconducting strips, separated by a thin insulating layer, are placed in a perpendicular magnetic field—the middle figure on page 102. When d-c current is applied to the primary, a d-c voltage is induced in the secondary. The vortexes in the secondary strip are magnetically coupled to those in the primary, so current-induced motion of vortexes in the primary exerts a force on the vortexes in the secondary. When this dragging force overcomes the pinning forces due to defects, the vortexes continuously move in the currentless secondary, and a d-c voltage is induced across the length of the secondary.

The two experiments show that the vortexes move, but not why. Nor do they explain what mechanism is responsible for generating a d-c emf along the superconductor when the vortexes move.



That a vortex cannot remain stationary in the presence of transport currents is demonstrated in the graph at the top of page 101. The boundary of the normal core remains stationary when the current density at the boundary does not exceed the critical current density of the superconductor. Therefore, the current density at the core boundary is just below its critical value.

However, if a transport current I_t is superimposed on the circulating vortex current, bottom of page 102, the vortex will move. The two current components will add on the right side of the vortex and oppose each other on the left side. The sum of the current I_t and the circulating current is sufficient to drive a small area at the right of the core into the normal state. At the same time, the current density at the left edge of the core is reduced below the critical value, and therefore drives a small portion at the left edge of the core from its normal state to its superconducting state. The net effect of the transport current is to cause the whole vortex, with its currents and fields, to move to the right, as indicated by the arrow.

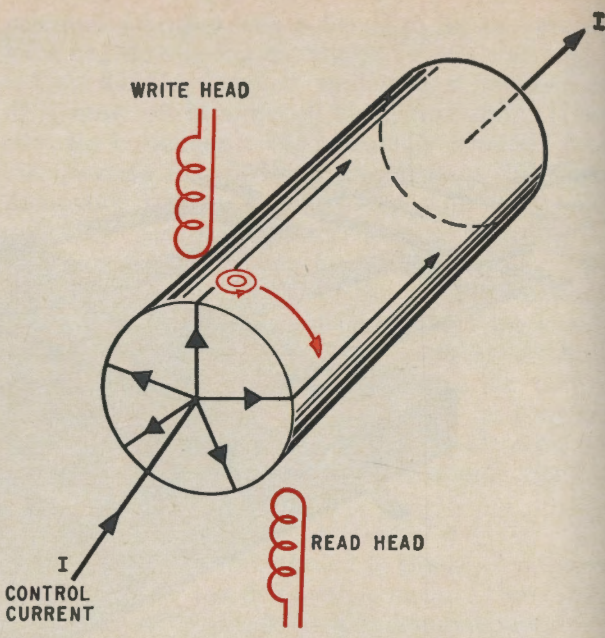
This picture of vortex motion can be used in more complicated configurations to predict where motion should occur. To find the magnitude of the driving force a simplified hydrodynamic approach can be used, and the difference in hydraulic pressure on both sides of the vortex can be calculated. According to Bernoulli's law, the pressure in a fluid decreases as the square of the fluid velocity. The pressure on the right side of the vortex (see the figure at the bottom of page 102), which carries a high current density, is lower than the pressure on the left side, where the current density is low, and consequently the vortex will tend to move to the right. This effect is similar to the tendency of rotating bodies to move sideways when immersed in a moving fluid,[14] a phenomenon first noted by a German scientist named Magnus about a century ago. The calculated magnitude of the Magnus force for superconducting vortexes is identical with the Lorentz force predicted by the flux-motion model.

A similar model explains the origin of d-c emfs induced by vortex motion. When a rotating cylinder is moving in a stationary fluid, a pressure difference develops because of the difference in fluid velocity on both sides of the cylinder, tending to pump the fluid in a direction perpendicular to the cylinder motion. In superconductors, the fluid consists of charged particles, and the hydraulic pressure is manifested as voltage. The voltage direction is such that the resulting electric current slows down the vortex motion. The magnitude of the induced voltage, when computed on the basis of the pressure due to the Magnus force, is again identical with the prediction of the flux-flow model where the voltage was incorrectly attributed to Faraday induction.

Applications of vortex motion

The ability to produce and detect a controlled motion of vortex lines in superconductors has great potential applications to energy conversion and computer devices. The arrangement at the top of page 101 could be used as a high-current, d-c generator and motor. Its current-carrying capacity is determined by the critical current of the superconductor used. Excess load current tends to slow down the motion of the vortexes and thus reduces the output voltage. Its equivalent internal resistance is just the flow resistance of the mixed state. Initial calculations show that such a generator would run with an efficiency of about 16%. Taking into account the energy required to refrigerate the system, the efficiency reduces to only 9%. However, it would require no brushes or commutators.

An immediate use of these generators would be charging high-current superconducting magnets, where the heat-conducting, high-current leads could be replaced by a single rotating shaft. A greater economy could be achieved when the moving magnetic field shown in the lower figure at the top of page 101 is produced by a stationary circuit carrying alternating currents in a three-phase arrangement. An alternate way of avoiding the need for rotating parts is to use the d-c transformer, middle of page 102, to step up a d-c current for charging a superconducting magnet. Current step-up is achieved by constructing many pairs of the type shown in the figure, with all the primaries connected in series and all the secondaries in parallel.



Shift register or nonrotating drum memories could be developed as an application of vortex motion. The control current causes the vortexes, in color, to rotate continuously around the cylindrical surface of the drum, while the drum remains stationary.

The use of these devices in other high-power, energy conversion applications is still limited. Cost and size of the refrigerating system still overshadows the merits of their simplicity. However, in naturally cold environments like those encountered in space missions, large-scale superconducting energy-conversion devices might be used to advantage.

Superconductive memories

In its simplest form, a continuous-sheet superconductive memory consists of the arrangement in the figure on page 103 with the structure of a single memory cell below it.

There are two orthogonal grids of lead drive lines above a thin superconductive tin sheet. The arrangement is similar to a bit-organized, coincident-current core memory with destructive readout. The selection of a single element in this array is made by sending current pulses in one of the x drive lines and one of the y drive lines simultaneously. The current level of one drive line is not sufficient to cause flux switching. When the combined field of the x and y pulses is higher than the critical field, it causes switching at the appropriate x-y intersection. A zigzag sense line links all the memory cells, and the appearance of a sense signal at its terminals indicates that switching has occurred at the addressed location.

The selection of the appropriate x line is performed by a tree-type network of cryotrons—switches that change from the superconductive state to the resistive state in the presence of a magnetic field. The currents flowing in the address lines provide the magnetic field that controls the superconductive state of the cryotrons, which determines the path of the current flow. Each binary combination of the address line currents corresponds to only one superconductive path that is chosen to carry the drive current to the selected memory location.

Recent experiments on the magnetic flux distribution on the surface of a superconducting film explain the switching, storage and readout action of the memory. When the drive currents terminate, some flux remains trapped along the diagonal of the intersection area as shown in color in the diagram of the cell. The building blocks of the memory cell apparently consist of microscopic superconductive vortexes (or bundles of vortexes). Switching occurs when the magnetic field beneath the drive lines' intersection is sufficient to cause the formation of pairs of equal and opposite vortexes. The current flowing at the memory plane drives the vortexes along the diagonal toward the opposite corners of the intersection area. When the driving currents terminate, the two vortex groups are attracted to each other but are prevented from moving together by pinning forces. Pinning forces arise from defects in the film and from the diamagnetic nature of the drive lines themselves. Thus, the vortexes are stored in the film.

When the memory cell is interrogated, the currents are applied to the drive lines in opposite directions. A driving force is exerted on the stored vortexes which enhances the mutual attraction between the two groups. When the combined attraction force exceeds the pinning force, vortexes from the two opposite groups begin to enter the intersection area and approach each other at high speeds. Since the polarity of the magnetic field (and of the angular momentum) is opposite in the two vortex groups, when vortexes meet at the center of the intersection area they annihilate each other until all the stored flux vanishes. During this process a voltage pulse is induced in the sense line. The polarity of the pulse depends on the relative direction of the stored flux.

From this model one can see that all the important characteristics of the memory cell such as critical currents, switching speeds, disturbs (the noise caused by a current passing in a drive, insufficient to cause switching) and sense-signal amplitude depend on the dynamics of moving vortexes in superconducting films.[15] Better understanding and control of such films are essential for better superconductive memories.

Storage and logic

It is also apparent that information bits could be moved from one location to another in a controlled way in superconducting films. Thus, both storage and logic operations could be performed at the same location.

The next example demonstrates some of the hidden possibilities of this form of vortex dynamics[16]. In the structure on page 104, a superconductive sheet forms the surface of a cylinder. Vortexes may be excited on the cylindrical surface by applying current to the write head and may be detected by voltages induced in the read head.

If a vortex is established near the write head and a direct control current I is applied to the surface in a direction parallel to the axis of the cylinder, the vortex will continuously circulate around the cylinder. When the vortex passes under the read head, its magnetic lines of flux induce a read voltage in the read head. The output is an alternating current; its frequency is proportional to the amplitude of the control current I, since that determines the circulation rate.

The device can operate as a shift register. Binary bits may be written along the cylindrical surface by applying pulses to the write head. The binary bit 1 may be represented by the presence of a vortex, while the binary bit zero may be represented by the absence of a vortex. The back and forth shifting of the vortex string may be controlled by the magnitude and polarity of the control current.

If there are many write and read heads along the length of the cylinder, a device analogous to a drum memory can be constructed. Binary digits are written onto the cylindrical surface by applying pulses to the write heads, while the control current I remains constant. This causes the bits being written onto the stationary drum to circulate along their respective tracks around the drum circumference at a fixed speed proportional to the control current. This is analogous to the physical rotation of the drum. This is the first time that current-controlled motion of storage patterns in a stationary medium has been achieved.

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